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Geotechnics and Seismic Considerations Manual

with a risk management approach for road infrastructure in
Central America

Topic: Slopes

PRESENTATION

In 1997, the Sectorial Council of Transport Ministers of Central America or COMITRAN identified the need to formulate technical regulations to enhance infrastructure resiliency in the face of natural phenomena caused by climate change. This is to ensure and optimize the logistics of people and goods and safeguard the safety of users and the large investments in the construction and maintenance of road infrastructure which is key to the social and economic development of Central America.

In this regard, priority has been given within the strategic areas addressed by COMITRAN to reduce the vulnerability of its infrastructure with the inclusion of climate change adaptation and risk management. It is important to note that, among the natural phenomena most affecting the region are hydrometeorological, seismic and volcanic. For this reason, COMITRAN promotes structural (infrastructure) and non-structural (technical regulations) measures, to ensure the connectivity and development of the region.

In 2016, joint work was initiated by the Japan International Cooperation Agency (JICA), COMITRAN and SIECA with the main objective of developing regulations to link various aspects of risk in the design and planning of road projects and contributing to enhance the resilience of infrastructure before the natural phenomena appear in the Central American region.

In this context, the Department of Adaptation to Climate Change and Strategic Risk Management (DACGER) of the Ministry of Public Works of El Salvador and GENSAI Project Phase II together with SIECA developed the required regulation upon the instruction of COMITRAN and involved geotechnical elements and seismic variables in the design and planning of Central American's road infrastructure.

This Manual was prepared jointly by a Central American consultant, experts from the Ministries of Transport in the region and with the support of Japanese specialists with cooperation funds granted by JICA office in El Salvador, to ensure the quality of this regional instrument and countries taking ownership of it within their government and private offices.

With the aim of supporting the reduction in the vulnerability of road infrastructure in the region, it is a pleasure to present the "Geotechnics and Seismic Considerations Manual with a risk management approach for road infrastructure in Central America. Topic: slopes.", is a technical document that countries in the region now have which serves as a conceptual guide with geotechnical methodologies consistent with the seismic variable, to be used in the planning stage and design of roads and slopes in the Central American road network.



Melvin Redondo
Secretario General

Geotechnics and Seismic Considerations Manual with a Risk Management Approach for Road Infraestructura in Central America

Topic: Slopes

This document was executed with the technical and financial cooperation of the Japan International Cooperation Agency, JICA, through GENSAI Project Phase II, in support of DACGER and SIECA.

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ABBREVIATIONS

AASHTO:	American Association of State Highway and Transportation Officials
AENOR:	Spanish Association for Standardization and Certification
AGIES:	Guatemalan Association of Structural and Seismic Engineering
ASTM:	ASTM International
ASIA:	Salvadoran Association of Engineers and Architects.
BCR:	Cost-benefit Ratio
CEPAL:	Economic Commission for Latin America and the Caribbean.
CEPRENAC:	Center of Coordination for the Prevention of Disasters in Central America and Republic of Dominica
COMITRAN:	Sectoral Council of Central American Transport Ministers
CPTU:	Static Penetration Test (CPT, Cone Penetration Test) with Interstitial Pressure Measurement (CPTU)
DACGER:	Department of Adaptation to Climate Change and Strategic Risk Management
DIN:	Deutsches Institut für Normung. German Standards Institute.
GTR:	Regional Technical Group
IDECA:	Spatial Data Infrastructure for the Capital District
IGN:	National Geographic Institute
JICA:	Japan International Cooperation Agency
NCDC:	National Center for Climatic Data, United States Department of Commerce
NHC:	National Hurricane Center of the United States
NSE:	Structural Safety Standards
MOP:	Ministry of Public Works
MOPTVDU:	Ministry of Public Works, Transportation, Housing and Urban Development
NPV:	Net Present Value
PGA:	Peak Ground Acceleration
RMR:	Rock Mass Rating. Geo-mechanical classification index of rock masses according to Bieniaswki.
RQD:	Rock Quality Designation.
SDP:	Safety Degree of probability
SEGOB:	Secretary of Government
SGG:	Geological Society of Guatemala
SMR:	Slope Mass Rating. Slope method proposed by Romana from the RMR.
SIECA:	Secretariat of Central American for Economic Integration.

USAID: United States Agency for International Development.
USGS: United States Geological Survey
USD: United States Dollar



CHAPTER 1

GENERAL ASPECTS

1.1 General Aspects

Road infrastructure constitutes an essential basis for the performance of national and regional economies, as it affects logistics and the flow of passengers. Roads generate various significant economic and social benefits.

The economic benefits generated by roads include providing producers access to consumers and giving consumers the opportunity to buy a higher quantity and quality product, thus encouraging the growth of the production sector. Socially, road infrastructure provides connectivity to markets, schools, hospitals and emergency care, leisure locations, and other conveniences.

During catastrophic disasters such as earthquakes, tsunamis or storms, roads have functions as evacuations routes and for emergency logistics. In the worst scenario, such as extensive damages along the Pacific coast by the tsunami, inland road networks are key for resilient recovery. The viewpoints on establishing redundant road network against natural disasters are important as well.

As stated above, construction of a safe and secure road network is required against geohazards, which are “events caused by geological, geomorphological, and climatic conditions or processes which represent serious threats to human lives, property, and the natural and built environment” (Solheim et al. 2005 “International Centre for Geohazards (ICG): Assessment, Prevention, and Mitigation of Geohazards” Norwegian Journal of Geology 85: 45–62). They cover almost all hazards affecting road infrastructure, such as slope slides, slope collapses, earth flows, debris flows, floods, erosion, and seismic motions. Most geohazards are linked to climate activity such as rainfall. In Central America, recent climatic changes have increased the intensity of rainfall and wind rate of storms, increasing geohazard events such as slope collapse/slide, debris or earth flows, and floods. Through their effects on the road system, geohazards damage infrastructure, threaten lives and livelihoods and cause secondary impacts such as disrupting traffic and water and energy supply services.

Road geohazard damage occurs non-seismic events such as mainly storm events, and from seismic events.

Non-seismic events have a high probability of occurrence (even less than 1.1 - 10-year return period storm event) and small damage levels (mostly less than one-lane width road closure or less than a day of inundation). Some of the deep slope slides and road subsidence/sinkholes occur during the annual peak of groundwater level after the raining season from December to January or some-days or months after a heavy rainfall event. Rockfalls or some slope collapses sometimes occur without any trigger of rainfall, but just through slope loosening or weathering.

Seismic events have a low probability (10-500 years or more return period of PGA: peak ground acceleration), but with most substantial damage levels on roads infrastructure, full-width road closure due to deep slope-side, bridge collapse, and continues damage on coastal roads due to Tsunamis.

As shown in Table 1.1, from 2009 to 2011, intense storm events were hitting Central America. It seemed to have calmed after 2011. Considering the historical ranking of Atlantic Hurricane regarding pressure, Maria in 2017 (which did not make landfall or cause damage in Central America) and Michael in 2018 were in the top eleven rankings. Potential of intense storm events are high as of 2 years ago to the present (HURADAT¹).

Storms that had hit Central America are divided into those occurring in the Atlantic Ocean and those in the Pacific Ocean. The case ratio of a storm originating from the Pacific Ocean in the last 20 years (1999-2018) was around 40%. Storms from the Pacific Ocean, even those that did not develop into hurricanes (defined as more than 119km/hour maximum wind rate), are characteristically of long-term rainfall with big rainfall amount for an event, due to the slow movement of the storm center, causing flow-type geohazard such as flood or debris flow, and slope collapse/slides.

The hurricanes from the Atlantic Ocean make landfall at the northern latitude of 14 degrees or more (Nicaragua, Honduras, Guatemala, Belies, or Mexico) in the Caribbean Sea. Its occurrence is from late September to early November (excluding Alex on 25 June 25- 2 July 2010).

Tropical Storm/Depression from the Pacific Ocean causes landfalls at north latitude of 13 degrees or more (Honduras, El Salvador, Guatemala, and Mexico). They occur from late May to early July, and late September to early November.

¹ HURADAT: Atlantic hurricane best track (National Hurricane Center; Hurricane Research Division, USA)

Table 1.1 Summary of Main Storm Events in Central America

A period from formation to dissipation	Storm Event/Origin	Summary of Damages
14-24 Sept. 1974	Hurricane Fifi / Atlantic Ocean	Passed along the northern coast of Honduras, made landfall on the southern part of Belize and crossed the central part of Guatemala from west to east (NHC). Most of the damages occurred in Honduras, where there were between 8,000 - 10,000 fatalities (NCDC 2013).
September 18 - September 30, 1982	Hurricane Paul /1982/ Pacific Ocean	Made Landfall at the El Salvador/ Guatemala Border in a north-northeast direction but suddenly veered to the east and returned to the Pacific Ocean again (NHC). Five days of rainfall caused severe flooding and slope collapse/slide. Throughout Central America, at least 1,432 people were killed, with most of the fatalities occurring in El Salvador and Guatemala (NHC).
22 Oct. – 9 Nov. 1998	Hurricane Mitch /Atlantic Ocean	Made landfall on the northern coast of Honduras and passed through the Pacific coastal areas of El Salvador and Guatemala (NHC). There were over 11,000 fatalities in Central America, with over 7,000 in Honduras alone due to catastrophic flooding (NCDC 2013). Damage on Road Infrastructure: Costa Rica (CEPAL 2013) Total losses: USD 24 million. Road damages: over 1,300 km of roads Bridge damages: more than 126 bridges Culvert damages: more than 1,000 culverts El Salvador (CEPAL 2013) Total losses: USD 850 million Damaged paved roads: 1,308 km Damaged unpaved roads: 2,665 km Bridge collapses: 2 Nicaragua (CEPAL 2013) Total losses: USD 148 million Damaged paved roads: 1,104 km Bridge collapses: 22 Bridges with structural damage: 49 Bridges with damage in its ramparts access: 26 Honduras (CEPAL 2013) Total losses: USD 525 million for damages on road infrastructure both on direct road infrastructure and indirectly on parked automobiles.
17-21 May 2005	Hurricane Adrian/Pacific Ocean	Made landfall along the Gulf in Fonseca in Honduras, moved in the northwest direction from the Pacific Ocean before dissipating several hours later (NHC). Damage on road Infrastructure: El Salvador (Government of El Salvador) Total losses: USD 12 million for road infrastructure.

A period from formation to dissipation	Storm Event/Origin	Summary of Damages
		Numerous road damages occurred through slope fall/ collapse/slide, flash floods, and fallen trees. Honduras (Government of Honduras) Only minor road flooding was reported.
1-5 Oct. 2005	Hurricane Stan/ Atlantic Ocean	Made landfall in the east coast of Mexico's Yucatan Peninsula from the Caribbean Sea in a NEE direction, traversing the peninsula to the Gulf of Mexico, and made landfall again in an SW direction at the northwest base of the Yucatan Peninsula, and dissipated in the Mexican Plateau (NHC). Fatalities occurred in: Costa Rica - 1, El Salvador - 72, Guatemala - 1,513, and Honduras - 6. Total losses were: Costa Rica – USD 20 million, El Salvador USD 356 million, Guatemala USD 988 million, and Honduras – USD 100 million (per government). Damage on Road Infrastructure: El Salvador (Government of El Salvador) Damaged National Highways: 4,680 km Bridge collapses: 2 Locations of road closures: 12, with one at CA1 near San Salvador.
4-10 Nov. 2009	Hurricane Ida/ Atlantic Ocean	Made landfall northeast coast of Nicaragua on the Caribbean Sea, turned north and exited to the Caribbean Sea on the northeast coast of Honduras (NHC). The damage was the effect of Tropical Depression E96 which had originated from the Pacific Ocean. Fatalities were in El Salvador with 199. Total losses were: Costa Rica - USD20 million, El Salvador - USD244 million, Nicaragua - USD2 million (per government). <u>El Salvador (Government of El Salvador)</u> Bridge damages: 55 Locations of road closures:132
29 May – 1 Jun 2010	Tropical Storm Agatha/Pacific Ocean	Made landfall near the Guatemala -Mexico border on the Pacific coast in a north-east direction and disappeared in Mexico at the base of the Yucatan Peninsula (NHC). Fatalities occurred in: El Salvador - 13, Guatemala - 174, Honduras – 18, and Nicaragua - 1. Total losses were: El Salvador - USD112 million, Guatemala - USD982 million, and Honduras - USD19 million. El Salvador, Guatemala, and Honduras declared states of Emergency in each country. Damage on Road Infrastructure: <u>El Salvador (Government of El Salvador)</u> Locations of road damages: 53 Bridge collapses: 8 Bridge damages: 45

A period from formation to dissipation	Storm Event/Origin	Summary of Damages
		<u>Guatemala (Government of Guatemala)</u> Locations of road damages: 42 A deep sinkhole occurred at a street in Guatemala City with 15 fatalities.
25 Jun – 2 Jul 2010	Hurricane Alex /Atlantic Ocean	Made landfall in Belize and crossed in a west-northwest direction to the Mexico/Guatemala border in the Yucatan Peninsula and exited to the Gulf of Mexico (NHC). Fatalities occurred in: El Salvador - 6, Guatemala - 2, and Nicaragua - 6. Total losses in USD was USD 21 million in El Salvador. Damage on road Infrastructure: <u>El Salvador (Government of El Salvador)</u> Locations of road damages: 12 Bridge collapses:2 Bridge damages:5 <u>Guatemala (Government of Guatemala)</u> Location of road damages: 81
23-26 Sept. 2010	Tropical Storm Mathur /Atlantic Ocean	Made landfall in the northern coast of Honduras in a west-northwest direction, passed to the Caribbean Sea and made landfall again at the southern part of Belize. It crossed the northern part of Guatemala in a west-northwest direction and passed Mexico before disappearing. (NHC). Fatalities occurred in El Salvador – 3. Total losses in El Salvador was USD27 million (Government of El Salvador). Damage on Road Infrastructure: <u>El Salvador (Government of El Salvador)</u> Locations of road damages:12 bridge collapse: 1 bridge damage:1
12 Oct. 2011	Tropical Depression 12E /Pacific Ocean	Declared as a tropical depression only on 12 October, but the area of weather disturbance formed on 6 October and affected Central America until late 13 October. Made landfall in the Guatemala/Mexico border along the Pacific Ocean from south to north and dissipated in the West Sierra Madre Mountain Range (NHC). Fatalities occurred in: El Salvador - 35, Honduras - 9, Nicaragua – 5. Damage in El Salvador was USD243 million (each government) Damage on Road Infrastructure: <u>El Salvador (Government of El Salvador)</u> Damages on roads: 41 Bridge collapses:8 Bridge damages:41 The total loss in road infrastructure was USD205 million, out of which USD172 million were for roads and USD33 million for bridges. <u>Nicaragua (Government of Nicaragua)</u>

A period from formation to dissipation	Storm Event/Origin	Summary of Damages
		Bridge collapses:6
20-26 Nov. 2016	Hurricane Otto/Atlantic Ocean cross over to the Pacific Ocean	Made landfall in southeastern Nicaragua at approximate 19km of the Nicaragua-Costa Rica border and passing the border (historical first Hurricane hit Cost Rica). The hurricane exited on the Eastern Pacific near the Gulf of Papagayo, Puerto Sandino Nicaragua (NHC). <u>Nicaragua (Government of Nicaragua)</u> Fatalities 4, missing person 5 <u>Costa Rica (Government of Costa Rica)</u> Fatalities 10, total losses - USD192 million
4-9 Oct. 2017	Hurricane Nate/Atlantic Ocean	Made landfall in northeastern Nicaragua, moved northeast into Honduras and went out to the Caribbean Sea at the southeast of Honduras, and passed Yucatan Channel, Central Gulf of Mexico, and then landfall into USA (NHC). Fatalities (missing persons) occurred in: Costa Rica-14, Guatemala-5 (3), El Salvador - 1, Honduras - 3(3), and Nicaragua-16(1), Panama-7 (each government). Road in Costa Rica (Government of Costa Rica) 117 road locations were affected, out of which 40 were not passable.
7-16 Oct. 2018	Hurricane Michael/Atlantic Ocean	Made landfall northwestward on the northeastern coast of Nicaragua, exited to the Caribbean Sea from the northeast coast of Honduras, turned northward, passed the Yucatan Strait and made landfall in the USA (NHC). Fatalities occurred in: El Salvador - 3, Honduras - 8, and Nicaragua - 4 (each government)

Source: CEPAL: Economic Commission for Latin America and Caribbean, CEPAL 2013: Assessment of the Damage Caused by Hurricane Mitch, NCDC: National Climatic Data Center, US Department of Commerce, NCDC 2013: The Dead List Atlantic Hurricane Since 1780, NHC: National Hurricane Center of the United States, NHC1995: National Hurricane Center of the United States.

Table1.2 shows the main seismic events (magnitude of more than 7.0 or fatalities 100 or more from 1968-2018 (50 years).

"The area along the Pacific Ocean is within the orogenic zone of the Pacific Rim with seismic and volcanic activities. Earthquakes in Central America can be classified according to its hypocenter and is discussed below. Due to the attenuation of the distance from the hypocenter, collapse of bridges is a rare case, but due to the fragile volcanic geology, the sliding of slopes with deep fault is induced.

A well-known example is the landslide in Las Colinas in the city of Santa Tecla which was induced by the El Salvador earthquake of January 2001. The landslide was generated by the paleosol (very degraded soil of volcanic origin) which was extremely weakened by its saturated condition and covered by a young, permeable and vitreous pyroclastic flow that triggered a deep and deadly landslide."

Type-S: Subduction zone earthquake in the Pacific Ocean (5 examples))

In the Pacific Ocean, seismic activity origin is an ocean trench earthquake with subduction of the boundary. Five (5) examples have epicenter ranging from 16 – 72 km offshore in the Pacific Ocean with the depth of the hypocenter ranging from 24 – 82 km.

Type-S_CO/PA: The boundary of the Cocos/Panama plates has no example.

Type-S_CO/CA: The boundary of the Cocos/Caribbean plates has four examples in El Salvador and Nicaragua. The January 2001 El Salvador earthquake caused the Las Colinas landslide, which had a head scarp of 100m width with moving soil distance of 750 m, Santa Tecla had peak ground acceleration (PGA) of 468 gals, and Boulevard Sur road in Santa Tecla had full-width closure of 800m length. The 1992 Nicaragua earthquake caused a tsunami reaching heights of up to 9.9 meters about 1000m from the normal coastline at Masachapa.

Type-S_CO/NA: The boundary of the Cocos/North American plates has one example, the 2012 Guatemala earthquake, which caused serious damage on the Pan-American Highway.

Type-OTF: Ocean transforms fault zone earthquake in the Caribbean Sea (two examples). Seismic origin in the Caribbean Sea was in the boundary zone of the Caribbean plate and North American plates, which was the Swan Islands Transform Fault in the Cayman Trench. There are two examples: the 2009 Honduras Earthquake and the 2018 Swan Islands Earthquake, both of which had the depth of the hypocenter at 10 km, affecting mostly Honduras. Both cases had tsunami warnings issued, but there was no observation of high tide.

Type-I: Inland earthquake (6 examples). Inland earthquakes had occurred in the plate boundary zones of the Caribbean/Panama plates in Costa Rica (2 examples) and Caribbean/North American plates in Guatemala (1 example); inland earthquakes in the crust of the Caribbean Plate in El Salvador (2 examples) and Nicaragua (1 example). The depths of the hypocenters were mostly 5 – 10 km, excluding the 2012 Costa Rica earthquake which had a depth of 40.8 km, which was possibly the subduction zone earthquake in the Pacific Ocean even if it was inland of the Nicoya Peninsula and on the boundary zone of the Caribbean/Panama plates. These three

examples were the deadliest earthquakes in 50 years from 1968-2018 because these were shallow and occurred directly underneath a densely inhabited district.

Type-I_CA/PA: Inland earthquake (Continental/oceanic convergent boundary of Caribbean/ Panama plates) has two examples in Costa Rica and affecting Panama.

Type-I_CA/NA: Inland earthquake (continental rift boundary of the Caribbean/North American plates) along the active Polochic-Motagua Fault System has one example in the 1976 Guatemala earthquake which was the deadliest earthquake with around 23,000 fatalities.

Type-I_CRCA: Inland earthquake (crust on Caribbean Plate) occurred inland in the Pacific Ocean side and had three examples. The 1972 Nicaragua earthquake was the second deadliest earthquake with between 4,000 - 11,000 fatalities. The 1986 San Salvador earthquake was the third deadliest with between 1,000 - 1,500 fatalities.

Table 1.2 Main Seismic Events

The magnitude of 7.0 or more, or fatalities of 100 or more in the last 50 years from 1969

Country	Name of event/ date of the Seismic Event/Epicenter	Features	Summary of Damages
Costa Rica	1991 Limón earthquake (or Bocas del Toro earthquake in Panama) / 22 Apr 1991/ 9.685°N 83.073°W Pandora, Valle La Estrella, Limon Province Costa Rica	Type-I_CA/PA, M7.7, 10 km depth	No. of fatalities: 127 (48 in Costa Rica, 79 in Panama's Bocas del Toro Province) Roads and bridges between the port town of Puerto Limón and the border town of Sixaola were destroyed. The earthquake caused a circa 3-meter tall tsunami
	2012 Costa Rica earthquake/ 5 Sept 2012/ 9.996°N 85.318°W, in the Nicoya Peninsula, 11km east of Nicoya, 24 km inland from the Pacific Ocean	Type-I_CA/PA M7.6, 15.4 km depth (Government of Costa Rica)	No. of fatalities: 2
El Salvador	1982 El Salvador earthquake/ 19 Jun 1982/13.31°N 89.34°W, Pacific Ocean 17 km offshore	Type-S_CO / CA, 6.0 (International Seismological Centre) M7.0, 82 km depth	No. of fatalities: 8 Total loss: US\$5 million
	1986 San Salvador earthquake/ 10 Oct 1986/ 13.35 ° N 89.34 ° W, East foot of the San Salvador volcano, San Salvador.	Type-I_CRCA, M5.4, 7.3km depth	No. of fatalities: 1,000-1,500 No. of houses damaged: 60,000 Total losses: US\$1,781 million

Country	Name of event/ date of the Seismic Event/Epicenter	Features	Summary of Damages
	2001 El Salvador earthquake/ 13 Jan 2001/ 12.83 ° N 88.79 ° W, Pacific Ocean 16 km offshore of the Usulután Department.	Type-S_CO / CA, M7.6, 39 km depth. PGA: La Libertad -1109 gal; Santa Tecla 486 gal	No. of fatalities: 844 (585 due to the Las Colinas landslide in Santa Tecla, Santa Tecla City reported 750 fatalities or more) No. of houses damaged: 108,226 Total losses: US\$1,781 million Location with road damages: more than 16,000.
	2001 El Salvador earthquake 13 Feb 2001/ 13.64 ° N 88.94 ° W, Cojutepeque	Type-I_CRCA, M6.6, 13 km depth	No. of fatalities: 315 CA1 had full width closed due to about 500 thousand m3 soil movement with the depth of soil covering the road of about 16m
Guatemala	1976 Guatemala earthquake/4 Feb 1976/ 15.32°N 89.10°W The northeastern part of the country. The closest town was Las Amates in the Izabal department.	Type-I_CA/NA, M 7.5, 5 km depth Motgua Fault	No. of fatalities: 23,000
	2012 Guatemala earthquake/4 Nov 2012/ 13.987°N 91.965°W The Pacific Ocean, 21 km offshore, roughly 35 km south of Champerico, a port and beach town in the Retalhuleu department in southwestern Guatemala.	Type-S_CO/NA, M7.4, 24.1 km depth	No. of fatalities: 42 The Pan-American highway was damaged The Guatemalan president declared a 30-day "state of calamity" for the most affected departments. It was subsequently extended to 25th July 2013.
Honduras	2009 Honduras earthquake/ 28 May 2009/16.73°N 86.22°W, Just north of Honduras' Bay Islands, Caribbean Sea, 30 km from Port Royal Roatan.	Type-OTF, M7.3, 10km depth	No. of fatalities: 7 Democracia Bridge on CA13 across the Ulúa river in El Progreso access to San Pedro Sula damaged due to subsidence /liquefaction.
	2018 Swan Islands earthquake /10 Jan 2018/ 17.469°N 83.520°W, Caribbean Sea, 44 km East of Great Swan Island in the Yucatan Basin.	Type-OTF, M7.6, 10km depth	No. of fatalities: 0 Road embankment failure
Nicaragua	1972 Nicaragua earthquake/ 12 Dec 1972/12.18°N 86.22°W In Lake Managua of Managua City side, 28 km from the city center.	Type-I_CRCA, M6.3, 10 km depth	No. of fatalities: 4,000-11,000
	1992 Nicaragua earthquake/ 2 Sept 1992/ 11.742°N 87.340°W, the Pacific Ocean 72 km offshore of the coast of Leon.	Type S-CO/CA, M7.7, 45 km depth	No. of fatalities: 116 including those from Costa Rica, mostly due to the tsunami reaching heights of up to 9.9 meters, reaching 1,000 m from the normal coastline at Masachapa.

Country	Name of event/ date of the Seismic Event/Epicenter	Features	Summary of Damages
	2014 Nicaragua earthquake/ 13 OCT 2014/12.576°N 88.046°W, the Pacific Ocean 51 km offshore of Nicaragua's Pacific coast, approximately 42 km west-southwest of the town of Jiquilillo.	Type S-CO/CA, M7.3, 40 km depth.	No. of fatalities: 3 in El Salvador

M: Magnitude. PGA: Peak ground cancelation in gal or cm/s²

Source: STACAweb (www.stacaweb.org): Early Warning System for Central America. (Additional information / modified by the government of each country, USGS: United States Geological Survey.

1.2 Concepts

Classification of road geohazards

Road geohazard damage in Central America can be classified as proposed in Table 1.3. For simplification of terminology, road damage includes collapse and temporary traffic disturbances with no damage to road infrastructure such as inundation. This classification addresses the typical types of geohazard adversely affecting roads, categorizing them based on the combination of location, movement, and the materials involved.

The road location refers to a geographically distinguishable portion of the road normally less than 1 kilometer. The road locations with slopes are classified into road location with mountainside slope and road location with valley side slope.

The standard risk management method is different for each type of movement, location, and material involved in a geohazard affecting a road infrastructure. This technical manual focuses on slopes with "mountainside fall or collapse," "valley-side collapse," and "slide" considering non-seismic risk such as storm impacts, and seismic risk.

Flow-type geohazard such as debris flow and inundation are covered in another manual, "SIECA/COMITRAN/JICA 2016: Hydrologic and Hydraulic Technical Consideration Manual for Road Infrastructure in Central America".

Table 1.3 Road Geohazards, by Location, Movement, and Materials Type

Location and movement type	Material factors				Road structures (e.g., bridge, road embankment)	Remarks
	Bedrock	Soil		Water		
		Debris	Earth			
Fall from the mountainside or collapse	Rockfall or collapse	Debris collapse	Earth collapse	N/A	Collapse of structures	Provide technical procedure in this manual
Collapse of the valley side or erosion of the river	Rock collapse or river erosion	Debris collapse or river erosion	Earth collapse or river erosion	N/A	Collapse of structures	
Slide	Rock slide	Debris slide	Earth slide	N/A	Slide of road embankment/ bridge foundation	
Flow	N/A	Debris flow	Earthflow	Flash flood or inundation	N/A	Provide technical procedure in another hydrologic/ hydraulic manual
Subsurface erosion	N/A	N/A	N/A	N/A	Road subsurface erosion (sinkhole/ settlement)	
Seismic motion including liquefaction, tsunami	N/A	N/A	N/A	N/A	Collapse of structures	

Source: Own elaboration, GENSAI Project Phase II JICA

Note: The classification limits of the risk movement and the types of materials are transitional. Some damages involve complex types of risks.

Basic concepts of road geohazard risk reduction

Geohazard risk reduction for new roads is to avoid costly locations for new road alignments through proper planning to avoid cost overruns, construction delays, and costly operation and maintenance. It can also help manage the negative social and environmental impacts of new roads and to plan the new road functions in coordination with local geohazard mitigation objectives.

Geohazard risk management for existing roads involves identifying and prioritizing important road locations to plan viable risk reduction measures and implement the measures by priority using indicative feasibility indexes such as benefit-cost ratio (BCR) or net present value (NPV).

Strategies for the different risk management level of roads

Risk management levels change by road strategies as appropriately shown in Table 1.4.

Table 1. 4 Example of Road Geohazard Risk Management Strategies, by Road Strategies

Stages	Expected measures for	
	Strategically important roads	Ordinary Roads
	High volume No detour or alternative roads Strategically important (e.g., logistic corridors connecting ports, airports to main cities; designated emergency logistic or evacuation route)	Low to medium volume Existence of detour or alternative road No strategic importance
Institutional setup	Designation as an important strategic road.	No designation as a strategically important road
Concept	Functioning under all weather conditions.	Acceptance of traffic suspension under abnormal weather conditions
Design/ Construction	A higher level of design safety degree of probability (SDP) against geohazard, utilizing indicative feasibility index.	Ordinary level of design safety degree of probability (SDP) against geohazard, utilizing indicative feasibility index.
Operation and Maintenance	Functionally operational even under extreme weather such as during storms.	Temporary road closing is a precondition for efficient road geohazard risk management. An efficient recovery maintenance system (staffing, machinery, etc.) are required to be set up

Source: Own elaboration

Promotion of projects for road geohazard risk reduction utilizing integrated consideration of non-seismic and seismic risk reduction

This manual summarizes technologies for non-seismic hazards such as storms, and seismic hazards on road slopes. The main purposes of this manual are to promote efficient investments for geohazard risk reduction on roads by providing risk estimation and indicative cost-benefit analysis results. Most measures contribute to risk reduction for both non-seismic and seismic causes: slope protection measures, structure/foundation reinforcement, groundwater drainage works for ground stability and road geohazard information system. The effect of these measures is evaluated as the increase in the Safety Degree of Probability (SDP) in years or a return period of

geohazard damage events on a road location. The annual risk reduction benefits of a road location can be estimated as the total of non-seismic and seismic risk reduction. Effective risk reduction investments for both non-seismic and seismic risks show high investment efficiency and is expected to be promoted.

The risk is estimated as the integral of the probability and potential loss due to road damage events of a location, such as potential annual loss under the current situation (currency per year).

First, evaluate the risk of a road location and then design based on the safety degree of probability (SDP) as the risk reduction target. The SDP is expressed as occurrence probability in years or return period (years), which is inverse of the annual exceedance of probability (%/year).

We can calculate using the design SDP the potential annual loss with planned measures (currency per year) and annual risk reduction benefits as the difference of the potential annual loss under the current situation minus the planned measures.

Table 1.5 shows the risk reduction target = Safety Degree of Probability (SDP) for Non-Seismic damage to a road location.

Table 1.5 Procedure for Setting the Design SDP for Non-seismic Damage of a Road Location.

Geohazard Type	Design SDP for non-seismic road damage
Mountainside fall or collapse	(1) Maximum SDP of assumed fall or collapse event with measures designed for slope stability (e.g., removal of unstable geo-materials, slope protection) or road protection (e.g., barriers, shelters).
Valley-side collapse or erosion	(2) The expected number of years of road damage occurrence is estimated as the assumed annual rate of expansion of slope failures with measures designed at the road valley-side. (3) The hydrological return period for events with measures designed where the peak flow rates/flow speed of flow-type geohazards (floods, debris flows, etc.) exceed the flow capacity/hydraulic resistance capacity of the stream.
Slide	(4) The probability of slide activation obtained from the following conversion formula for design Factor of Safety (FoS) for slide-type geohazard. $SDP = 500 \times (FoS - 1)^*$ where SDP: Safety Degree of Probability (years) FoS: Factor of Safety as the resistance force divided by the sliding force.
Flow	Same as (3) above

Source: Own elaboration, GENSAI Project phase II JICA

Note: (*) Since there is no standard method for converting FoS to SDP, the formula was initially proposed by the JICA Expert Team for Project GENSAI 2. It is an empirical formula proposed from Japanese cases, not mandatory to follow. Simply set $FoS = 1.2$ which is equal to 100-years probability and set $FoS = 1$ to 0-year probability. $FoS = 1.2$ is the common target FoS for slide type slope problems for major arterial roads and cases where slips occur again after a measurement is very rare. $FoS = 1.2$ was assumed to be equivalent to 100-years probability, taking into consideration the fact that no safety case had been verified for more than 100-years after the measures, the unforeseen cases on the natural conditions for design and quality in the construction have been taken into consideration.

Table 1.6 shows the design peak ground accretion (PGA) for seismic road damage of a road location. The design PGA can be converted to the design SDP by using another analysis result of the PGA-return period of a location.

Table 1.6 Procedure for setting the Design PGA for Seismic Damage of a Road Location

Geohazard Type	Design PGA for seismic road damage
Mountainside fall or collapse	(1) critical PGA obtained from seismic slope stability analysis for the countermeasure target geo-materials
Valley-side collapse	Same as (1) above
Slide	Same as (1) above
Flow	(2) Countermeasure target PGA with the scenario of geo-materials fall/collapse/slide into the stream resulting in flow-type geohazard at the downstream crossing with the road
Seismic motion, including liquefaction	(3) Countermeasure target PGA obtained from seismic structural analysis (4) Countermeasure PGA obtained from seismic liquefaction analysis

Source: Own elaboration, GENSAI Project phase II JICA

1.3 Background

The Secretariat of Central American Economic Integration (SIECA), as part of its efforts, has made the creation of instruments that help the technical integration of the Central American countries, within which manuals and technical documents have been prepared for this purpose, carried out by means of cooperation with other institutions, both regional and international.

One of the institutions with which these works have been carried out has been the Japan International Cooperation Agency (JICA), an entity with which in 2015 the agreement was made to carry out the "Manual of Hydrological and Hydraulic Technical Considerations for the road infrastructure of Central America" for which, through an agreement of the Council of Ministers of Transport of Central America (COMITRAN), it was agreed to form a Regional Technical Group (GTR) in which there was representation of all the Central American countries to carry out the preparation of this manual and was designated in turn, as technical coordinator, to the Department for Adaptation to Climate Change and Strategic Risk Management (DACGER) of the Ministry of Public Works, Transportation, Housing and Urban Development (MOPTVDU) of El Salvador.

The preparation of the manual ended in February 2016 and always with the collaboration of JICA, the process of dissemination was carried out in all countries, a process that lasted between October 2016 and March 2017.

Based on the process above, the need to continue with the elaboration of other technical documents in other areas related to risk management and adaptation to climate change of the infrastructure that is the responsibility of the transport ministries of the Central American region was recognized. Therefore, through agreement No. 100-2017 of the XXXVIII COMITRAN, held in the city of San José, Costa Rica, in June 2017; the ministers instruct SIECA to seek mechanisms and the necessary cooperation to continue to the elaboration of these documents. It is also created through agreement No. 104-2017 of the XXXVIII COMITRAN, the Regional Commission for Preventive Management of Risk and Adaptation to Climate Change of Infrastructure (CR-GRACC), which will be the one that will follow up on these types of topic.

For this reason, in July 2018, an agreement was reached between JICA, SIECA and the MOPTVDU of El Salvador, to carry out the process of preparing the "Manual of Geotechnical and Seismic Considerations, with a Risk Management Approach for the Central American Road Infrastructure. Topic: Slopes" through the "Project for the Development of Capacities of the Department of Adaptation to Climate Change and Strategic Risk Management for the Reinforcement of Public Infrastructure in El Salvador (GENSAI, and II) ", a project that is in a second stage of cooperation in conjunction with

the MOPTVDU through the DACGER technicians. From this agreement, the CR-GRACC activates the Regional Technical Group (GTR) with a focus on geotechnical issues, instructing to support the implementation of the Central American Handbook through agreement No. 122-2018 of the XXXIX COMITRAN. The process of preparing this manual was carried out at the DACGER facilities, in the city of San Salvador, between July 2018 and February 2019.

1.4 Objectives

Overall objective

Make available to six countries in Central America (Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, and Panama) a technical document that defines concepts to guide in a regulated manner the actors involved in the planning, design, and construction of road projects.

Specific objectives

- Contribute to the reduction of the vulnerability of the existing and projected Central American infrastructure, specifically in the issue of slopes.
- Promote investment in risk reduction by geohazards in road infrastructure.

1.5 Scopes

This manual has been developed to be consistent with all the standards authorized and applied in each Central American country. However, if there are inconsistencies with the standards or norms of each country, priority must be given to the standards and norms of each country.

The manual presents a series of geotechnical guidelines and seismic criteria that constitute a conceptual and methodological guide for the investigation and determination of geotechnical and seismic parameters for the technical consideration in the design and analysis of the stability of road slopes and the protection of these against the geological type threats.

This manual mainly deals with roads with adjacent slopes, but the technique can also be applied to reduce the vulnerability in bridges and drains of culverts.

The manual includes in its annex's techniques of risk management and evaluation of the probability of events that generate road damages, potential damages, risks, benefits of risk reduction, and effectiveness/efficiency of cost-benefit.

1.6 Diagnosis

Regional

In Central America, there is no systematic methodology or specific regulations for the regulation of slope stability analysis in terms of road infrastructure works and works of step.

In the formulation of the terms of reference, for construction projects that include the risk reduction of road vulnerability, Guatemala and El Salvador do not have a reference document to establish these criteria to evaluate the geotechnical parameters in road construction, works of step and slopes. Also, Guatemala, Nicaragua, and Panama have not developed a manual of standard specifications for road construction but refer to the Central American Manual of Specifications for the construction of regional roads and bridges; 2001, 2nd Edition; 2004.

In all the countries of Central America, the ratification of the permits for the construction plan for the environmental license and the viability of investment for the road works depend on other institutions, in addition to the Ministries of Transport. However, specialized geotechnical institutions that carry out the revision and approval in the ratification of construction projects, to date, do not exist.

All countries have topographic maps and geological maps on the less detailed scale of 1:250,000 for their territories; A scale of 1:50,000 or more detailed is needed to cover all territories. Aerial photographs exist at a scale of 1:20,000. All this information is essential for road vulnerability reduction studies.

The GTR members of El Salvador and Guatemala confirmed that they have an inventory of recent road damages caused by weather events and damage by earthquakes and volcanoes to some extent.

Except for Costa Rica, which has a geology department for surveying and interpreting field information, the rest of the member countries do not have any format to enter and store data on their lithological characteristics, including the geological structures obtained through recognition on the field.

All countries have geotechnical criteria, including seismic risk for the construction of roads and bridges. Only Nicaragua has geotechnical guidelines related to climate change in a publication called "Geotechnical Guide with a focus on climate change" that was printed in the year 2017.

Each country has a special consideration of the geotechnical problems caused by climatic events and has adopted measures such as adequate drainage system, protection against erosion, cutting of slopes for a stable angle and improvement of geomaterials.

The need for this manual arises from an evaluation methodology that considers climate change for slopes, bridges, and road structures. The evaluation contains three basic phases: basic geological study, geotechnical exploration, and slope stability analysis.

In the region, there is no technical capacity to assess actual/potential road losses, including traffic or other indirect losses, as well as the benefits of risk reduction through proactive measures.

National

Table 1.7 shows a list of documents provided by the countries, as well:

Costa Rica developed manuals and supplemented them with specifications for road/bridge construction, foundation code, guidelines for the seismic design for bridges, geotechnical code for bridges.

Guatemala contemplates in its guidelines, the environmental impact without consideration of climate change; for geotechnical tests uses international standards, there is a private association of structural engineering and seismic, also have a geological society where they have knowledge of the geotechnical procedure on roads but has not formulated a manual for the uses of planning and design for public works.

El Salvador is using the SIECA Central American manuals for roads and bridges, but these documents don't include in the planning and design of measures for slope geotechnical problems. The technical standard for the design of earthquakes of 1997 is used, but it is 20 years old, so it does not include the recent experience of seismic damage in the region.

Honduras has a manual with general specifications for the construction of roads, use international standards applicable to tests, do not have a specific geotechnical guide applicable to roads, bridges, and slopes.

Nicaragua, in its technical specifications for road construction, does not detail the geotechnical analysis, including the NIC-2000 section on excavations and earthworks.

Panamá is in the process of updating the structural regulation based on the latest design models, considering the combined loads that can affect a structure, seismic requirements, etc. Now, it is not clear what guidelines will be, so it is not established if they include a geotechnical investigation and design criterion. But they have formulated the manual for the approval for the implementation of projects called "Manual of Requirements and updated General Standards for the revision of plans, recommended parameters in the design of the system of streets and storm drains according to the requirements of the Ministry of Public Works."

Table 1.7 Information provided by the countries

Country	Documents	Author
Costa Rica	Manual of general specifications for the construction of roads, and bridges; 2010	Ministry of Public Works and Transportation (MOPT)
	Code of foundations of Costa Rica, First Edition; 1994, Second Edition; 2009	Costa Rican Geotechnical Association. Costa Rica Foundation Code Commission
	Guidelines for the seismic design of bridges; 2013	Federated College of Engineers and Architects of Costa Rica; Permanent Commission for the Study and Revision of the Seismic Code of Costa Rica
	Geotechnical Code for Slopes of Costa Rica, first edition; 2015	Costa Rican Geotechnical Association, Costa Rica Editorial Technology
Guatemala	National and International Public Bidding Base No. DGCYT-2; 2003	Government of the Republic of Guatemala, Ministry of Communications, Infrastructure and Housing
	Geotechnical and Microdonation Studies NSE 2.1-10	Guatemalan Association of Structural and Seismic Engineering: AGIES
	Structural Safety Standards for the Republic of Guatemala, NSE 2.1; 2018	Guatemalan Association of Structural and Seismic Engineering: AGIES
	Movements of Hillside in Guatemala	National Geographic Institute: IGN
	Geological Map of Guatemala	National Geographic Institute: IGN
	Geotechnics and structural design of the pavement	Geological Society of Guatemala: SGG
El Salvador	Central American Manual of Specifications for the construction of regional roads and bridges; 2001, 2nd Edition; 2004	USAID, SIECA, COMITRAN
	Central American Manual for Risk Management in Bridges; 2010	CEPRENENAC, AECID, SIECA
	A basic guide for the elaboration of state and municipal atlases of hazards and risks; 2006	Government Secretariat, SEGOB, Mexico; CENAPRED
	Technical Standard for Earthquake Design; 1997	Salvadoran Association of Engineers and Architects, ASIA
	Manual of Protection Works in Slopes	GENSAI, MOPTVDU, JICA
	Manual for the monitoring of landslides	GENSAI, MOPTVDU, JICA
Honduras	Pavement design and road maintenance (Volume IV); 1996	Secretariat of State in the Offices of Public Works, Transportation and Housing.
	General specifications for construction (Volume V); 1996	Secretariat of State in the Offices of Public Works, Transportation and Housing.
	International standards applied to trials	Summary

Country	Documents	Author
Nicaragua	Geotechnical Guide (With a focus on climate change); 2017	Ministry of Transport and Infrastructure of Nicaragua
	Topographic Maps of Nicaragua	National Geographic Institute
	General Specifications for the Construction of Roads, Streets, and Bridges; 2000	Ministry of Transport and Infrastructure of Nicaragua
	National Construction Regulations RNC-07; 2007	Ministry of Transport and Infrastructure of Nicaragua
	Vulnerable points identified in the Road Network of Nicaragua	Various institutions
	Terms of Reference for Studies and Designs in the way of Example; 2000	Ministry of Transport and Infrastructure of Nicaragua
	Technical specifications for construction projects (2 sample files)); 2000	Ministry of Transport and Infrastructure of Nicaragua
Panamá	Structural regulation of Panama; 2014	Technical Board of Engineering and Architecture, 2014
	(Tender) Design and Construction for the Rehabilitation of the Circunvalación de Pese-Bahia Honda-El Ciruelo pose and Rincón Hondo road-the Bancola Esquiguita province of Herrera; 2018	Ministry of Public Works of the Republic of Panama
	Manual of Requirements and General Standards updated for the revision of plans, recommended parameters in the design of the street system and storm drains according to the requirements of the Ministry of Public Works.	Ministry of Public Works -Directorate Executive of Studies and Design Department of Review of Plans.

Source: Own elaboration



CHAPTER 2

PRELIMINARY ACTIONS FOR GEOTECHNICAL STUDIES

CA-1. Los Chorros, Colón, La Libertad, El Salvador

PRELIMINARY ACTIVITIES TO GEOTECHNICAL STUDIES

The preliminary investigation to a geotechnical study is important for the formation of criteria on the conditions and lithological, hydrological, hydrogeological and seismic characteristics that a professional or contractor must know before agreeing on a project; this saves time and future resources.

This section addresses issues related to the previous and viability studies as well as the preliminary project of a geotechnical study, specifies geological and geotechnical research works, details criteria that the designer must take into account in project planning that includes slopes and/or hillsides on roads and guides on the documents that the professional can consult when carrying out a geotechnical analysis, documents that allow him to form criteria for the superficial recognition of the area of interest.

The documentary information and the field visit will forge details about lithological units and their characteristics, approximate measurements, location of watercourses, possible mass movements.

The content of geo-structural maps is briefly presented to pursue a rapid kinematic idea in the interpretation of maps and relationship with the outcropping units in the field visit. The use of tools such as the Geographic Information System (GIS), the use of GPS for georeferencing points of interest is other topics described, followed by the types of tests that can be performed in the field and spatial distribution.

Limitations are presented such as the lack of unified criteria in the Central American countries in the implementation of field tests, a distance interval of the tests of depth and horizons, and its descriptions for the construction of new and existing roads.

Table 2.1 shows the phases before geotechnical studies, included in previous studies and feasibility and preliminary project.

Table 2. 1 Phases before geotechnical studies

Phases before the project	Characteristic activities	Geological-geotechnical research work
Previous and viability studies	Visit and previous field recognition	– Recognition of soils and rocks – Faults and structures. – Hydrological data, drainage – Geomorphology, slope stability, subsidence, flooding, etc. – Geo-environmental problems – Accesses and situations of investigations in situ.
	Revision of information	– Topography and relief. – Hydrology and hydrogeology. – Regional geological maps. – Geological history. – Seismicity and other geological risks
	Photo-interpretation	– Aerial photography and remote sensing. – Geomorphology. – Lithologies and structures. – Geological risks. – Cartographies of synthesis.
Preliminary Project	Geological-geotechnical cartography (scale 1: 5,000 - 1: 10,000)	– Lithostratigraphy and structure. – Geomorphology and hydrogeology. – Classification and properties of materials.
	Hydrological-hydrogeological data	– Identification of flood zones, karstic, runoff, etc. – Regional y local.
	Basic geotechnical research ⁽¹⁾	– Probes and test pits. – Geophysical prospecting. – Laboratory tests.

⁽¹⁾ Basic research: they refer to spaced soundings and identification tests, mainly

Source: González, 2002.

2.1 Criteria to be considered by the designer before road planning

Before the road planning, the mechanical behavior of the soils and the rocks, the knowledge of the techniques of investigation of the subsoil, both mechanical, instrumental and geophysical, as well as the methods of analysis of the terrain, should be considered, in Table 2.2, a general sequence of criteria to be considered is listed.

Three types of models must be defined to conceive the full development:

Geological model, involves the lithological units of the area to be studied and structures with kinematic interpretation, besides defining weathered zones, description of discontinuities, characterization of the rock mass and hydrology. Generally, drilling at different depths requires depending on the objective to be achieved. It should represent sections of two dimensions models or three dimensions models.

Geotechnical model is based on the geological model. It consists of the interpretation of the deformation of the soils and rocks in the present units of the area of interest. It makes a classification about the characteristics of the structures, the tensional state, and the resistance. It should include failure criteria.

Geotechnical model of behavior represents the response of the land during construction and after it.

Table 2. 2 Criteria to be considered by the designer before planning the road

Item	Criteria
1	Identification of materials and processes in the outline of the project.
2	Definition of geomorphology, structure, lithology, and the conditions of surface and underground water.
3	Geological-geotechnical conditions of the subsoil.
4	Spatial distribution of materials, structures, and discontinuities
5	Hydrological, tensional and environmental conditions. Characterization of geotechnical and hydrological properties
6	Characterization of geological materials used in construction, extraction, and environmental protection work
7	Geological-geotechnical behavior under the conditions of the project
8	Evaluation of the mechanical and hydraulic behavior of soils and rock massifs. Prediction of the changes of the previous properties over time
9	Determination of the parameters that should be used in stability analysis for excavations, earth structures, and foundations.
10	Analysis of the terrain conditions to define the best stabilization against leaks, settlements, slope instability, landslides, etc.
11	Considerations against geological risks and environmental impacts.
12	Verification of the procedure implemented.

Source: Adaptado de González, 2002

2.2 Surface survey of the section where the engineering work will be carried out

The objective of making a visit and prior field recognition is to gather all the information that allows making a geotechnical study Suitable to the conditions of the site and that allows obtaining the complementary information that will be required to carry out the project to be planned.

2.2.1 Identification of the section and study area

According to basic criteria for road geotechnical studies, the Secretary of State for Public Works (Secretaría de Estado de Obras Públicas), Dominican Republic, the section where the engineering work is planned must be identified to define an area of study, which must cover a wide area on both sides of the possible layout. The width of the study area should allow identifying the geomorphological units of the area, such as:

- Channels
- Ejection cones (colluvial fans)
- Landslides
- Cracked slopes
- Sliding hillsides
- Swamps
- Flooding areas
- High water Table
- Building materials for the track, and others

2.2.2 Geological Recognition

The surface geological survey must include at least:

- Visual description of the different types of rocks that emerge
- The degree of weathering of the rocks
- Zoning of sets of discontinuities (etc. geological joints) on slopes
- Faults and defects of the rocks
- Visual description of the different types of soil

2.2.3 Approximate measurements in the field

In the field, measurements should be taken, and attention should be paid to certain considerations, which are shown in Table 2.3, showing in categories the areas that the professional can obtain approximate information in the field visits.

Table 2. 3 Approximate measurements in the field

Category		Factors	Measurements			
Characteristics of the slope		Height	0 to 5 m	5 to 10 m	10 to 20 m	>20 m
		Maintenance / Cleaning	Minor	Moderate	High	Very High
		Angle	Soil	<30°	30°≤ Angle≤40°	40°≤ Angle≤60°
			Rock	Category <2	2≤ Angle ≤4	4≤ Angle ≤8
		Irregularities	None	Minor	Moderate	Higher
		Section type of cut	Box-shaped cross section	Box-shaped with pavement faults	Balcony	Balcony with pavement faults
		Fall catchment area	Class 1. 95% to 100 %	Class 2. 65% to 94%	Class 3. 30% to 64%	Class 4. <30%
	Vegetation	Body	Dense/bush	Dense /herbaceous	Semi naked/ herbaceous	Naked
		Crown	Populated/arboreal	Populated/ Shrubby, semi naked / arboreal	Populated/herbaceous, semi naked/ shrubby.	Naked, semi-naked/herbaceous
Weather		Annual average precipitation (mm)	≤ 200	200≤ precipitation ≤500	500≤ precipitation ≤850	>850
		Infiltration/ present water	Without humidity	Humid/wet	Dripping	Water runoff
Geology	Sedimentary rocks	Scouring at the foot of each layer	0 to 0.3	0.3 to 0.6	0.6 to 1.5	> 1.5
		Degree of inter-stratification	1 to 2 weak interstrata < 15 cm	1 to 2 weak interstrata > 15 cm	More than 2 weak interstrata < 15 cm	More than 2 weak interstrata > 15 cm
		Channel formation	Depth ≤ 5 cm	5≤ Depth ≤10	10≤ Depth ≤20	Depth >20 cm
			Width ≤2 cm	2≤ Width ≤5 cm	5≤ Width ≤10 cm	Width > 10 cm
			Very separated	Very continuous	Very continuous	Very continuous
	Crystalline rocks	Type of rock	Homogeneous / solid	Small faults / strong veins	Schists / shear zone < 15 cm	Weak pegmatites / micas / shear zone> 15 cm
		Degree of projection	0 to 0.30	0.30 to 0.60	0.60 to 1.20	> 1.20
		Degree of erosion	Recent	Weathered/discolored	Slightly altered/attenuated	Altered
		Discontinuities	Block size (m³)	<0.30/<0.50	0.30 to 0.60/<0.5 to 20	0.60 to 1.50/<2 to 6
			Group of	1	1 random	2
						> 2

Category		Factors	Measurements			
		discontinuities				
		Persistence/orientation	<3m / dip into the slope	>3m / dip into the slope	<3m / orientation towards the road	>3m / orientation towards the road
		Crack (mm)	Closed	0.1 to 1	1 to 5	>5
		Erosion conditions	Recent	Weathered/discolored	Filled with granular material	Filled with clay material
		Friction	Rough	Wavy	Planar	Smooth planar
	Blocks	Block size (m)	<0.30	0.30 to 0.60	0.60 to 1.50	>1.50
		Block shape	Tabular	Cubic	Angular cubic	Round smooth/flat with an inclination towards the road
		Landslides/Displacements	Cracks in the crown of the slope	Considerable cracking and subsidence	Accumulation of the material at the foot of the slope	Deformation in a step shape
	Residual soils	Weatherization profile	B-C Horizon	B Horizon	A-B Horizon	A - Horizon
		Surface runoff	Formation of small torrents	Less than ½ of cut presents torrents and channels	More than one half of the cut presents torrents and channels	Detachment and concentration of drag solids in the foot
		Contact soil on rock	Presence of fractured rocks in less than a quarter of the slope	Cubic rock projections with size from 30 to 60 cm	Rocks with the corrugated friction surface	Rocks with the flat planar friction surface

*Source: Proposal of indicators for the management of cut and embankment slopes.

Garnica and others, 2017.

2.2.4 Location of permanent, intermittent and ephemeral streams

The measurement of the position of a stream (defined as the segment of successive tributaries) within the hierarchy of the drainage network, is the basis for the quantitative analysis of the network.

The smaller permanent streams are called first-order streams; two first order streams join to form a second-order stream, two-second order streams join to form third order streams, and so on, see figure 2.1. Small inflow streams to a higher order sequence do not change their order number, Strahler, 1964.

The ephemeral streams are in the highest part of the river basin and as the slope of the basin descends, and the water Table is located below the riverbed it is an intermittent stream; the permanent streams are in the lower part of the river basin, and the water Table is located above the bottom of the channel.

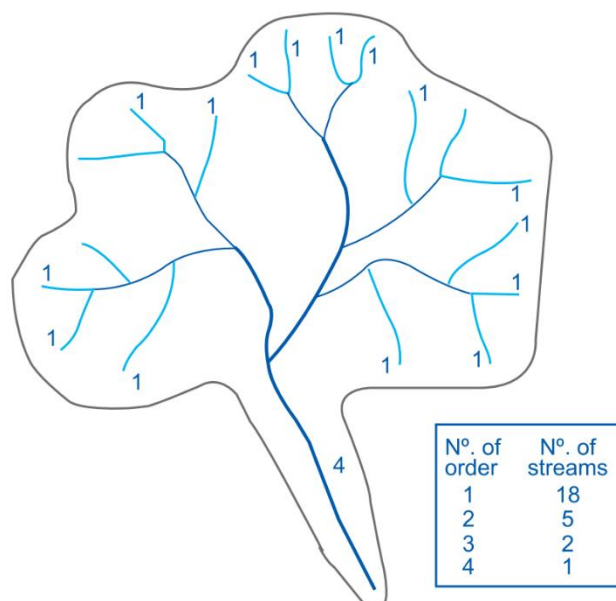


Figure 2. 1 Location of streams of the first, second, and third order

Source: <https://es.slideshare.net/lviasusviasus/cuencas-reconocimiento>

To a better understanding of each of the types of streams, each of them is defined below:

The ephemeral stream is one that only carries water when it rains and immediately afterward.

The intermittent stream is the one that carries water most of the time, but mainly in the rainy season; its contribution ceases when the water Table descends below the bottom of the channel.

The permanent stream contains water all the time because even in the dry season it is continuously supplied since the water Table always remains above the bottom of the channel.

2.2.5 Identification of mass movement sites

By mass movement is understood the displacement of the land that becomes a hillside or a slope, towards the outside of it and in a downward direction.

The classification of mass movements with the engineering perspective described by J. Montero, 1991 can be seen in Tables 2.4 and 2.5.

Table 2. 4 Mass displacement¹

Creeping	In rock	In soil	On slope	In soil
Landslide	Translational (blocks, wedges)	Rotational / Translational	Rotational / Translational	
Lateral propagation	In rock	In soil		
Detachment	Overturning, fall, jumping, bearing.			
Runoff		Collapse		
Subsidence	Subsidence associated with underground excavations or descent of the water Table.			

¹ Its behavior obeys the mechanical laws of solids essentially.

Source: J. Montero, 1991

Table 2. 5 Mass transportation²

Flow		Detritus or mud	Debris, mud or dirt
Avalanche	Of rock	Of rocks or detritus	Detritus
Varnes	Rocks	Rocks and detritus	Detritus and dirt

² Its behavior obeys the laws of the hydraulics and mechanics of fluids; transition between water erosion and mass displacement essentially.

Source: J. Montero, 1991

The following describes a series of criteria that can help identify sites with possible mass movements:

Steep slopes

The most common cause of steep slope collapses is the sliding along with the contact with the rock of residual or colluvial soils. The weathered or loose material cannot be maintained with the same slope as the rock; a rain or cut at the foot of the slope can activate the sliding of the overlying rock, figure 2.2.



Figure 2.2 It shows a partially weathered rock plane with landslide along with the contact.

Source: Aguacatán, Guatemala

Drainage and filtration concentration areas

In a hydrographic basin, the highest part formed by ephemeral tributaries is the area where the greatest number of streams exists, as the topographic level of the basin decreases, the number of streams decreases and order increases, passing from intermittent to permanent streams. Figure 2.3 represents a series of channels of ephemeral streams in the upper part of the hydrographic basin, interrupted by the passage of a road. Figure 2.4 shows traction cracks sliding downhill due to soil filtration, saturation, hydrostatic pressure, and soil weight gain.



Figure 2.3 Drain concentration in a road cutting



Figure 2.4 Traction cracks caused by filtration and hydrostatic pressure. Taken on road CA-14 Guatemala

Source: <http://www.estechareproducciones.com/imagen/gunitados-taludes-, concencarreteras.jpg>

Areas of concentration of fractures

The quality of the rock mass is related to the number of fractures that it presents, a rock mass of very bad quality is one that presents numerous intensely weathered joints with fillings (Figure 2.5). The spacing is less than 0.05 m, gaps with clay fillings and an RMR (rock mass rating) equal to 3; Hoek and Brown, 1998.



Figure 2.5 Concentration of fractures in road cut slope.

Source: Aguacatán Guatemala, km 348 +440 RN7W

Strong Slopes

It is considered an extremely strong slope when its inclination is greater than 55% causing strong denudation processes (rock detachment or superficial part of the ground), Mora and others, 1992. Or it is susceptible when the soil has an effective friction angle greater than 30 °; Bieniawski, 1989. Figures 2.6 and 2.7 show cases on steep roads with a strong slope that have had material detachment.



Figure 2. 6 Road CPA-Cope- Marta, District of La Pintada, Province of Coclé, Panama Km 2+500



Figure 2. 7 Roads in Aguacatán Guatemala km 343 + 380 RN7W.

Structures with a dip in favor of the slope

To measure a stratigraphic plane the North is taken as reference either from 0° to 360° (example: N 64° , N 125° , N 240°) or from North 0° to 180° and indicating the direction in which it is measured, West (O) or East (E) (example: N 37° E, N 150° W).

The dip of a plane either: stratification, joints or fault plane, is the line of maximum slope in that plane, figure 2.8 (perpendicular to the direction of the plane) and a horizontal plane, measured on a vertical plane. See figure 2.9 to see the difference between the actual dip and apparent dip.

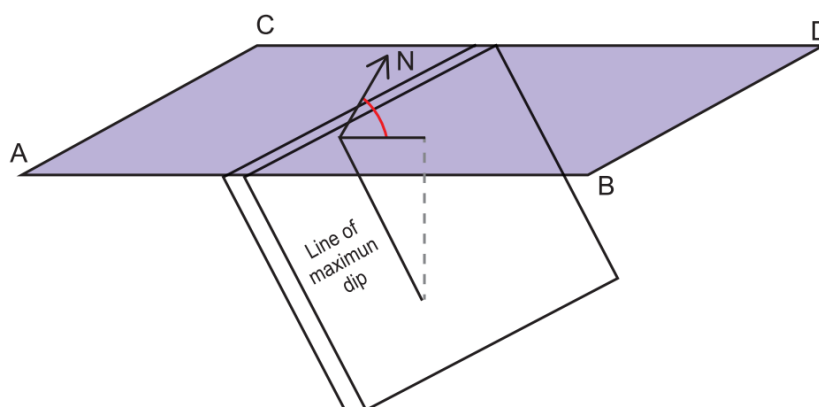
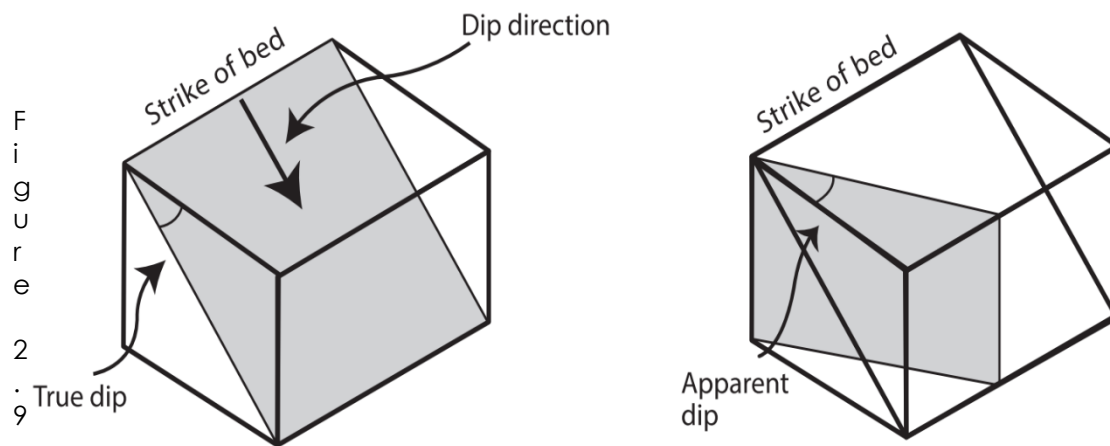


Figure 2.8 Indicates the maximum slope line of a structural plane



Actual dip and apparent dip

Source: es.slideshare.net/georgehsterling/geologia-estructural-orientacion-de-estructuras

2.3 Documentary Research

The documentary research is a fundamental part of the knowledge, analysis, and procedure before the construction of road work. Through documents that reflect the geology, hydrology, topography, geomorphology, structures, and history of the area, among others; the professional can theoretically know some conditions of the site and formulate empirical criteria of the characteristics that the zone contains, which is basic in the development of the work.

Due to the importance of cartographic information in documentary research, a conceptual extension is made of different types of maps that can provide information for the design of the geotechnical campaign.

2.3.1 Thematic Maps

They are maps based on topographic maps that represent any geographic phenomenon of the surface of the earth. They pursue well-defined objectives. They refer to the representation of certain characteristics of distribution, relationship or regionalization of real objects (soils, geology, vegetation, etc.) or abstract concepts.

To represent numerical variables, they use all kinds of visual resources, such as surfaces of different colors, arrows to indicate the movement of a phenomenon (flows, sometimes have a thickness proportional to their magnitude), the drawing of lines joining points of equal value (isolines), circles not symbols of size proportional to the numerical value.

Surface map with a classification of soils and rocks

The delimitation and cartography of rock units or "homogeneous" soils in terms of their physical and mechanical properties, such as strength, deformability, durability, permeability, etc., is based on geological properties that have a greater relationship with geotechnical properties. The mineralogical composition and the lithology are directly related to the density and plasticity of the soils. In the rocks, the composition determines the hardness, strength, alterability, etc. The texture and mineralogical structure are also aspects that provide information about the mechanical behavior of materials about porosity and density. The hydrogeological conditions provide information on the consistency of soils and the conditions of alteration in soils and rocks. In the case of rock masses, the frequency, distribution, and type of discontinuities, the degree of fracturing and the degree of alteration or weathering provide information about the resistance, deformability, and permeability. Gonzales et al., 2002.

The geotechnical parameters to be represented in the geotechnical cartographies, according to the scale and purpose of the map, of the available information and data are:

- Density
- Porosity
- Consistency and activity
- Permeability
- Simple compression and tensile strength
- Resistant parameters
- Deformability
- Durability or alterability

Also, in the specific maps as thematic or integrated maps, other properties, and geotechnical aspects are included according to the applications pursued.

Hydrogeological Conditions: They provide information on the consistency of soils and the conditions of alteration in soils and rocks. In the case of rock masses, the frequency, distribution, and type of discontinuities, the degree of fracturing and the degree of alteration or weathering provide information on the resistance, deformability, and permeability. The hydrogeological aspects are great importance in geotechnical maps used for planning, exploitation of water resources, and other works that are related to water conditions.

The hydrogeological data in the geotechnical maps foresee hydrogeological changes and provide information to control these changes. Among the most important are

studied: distribution of water and its content in materials, lakes, rivers, confined aquifers, permeability, water quality, etc.

Los datos hidrogeológicos en los mapas geotécnicos prevén cambios hidrogeológicos y aportan información para controlar dichos cambios. Entre los más importantes se estudian: distribución del agua y contenido de ella en los materiales, lagos, ríos, acuíferos confinados, permeabilidad, calidad del agua, etc.

Geomorphological Conditions: In the geotechnical application, geomorphological information is needed to develop geotechnical maps, which are great importance about the physical characterization of the territory. It provides information about useful processes in engineering works, such as topography, elements of the relief, origin evolution and age of the geomorphological elements, relationship with hydrogeology, predictions of erosion processes, movement of hillsides, etc.

Geodynamic Processes: Geotechnical maps should include the dynamic nature of the geological environment providing information on external and internal dynamic processes:

- Location and extension of processes
- Age
- Limits and morphological and associated features
- Conditions, causes and conditioning factors
- Forecasts of potential processes

About geodynamic processes, geological risks play a very important role since they can affect populated areas, infrastructures, and constructions.

2.3.2 Structural maps

This type of maps is the representation in a plane of the different morphologies present in the terrain

Relief

The relief includes the set of forms present in the terrain, elevations and depressions and their different lateral relations. They are components of the relief, the mountains, the valleys, the plains, the slopes, and other elements that create the natural landscape. It is important to highlight that the relief involves three dimensions equivalent in concept to the length, width, and height of any regular object, each of these dimensions can be related to a plane that is perpendicular to the other two.

El relieve comprende el conjunto de formas presentes en el terreno, elevaciones y depresiones y sus diferentes relaciones laterales. Son componentes del relieve, las montañas, los valles, las planicies, los taludes y demás elementos que conforman el paisaje natural. Es importante resaltar que el relieve involucra tres dimensiones equivalentes en concepto al largo, ancho y alto de cualquier objeto regular, cada una de esas dimensiones puede ser relacionada con un plano que es perpendicular a los otros dos.

Reference Planes

It has been universally accepted to use two vertical planes and one horizontal plane for the graphic representations of the objects. These planes are intercepted one by one; and at a point called "origin," all three will be intercepted. The lines of intersection plane to plane, form axes of rotation (Cartesian axes) that serve as a linear reference, that is, to measure relative values to the different dimensions.

Topography

The topography includes the set of techniques for measuring and representing areas of the earth's surface. The form of representation used by the topography is the topographic map, which is the bounded projection of the land with some specifications concerning the needs for which it is carried out. A topographic map is the one that expresses the shape, dimensions, and distribution of the morphological features of the earth's surface. Such three groups of features are; a) relief, including hills, valleys, plains; b) hydrography, which includes seas, lakes, rivers, channels, marshes, etc.; and c) works and constructions, including cities, railroads, roads, etc.

In the topographic map, points on the ground surface are represented; consequently, the coordinates are geographic and are related to the main north-south and east-west planes of the planet. The height is the vertical distance to sea level, and its value is written accompanying the location, in a square at the bottom of the map or at an angle of the map, called the legend.

Cuts and profiles

The total horizontal distance in a topographic map will depend on the "slope" of the terrain, understood as such, the angle m formed by the line joining two points A and B in the ground with the horizontal. Here is a concept that links horizontal distance between two points and the height difference between them. The determination of the slope on the map provides useful information about the abruptness of the terrain, which is very important in civil works and specifically in road construction.

Geological Cartography

The main elements to show in a geological map are title and scale, UTM coordinates and longitude and latitude, northern arrow (graphic scale), lithological units and geological and tectonic symbols, topographic symbols example: rivers, name of the authors, places of the work, date of mapping, legend, general symbology of the geological map, block diagram of the lithological units (3D).

2.3.3 Geological structure maps

The purpose of this type of maps is georeferenced those structures as fault planes, stratification orientations, discordances, folds, etc. that change the behavior of rocks or soils punctually or prolonged. It is basic in the planning of sampling and laboratory tests; it improves the criterion of the professional to determine the zones of greater resistance and zones where it requires intervention through the strengthening of the ground or unstable rock.

Include a series of tracings depicting failures, main geomorphologic features are highlighted, as graben or flower structure (anticline structure flanked by two reverse faults high angle, a product of a compression event).

Main macrostructures that make up the geological structure map

Fragile deformation structures

Fractures: Fractures and shear microfractures and faults. Characterization of the surfaces of fractures. Origin of the fractures.

Faults: Fault and fault zone. Fault surface and associated structures. Fault rocks. Jump and separation of the fault. Types of faults according to the fault scarp (inverse faults, thrust faults, normal faults, strike-slip faults). Kinematic criteria of the fault

Ductile deformation structures

Folds: the scale of the fold, geometric elements of one or several folded surfaces, symmetry. Classification of the folds: a) by its orientation, b) by the shape of the folded surfaces, c) by the style of the folded layers (Ramsay classification). Folding mechanism: folds associated with faults, folds due to density contrast, etc.

Foliations: Planes of the tectonic origin or visible structure in certain rocks that have been subjected to stress or that their constituent minerals have been reoriented according to the plane of schistosity or foliation. (Dictionary of geology, Alain FOUCAULT, 1985).

Lineations: It is known as the intersection of two geological planes: Stretching lineation, fold axes, the intersection of planes, the orientation of minerals.

Shear zones: geometric characteristics, types of shear zones, geometry and distribution of internal deformation, mylonite. Kinematic criteria: determination of the shear direction, progressive deformation of the shear zone.

Interpretation of geo-structural maps (basic)

In a geological structural map, the efforts and types of stress suffered by rock masses, deformations, faults, and folds are shown in symbologies, see Table 2.6 for contact lines and basic structural symbols.

One layer is affected by the maximum principal stress (σ_1), intermediate principal stress (σ_2), and minimum principal stress (σ_3), figure 2.10. The orientation of the stress in the rock layer determines the type of fault (normal, inverse, directional or combined depending on the angle at which it moves); see figure 2.11, 2.12, 2.13 and 2.14.

In a directional fault the principal stress is located approximately 15° from the principal shear, at 60° from the principal shear other faults called Riedel (R') are formed and at 90° the decompression zone, Figure 2.14. Within the principal shear in a directional failure and the failure R,' the compression of the rocks causes folding and cracks in the echelon that determines the direction of the effort in the field. When the displacement of a fault occurs, in the plane where it slides, there are marks such as mineralization, stretching lineation, crescent concavities, perpendicular fractures to the drag that help the interpreter of structural rocks to define the type of movement and to classify the faults. Figure 2.15 contains the parts of a fold.

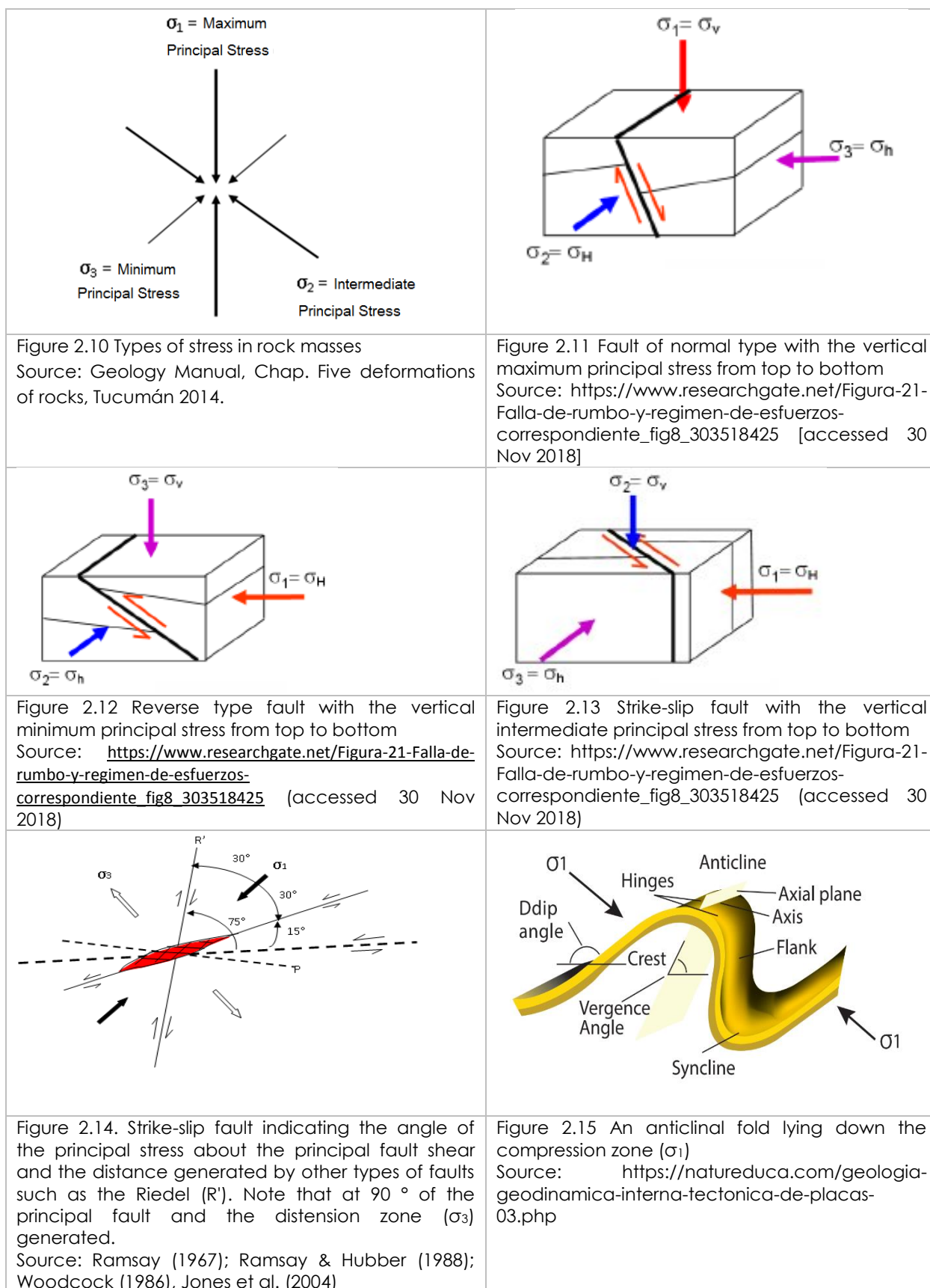
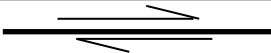
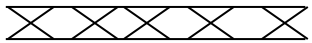
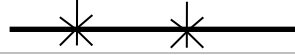
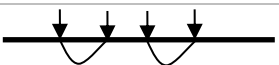


Table 2. 6 Contact lines and basic structural symbols

Name	Symbol
Normal contact	
Discordant contact	— — — — —
Mechanical contact	—————
Inferred fault	- . - . - . - . - .
Normal fault	
Strike-slip fault (sinistral or dextral course and its components)	
Thrust fault	
Fault with an indication of subsidence	
Milonitized zone	
Anticline	
Syncline	
Tumbled anticline	
Tumbled syncline	
Dip	
Schist	

Source: presentation of geological maps. Dra. Elena González Cárdenas.

Geological structure sections

A geological structure section is a vertical section to show the disposition of rocks and structures at depth. The geo-structural sections arise to perceive structures three-dimensionally (faults, folds, lithological contacts, stratigraphic dips, etc.), which is one of the problems that arise when interpreting a geological map. A geological structure section uses all the available data on the surface of the land, to show with a high degree of certainty the configuration of the subsoil. For greater precision, it is adjusted with drilling and seismic drilling.

3D Model

A three-dimensional geological structure model consists of a representation of geological elements of space such as lithology, structures, geomorphology, geomechanics, hydrology.

2.3.4 Shapes and georeferencing. Datum 84 UTM projection

A GIS (geographic information system) is a system capable of storing, displaying, and analyzing georeferenced information, Burrough, 1986.

It is a useful tool to integrate different types of data, from different sources in digital format, Shepherd, 1991.

Shapes are vector layers with thematic information in Shapefile format. In these layers is the thematic information ordered: hydrology, geology, access, etc. Georeferencing is the use of coordinates in the cartographic representation or a GIS.

In this way, based on the principle of superposition of layers and the handling of data in spatial form, the GIS analyzes the georeferenced data. In this way it is possible to manage the crossing of the information in a controlled manner, monitor the evolution of the projects and generate reports according to the need, in the form of maps or descriptive data. The results of the projects of a quick and comprehensive visualization are available for persons outside the specialties of geological-geotechnical environment.

Bonham-Carter, 1994, summarizes the uses of GIS in geology and geotechnics.

- a) In geological cartography and geotechnical: it is possible an orderly consultation of the whole geological chart and geotechnical data, as well as the direct manipulation of the data of samples and observations.
- b) Environmental analysis or geological-geotechnical risks: stability study of slopes, gravitational flows, earthquakes, volcanic risk, flood, coastal erosion, pollution, among others
- c) Territorial organization: rational land use, landfill areas, road geotechnics, etc.
- d) Soil management: erosion, adequate use of the soil, climatic factor
- e) Infrastructure and availability of resources: a study of the available elements in a place, such as roads, water, energy, sand, gravel, etc. Necessary in the evaluation of any economic project.
- f) Control and management of geological projects: through precise routines, it is possible to follow the evolution of geological projects and obtain temporary and economic parameters.

Global-GPS positioning system

Usual GPS

It is a geographic location system of points on the surface of the earth based on satellite positions. Its accuracy varies between a few meters to several meters.

Differential GPS

Its accuracy is centimetric, depending on the quality of the GPS receiver and the technique used to make the measurement. Its correct name is NAVSTAR-GPS.

Civil applications of NAVSTAR-GPS systems

- Precision navigation
- Hydrographic inspections
- Recognition of objectives
- Seismic inspections
- Recognition of excavations
- Making maps
- Location of banks
- Air navigation
- Positioning and land navigation, among others.

The GPS is composed of:

- The segment of space made up of satellites
- Control segment formed by a series of control stations
- User Segment formed by GPS receivers, where they interact with each other to determine the position.

Coordinate system

In most GPS devices, by default, the position format is latitude and longitude in degrees, minutes and seconds. The choice of the coordinate system will not affect the quality of the position.

It is recommended to use plane coordinates since distances and surfaces can be determined easily.

Datum

According to Fallas, Jorge (2003): cartographic and datum projections are a set of measurements that define the orientation of a determined ellipsoid on the earth's surface, and it helps to make the geographic coordinate system faithfully represent the place where the study is made, corrected for geoid irregularities.

The datum defines the following aspects (Inter-American Geodetic Survey, 1950)

- Ellipsoid in use
- The location (initial position) and orientation of the north (initial azimuth)
- The distance between the geoid and the ellipsoid at the initial location, figure 2.16.

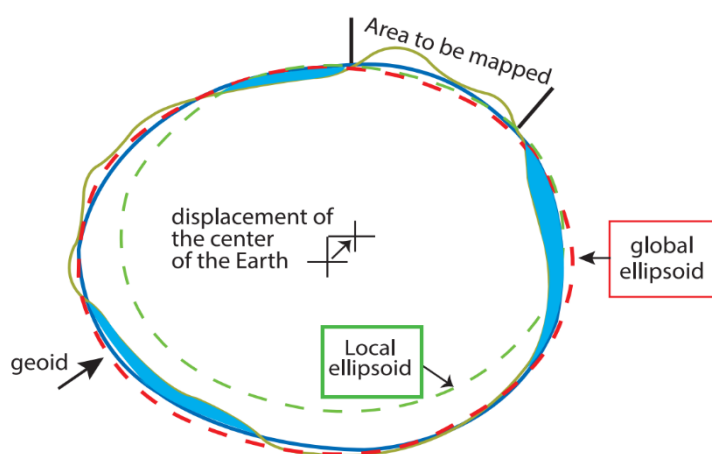


Figure 2.16 graphic comparison between a global and a local ellipsoid.

Source: IDECA, 2013

The datum establishes a permanent reference surface for the mapping of a country or a continent. Parameters defined for the maps generated by the National Geographic Institute of each Central American country are;

Datum: Ocotepeque. The North base of the datum is in the department of Ocotepeque Honduras, at a height above sea level of 807 m. V.J Hanrahan established it in December 1934.

The WGS84 (World Geodetic System, 1984) is the datum used by most GLOBAL POSITIONING SYSTEMS (GPS) to record positions (coordinates) in the earth.

Guatemala has a local GTM (Guatemala Transversal Mercator) projection, where the Projection: Transverse Mercator (Gauss Kruger type) is converted into a single local area. The reason why the National Geographic Institute opts for this modification is that Guatemala is divided into two UTM areas (Universal Transverse Mercator) on the 15th and the 16th. To facilitate the management of the geographic data of the republic and standardize the projections, the GTM is created and cover the entire territory.

Projection

System of representation of the curved surface of the earth on a plane In Central America is the UTM (Universal Transverse Mercator) projection.

2.3.5 Landslide record

The prior knowledge of the historical behavior of the area susceptible to move will be part of the professional criterion, knowing the type of movement and its activity are part of the factors to be considered for the study and subsequent stabilization.

Below are some parameters, factors, and activities that should be documented as part of the basic information needed in the stability analysis:

- Landsliding location (place, kilometer, coordinates, others)
- Type of landslide
- Topography and slope.
- -Geology
- Physical, mechanical properties of the soils and classification of the rock mass
- Water Table conditions
- The humidity of the land
- Thicknesses and degree of weathering, and others

2.4 Geotechnical Study Planning

In the geotechnical planning, the prior knowledge of the lithological units and the behavior of the structural kinematics that has caused the mechanism of tilting or deformation due to the tensional stresses to the rocks are required. Define the limits of the units of greater or lesser resistance and relate them either as a product of microelectronics or by weathering where the hydrological and climatic factor gradually degrades the minerals contained in the matrix of soils and rocks.

With a clear vision of the incident properties in the rock mass, the types of soundings, the orientation, and depth of them are quantified. The number of samples and location is determined. The number of piezometers is established to check the behavior of the groundwater. The orientation of the electrical lines is determined in the exploration of possible cavities; in the application of the electrical resistivity methods, and in the detection of the boundaries of the stratification, planes of failure and fracturing of the rocks.

Then determine possible solutions that guarantee, depending on the scope of the project, stability, and improvement of the soils.

Bellow, the characteristics to be considered in the planning of the geotechnical study are presented in an orderly manner:

1. Determine the geological conditions of the work area
 - Type and characteristics of geological materials
 - Characteristics of the rock massifs
 - Orientation and characteristics of discontinuities
2. Know the geological problems that may affect the construction
 - Important leaks
 - Tectonic zones, singular structures, and cavities
 - Anisotropic tension states
 - Soft and expansive grounds
 - Aggressive or reactive rocks
 - Abrasive and hard rocks
3. Quantify the data and parameters of the land necessary for the design of the work
 - Resilient and deformational properties of soils, rocky matrix, and rock mass
 - Data for geotechnical classifications
4. Provide criteria for the design

2.4.1 Determination of types of field soundings

Table 2.7 shows the types of field geotechnical sounding with soil sampling. The Table details the type of material, maximum depth that can be drilled, serves as a guide for determining the sounding type to be performed.

Before defining what type of sounding will be carried out, it may be useful to answer the following questions:

- What is the type of geo-material to be drilled?
- What kind of samples do I need to obtain?
- What is the depth I need to reach?
- What kind of parameters do I want to obtain?

Table 2.7 Determination of test types in the field

Geotechnical sounding	Rotation probing	They can drill any types of soil or rock, with different inclinations, the usual depth does not exceed 100 m, but it can be deepened up to 1,000 m.
	Soundings with helicoidal drill	It is limited to soft and cohesive soils; the type of sample obtained is altered. There are manual probes that reach 2-4 m and mechanics that reach 40 m in depth.
	Soundings with percussion drill	Used for granular and cohesive soils; it can cross soils of the firm to a very firm consistency. The normal depths are 15 to 20 m and can reach 40 m.
	Test Pits	Excavations carried out by mechanical means allow direct observation of the ground, sampling, and practice tests.

Source: González and others 2002

It is important to clarify that it is possible to carry out a combination of these soundings in the same point depending on what one wants to analyze, the type of structure and the degree of compactness of the soil.

2.4.2 Test Pits

In a study of slopes, it is advisable to exhaust the most economical methods, including the pits, and as research progresses, if necessary, apply more far-reaching techniques such as rotation soundings, SPT, geophysical methods, among others. When the sliding plane is superficial, it is enough to drill one or several test pits to determine the landslide and the water Table. For example, in the landslide of kilometer 71 + 050 of CA 11, immediately on the border of El Florido, Honduras; Figure 2.17, 2.18, and 2.19; were positioned at the foot of the slope the water Table was below -2.2 m depth. With the knowledge of the landslide plane, the water Table and the volume of the sliding material, the researcher can suggest criteria for the stabilization and restructuring of the section affected by the landslide without resorting to more far-reaching methods.

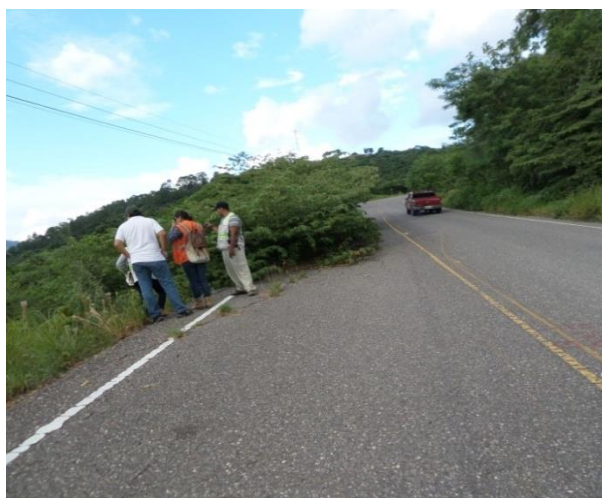


Figure 2.17 Sliding at km 71 + 050 border El Florido, Honduras CA 11

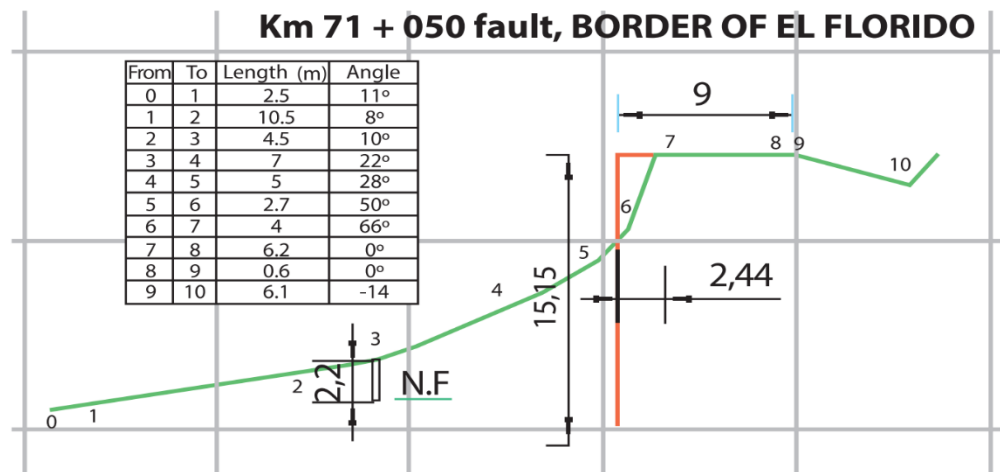


Figure 2.18 Morphology of the slope of the km 71 + 050 fault of the CA 11. In the section of 6-7 (red color) slipping slip of 2.44 m inside the road (section of 7-8). Section of 2-3 construction of pits and location of the water Table at -2.2 m and 15 m from the level of the road

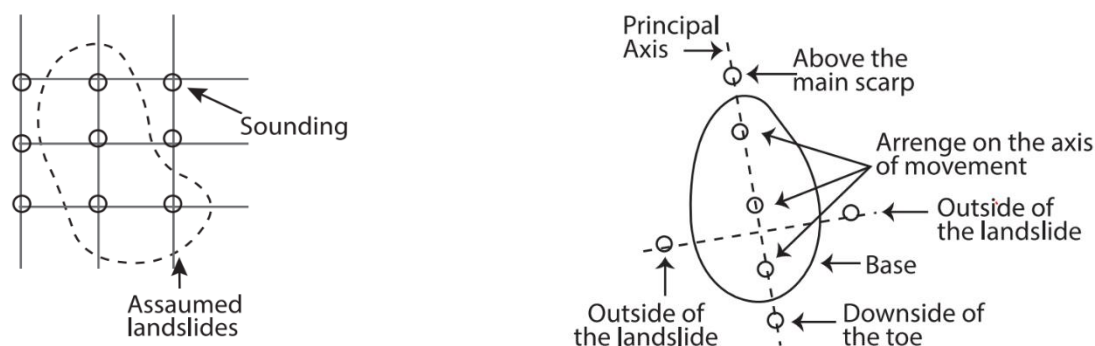


Figure 2.19 Pit with presence of water at -2.2 m depth, in clayey soil

2.4.3 Quantification

The number of soundings and the depth to reach depends on the resistance of the terrain, filtrations, deformability, etc., should reach the level of the most stable substrate of the stratigraphic column. The number of soundings depends on the objectives and the representativeness of the area under investigation.

In the case of a susceptible landslide, a surveying mesh with soundings in each intersection of the mesh is planned. For the detection of a slip zone, the stratigraphic profiles are determined to obtain the properties of the soils and rocks that affect the sliding behavior of the slope, as figure 2.20 (a) and (b).



a) Suggested location of soundings in an area where a landslide is suspected, (9 soundings)

b) Suggested location of soundings in an active landslide zone, (7 drillings)

Figure 2.20 Location of slope soundings. Suarez, 2009.

For the depth of the soundings, there is no defined rule. One criterion is geological and geotechnical zones, for example: if there were three zones where zone 1 is of least resistance, zone two of medium resistance and zone three of high resistance; It is advisable to cross zone one and two, penetrate at least five meters in the zone, three. The stratigraphy and lithological structures associated with sliding should be considered.

2.4.4 Scope of tests for mass movements

The tests must be planned, representative, and must reach the objectives for which they are programmed. For example, if we need to know the actual thicknesses of the stratification in sedimentary rocks, the sounding should be oriented perpendicular to the inclination of the stratification planes and ensure that the units that cut are representative of the formation being investigated. Equal to define the planes of sliding of a fault, the sounding must cross it of minimum 5 m ensuring that the final terrain of the sounding does not represent risks of instability. Otherwise, the sounding will be unsuccessful, and it should be considered as a sounding that did not reach the objective — repeated in the same place and with the same orientation.

When you have geophysical studies and drill to corroborate the results, the researcher should consider the orientation of electrical profiles, resistivity or other applied, and guide the soundings in the same direction so that the results are representative. Otherwise, there may be significant variations in the results.

Bellow, there is a list of the scope of a geotechnical study for road slopes, depending on the characteristics of the slope, some or all of those mentioned can be known

- Identify and characterize the weakest formations that can affect movement
- Identify the most resistant formations that can limit the extension of the fault zone
- Locate groundwater levels, pressures, and water characteristics
- Identify the subsurface distribution of materials
- Quantify the physical properties of the materials (humidity, gradation, plasticity, resistance to cutting, etc.) for later use in the stability analysis
- Place instruments for measuring deformations or water levels
- Determine geotechnical parameters such as RQD
- Corroborate the geophysical tests

2.4.5 Minimum tests proposed

One test must be performed for each stratum of soil (the stratum being understood as the horizontal layer that differs by its color, texture, structure, consistency, and reaction or pH of the other layers) found in the lithological profile of the pit.

If there is no lithological contrast in the profile of the pit, the depth must be subdivided into sections that are not less than 0.50 meters or greater than 1.50 meters to obtain a representative sample. On each horizon take a representative segment of the unit.



CHAPTER 3

GEOTECHNICAL STUDY FOR SLOPES

CA-04, La Libertad, El Salvador

Regional knowledge of geology, seismicity, and hydrogeological conditions provide the first guideline or what is expected from the behavior of slopes in construction sites. Determine the parameters required for the design of slopes is an important task because it is present in any construction activity: linear, extractive or movement below the surface, it is necessary to calculate the resistance of the materials to shape them adequately.

It is necessary to know adequate measurement techniques for the soils and rocks, and the structures to obtain accurate terrain conditions.

It is convenient to rely on laboratory activities to obtain results that support those compiled in the field and sometimes requires seismic methods and rotation or percussion soundings to know the conditions of the subsoil.

The study of slopes is multidisciplinary because professionals from different areas of engineering must participate: seismologists, hydrologists, geotechnical engineers, civil engineers, geologists, and others.

3.1 Research in situ

From the *in-situ* research, the parameters and properties that define the conditions of the land where the project will be built, are obtained. See Table 3.1

Table 3. 1 Parameters and properties that define the terrain conditions

1. Determine the geological conditions of the work area.	- Type and characteristics of geological materials - Characteristics of rock masses - Orientation and characteristics of discontinuities
2. Know the geological problems that can affect the construction.	- Important leaks. - Tectonized areas, singular structures, and cavities - Soft and expansive grounds. - Aggressive or reactive rocks. - Abrasive and hard rocks.
3. Quantify the data and terrain parameters necessary for the development of the work.	- Resistant and deforming properties of soils, rocky matrix, and rocky massif. - Data for geotechnical classifications. - Resistant and deforming properties of soils, rocky matrix, and rocky massif. - Data for geotechnical classifications.
4. Provide criteria for the design.	

Source: González 2002

3.1.1 Water Table

According to the Royal Academy of the Spanish Language; the phreatic level corresponds to the upper part of a groundwater Table (groundwater at a relatively low depth below ground level), or an aquifer in general (figure 3.1), unlike the piezometric level. It is considered as the altitude or depth (about the surface of the soil) of the boundary between the water Table and the vadose zone in an aquifer.

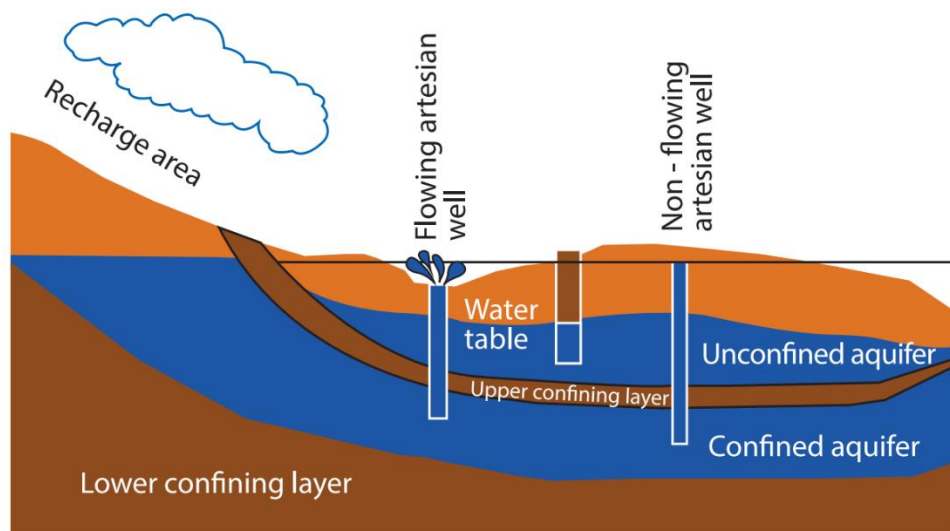


Figure 3. 1 Phreatic level, superficial part of a phreatic layer

Source: <https://www.slideshare.net/MarianelaDiaz4/aguas-en-los-suelos>

In each hand-drilling, piping, excavation, and sounding, the variation of the water Table must be recorded carefully. When groundwater is found or when saturated impermeable soils are crossed, fast reading piezometers must be installed to observe the water Table for a considerable time and to determine its behavior with time changes.

The phreatic level can be found at different depths depending on the geological and climatic circumstances, generally due to the meteorological conditions that recharge the aquifers. The water Table is not horizontal but irregular; Table 3.2 refers to the geological formation and its behavior about water. Table 3.3 presents the types of aquifers according to their structure and functioning.

Table 3.2 Geological formations and their behavior against water

		Storage capacity	Drainage capacity	Transmission capacity	Formations
AQUIFERS	→	HIGH	HIGH	HIGH	Gravels, sands, limestones
AQUITARD	→	HIGH	MIDDLE-LOW	LOW	Limes, silty and clayey sands
ACUICLUDOS	→	HIGH	MUY BAJA	NULL	Clays
ACUIFUGOS	→	NULL	NULL	NULL	Granites, gneisses, marbles.

Source: González and others 2002.

Table 3.3 Type of aquifers according to their structure and operation.

RELEASE	→	Release of water by desaturation	They release water by desaturation, the water that is stored in the water they have stored.
CONFINED OR CAPTIVATED	→	Elastic water elimination	They are isolated in the subsoil, surrounded by waterproof materials on all sides.
SEMICONFINATED	→	Recharge drain or vertical drip	The materials that surround them are not all waterproof.

Source: González and others 2002.

The soil is a material with the variable arrangement of particles that leave between them a series of pores connected to form a complex network of channels of different magnitudes that communicate both with the surface of the ground and with the fissures and cracks of the mass. Hence, the water that falls on the ground runs off, and part infiltrates by gravity to deeper impermeable layers, forming the so-called *water Table*. The upper limit of this watery mantle is called the *water Table*. The water that passes through the pores through the ground is known as *gravitational water*, and that which is below the *water Table* is called groundwater. When the movement of gravitational water through the soil is suspended, part of the water is retained in the pores and on the surface due to *surface tension* and adsorption forces. In figure 3.2, the names appear according to the state of the water on the ground.

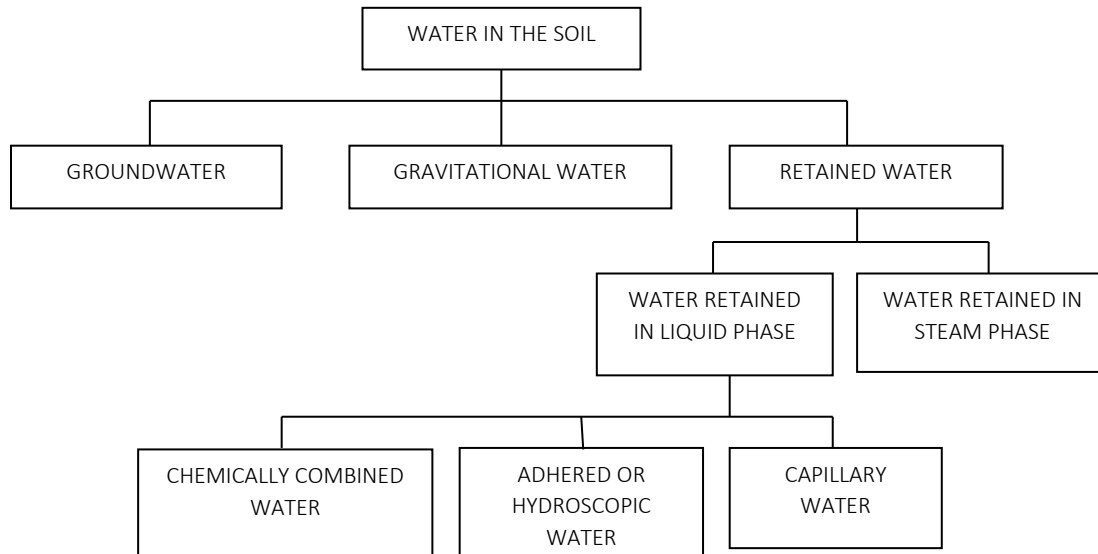


Figure 3. 2 Names of the water according to the state in which it is in soil

3.1.2 Hydrogeological conditions

The hydrogeological parameters characteristic of geological formations is based on four basic parameters in terms of their behavior concerning the water they can contain and transmit; see Table 3.4 for more details and Table 3.5 shows methods for evaluating hydrogeological parameters.

Table 3.4 Hydrogeological parameters characteristic in geological formations

Porosity	It is the relation between the volume of holes and the total volume of the rock.
Storage coefficient	Represents the ability to release water from an aquifer. It is defined as the volume of water that can release a prism of unitary base and height of the aquifer when the piezometric level falls one meter.
Permeability	Evaluates the ability to transmit water from a formation according to the texture, without relating it to its structure or geometric shape.
Transmissivity	Evaluates the capacity to transmit water from aquifers, considering: texture of the aquifer, structural or geometric characteristics.

Source: Own elaboration based on González and others 2002

Table 3.5 Methods of evaluation of hydrogeological parameters

Pumping tests	It is the most complete and reliable method for calculating the hydrogeological parameters of an aquifer. It consists of pumping a well, in principle at a constant flow, and analyzing the decrease in piezometric levels.
Injection tests	They are practiced in situ, and the most frequent is the Lugeon test in rock and Lefranc in soils, Matsuo and others.
Tests with tracers	It consists of injecting a tracer in a point of the aquifer and observing its arrival to another point of the same aquifer, determining the transit time between both points. The flow velocity and direction, permeability can be obtained.

Source: Own elaboration based on González and others 2002

3.1.3 Lithology and geological structure

LITHOLOGY

Lithology is part of the geology that studies rocks, their grain size, the shape of physical and chemical particles, mineralogy and cementing material through petrography. Geology studies materials and classifies them according to their genesis or formation (Abramson, 1996)

Each type of rock has a specific susceptibility to landslides. When several types of rock form a slope, the geotechnical behavior of the set is different from that of each separate material. The properties of each type of rock, the characteristics of its discontinuities and, in turn, the weathering of the properties and discontinuities within the whole must be studied. Table 3.6 gives a general classification of the various geological materials and lithological characteristics.

Table 3.6 General classification of the various geological materials for engineering

Type of material	Formation	Lithological characteristics	Characteristic structures
Rock	Igneous metamorphic	Rock formed by mineral crystals.	Geological structure Fractures
	Sedimentary (the type of rock must be defined in the most detailed formation possible)	Rock formed by cemented grains, deposited in layers.	Stratification plans.
Weathered rock (saprolite)	Igneous Metamorphic Sedimentary	Some features of the rock remain, but this one is decomposed, in the discontinuities.	Geological structure Discontinuities. Weather condition
Soil	Residual	Weathered rock in which the physical characteristics of the rock no longer appear.	Geological structure Discontinuities. Physicochemical properties
	Alluvial Colluvial Loess	Group of particles or blocks of soil or rock.	Propiedades físicas.
Heterogeneous materials	Rock Weathered rock ground	A mix of different materials in the same profile.	Geological structure Discontinuities. Methodization Physicochemical properties.

Source: Landslides and stability of slopes in tropical areas. Suarez Días, J.

Intrusive igneous rocks

According to the book *Slides and stability of slopes in tropical zones*, the intrusive igneous rocks "are the product of magma cooling before it surfaces to the surface. This type of rocks forms 98% of the volume of the earth's crust, although in the surface sedimentary rocks are more common and in a lesser proportion the igneous and metamorphic ones". Table 3.7 makes a general classification of intrusive igneous rocks.

Table 3.7 General classification of intrusive igneous rocks

Granite	Granite is a coarse-grained acid igneous rock, composed mainly of quartz, feldspars and some mica with some other secondary components.	
Greenstone	An intermediate coarse-grained igneous rock composed mainly of feldspars, plagioclase, as well as hornblende, which is a green ferromagnesian material. The content of quartz can reach up to 10%. The rock has a color that varies from greenish white to green, depending on the hornblende content.	
Dolerite	It is a basic igneous rock with a high content of magnesium, calcium, or sodium in its chemical composition. Approximately half of the mineral composition is constituted by the ferromagnesian olivine pyroxene, and hornblende. Its color varies from grayish-green to dark green. The darker color indicates a higher iron content. When weathering produces iron and brown clay hydroxides	
Gabbro	It is essentially composed of plagioclase and pyroxene and may have small amounts of quartz; its color is mottled gray. The size of the crystals is greater than that of Dolerite.	

Source: Own elaboration based on *landslides and stability of slopes in tropical zones*. Suarez Días, J. Photos available in: las rocas ígneas características y algunos ejemplos-youtube https://www.youtube.com/watch?v=a9a_5G6pgdA

Volcanic or igneous extrusive rocks

From the book *Landslides and stability of slopes in tropical zones* "volcanic or pyroclastic rocks also known as extrusive igneous rocks are the product of the crystallization of materials expelled by volcanoes," Table 3.8 gives a general classification of extrusive igneous rocks.

Table 3.8 General classification of extrusive igneous rocks

Rhyolites	It is the exclusive fine-grained component of granite magma that escaped from the surface through a volcanic eruption and has some granite-like characteristics. Mega crystals of quartz or feldspar give the rhyolites differences in character and behavior.	
Tuff	Volcanic tuffs are rocks formed by loose material thrown by an erupting volcano. They are very porous and rich in glass materials. Occasionally, the tuffs have deposits of clay, expansive materials, or unstable clays.	
Andesite	Andesite is a fine-grained volcanic rock, found as lava flow and occasionally, as small inclusions. Generally, it is dark in color. The constituent minerals are essentially plagioclase, hornblende, and biotite with very little quartz.	
Basalts	Basalt is a basic fine-grained igneous rock, formed by a volcanic eruption that crystallizes very quickly. The mineral composition of basalt is approximately half pyroxene and half plagioclase, up to 5% iron oxide.	

Source: Own elaboration based on landslides and stability of slopes in tropical zones. Suarez Días, J. Photos available in: las rocas ígneas características y algunos ejemplos-youtube https://www.youtube.com/watch?v=q9a_5G6pgdA

Metamorphic rocks

The book Landslides and stability of slopes in tropical zones describe that metamorphic rocks "are in the result of Metamorphism or recrystallization of igneous and sedimentary rocks, in this process the rocks are subjected to textural and mineralogical changes, in such a way that their original characteristics are altered or completely lost." In Table 3.9, a classification is made, and a brief description of metamorphic rocks is shown.

"The behavioral characteristics of the slopes in healthy metamorphic rocks depend on their fracturing and banding patterns (texture and structure microstructure). The foliation and schistosity present in some metamorphic rocks make them very susceptible to weathering".

Table 3.9 Type of metamorphic rocks

Quartzite	They are metamorphic rocks, formed by quartz, sometimes with traces of Muscovite, Ortoclase, Albite. They derive from metamorphism on sandstones.	
Neis	It is a banded or foliated rock, in which bands of light color, quartz and feldspar form parallel microstructures with bands of other minerals such as biotite and hornblende and in some cases pyroxene. Muscovite usually accompanies the biotite.	
Shale	Consist of flat crystals of micas, green chlorite, hornblende, quartz. The crystals are tubular and align so that the failure of the rock easily into flat fragments. The shales are very unstable materials on the slopes due to their microstructure and the ease with which they weather.	
Serpentinite	Color slightly greenish to yellowish green. Fibrous appearance and soft to the touch. Marbled texture. Main component serpentine, talc, magnetite, chlorite, etc.	
Slate	It is a hard rock formed under the influence of very high stresses on clay sediments. The crystallization process forms laminar minerals such as chlorite and sericite and some quartz grains. Sometimes, the rock has many planes of cleavage, in such a way that flat sheets of rock are formed that are used as a construction material. Sometimes, these layers or sheets are very thin and fissile.	
Filita	It is a rock like slate but has flat oval crystals like tree leaves, which give the planes of cleavage or exfoliation a characteristic texture. These planes of cleavage are crossed by fractures that often have a geometric pattern. It is a rock like slate but has flat oval crystals like tree leaves, which give the planes of cleavage or exfoliation a characteristic texture. These cleavage planes are crossed by fractures that often have a regular geometric pattern, causing the rock to failure into rhombohedral or rectangular shapes. It causes the rock to failure into rhombohedral or rectangular shapes.	
Marble	Formed of limestone rocks subjected to temperature and pressure. The basic component is calcium carbonate (90%). There are several colors (white, brown, red, black, gray, etc.)	
The Chert	It is an organic and inorganic precipitate of silica. Silica is mainly cryptocrystalline quartz. The chert can occur in the form of precipitation or nodular.	

Source: Own elaboration based on landslides and stability of slopes in tropical zones. Suarez Días, J. Photos available: <http://geologiaonline.com/rocas-metamorficas/>

Sedimentary rocks

According to the book Landslides and stability of slopes in tropical zones, " *Sedimentary rocks are formed by the sedimentation and cementing of clay particles, sand, gravel or ridges.*"

" *Its stability characteristics generally depend on the size of the grains, the stratification planes, the normal fractures to the stratification and the degree of cementation* "; Table 3.10 shows the characteristics, and in Table 3.11 a general classification of sedimentary rocks plus a brief description of each is made.

Table 3.10 Characteristics of sedimentary rocks

Rock	Component	Characteristic
Conglomerate	Large rounded particles of rock and fragment of minerals.	More than 50% of grains greater than 2 mm and less than 25% of clay
Gap	Angular rock particles and mineral fragments.	More than 50% of grains greater than 2 mm and less than 25% of clay
Sandstone	Rounded minor particles of rock.	More than 50% of the grains between 2 and 0.06 mm and less than 25% of clay
Limonite	Silt particles.	More than 50% of grains less than 0.06 mm and less than 25% clay
Arcillolite	Clay particles.	More than 50% clay.
Lodolite	Clay rocks with high silt content.	More than 50% of silt
Limestone	Calcite grains	More than 50% calcite and less than 25% clay

Source: Own elaboration based on Landslides and stability of slopes in tropical zones. Suarez Días, J.

Table 3.11 Types of sedimentary rocks

Sandstone	Sandstones are a form of sand hardened by geological processes. The size of the grains varies from 60µm to several mm, and are cemented by other minerals, often by precipitated quartz. They are classified according to the size of their grains as fine, medium, or coarse and according to the nature of the cementing materials. Although sandstones tend to be resistant, they are sometimes relatively weak when their cementation has been poor.,	
lutaceous rock, mudstone, or pelitic rock	Rocks containing significant amounts of clay are referred to as shales, siltstones, and mudstone. The shales are one of the most complex materials for slope stability. According to the degree of solidification, the shales vary in their behavior. The shales of low grade tend to disintegrate after several cycles of drying and wetting.	
Limestones and dolomites	Limestone is a sedimentary rock with more than 50% calcium carbonate. The limestones in which the calcite is replaced by dolomite, a product with high magnesium content is called dolomites. This rock is usually hard and compact, but there are geotechnical problems related to the dissolution of CaCO ₃ . There is a variety of rocks in the limestone family depending on the amounts of calcium carbonate, sand, silt, marine animal shells, and clay. They are bluish gray, but there are also white and other colors. In the limestones, large caverns can be formed that act as internal conduits of the groundwater, which can lead important quantities of water from one place to another and facilitate the general infiltration. The denudation of the limestone rocks caused by the infiltration of rainwater forms a karstic topography.	
Evaporites	Evaporites include gypsum, anhydrite, and halite. They are generally associated with mudstones, siltstones, and limestones, forming layers of evaporites.	

Source: Own elaboration based on Landslides and stability of slopes in tropical zones. Suarez Días, J. Photos available in <https://www.piedraspara.com/tipos-de-piedras/rocas-sedimentarias/>

Residual soils

Residual soils are referred in "Landslides, and stability of slopes in tropical zones" as *the product of weathering rocks and their behavior depends on the properties of the original rock and the degree of decomposition, Figure 3.3, Table 3.12. Landslides are very common in residual soils, especially during periods of intense rainfall*".

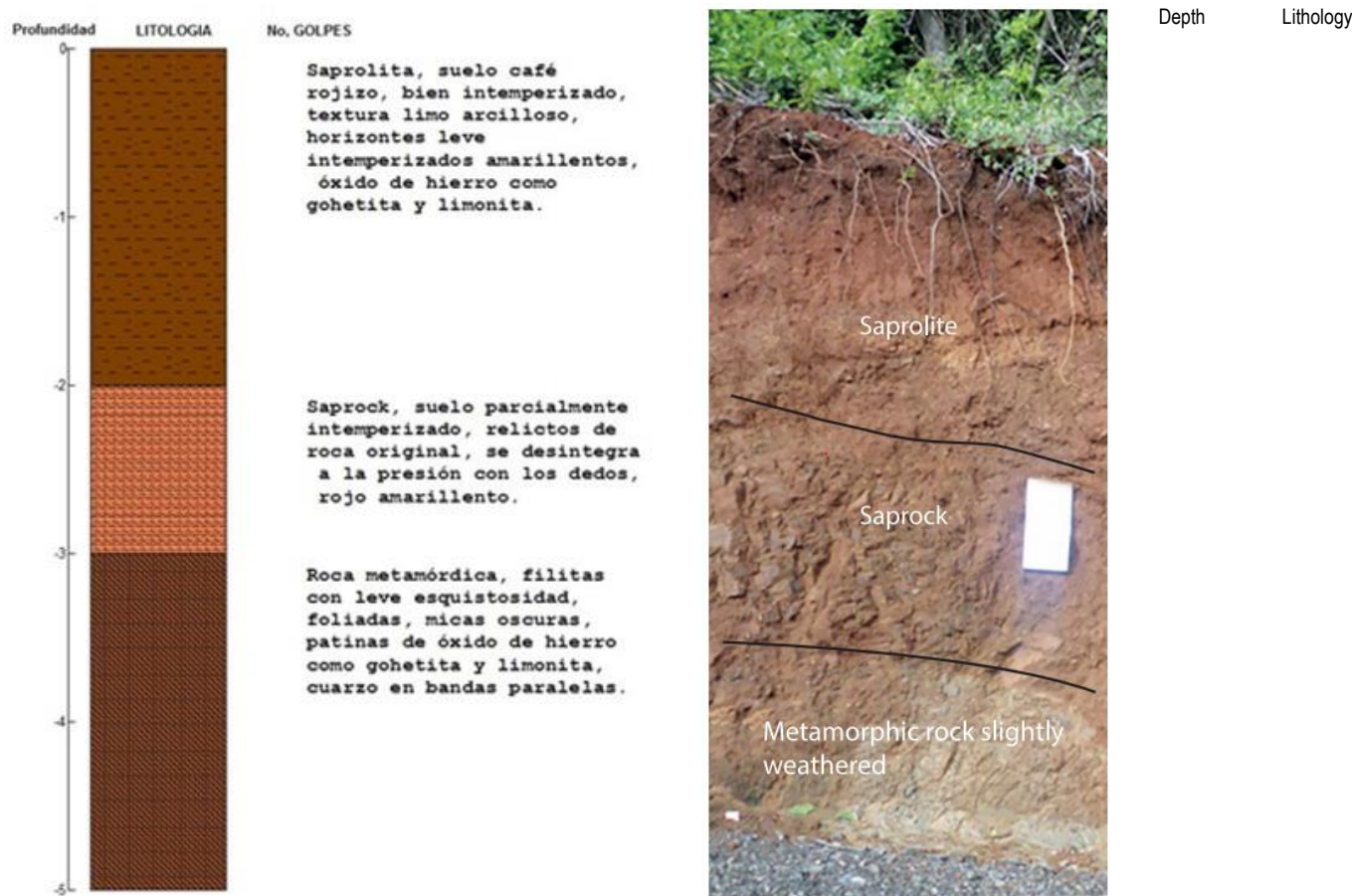


Figure 3. 3 Residual soil in weathered metamorphic rock. Roatán, Honduras.

Table 3.12 Classification of residual soils

Alluvial soils	The alluvial soils are deposits transported by the water in movement and deposited when the speed of the water has diminished; These materials may be of fluvial or lacustrine origin and may contain fine, coarse or intermixed particles. The alluvial deposits are generally stratified, and the permeability in the horizontal direction is greater than in the vertical direction. Alluvial soils, composed of clay tend to be soft, and sandy soils tend to be loose. Due to their lack of cementing, alluvial materials are prone to erosion and landslides.
Organic deposits	Deposits of organic materials, peat deposits, or organic material that has not completely decomposed, due to its high-water content. Organic deposits are sometimes stratified with other elements such as silt or sand or interspersed with clay. These materials are very problematic for the execution of excavations due to their very low shear strength. It is common for organic materials to flow when excavating or liquefying in seismic events.
Colluvial soils	Colluvial or colluvial soils are hillside deposits, the product of rock or soil landslides and slides and are very susceptible to landslides
Wind soils	The wind transports the aeolian soils and varies from dunes to Loess, which are deposits of fine sand and silt. Generally, they have very little vegetation, and the materials are very rich in quartz and not very dense. The main problem of wind deposits is erosion.

Glacial soils

The glacial deposits are transported by the glaciers, which, when the temperature increases, thaw and these glacial deposits of soil are formed. Glacial deposits can vary in grain size composition, from large boulders to clays.

Source: Own elaboration based on landslides and stability of slopes in tropical zones. Suarez Días, J.

Geological structures

The geological structure is one of the factors that most influence the stability of an excavation; Table 3.13 shows the type of geological structure and the geotechnical problems. Table 3.14 presents the types of discontinuities, and Table 3.15 describes the requirements to identify discontinuities in faults.

In folded and stratified rocks, the orientation of the strata conditions the behavior against stability.

His influence is as follows:

- Diving off the structure concerning the road
- Direction of stratification to the road
- Types of creases

Table 3.13 Geological structures and geotechnical problems

Geological structures and geotechnical problems		
Geological structures	Characteristics	Geotechnical problems
Faults and structures	Very continuous surfaces variable thickness	Failures, instabilities, accumulation of tensions, leaks, and alterations.
Stratification plans	Continuous surfaces little separation	Unstable failures and leaks.
Discontinuities	Slightly continuous surfaces Closed or little separated	Unstable failures, leaks, and alterations.
Folds	Great continuity surface	Instability, leaks, and stresses conditioned to orientation.
Foliation and schistosity	The surface of little continuity and closed	Anisotropy depending on the orientation.

Source: Own elaboration based on González and others 2002

Table 3.14 Types of discontinuities

Types of discontinuities		
Discontinuities	Systematics	Singular
Planar	Stratification plans. Rolling plans. Joints or joints. Schistosity planes.	Faults Dykes. Disagreements
Linear	The intersection of planar discontinuities. Lineations	Folding axes.

Source: Own elaboration based on González and others 2002

Table 3.15 Discontinuities and requirements

Discontinuity	Requirements
Failures	Know the regional and local tectonic structure
	Structural analysis
	Identification of faults and their classification according to the origin, age, type, and geometry
	Identification of fault filling, its resistance, and expansiveness
	Know the hydraulic transmissibility
The representation of the planes is through stereographic projection.	

Source: Own elaboration based on González and others 2002

Description of discontinuities

- Orientation
- Spacing
- Continuity and persistence
- Rugosidad
- The resistance force of the walls
- Opening
- Filling
- Leaks

Orientation description

The orientation of a plane refers to the position of a plane in space defined between two angles: the bearing and the inclination of the plane.

The orientation and inclination of the stratigraphic planes contained in a section determine the stability of the slope. A stratigraphic plane opposite to the line of the road provides stability in the walls of the slope, contrary to the planes that dip towards the road, are susceptible to landslides.

The orientation of a discontinuity in space is defined by its direction of dip (direction of the line of maximum slope of the plane of discontinuity concerning the north) and by its dip (inclination concerning the horizontal of the said line). The compass makes its measurement with an inclinometer.

The discontinuities have characteristics that identify and zoning a slope; Table 3.16 describes the spacing of the discontinuities; Table 3.17 presents the description of measuring the continuity of the discontinuities; Table 3.18, the roughness of discontinuities and Table 3.19 opening of discontinuities.

Table 3.16 Description of spacing in discontinuities

Description	Spacing
Extremely together	<20 mm
Very together	20 – 60 mm
together	600 – 200 mm
Moderately together	200 – 600 mm
Separated	600 – 2,000 mm
Very separate	2,000 – 6,000 mm
Extremely separated	>6,000 mm

Source: International Society for Rock Mechanics, ISMR, 1981

Table 3.17 Description of continuity of discontinuities

Continuity	Longitud
Very low continuity	<1 m
Low continuity	1 – 3 m
Medium continuity	3 – 10 m
High continuity	10 – 20 m
Very high continuity	>20 m

Source: International Society for Rock Mechanics, ISMR, 1981

Table 3.18 Description of the roughness

Staggered	Wrinkled	I
	Smooth	II
	Polished	III
Wavy	Wrinkled	IV
	Smooth	V
	Polished	VI
Flat	Wrinkled	VII
	Smooth	VIII
	Polished	IX

Source: International Society for Rocks Mechanics, ISRM 1981

Table 3.19 Opening description

Opening	Description
<0.1 mm	Very close
0.1 – 0.25 mm	Close
0.25 – 0.50 mm	Partially open
0.50 – 2.5 mm	Open
2.5 – 10 mm	Moderately broad
>10 mm	Wide
1 – 10 cm	Very wide
10 - 100 cm	Extremely wide
>1 m	Cavernous

Source: International Society for Rocks Mechanics, ISRM 1981

Description of resistance in the walls

It influences the cut resistance and its deformability. It depends on the type of rock matrix, the degree of alteration, and the existence or not of the filling. In healthy and clean discontinuities, the resistance would be the same as that of the rock matrix, but it is generally less due to the weathering of the walls: alteration processes affect the discontinuity planes to a greater degree than to the rocky matrix.

The resistance can be determined in the field with the Schmidt hammer, by applying it directly in the plane of the discontinuity. With the obtained values, the rock can be classified by its resistance, Table 3.20.

Table 3.20 Classification based on the strength of the rock

Simple compression resistance (MPa)	Description
1-5	Very soft
5-25	Soft
25-50	Moderately hard
50-100	Hard
100-250	Very hard
>250	Extremely hard

Source: Miller, 1965.

Miller, 1965, presents a correlation for the Schmidt hammer between compressive strength, rock density, and rebound, see figure 3.4, however, this figure is by way of example since each Schmidt hammer contains a unique comparative Table.

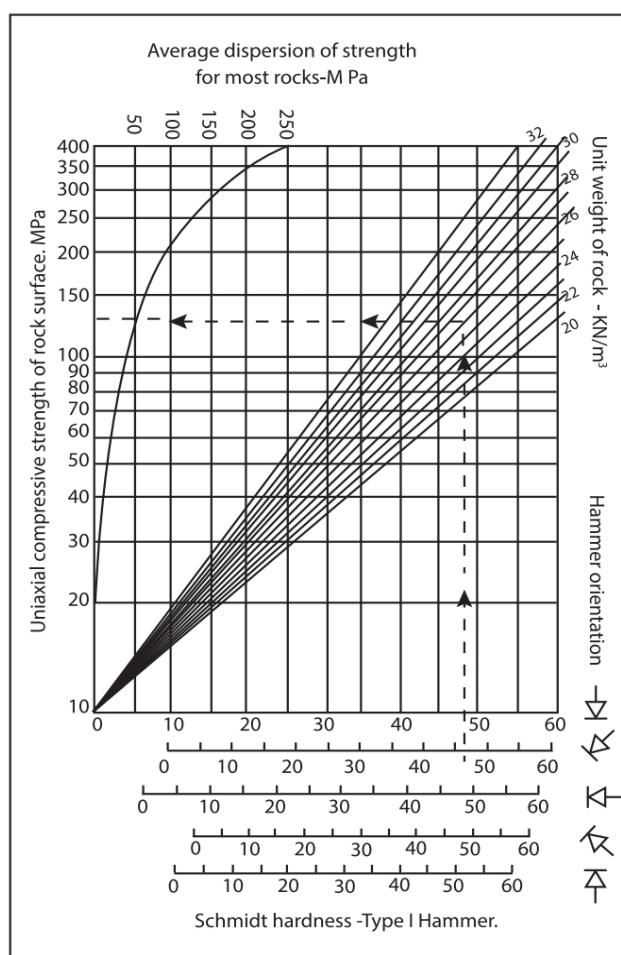


Figure 3. 4 Correlation for the Schmidt hammer between compression strength, rock density, and rebound (Miller, 1965)

Filling description

The filling can be different from the rock and with variable physical and mechanical properties. It must be considered that, if they are soft or altered materials, they can suffer important variations in their short-term resistant properties if their moisture content changes or if there is some movement along the joints.

Characteristics of the landfill must be described in outcrop:

- Nature (material identification, mineralogical description, and grain size)
- Thickness or width (measured directly with a ruler)
- Resistance to cutting (the soil and rock classification Table can be used for its simple compressive strength, as shown in Table 3.21).
- Permeability (is conditioned by the matrix and the number of fractures of the rock mass)

Table 3.21 Approximate estimation and classification of the resistance to simple compression of soils and rocks from field index

Sort	Description	Field identification	Approximation to the range of simple compression resistance (MPa)
S ₁	Very soft clay	The fist easily penetrates several cm.	<0.025
S ₂	Weak clay	The finger easily penetrates several cm.	0.025-0.05
S ₃	Firm clay	It takes a little pressure to sink the finger.	0.05-0.1
S ₄	Rigid clay	It takes a strong pressure to sink the finger.	0.1-0.25
S ₅	Very rigid clay	With some pressure, it can be marked with the nail.	0.25-0.5
S ₆	Hard clay	It is marked with difficulty when pressing with the nail.	>0.5
R ₀	Extremely soft rock	Se puede marcar con la uña.	0.25-1.0
R ₁	Very soft rock	The rock crumbles when hitting with the tip of the hammer. With a razor, it is easily carved.	1.0-5.0
R ₂	Soft rock	It is carved with difficulty with a knife. When striking with the tip of the small hammer marks are produced.	5.0-25
R ₃	Moderately hard rock	It cannot be carved with the knife. It can fracture with a strong hammer blow.	25-50
R ₄	Hard rock	It takes more than one hammer blow to fracture it.	50-100
R ₅	Very hard rock	It takes many hits with the hammer to fracture it.	100-250
R ₆	Extremely hard rock	When hit with the hammer, only splinters are thrown.	>250

Source: International Society for Rock Mechanics, ISMR, 1981

Leaks

When the flow circulates through the rock matrix which is directly related to the porosity, it is called: primary permeability; and when the flow circulates through the discontinuities, it is called: secondary permeability. Table 3.22 makes observations regarding leaks in discontinuities, with filling and without filling.

Table 3.22 Description of leaks in discontinuities

Sort	Discontinuities without filling	Discontinuities with filling
I	Very flat and closed board. It appears dry, and it does not seem possible that water circulates.	Consolidated and the dry filling do not seem possible circulation.
II	Dry board without evidence of water flow.	Wet fill but without free water.
III	Dry board but with evidence of water flow	Wet fill with an occasional drip.
IV	Wet board but without free water.	Filling with wash samples, continuous flow (estimate flow)
V	Joint with ooze, occasionally dripping but without continuous flow.	Locally washed fill, considerable flow according to preferred channels (estimate flow)
VI	Joint with a continuous flow of water (estimate the flow rate in l/min and the pressure,	Fully washed padding, high water pressures.

Source: International Society for Rock Mechanics, ISMR, 1981

3.1.4 Definition of the type of failure in rock and soil

Table 3.23 shows the types of failure in soil and rock with a brief definition

Table 3.23 Definition of the type of failure in rock and soil

TYPES OF FAILURE		
	Failure types	Definition
SLOPES IN SOILS	Approximately circulates	The most frequent, with its lower end at the foot of the slope, (foot slip) when this is formed by homogeneous terrain or by several strata of homogeneous geotechnical properties.
	Almost circular, but passing under the foot of the slope	When a slip surface is deep
	Flat surface	When the slope composes different strata or layers. It is considered "infinite" when the contact surface is parallel to the slope, between the surface terrain (colluvial or residual) and underlying rock.
	Polygonal surface	Formed by several flat sections.
SLOPES IN ROCK	Flat failure	It occurs in favor of a preexisting surface: stratification, tectonic joints, failure, etc. The basic condition discontinuities are diving in favor of the slope and with its same direction.
	Wedge failure	Sliding of a wedge-shaped block formed by two planes of discontinuity in favor of the intersection line.
	Stratus overturning	Rocky massifs with strata diverging from the inclination of the slope and direction parallel or subparallel to it.
	Failure by buckling	It occurs in favor of stratification planes in favor of the slope with a greater dip than the angle of internal friction.
	Curved failure	It can occur in soft rocky massifs and massifs that are highly altered or intensely fractured.

Source: Own elaboration based on González and others 2002

3.1.5 Geological-geotechnical cartography at scale between 1:2000 and 1:500

The International Association of Engineering Geology (IAEG) has no standard procedure, due to the complexity of the geological environment and the different purposes and applications of the geotechnical maps. There being differences of the maps concerning the data presented as to the form of present them; Table 3.24 makes a cartographic representation of the basic cartographic elements for geotechnical maps. Figure 3.5 exemplifies how geotechnical data from geotechnical tests can be presented.

Information on the characteristics and geotechnical properties of the soils and rocks should be presented on the map:

- Assignment of geological-geotechnical properties to different lithological assemblies or units established.
- Delimitation of homogeneous units concerning some property (resistance, density, plasticity, degree of fracturing, degree of alteration, etc.)
- Zoning of geotechnically homogeneous units and assignment of quantitative values.
- The data represent them by isolines of quantitative values.

It is common to use standard geomorphological and geological graphic symbols, but not the letters and numbers that are used to define the lithologies and ages of geological formations, as they do not provide information on their physical and mechanical properties.

Usually, it also includes geological-geotechnical classifications of materials, columns of soundings, sheets of test results, and photographs of some aspects of geotechnical interest.

The legend must detail and clarify the information contained in the map, being frequent that it is wide and explicit, and that includes classification Tables and complementary data.

Table 3.24 Cartographic representation of the basic elements in geotechnical maps

Scale	Classification of soils and rocks	Geological-geotechnical properties	Hydrological conditions	Geomorphological conditions	Dynamic processes
Little	Colors and patterns. Letters and numbers	Colors and patterns	Symbols and numerical values	Level curves Punctual symbols for geomorphological	Symbols

Scale	Classification of soils and rocks	Geological-geotechnical properties	Hydrological conditions	Geomorphologic al conditions	Dynamic processe s
				elements.	
Average			Contours and lines Numerical values	Level curves Limits and morphological features of detail.	
Big		Colors and patterns Numerical values Diagrams and graphs	Isovalue lines Numerical values		Contours and lines

Source: González and others 2002

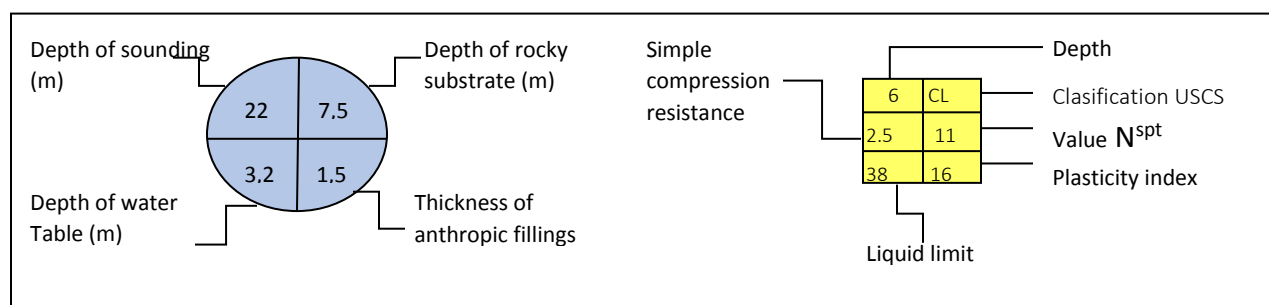


Figure 3. 5 Example of a diagram for the representation of geotechnical data from drilling or testing.
Source: González and others 2002.

As for the legend, it must detail and clarify the information contained in the map, being frequent that it is broad and explicit, and that it includes classification Tables and complementary data. In the leaves can be included, next to the legend, auxiliary or complementary small-scale maps, much smaller than the geotechnical map.

3.2 Test pits in weathered soils or rocks

Sampling in pits or other soil excavation, altered or unchanged samples may be taken. The altered samples are extracted with shovels or manual methods by inserting them in sturdy plastic bags. The amount of sample to be taken depends on the granulometry of the materials and the type of tests to be carried out; Figure 3.6 exemplifies the volume of the sample applied to the different tests. Table 3.25, presents a record in test pits.

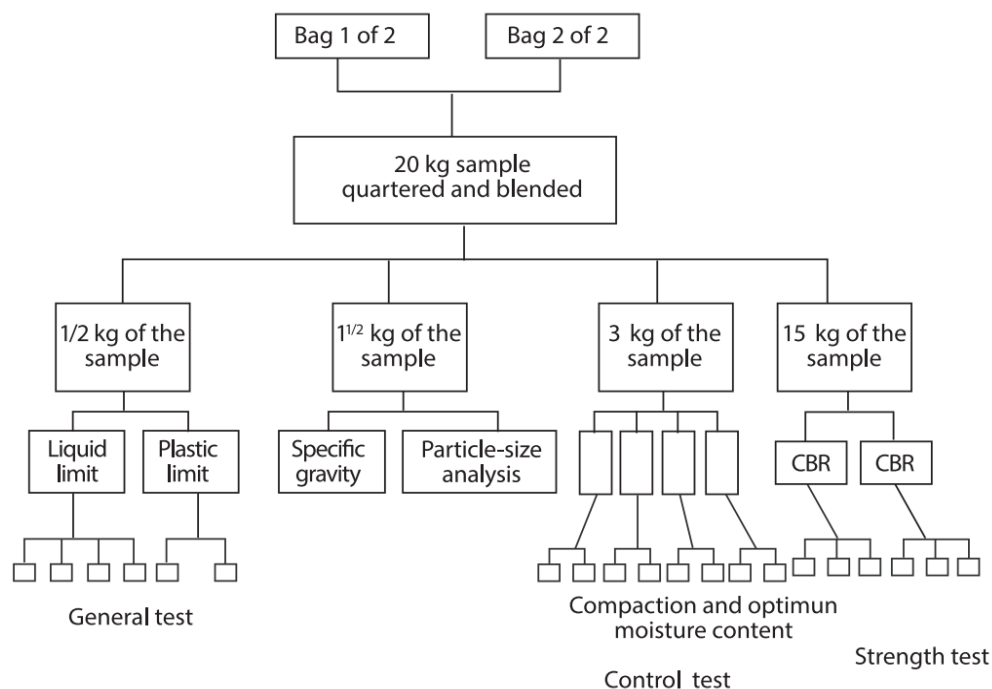


Figure 3. 6 Process of the quartering of altered samples. Crespo, 1980.

Table 3.25 Registration in soil pits

WORK:			
SOIL PIT:		MACHINERY:	
LOCATION:			COORDINATES
DATE OF IMPLEMENTATION:			X:
SUPERVISOR:			Y:
DEPTH: from (m)	to (m)	DESCRIPTION	COLUMN
PHOTOGRAPHY: (At the time of taking a photograph, a sheet or a blackboard is placed on one side of the wall of the pit, with the following information: Number of the pit, depth of the pit, location in coordinates of the pit, will help to identify them in office at the time of tabulation of information).			
OBSERVATIONS:			

Source: Own elaboration based on González and others 2002

■ Altered samples

Altered samples are disaggregated or fragmented material, in which special precautions are not taken to preserve the characteristics of structure and humidity; opportunely it is convenient to know the original water of the soil; samples are taken; they are packaged and transported appropriately.

Altered samples of soils may be obtained from an excavation, from a front either cut or bank or from drilling carried at depth.

■ **Unchanged samples**

The unchanged samples have the structure, and the humidity that the soil has in the sampling place is conserved. Unaltered samples will be obtained from thin soils that can be carved without disintegrating.

Obtaining can be done on the floor or one of the walls of an excavation, on the surface of the ground or the ground.

Table 3.26 presents a summary of the procedure for taking samples on open, altered, and undisturbed slopes and wells.

Table 3.26 Sampling procedure for altered and unaltered materials

Altered samples		Unchanged samples	
Collection of individual samples from an open pit (well 1.50 x 1.50 m section and depth required.)		Sampling normally of 0.30 x 0.30 x 0.30 in a flat surface.	
Process	– The dry and loose part of the soil is reduced to obtain a fresh surface. – A sample is taken in each layer in a container, and an identification card is placed. – Samples are sent in bags to the laboratory.	Process	– The surface of the land is cleaned and smoothed, and the outline of the piece is marked. – A trench is dug around this. – Deepen the excavation and cut the sides of the piece, using a thin blade knife. – The piece is cut with the knife and removed from the hole. – The face of the extracted piece that corresponds to the ground level is marked with any signal to know the position it occupied in the place of origin. The edges of the sample are chamfered, and three layers of hot paraffin are applied with a brush. – If the sample is not going to be used soon, it needs additional protection to the three layers of paraffin. This protection consists of wrapping the sample with a soft cloth, tying it with a string. The whole sample is immersed in molten paraffin as many times as necessary. If the sample is sent to a distant laboratory, after the coating with paraffin, it should be packed with sawdust, straw, or paper in a small box.
	Individual samples taking by boreholes		Sampling in open pit or wall of a cut

Altered samples		Unchanged samples	
Process	- The excavated soil is placed in a row with the proper order. - A representative portion of each soil class found is taken and placed in separate bags with their corresponding identification. - The bags with the material are sent to the laboratory	Process	- The face of the surface is carefully cleaned and smoothed, and the outline is marked. - It is excavated around and back forming the piece, for this a thin blade knife is used. - The piece is cut with the knife and carefully removed from the hole. The upper face is marked. - Paraffin, for transfer to the laboratory.
Integral samples, taking either from open ditches or cuts.		A sampling at a depth of a sounding	
Process	- The superficial skinning layer is removed. - The dry and loose material is removed to obtain a fresh surface from which to obtain the sample. - A waterproof tarpaulin is spread at the foot of the slope to collect the sample - A vertical channel of the uniform section is excavated from top to bottom, depositing the material in the waterproof tarpaulin - All excavated material is collected, placed in a bag with its identification tag, and sent to the laboratory.	Process	- Through drill bits drill to the desired depth. - The unaltered sample is removed with a Shelby tube, which consists of a thin-walled metal tube and sharp end. - It is forced inside the ground, not with blows. - Once the sample is obtained, it is labeled, with an arrow, it indicates the lower and upper part of the sample and the range of depth that was obtained. - The ends of the Shelby tube are paraffined and sent to the laboratory.

Source: Own elaboration based on Crespo, 1980

The descriptions of the geotechnical testification process in drilling are divided into basic, drilling methods and drill progress Table 3.27.

Table 3.27 Information for the registration of geotechnical testimony in drilling

Basics	- Project - Name and reference number - Probe number - Coordinates - Tilt and orientation - Date - Contractor - Supervisor - Driller
Drilling method	- Machine - Type of perforation - Diameter - Characteristics of drilling tools, mud types, types of circulation (direct or reverse) - Other technical characteristics
Progress of drilling	- Maneuvers - Meters of advance - Speed of advance - Resistance to advance - Recovery percentage in each maneuver - Losses and leaks of fluids - Instabilities of the walls

	- Water levels - Number of hits for Inca taking samples - Tests carried out, etc.
--	---

Source: Own elaboration based on González and others 2002

If an altered sample reaches the laboratory with moisture that allows its easy disintegration, it is not necessary to submit it to a drying process. Otherwise, the sample must be dried either by spreading it in the sun on a clean surface or by placing it on a tray or tray inside a low-temperature oven (50 ° C) or drying it slowly and carefully on a hot stove low.

■ **Disintegration of the altered samples**

Its purpose is to bring it to a state like that which will be presented in work during the construction process, should prevail the criteria of the engineer to decide how far to carry out the process of disintegration of the material according to, equipment and construction procedure.

Procedure for disaggregation of altered samples

- Use a wooden mallet of 9.5 cm per side and 15 cm in height with a magician coming out from the back face of the base and weighing approximately 1 kg. The mallet is usually lined at the base with a leather cover.
- The material is sifted through a No. 4 mesh (4.76 mm), and the retentate is placed on a tray and macerated, dropping the wooden mallet on the material vertically and from an approximate height of 20 cm.
- Once the sample retained in the mesh No. 4 (4.76 mm) has been disintegrated, it is mixed with the one that passed said mesh and is subjected to the quartering process.

Quartering process

- With the disintegrated sample, a cone is formed by placing the material in the vertex of the cone with a shovel and allowing it to adapt.
- With the same shovel, which must be rectangular, a truncated cone of about 15 cm in height is formed and divided into quadrants using a ruler.
- The material of two opposite quadrants is mixed, and the operation is repeated until the desired amount is obtained

3.3 Vertical or inclined probes

Each slope represents different characteristics, and the criterion of the professional in charge of the project must prevail. In section 2.4.3 quantification figures 2.20 are presented, which shows the number of surveys for slopes where the failure limits are not known (it is suspected that a slip can occur) and when the fault limits are known (active landslide).

The number depends on the objectives and scope of the investigations, as well as the representativeness of the area investigated by each survey. The depth must pass the deepest substrate that could be affected by structures, leaks, deformations, etc.

3.3.1 Rotation probes

Rotary drilling with a battery and obtaining a continuous core is the most widespread procedure to obtain samples in any geotechnical investigation. Figure 3.7 shows a machine for Long-year rotation probes 38.

With this method, witnesses can be obtained in any terrain, although in soft cohesive soils, large bowls and silt, precautions must be taken. The depths reached in geotechnics do not exceed 100 m, but this type of equipment can drill up to 1000 m. González, 2002.

In this drilling procedure, a cutting crown is required, located at the mouth of the sample receiver tube. The crown can be of two types depending on the material used in manufacturing:

- The diamond crowns: they have a steel body that is attached to a matrix, formed by a metallic alloy containing diamonds, composed of tungsten carbide and bronze powder. Figure 3.8.
- *Widia* crown: The body of the crown is made of steel and prisms of *widia* (Tungsten carbide, with 10% cobalt to give shock resistance) are embedded in the cutting edge. Figure 3.9.



Figure 3. 8 Long-year rotation machine 38
R & R perforations



Figure 3. 7 Diamond crowns. R & R
perforations.



Figure 3. 9 Widia crowns. R & R
perforations.

The rotating batteries can be a single or double tube. In the single tube, the drilling fluid washes the entire surface of the core, and there may be losses in recovery. In the double tube, the water descends by the contact of both tubes. It is even at the base of the crown where witnesses can be washed.

3.3.2 Percussion probes

It is used both in granular soils and in cohesive soils, being able to traverse soils of the firm to a very firm consistency. It can reach depths of 30 or 40 m, being the most frequent from 15 to 20 m.

■ SPT tests (Standard Penetration Test)

The ASTM D 1586 Standards define it as a field test that measures the resistance to soil penetration by dynamically driving a sampler that has a standardized manner.

The drilling system consists of the jacking of steel pipes by hitting a 120 kg mace that falls from a height of 1 m. The necessary strokes for the penetration of each section must be counted, which allows knowing the compactness of the ground traversed, see figure 3.10 and figure 3.11.



Figure 3.10 Percussion sounding. Geotec, S de R.L.

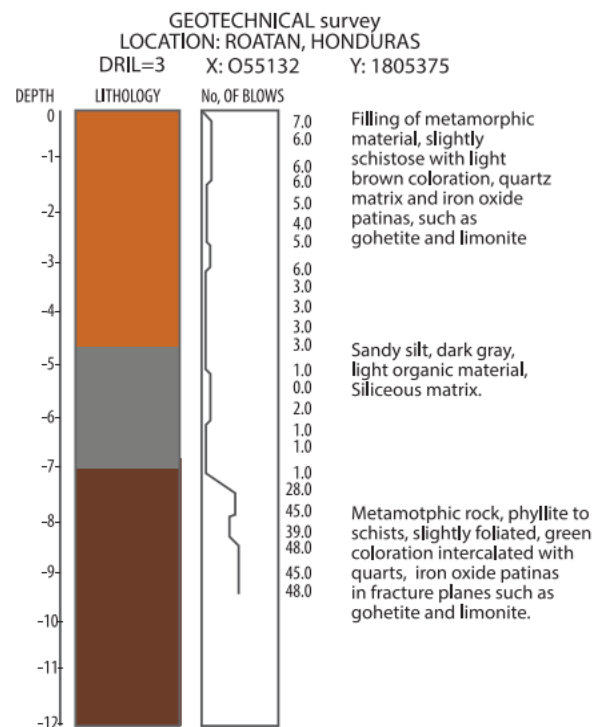


Figure 3.11 Soil compactness, a survey conducted in Roatán, Honduras

It is applied to all types of soil and even on soft and altered rocks. Drill to the desired height for the test. The general steps are:

- Before starting the standard penetration, the hole is cleaned with a depth of 30 cm, taking samples and describing them visually.
- Once the hole is cleaned, penetration is carried out. Arming the sample and twisting each of its pieces well.
- Screw the sample to the rods in such a way that they cover the depth that is being drilled.
- Place the sample tap and insert it into the hole formed with the hole in the cleaning.
- Place the hammer on top and attach the anvil to the top of the sampling rods. Rest the dead weight of the sample, rods, anvil, and weight of the unit at the bottom of the well.
- Mark the starting depth to the nearest 0.1 ft. (0.30 m). Compare the depth of sampling start to the cleaning depth.
- Mark on the drill rods at three intervals of 0.5 ft (0.15 m) for the advance of the sample under the impact

- Impel the sample with 140-lbf (623-N) hammer blows and count the number of strokes applied in each 0.5-ft (0.15-m) increment until one of the following occurs:

A total of 50 strokes have been applied during any of the three increments of 0.5 feet (0.15-m) described. A total of 100 strokes have been applied. There is no observed advance of the sampler during the application of 10 successive blows of the hammer.

- Record the number of strokes (N) needed to advance from the sampler to every 0.5 ft (0.15 m) of penetration or fraction thereof.
- The first 0.5 feet (0.15 m) is considered a seating unit. The sum of the number of strokes required for the second and third tranches of 0.5 feet (0.15 m) each is called "standard penetration resistance" or "N value."

Factors that affect the result

- Preparation and quality of the sounding: cleaning and stability of the perforation walls
- Boom length and bore diameter: conditional the weight of the element to be driven and the friction with the walls of the borehole
- Beating device: It can be manual or automatic, there being notable differences between the results of both. The automatic devices guarantee the application of the same impact energy in all cases

Terzaghi and Peck, 1948; When the test is carried out below the water Table, the following correction is used (applicable to low permeable soils, silt, and fine sand). $N = 15 + ((N' - 15) / 2)$

Valid for $N' > 15$, where N is the corrected value and N' is the measured value.

The comparison between SPT and the angle of internal friction in granular soils is shown in Table 3.28. Table 3.29 compares the type of soil and resistance, for granular soils.

Table 3.28 Comparison between SPT and the angle of internal friction in granular soils

N (SPT)	Compactness	Internal friction angle (ϕ)
0 – 4	Very loose	28
4 – 10	Loose	28 - 30
10 - 30	Medium dense	30 - 36
30 - 50	Dense	36 - 41
> 50	Very dense	>41

Source: González and others 2002

Table 3.29 Comparison of soil type and resistance in granular soils

Type of soil	Loose	Medium dense	Dense
Non-plastic slime	26 - 30	28 - 32	30 - 34
Fine uniform to medium sand	26 - 30	30 - 34	32 - 36
Well graduated sand	30 - 34	34 - 40	38 - 46
The mix of sand and gravel	32 - 36	36 - 42	40 - 48

Source: González and others 2002

■ Static penetration test, CPT (CONE PENETRATION TEST)

The CPT test is standardized by the ASTM D-3441 standard and consists in vertically pressing a cone into the ground at a constant speed of 10 and 20 mm / sec.

It measures the reaction of the soil to the continuous penetration of a conical tip by two parameters:

- The tip resistance (q_c) and
- Lateral friction (f_s)

The test is carried out mainly in soft clays, soft silts and medium fine sand deposits (it does not work in gravel or cohesive deposits of great hardness)

Piezocone, CPTU

Static Penetration Test (CPT, Cone Penetration Test) with Interstitial Pressure Measurement (CPTU), is standardized by ASTM D-5778; is a versatile, fast and accurate method for determining the geotechnical parameters of soils ranging from coarse sands to clays.

It is an equipment that in addition to measuring (q_c) and (f_s), records the interstitial pressures (u) that are generated when driving; It is also possible to install additional temperature sensors, inclination, etc.

Process:

A conical tip is pressed into the ground at constant pressure and constant speed, measuring the necessary force for the penetration of the cone.

Are made in granular soils and cohesive soils of soft consistency.

The presence of boluses, gravel, cemented soils, and rock produces rejection and damage to equipment.

Are used for the calculation of foundations and provide continuous information about the tested land.

Main advantages:

- Provides a continuous stratigraphy, identifying small lenses and layers.

- Rapid data collection and interpretation (2 to 3 times faster than conventional methods)
- Environmentally friendly. Does not produce waste or requires water.

■ **DPSH Test (DYNAMIC PROBING SUPER HEAVY)**

It is one of the dynamic penetration tests and can be performed at depths greater than 25 meters. The mace is 63.5 kg with the height of fall of 0.75 m. The strokes required for driving are recorded every 20 cm (N20). Table 3.30 shows the resistance tests in situ.

Table 3.30 Shows the resistance tests in situ

In situ resistance tests	In soils	Standard Penetration Test (SPT)	
		Dynamic Penetration Test	Blur Tests
			DLP test (Dynamic Probing Light)
			DPM test (Dynamic probing Medium)
			DPH (Dynamic Probing Heavy) test
			DPSH test (Dynamic Probing Super Heavy)
	On a rocky matrix	Static Penetration Test (CPT)	
		Windlass Test (Vane Test)	
		Sclerometer or Schmidt's hammer	
	On discontinuities	Spot load test	
		Cut resistance test	
	Deformability	Tilt Test	
		On soils	
	Seismic methods	On rocks	Pressure testing
			Plate load test
			Diatometer test
			Plate load test
			Flat-Jack test

Source: Own elaboration based on González and others 2002

3.3.3 Probes with a helical auger

Its use is limited to relatively soft and cohesive soils. Among its advantages is the low cost and ease of movement and rapid installation of equipment.

The probes include those made manually with depths between 2-4 m and diameter of 1-2 inches and mechanics, for depths of about 40 m and diameters of 3,4, 6 and 8 inches.

A normal auger obtains an altered sample. Hollow auger allows to obtain undisturbed samples without extracting to the surface the maneuver, and they are formed by a central tube of greater diameter than in the normal ones.

3.3.4 Geotechnical geological witnesses

It consists of the lithological-geotechnical description of the witnesses and samples obtained from drilling and drilling data; in Table 3.31, it presents a soil survey record, and in Table 3.32, a record is presented in rock sounding.

Table 3.31 Soil survey record

Company		Soil survey register								
Project:										
Sounding No.:		Situation:			Coordinates:		X: Y: Z:			
DATE:		DEPTH:			SHEET:					
DEPTH (m)	LENGTH SECTION (m)	WATER TABLE	COLUMN	DESCRIPTION	SAMPLES	No. BEATS S.P.T/MI	LIMITS OF ATTERBERG		HUMIDITY (%)	CLASSIFICATION U.S.C. S
							LL (%)	IP (%)		
OBSERVATIONS:										
MI: Unaltered sample MA: Altered sample SPT: Standard Penetration Test					TP: Paraffinized witness. N.F.: Water Table MNC: Sample not achieved					

Source: González and others 2002

Table 3.32 Rock sounding record

Company				Soil survey register								
				Project:								
Sounding No.:		Situation:				Coordinates:		X: Y: Z:				
DATE:				DEPTH:				SHEET:				
DEPTH: (m)	LENGTH SECTION (m)	WATER TABLE	COLUMN	DESCRIPTION OF THE WITNESS				SAMPLE	RECOVERY (%)	R.Q.D (%)	FRACT. N/30 cm	DISCOUNT:
OBSERVATIONS:												
MI: Unaltered sample MA: Altered sample SPT: Standard Penetration Test								TP: Paraffinized witness. N.F.: Water Table MNC: Sample not achieved				

Source: González and others 2002

3.3.5 Stratigraphy

Study the succession of sedimentary deposits, usually arranged in layers or strata.

Starting from this concept, each stratum has specific physical, chemical and biological characteristics that change horizontally and vertically, some of these typologies present in the stratigraphic sequence are: granulometry, orientation of the stratification, dip of the stratification, inclination, joins, folds, contacts, discordances, faults, lithological deformations due to compression and distention efforts, leaks, alterations, etc.

The road stability is determined by the resistance and constancy of the stratum where the sub-base lies, a change of stratification requires changes of analysis in soils to determine their characteristics and define the stability of the road sequence.

The dips of strata in favor of the road generally produce landslides of the horizons of soil or rocky fragments depending on their geotechnical characteristics.

The faults and joints present in a lithostratigraphic sequence are always areas of weakness and require special treatment, also allowing the flow of groundwater trigger factor of landslides.

The folding represents zones that have undergone compression and distension. Therefore, the resistance of the material is variable, although it represents the same lithology.

The lithological changes produced in contacts, discordances, faulting, folding, etc. they represent resistance changes in the roadbed. Figure 3.12 outlines the geomorphology in the bed of a river, consisting of an alluvial unit, interstratified shales, and carbonates. The sequence is repetitive. However, a normal fault has dismantled the order of the strata requiring a more detailed analysis to be able to correlate. A similar interpretation must be made in the project section to determine lithological and structural contrasts, consequently resistance changes.

Note that in figure 3.12, probes 01 and 02 (S-01, S-02) are vertical. The whole completely cuts the contacts of the lithological units, the lithological columns represent the section cut by the hole; the S-03 is inclined because the stratification is vertical and when inclining it the greater information of the obtained unit, just as the S-04 was oriented to know the contact between the shale and carbonate rocks below the surface. The configuration of the soundings allows to determine structures and lithology at the same time, a better geological model of the subsoil is obtained.

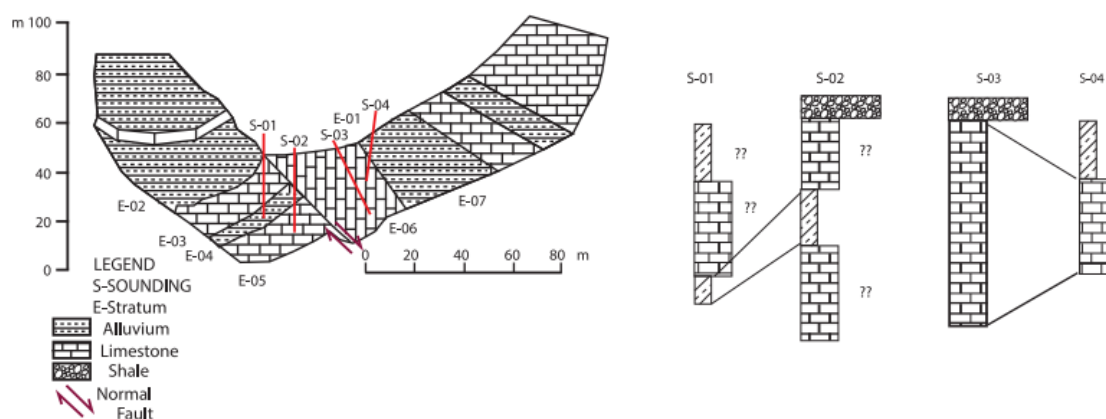


Figure 3.12 Profile and lithological columns
Source: Own elaboration

3.3.6 RQD

The RQD (Rock Quality Designation) index represents the relation between the sum of the lengths of the witness fragments greater than 10 cm and the total length of the section considered. Table 3.33 presents the values of the RQD and its quality.

$$RQD = \frac{\sum \text{length of witness pieces} > 10 \text{ cm}}{\text{total length}} \times 100$$

Table 3.33 RQD values and their quality

RQD (%)	Quality
< 25	Very bad
25 - 50	Bad
50 - 75	Average
75 - 90	Good
90 - 100	Very good

Source: Deere, 1989

For the estimation of the RQD, only the fragments or witness pieces of fresh material are considered, excluding those that present a significant degree of alteration (from grade IV inclusive) for which an RQD = 0% is considered. The measurement of the RQD must be made in each maneuver of the sounding or each lithological change, is recommended that the length of maneuver does not exceed 1.5 m. The minimum diameter of the witnesses must be 48 mm. The measurement of the length of the control is made on the central axis thereof, considering the fragments with at least one complete diameter. Figure 3.13 shows the process to measure and calculate the RQD.

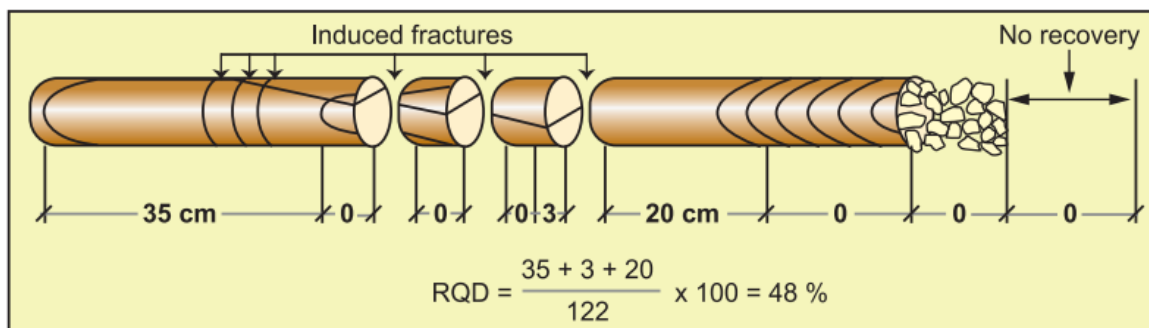


Figure 3.13 Process to measure and calculate the RQD. González (2002)

3.3.7 Instrumentation for on-site geotechnical testing

Its purpose is to determine the behavior and characteristics of the land to predict its evolution against loads, movements, thrusts, and other actions, both natural and induced by the works.

Table 3.34 contains tests carried out in situ to obtain the geotechnical properties (resistance, deformability, permeability) and the type of material where it is practiced. Table 3.35 presents resistance tests carried out at the construction site, for deformability tests, see Table 3.36.

Table 3.34 In situ tests: geotechnical properties and type of material

Geotechnical property	Type of material	
	Soils	rock
Resistance	- Penetration standard (SPT) * - Dynamic penetration - Static penetration and CPTU - Mountain (vane test) *	- Schmidt hammer - Point load. - Direct cut.
Deformability	-Load plate -Pressiometers *	-Dilatometer. -Load plate. -Cat in flat
Permeability	-Lefranc* -Gilg Gavard* -Matsuo** -Haefeli**	-Essays Lugeon *.

* Testing in surveys. ** Tests in pits and ditches.

Source: González and others, 2002

Table 3.35 In situ resistance tests

Test	Place	Description	Features	Results
Standard penetration (SPT)	Inside soundings.	Resistance to the penetration of a point by hitting with normalized energy	In soils, especially in non-cohesive materials.	N value of resistance to penetration that can be correlated with geotechnical parameters.
Dynamic Penetrometer	From surface to a depth of ≈25 m.	Measurement of the resistance to the penetration of a point by hitting with normalized energy	Types: DPL, DPM, DPH, and DPSH. No samples are obtained.	Indirect measurement of the resistance of the land through the NB value, which can be related to the SPT
Static Penetrometer	From surface to a depth ≈ 30 m.	Continuous recording of the resistance to the penetration of a tip and a piston rod using pressure	In granular and soft cohesive soils, a piezocone installed measures interstitial pressures. You do not get samples.	Endurance, lateral friction and interstitial pressures.
Windlass	Inside soundings.	Measurement of the torque required to failure the ground	In saturated soft cohesive materials	Resistance to cutting without drainage.
Schmidt hammer	On rock surface.	Measurement of the rebound recorded when performing a percussion with the hammer in the chosen area.	It allows testing of rocks and discontinuities.	Simple compressive strength of the material from correlations
Point load (PLT)	On rock samples.	Measurement of the load required for failure a sample by compression between tips	On witnesses of soundings or fragments of rock	Simple compressive strength of the material from correlations
Cut in situ	In galleries, ditches, and wells.	Measurement of the tangential tension necessary to produce the failure through a discontinuity subjected to a certain normal load	The Hoek cell can be used for small samples or field controls.	Resistance to cutting a discontinuity plane

Source: González and others 2002

Table 3.36 In situ deformability tests

Test	Place	Description	Features	Results
Loading plate in soils	Ditches, wells and on the surface.	Measurement of the deformations produced when applying known vertical loads through a smooth and rigid plate.	The plates can have variable dimensions (30 x 30 to 100 x 100 cm).	Young's modulus and ballast coefficient
Loading plate in rocky massifs.	In galleries and tunnels	Measurement of the deformations produced when applying known loads using a smooth and rigid plate.	The plates can have variable dimensions (30 x 30 to 100 x 100 cm). It is difficult to apply loads > 200 t.	Young's module
Pressure gauge (in soils)	Inside soundings.	Measurement of the deformation of the land when applying a series of controlled pressures in soils.	Applicable in materials with $E \leq 6,000$ MPa. It can exert pressures up to 20 MPa.	Pressure deformation module.
Dilatometer (rock)	Inside soundings.	Measurement of the deformation of the terrain by applying a series of controlled pressures on rocks	Applicable in materials with $E \leq 15,000$ MPa. It can exert pressures up to 20 MPa.	The module of dilatometric deformation.
Flat-Jack	On surface, galleries, tunnels.	Measurement of the deformation along a groove created in the rock	Up to 70 MPa.	Deformation module and tensional state

Source: González and others 2002

3.4 Piezometers, Tests for Permeability and Flow-pass Detection

3.4.1 Piezometer

It is the instrument used to determine the water pressure in the ground or water level in boreholes. Classification of piezometers: They can be an open tube, pneumatic, or vibrating cable. The use depends on the performance characteristics of the piezometer and its accuracy. Figure 3.14 shows an example of a piezometer for monitoring groundwater.

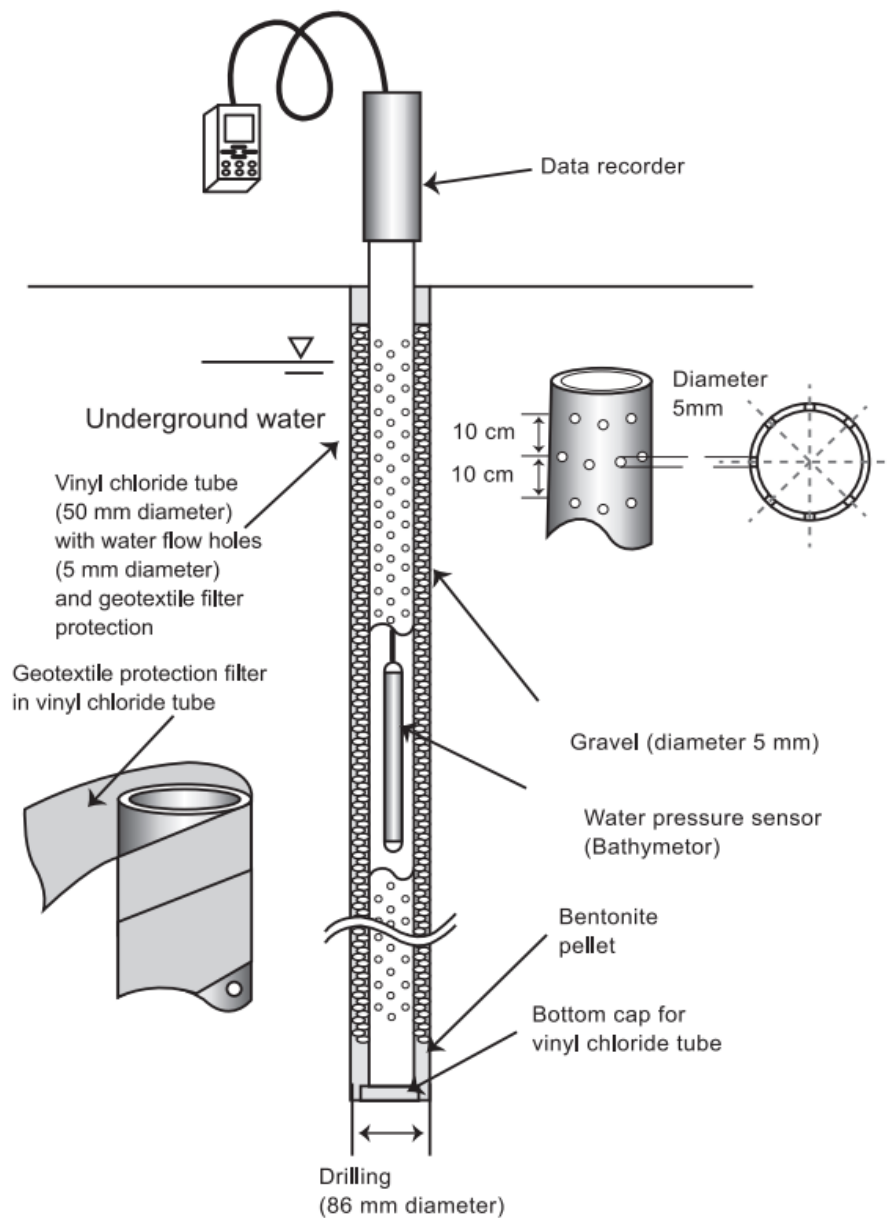


Figure 3.14 Monitoring of groundwater (piezometer)

Installation of the piezometer

The most common installation is through vertical drilling. The tip of the piezometer should be placed inside a sandbag in the specific area where you want to measure the pore pressure.

The length of this bag must be greater than four times the diameter of the perforation and preferably not greater than 30 centimeters. It is recommended to use washed sand with particle sizes between 0.2 and 1.2 millimeters.

Bentonite is usually used as a seal above the filter bag, and if the piezometer is not installed at the bottom of the borehole, a bentonite seal should be placed below the filter bag.

The length of the bentonite seal is between 30 and 50 centimeters in length. The remaining length of the sounding is filled with a slurry of cement and bentonite. Once the piezometer is installed, it is important to build a surface inspection box, which must have a lock type security system.

Use of piezometers in landslide studies

They are installed as part of the site investigation and on occasion before the information is available on the location of the fault surface.

3.4.2 Permeability test in drilling hole

It measures the coefficient of permeability in permeable or semipermeable soils, of granular type, located below the water Table, and in very fractured rocks. The test is carried out inside the borehole and can be carried out during the execution of the drilling.

The procedure consists of filling the well with water and measuring the flow rate necessary to maintain the constant level (permanent regime test) or to measure the rate of descent of the water level (variable rate test). The intake flow measurement should be done every 5 minutes, keeping the level constant in the mouth of the sounding for 45 minutes. If the admission is very high, it should be measured every minute during the first 20 and then every 5 minutes until it reaches 45 minutes.

Before measuring times and flows, the water drilling must be filled, observing that the air is expelled and that the level and speed of descent is stabilized, which indicates that it has reached the permanent regime. Table 3.37 is a format with the variables that must be considered when making a permeability test in a drilling hole.

Permeability test in a drilling hole

Table 3.37 Format for permeability test in a drilling hole

PROJECT		PROF. OF TEST: FROM (m) to (m) PROBE No.	
ÁREA	DATE:	TEST N°.	
LITHOLOGY OF THE SECTION:	START TIME:	TEST PERFORMED	TYPE OF TEST
	FINAL TIME:	Under N.F	Infiltration
		Top N.F	Pumping
		Artisan built well	Recovery
			Abasement
		CONDITIONS OF THE MEASURES	
		Abasement	Cylinder
			Diameter = cm
			Coating
		Hydrometer	
Test tube			
h_1	Height of water in the coating above ground level	cm	Z: Descent of the level concerning time. Δh_i = Loss of charge per unit of time
h_2	Depth of the coating	cm	
h_a	Depth of water Table measured from ground level	cm	
L	Length of the test section	cm	
d	Inner diameter of the HW coating	cm	
D	Diameter of the HQ test section	cm	
Δh	Loss of charge	cm	
t_1	Trial start time	Sec.	
t_2	Time that test ended	Sec.	
H_1	Hydraulic load at the start of the test: $H_1 = h_1 + h_a$	cm	
H_2	Hydraulic load at the end of the test: $H_2 = H_1 - \Delta h$	cm	
TEST TIME			
$t(\text{min})$	$z(\text{cm})$	$\Delta h_i (\text{cm})$	GRAPH
0			
1			
2			
3			
CALCULATION OF THE PERMEABILITY COEFFICIENT			

$k = \frac{d^2 \ln \left[\frac{L}{D} + \sqrt{1 + \left(\frac{L}{D} \right)^2} \right] \ln \left(\frac{H_1}{H_2} \right)}{8L(t_2 - t_1)}$	=	cm/sec
OBSERVATIONS:		

Source: Own elaboration for this manual

3.4.3 Registration of groundwater for the detection of the flow path

The record is made to plan the underground drainage of groundwater for the stability of the slope. The record can find the flow of passage or the target aquifer to be drained. The recording is carried out in a well with a screened pipe installed.

The measuring equipment is an electrical tester with a cable connection to the weight of the tip of the iron bar, which will measure the specific electrical resistance (Ωm) or the electrical resistance (Ω). The length of the cable that connects to the weight of the tip of the iron bar must be greater than the target. The salt should be mixed in the water tank at an electrolyte concentration of approximately 1% before placing it in the well.

The registration work must be carried out after any rain event.

The electrical resistance of the groundwater in the well should be measured at intervals of 0.5 m as the initial value.

The electrolyte solution, as indicated above, should be pumped into the well with a plastic hose.

Measure the specific electrical resistance at a 50 cm interval from the depth of the well in 10, 30, 60, 120, and 180 minutes after placing and mixing the salt solution in the well. If there is an underground water passage, the salt water can be replaced with pure water in the flow path, and the electrical resistance of the groundwater will increase.

An example of the groundwater log chart is shown in Figure 3.15. The electrical resistance increases as time pass to certain depths of the groundwater flow path.

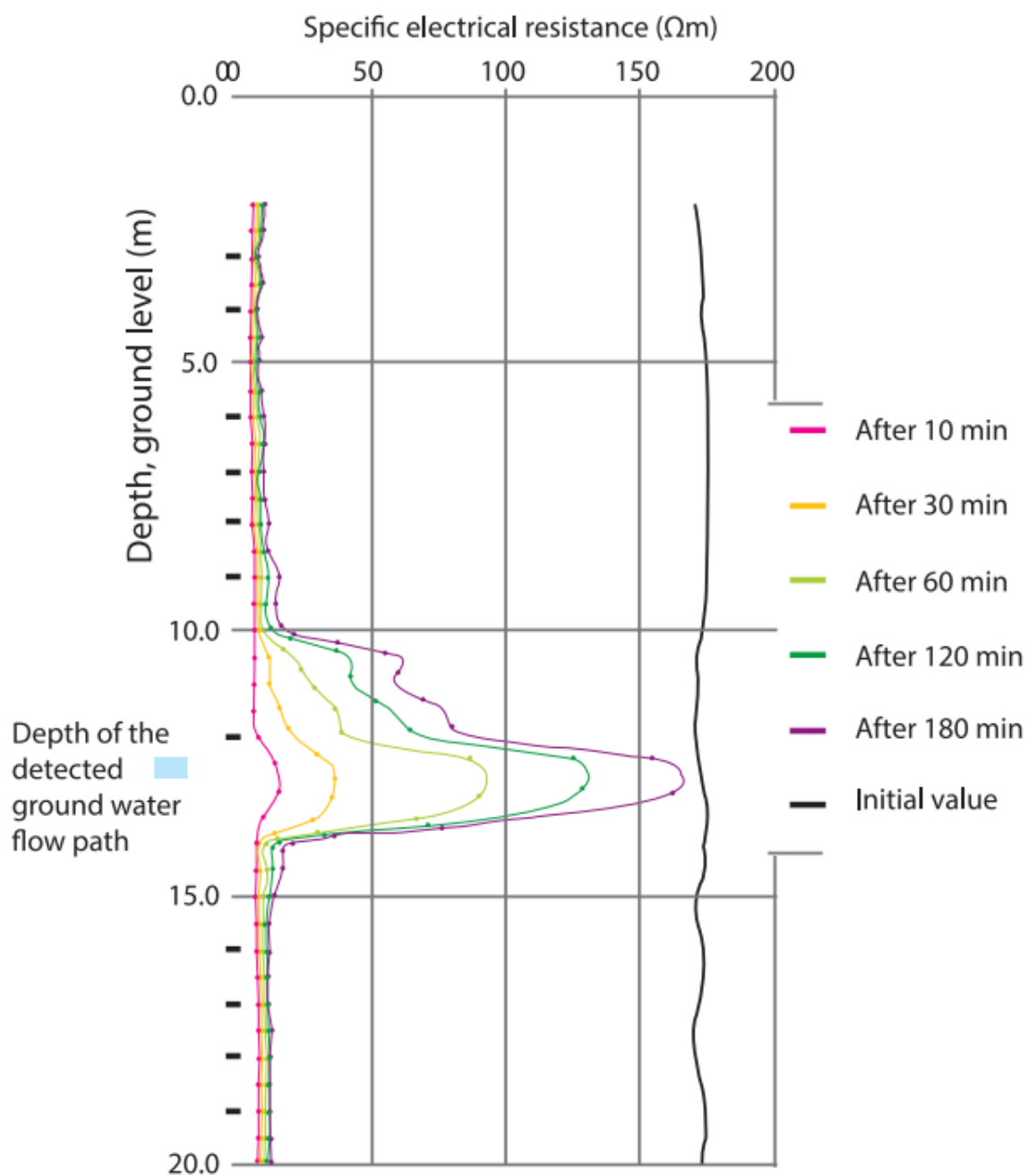


Figure 3.15 Example of the result of the underground water register

3.5 Surface geophysics

Its purpose is to determine the resistivity of the rocks, internal structure, and above all, the water content.

3.5.1 Electrical methods

In Table 3.38, a classification of the electrical methods is made: vertical electric probes, electric pits, and dipole-dipole with the procedure to carry out each one of them. Figure 3.16 shows equipment for electrical probes; figure 3.17 shows electrode piling on the electric line; figure 3.18 shows electrical laying on the electric sounding line.

Table 3.38 Classification of electrical methods and procedure

Electrical method	Process
Vertical electric probes (VEP)	– The Schlumberger configuration is generally used. – The current electrodes A and B are separated successively from the central point, following a straight line and measuring the resistivity in each arrangement. – As the electrodes are distanced, the apparent resistivity corresponds to a greater thickness of the stratum. – The results obtained from the VEP is the variation of the resistivity with the depth at the central point investigated. – Reaching depths are between 0 to 200 m.
Electric drilling (EG)	– Wenner configuration is used, where the distances between electrodes A - M, M - N, and N - B are equal, moving the device laterally along a selected profile. – Lateral variations of the apparent resistivity are detected at a seemingly constant depth. – The depths of investigation are between 0 and 50 m.
Dipole-dipole	– The dipole MN is placed laterally to the AB and aligned with it. – Keeping the dipole AB fixed, the MN moves successively. – Then, move step AB and repeat the process.

Source: Own elaboration based on González, 2002



Figure 3.16 Equipment for electrical probes.
Courtesy of: Applied Geoscience



Figure 3.18 Thrust of electrodes for electrical probes. Courtesy of Applied Geoscience



Figure 3.17 Electrical laying and electrode driving in electric soundings, Courtesy of Applied Geoscience

3.5.2 Seismic methods

Seismic refraction

It is the most widely used method; it studies the propagation in the field of artificially produced seismic waves with which an approximate image of the stratigraphy of the terrain can be obtained.

The contacts between the geological bodies with different speed of transmission of the seismic waves, define separation surfaces in which the waves undergo refraction, reflection, or diffraction.

Application:

It is used to determine the depth of the rocky basement or stratigraphy of the subsoil.

Explanation of the speed of waves S (V_s) and velocity of waves P (V_p) for determination of the mechanical parameters (Poisson's coefficient and Edin elasticity-deformation modules, and the dynamic modulus (Young), volumetric and geometric compressibility. It establishes the conditions of the rock (weathering, fracturing).

It is used to determine the depth of the water Table.

Geotechnical classification of rocks. Definition of Barton's Q index.

Estimate of fracture index (RQD), density (sedimentary rocks), porosity (sandstones).

Determination of the excavation ability, rippability (the ability of a rock to be fractured and moved by a heavy machine).

Seismic reflection

It is mostly used for the definition of deep geological structures.

It consists of measuring the arrival times of the seismic waves, generated by an appropriate energy source (hammer, pistol, weight drop, dynamite, etc.) and measuring the time of those waves once reflected in the different layers or interfaces with enough acoustic impedance contrast.

The most used method to reorder the traces is the CMP (Common Midpoint) with which they obtained trace has a considerable improvement in signal/noise ratio).

The set of all CMP traces is the so-called Reflection Seismic Section, which is the result of this method. This section is an image of the subsoil that represent the irregularities of the terrain and that is equivalent to a cut of the terrain with the distribution of the lithologies, definition of the network of faults and fractures, characterization of the rock mass by means of its seismic velocity (reflected P waves) and degree of fracturing.

Applications

- Stratigraphy at depth (determination of the geometry of the terrain)
- Fracturing the ground and locating faults
- Determination of rock quality by reflected wave velocity analysis
- Structural studies for mining, tunnels, dams, aquifers
- Terrain sections for energy resources (gas)

3.5.3 Other methods

There are other methods which are shown in a generalized manner, and classification of geophysical tests is presented in Figure 3.19.

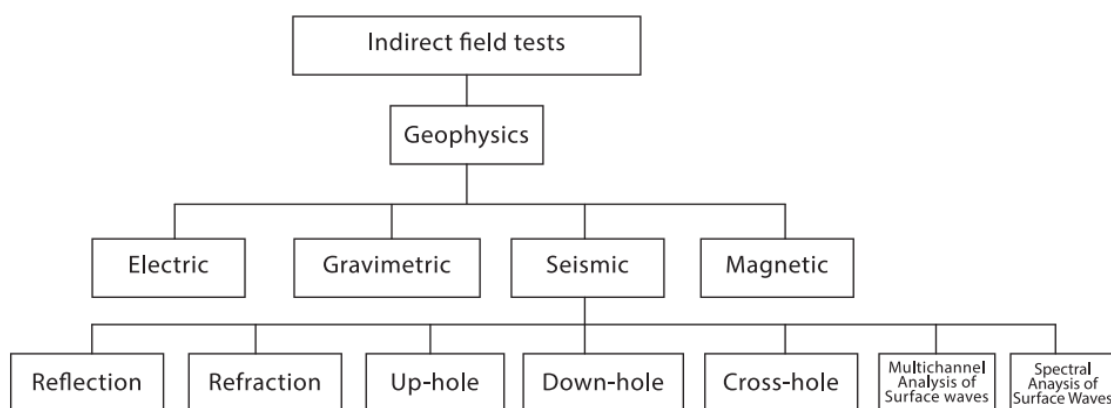


Figure 3.19 Classification of seismic methods.

In Table 3.39, classifies geophysical methods, subdivides them into techniques and presents applications, it is recommended that for the application of geophysical techniques be a specialized professional in the field who is responsible for the logistics of the method, obtaining results and interpretation of the information.

Table 3.39 Classification of geophysical methods

Métodos	Técnicas	Aplicaciones
Electric	Vertical electrical probes	Geological interpretation for the degree of alteration, volume of materials, water content, and salinity.
	Electrical drilling	<i>Same as the previous one but for the study of its lateral variation.</i>
	Dipole-dipole	<i>Same as the previous one but for the study throughout the section.</i>
Seismic	Seismic refraction	Thickness of coating layer, excavation ability, soil volume of borrow areas, rock mass quality, foundation conditions.
	Seismic reflection	Deep geological research in underground works and hillsides.
Electromagnetic (EM)	EM in frequency domain	Geological interpretation, degree of alteration, water content, and salinity.
	EM in time domain	<i>Same as above but at great depths</i>
	Very-low-frequency (VLF-EM)	Resistivity of ground surface, geological interpretation, and lateral variations.
	Geo-radar	Empty, lithological contacts, investigation of the backfill of structures, etc.

Métodos	Técnicas		Aplicaciones
Gravimetric	Gravimetry		Lithological contact with density contrast, soft soils, cavities, dissolution zones, fault zones.
	Microgravimetría		Same as above but in more detail.
magnetic	Magnetometry		Empty, clay fillings, buried pipes, faults, dikes, mineralized masses.
Seismic in sounding	Cross-hole		Probe lithology, P and S wave velocities, dynamic modules, resistant properties, excavation-ability, the thickness of overlayer
	Down-hole Uphole		
	Seismic tomography		Geological interpretation, cavities, dynamic nodules, speeds of slings P and S, resistant properties, fracture zones, zones of alteration, excavation ability, thickness of overlayer.
Geophysical testimony (inside the sounding)	Electric	Electrical resistivity Spontaneous potential Electric conductivity Electrical tomography	Resistance of the material, lithological sequence, fractures, salinity of the water.
	Nuclear or radioactive	Natural gamma Spectral Gamma Neutron Gamma-Gamma	Clay investigation, water content, soil density.
	Sonic or acoustic		Mechanical properties, degree of fracturing, lithological sequence.
	Fluids	Temperature Conductivity Flow rate	Point s of inflow of water to the sounding, phreatic levels.
	Geometric	Caliber Diameter Reastration of T. V	Boundary of the sounding, gaps and fractures, the orientation of discontinuities.

Source: González and others 2002

3.6 Laboratory work

The types of tests performed on soil and rock in the laboratory are shown in Table 3.40. The tests are regulated, and usually, the ASTM (American Society for Testing and Materials) or INV (National Institute of Roads) is used.

In the case of Costa Rica, it has regulations equivalent to the ASTM, for some types of tests

Table 3.40 Types of tests carried out in laboratory on soil and rock

Lithology	Type of test	Standard
In soil	Granulometry	ASTM D422
	Limits of Atterberg	ASTM D4318
	Classification	ASTM D 2487
	Specific weight and humidity	ASTM C-566 ; ASTM C-127; INV E-222, INV E-223, INV E-224,
	Density and natural humidity	ASTM D4254, D1556 y D2216
	Permeability (constant load method)	ASTM D 2434
	Consolidation	ASTM D 2435
	Direct cut	ASTM D 3080, INVE 154-07
	Unconfined compression	ASTM D2166
	Triaxial test	ASTM D4767
	Laboratory compaction test	ASTM D4D698
	Content in organic matter	ASTM D-2974
	Size and shape of the particles	ASTM C-1260
	Moisture content	ASTM D2216
	Analysis of particle size	ASTM C-136
In rock	Spot load test	ASTM D5731
	Simple compression test	ASTM D2938
	Tensile strength test	ISRM Doc N°8 1977
	Triaxial compression test	ASTM D2664

Source: Own elaboration.

3.6.1 Classification of soils

The classification of soils is based on the granulometry. They can be classified into four large groups according to the standards: USGS, AASHTO, DIN, ASTM, AENOR, and others.

Soil geotechnical classifications (USGS unified system, Casagrande plasticity chart), figure 3.20 and Table 3.41; and rocks (based on different physical and mechanical properties), plus the application of expressions and empirical correlations and field indices allow the evaluation of geotechnical properties and provide quantitative data.

The soil classification system according to AASHTO is presented in Table 3.42, which also includes the calculation to determine the group index, Table 3.42 and the classification chart silty-clayey fraction figure 3.21 and Table 3.44 is the classification of soil according to its granulometry.

The geotechnical units and their spatial distribution are generally established based on the lithology, origin and geological characteristics of the materials, observations, field measurements, photointerpretation and, in cases where it is possible or necessary, from the conducting surveys, in situ tests and analysis of samples in the laboratory. According to the scale of the map and the available data, these are defined with a different degree of homogeneity.

The IAEG (International Association for Engineering Geology and the Environment 1981) proposes a procedure to follow for the classification and description of soils and rocks with a view to geotechnical cartography, including the following aspects:

Classification and geological-geotechnical description of soils:

- *Name and Type*: the grain size, organic matter, plasticity, type of genetic deposit
- *Material description*: color, shape and composition, state of alteration, resistance
- *Additional geological information*: name and age of the geological formations
- *Fillers and anthropic materials*, landfills

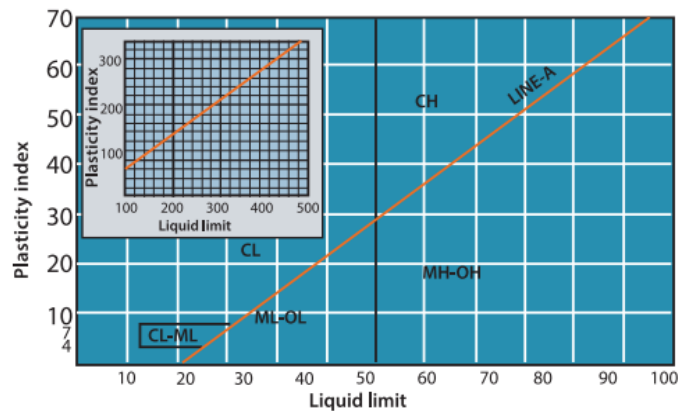


Figure 3.20 Plasticity Charter of Casa Grande. (González de Vallejo 2002)

Table 3.41 Unified Soil Classification System (USCS)

Field identification procedures (excluding particles larger than 7.6 cm and basing fractions on estimated weights)						Group symbols	Typical names		
Coarse-grained Soils More than half of material is larger than No. 200 sieve size.	(The No. 200 sieve size is about the smallest particle visible to the naked eye)	Gravels - more than half of coarse fraction is larger than No. 4 sieve size	For the visual classification the ¼-in. Size may be used as equivalent to the No. 4 sieve.	Clean gravels (little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes	GW	Well-graded gravels, gravel-sand mixtures, little or no fines.		
					Predominantly one size or a range of sizes, with some intermediate sizes missing	GP	Poorly graded gravels or gravel-sand mixtures, little or no fines		
				Gravels with fines (appreciable amount of fines)	Nonplastic fines or fines with low plasticity (for identification procedures see ML group below)	GM	Silty gravels, gravel-sand-silt mixtures		
					Plastic fines (for identification see CL below)	GC	Clayey gravels, gravel-sand-clay mixtures.		
		Clean sands (little or no fines)		Wide range in grains sizes and substantial amounts of all intermediate sizes missing	SW	Well-graded sands, gravelly sands, little or no fines.			
				Predominantly one size or a range of sizes with some intermediate sizes missing	SP	Poorly graded sand or gravelly sands, little or no fines.			
		Sands with fines (appreciable amount of fines)		Nonplastic fines or fines with low plasticity (for identification see ML below)	SM	Silty sands, sand-silt mixtures.			
				Plastic fines (for identification see CL below)	SC	Clayey sands, sand-clay mixtures			
		Identification Procedures on fraction smaller than No. 40 Sieve Size							
		Fine-grained soils More than half of material is smaller than N.° 200 sieve size		(The No. 200 sieve size is about the smallest particle visible to the naked eye)	Silt and clays Liquids limit is less than 50		Dry Strength (Crushing Characteristics)	Dilatancy (Reaction to shaking)	Toughness (Consistency near PL)
None to slight	Quick to slow		None				ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity.	
Medium to high	None to very slow		Medium						CL
slight to medium	Slow		Slight				OL	Organic silts and organic silty clays of low plasticity	
Soils and clays Liquid limit is greater than 50	slight to medium		Slow to none		Slight to medium	MH	Inorganic silts, fine micaceous sandy or silty soils, elastic silts		
	High to very high		None		High	CH	Inorganic clays of high plasticity, fat clays.		
	Medium to high		None to very slow		Slight to medium	OH	Organic clays and silt of medium to high plasticity.		
Highly organic soils			Readily identifiable by color, odor, spongy feel and frequently by fibrous texture.			Pt	Peat and other highly organic soils.		
Soils that have characteristics of two groups are designated by the combination of the two symbols, e.g., GW-GC, well-graded mix of sand and gravel. All sieve sizes refer to U.S. Standard									

Source: Lambe and Whitman, 1981

Table 3.42 AASHTO Soil classification System

Table 3-42 AASHTO soil classification system												
Classification	Granular materials (35% or less passes through the No. 200 sieve)							Clay silty materials (more than 35% for the No. 200 sieve)				
Group:	A-1		A-3	A-2-4				A-4	A-5	A-6	A-7 A-7-5 A-7-6	
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7					
Percentage passing: N°10 (2mm) N°40 (0,425mm) N°200(0,075mm)	50 máx. 30 máx. 15 máx.	- 50 máx. 25 máx.	- 51 mín. 10 máx.	- - 35 máx.				- - 36 mín.				
Characteristics of the fraction passing through the sieve N ° 40 Liquid limit Plasticity index	- 6 máx.		- NP (1)	40 máx. 10 máx.	41 mín. 10 máx.	40 máx. 11 mín.	41 mín. 11 mín.	40 máx. 10 máx.	41 mín. 10 máx.	40 máx. 11 mín.	41 mín. (2) 11 mín	
Main constituents	Fragments of rock, gravel, and sand		Fine sand	Gravel and sand clayey or silty				Silty soils		Clay soils		
Characteristics as undergraduate	Excellent to good							Poor to bad				
(1): Not plastic. (2) The plasticity index of subgroup A-7-5 is equal to or less than LL minus 30; the plasticity index of subgroup A-7-6 is greater than LL minus 30												

Source: <https://www.civilexcel.com/2012/02/clasificacion-de-suelos-por-los-metodos.html>

Table 3.43 Calculation to determine the group index

Group Index:

$$IG = (F-35) \cdot (0,2+0,005 \cdot (LL-40)) + 0,01 \cdot (F-15) \cdot (IP-10).$$

Being:

F: % passing the sieve ASTM n°200.

LL: Liquid limit.

IP: plasticity index

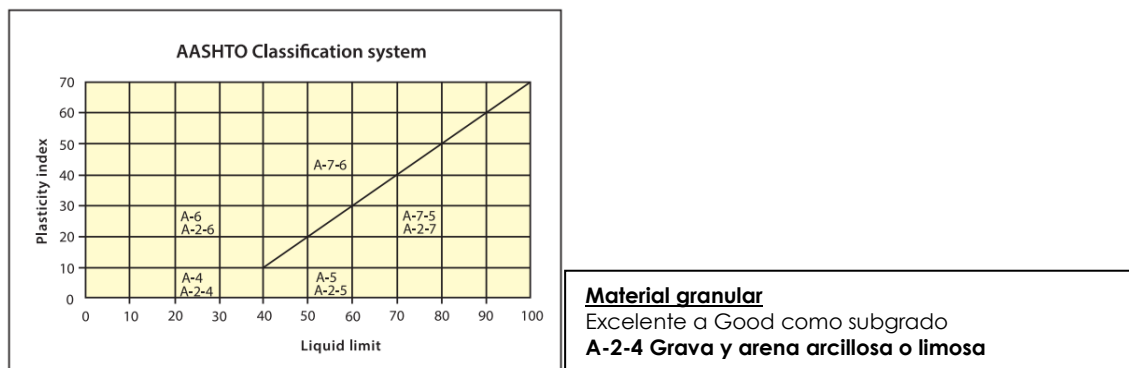
Source: <https://www.civilexcel.com/2012/02/clasificacion-de-suelos-por-los-metodos.html>

Figure 3.21 Classification chart silty-clayey fraction AASHTO.

Source: Practical civil engineering (2012). <http://ingenipra.blogspot.com/2012/08/clasificacion-de-suelos-por-los-metodos.html>

Table 3.44 Soil classification according to its granulometry.

Types of soil	Description
Gravel	Grain size between about 8 - 10 cm and 2 mm; It is characterized because the grains are directly observable. They do not retain water because of the large empty spaces between particles.
Sand	Covered between 2 and 0.060 mm, they are still visible to the naked eye. When they are mixed with water, continuous aggregates are not formed but are easily separated from it.
Silt	Particles between 0.060 and 0.002 mm. They resist water better than gravels and sands. If a slime-water paste is formed, if it is placed on the hand when striking with the hand, the water is easily segregated.
Clays	Particles formed by sizes smaller than 0.002 mm. Chemical transformations are needed to reach these sizes. Large water absorption capacity.

Source: Own elaboration based on González and others 2002

Description and lithological classification of rocks

In the description and classification of a rocky outcrop with geotechnical purposes, the characteristics of the rock matrix, the rock mass, and the discontinuities must be considered:

- **Characteristics of rock matrix:** color, texture, factory, porosity, alteration and weathering, resistance.
- **Solid rocky characteristics:** structure, orientation, and inclination, number of families of discontinuities, size, and shape of the blocks, degree of weathering
- **Characteristics of the discontinuities:** (see Table 3.45 to 3.49).

Table 3.45 Properties of the rock matrix and methods for its determination

	Properties	Determination methods
Identification and classification properties	Mineralogical composition	Visual description Optical and electronic microscopy. X-ray diffraction.
	Factory and texture	
	Grain size	
	Colour	Laboratory techniques.
	Density (ρ)	
	Specific weight (γ).	
	Moisture content	Permeability test.
Mechanical properties	Permeability (coefficient of permeability, K)	
	Durability	Alterability tests.
	Alterability (index of alterability)	
	Simple compressive strength (σ_c)	Uniaxial compression test. Spot load test. Hammer Schmidt.
	Tensile strength (σ_t)	Direct tensile test. Indirect traction test.
	Sonic wave velocity (V_p , V_s)	Speed measurement of elastic waves in the

	Properties	Determination methods
		laboratory
	Resistance (parameters of c and ϕ)	Triaxial compression test.
	Deformability (elastic deformation modules, static or dynamic: E , ν)	Uniaxial compression tests. Sonic speed test

Source: González and others 2002

Table 3.46 Classification of rock masses by the number of families of discontinuities

Type of rocky massif	Number of families
I	Massive, occasional discontinuities
II	A family of discontinuities
III	A family of discontinuities plus other occasional ones
IV	Two families of discontinuities
V	Two families of discontinuities plus other occasional ones
VI	Three families of discontinuities
VII	Three families of discontinuities plus other occasional families
VIII	Four or more families of discontinuities.
IX	Brewed

Source: International Society for Rock Mechanics and Rock Engineering, ISRM, 1981

Table 3.47 Description of the block size according to the number of discontinuities

Description	J_v (discontinuities / m ³)
Very large blocks	< 1
Large blocks	1 - 3
Medium size blocks	3 - 10
Small blocks	10 - 30
Very small blocks	> 30

Source: International Society for Rock Mechanics and Rock Engineering, ISRM, 1981

Table 3.48 Classification of rock masses according to the size and shape of the blocks

Class	Type	Description
I	Massive	Few discontinuities or with very large spacing.
II	Cubic	Approximately equidimensional blocks.
III	Tabular	Blocks with a dimension considerably smaller than the other two.
IV	Column	Blocks with a dimension considerably greater than the other two.
V	Irregular	Great variations in the size and shape of the blocks.
VI	Crushed	Massive rocky, very fractured.

Fuente: International Society for Rock Mechanics and Rock Engineering, ISRM, 1981

Table 3.49 Evaluation of the degree of weathering of the rock mass

Weathering degree.	Type	Description
I	Fresh	No signs of weathering appear.
II	Slightly weathered	The discoloration indicates alteration of the rocky material and discontinuity surfaces. The whole rocky set is discolored by weathering.
III	Moderately weathered	Less than half of the rock mass appears decomposed and/or transformed into soil. The fresh or discolored rock appears as a continuous structure or as isolated cores.
IV	Highly weathered	More than half of the rock mass appears decomposed and/or transformed into soil. The fresh or discolored rock appears as a continuous structure or as isolated cores.
V	Completely weathered	The entire rock mass appears decomposed and/or transformed into soil. The original structure of the rock mass is preserved.
VI	Residual soil	The entire rock mass has been transformed into soil. The structure of the massif and the material factory has been destroyed.

Source: International Society for Rock Mechanics and Rock Engineering, ISRM, 1981

3.6.2 Granulometric distribution

For the granulometric analysis, the dry method is used for particles of sizes greater than 0.075 mm. Granulometry by sedimentation using the hydrometer (wet method) is for sizes equal to or less than 0.075 mm.

- **Procedure for dry analysis**

- A representative sample of the soil is taken
- It dries and disintegrates
- It is passed through a set of sieves (whose sizes tend to decrease in a geometric progression of ratio 2) by shaking the set
- The weight retained in each sieve is weighed, so that, knowing the initial weight of the sample, the percentage of material is determined
- With this data, the granulometric curve can be elaborated

- **Plasticity**

The granulometry provides a first approximation to the identification of the soil, but sometimes it is unclear (silty-clayey sand, for example), some indices are used, derived from agronomy, which define the consistency of the soil based on the water content, through the determination of humidity: water weight of the soil divided by the weight of the dry soil (the weight of the water is determined by the difference between the

weight of the soil sample before and after drying it in an oven for the time necessary for it to evaporate that water).

Atterberg defined three limits:

Consistency separates the state of dry solid and semi-solid.

Plastic limit (Wp), separates the semi-solid state of the plastic.

Liquid limit (WL), separates the plastic state of the semiliquid.

The plastic and liquid limit, are the most used in practice, is determined with the fraction of soil that passes through the sieve N °. 40 (0.1 mm).

Once the Wp and WL are determined, a representative point of each soil sample can be obtained in the Casagrande plasticity chart, representing the ratio of the liquid limit, WL, to the plasticity index, $I_p = WL - W_p$ represents the humidity interval to go from the semi-solid state to the semi-liquid. See figure 3.20, Casa Grande plasticity chart.

3.6.3 Condition of soils: porosity, vacuum index, specific weight, humidity, Saturation grade (others)

Procedure for analyzing the behavior of soils before external actions (foundations, excavations, etc.)

- Identification of the type of soil, determining its granulometry and plasticity, to which organic matter is added.
- Determination of its real state (the previous tests are done by drying and disintegrating the sample, without conserving the initial structure) that is, relative proportions of solids, water, etc.
- From the real state, considering, its initial tensional state, the response of the soil must be studied in front of the changes, which in this state induce external actions.

The initial state of the soil must be defined:

- Relative
- Void ratio
- Moisture content

The indices to define the state of the soil are porosity n (the relationship between volume, voids, and apparent volume). Pore index e (the relationship between the volume of voids and the volume of solids). The vacuum index varies between 0.30 and

1.30, although in very soft soils and with organic matter, it reaches values of 3 or more. Table 3.50 presents the properties of coarse-grained soils and in Table 3.51, the properties of fine-grained soils.

Table 3.50 State properties of coarse-grained soils

Coarse-grained floors	Relative density D_r (%)	Dry density γ_d (ken / m ³)	Humidity W (%)	Vacuum index e
Very loose	0-40	<14.0	>16	>0.9
Loose	40-60	14.0-16	12-16	0.65-0.9
Medium dense	60-80	16.0- 17.5	8-12	0.55-0.65
Dense	80-90	17.5-18.5	6-8	0.4-0.55
Very dense	90-100	>18.5	<6	<0.4

Source: González and others 2002

Table 3.51 Properties of fine soil conditions

Fine soils	Fluency Index, IL	Dry density γ_d (kN / m ³)	Humidity W (%)	Vacuum index e
Very soft	1.00-0.80	<1.40	>55	>1.30
Soft	0.80-0.65	1.40-1.55	40-55	1.0-1.3
Average	0.65-0.40	1.55-1.70	25-40	0.7-1.0
consistency	0.40-0.25	1.70-1.80	15-25	0.5-0.7
Hard	<0.25	>1.80	<15	<0.5
Very hard				

Source: González and others 2002

The following parameters are used to estimate the relative concentration of solids and water, see Table 3.52:

Table 3.52 Parameters to estimate the concentration of solids and water

Specific gravity of particles, G	It is the average value corresponding to the various particles. It is determined in the laboratory by measuring the volume occupied by a particle sample (dry and disintegrated and of known weight) by displacing a volume of liquid in a container full of water and previously assessed (pycnometer).
Specific dry weight, γ_d	Relationship between the weight of solids in the sample (without considering the water it contains) and the apparent volume it occupies.
Saturated apparent specific weight, γ_{sat}	Relationship between the weight of solids plus the weight of the water in the holes (assuming saturated soil even if it were not), and the apparent volume of the reference element.
Apparent specific weight, γ_{ap}	It is the relation between the weight of the sample (solids plus water that it contains) and its apparent volume.
Specific weight of water, γ_w	The interstitial fluid.
Humidity, W	Relationship between the weight of the water contained in the sample and the weight of its solids, to be determined by drying in an oven.
Degree of saturation, S_r	Relationship between the weight of the water contained in the sample and the weight it would contain if saturated.

Source: Own elaboration based on González and others 2002

3.6.4 Shear strength

The resistance to the cutting of the soil cannot be considered as a single and constant parameter, it depends on its nature, structure, links, deformational level, etc., and very specifically, its tensional state and the fluid pressure that fills its pores (water or water and air).

The criterion of failure in more widespread soils derives from what is proposed by Coulomb, where it relates normal effective tensions and tangential tensions acting on any ground plane. Figure 3.22 shows the criterion of failure in soils. Figure 3.23 shows the rupture envelope and the Mohr circle in a possible and impossible state.

The criterion states that, for saturated soil, the cut resistance is given by the expression:

$$\tau = c' + (\sigma_n - u) \tan \phi'$$

τ = Resistance to the cut of the ground in favor of a certain plane.

σ_n = normal total voltage acting on the same plane.

u = interstitial pressure.

c' = effective cohesion.

ϕ' = effective internal friction angle.

The above equation represents a straight line in space (ϕ', τ) that is often referred to as a resistance line or ground failure envelope. Figure 3.21 shows the line of rupture, the zone with possible states of rupture and the zone with impossible states. Figure 3.22 represents three circles of Mohr in space (ϕ', τ) that in principle, would represent three voltage states of a soil element.

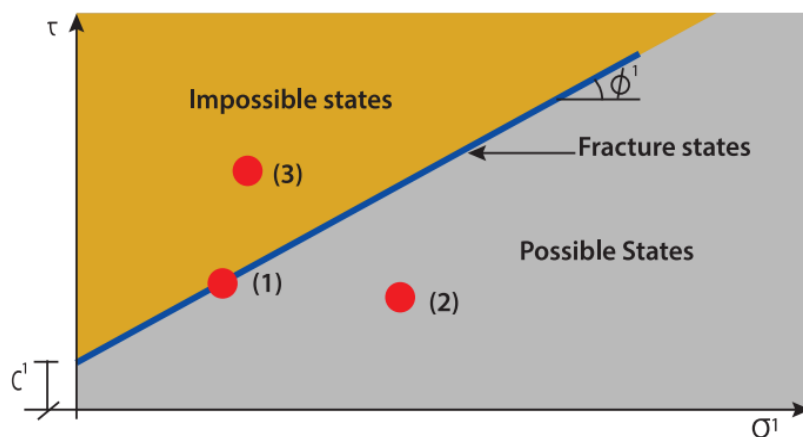


Figure 3.22. Soil failure criterion. González and others 2002

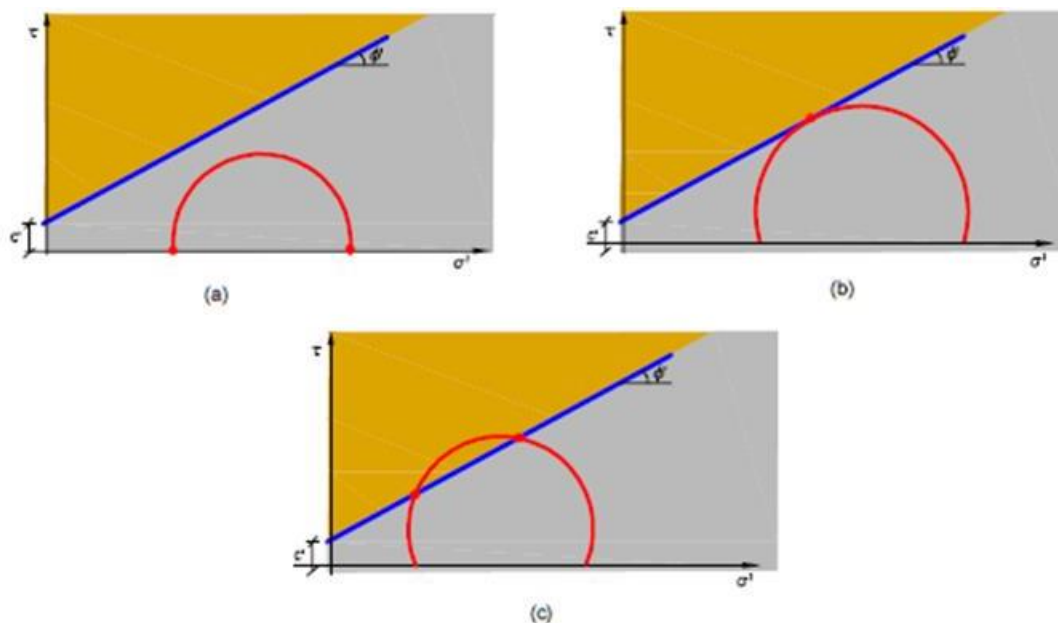


Figure 3.23 Failure envelope and the Mohr circle. State possible (a and b) and impossible (c).
Source: González and others 2002

3.7 Contents of the geological/geotechnical study

Field and laboratory tests, geology and seismic aspects, presence of water Table, analysis of field and laboratory results, assessments of the carrying capacity of the land, calculation of settlements should be included in the geological/geotechnical study, in the Table 3.53 shows a generalized content for a geological/geotechnical study.

Table 3.53 Shows the general content of a geological-geotechnical study

Introduction	Indicates the scope of the geotechnical study and to what type of work is directed. It is recommended to make clear the name of the project for which the report was prepared and indicate the entity that requests it, so that it may be used for other purposes.
Project description	Where the use of the building is indicated, construction materials (steel, concrete, wood, etc.), the order of magnitude, of the loads considered, the height of the building, extension in the plan, description of architectural and structural features.
Objectives	Indicate general and specific objective that will allow reaching with the study.
Methodology	It consists of the procedures used to carry out field research, laboratory, sources of information, data processing, and analysis methods.
Field tests	Equipment used
	Process
	Applicable standards
	Number of probes
	Depth of soundings

Laboratory tests	Number of samples obtained
	Justification of the method used to achieve objectives
	Preparation and processing of samples
	Obtaining geotechnical parameters (internal friction angle, cohesion, shear stress, etc.)
Geology	Posing of solutions
	Analysis of regional and local geology to determine geological risks (geological faults that can cause liquefaction or movements, presence of collapsible or expansive soils, orientations and dips of lithological structures, characterization of soils and rocks, hydrogeology, among others)
Seismic aspects	Classification of the zone according to the simulated threat (null, low, intermediate, elevated) and determination of the coefficient of horizontal and vertical acceleration (PGA = horizontal acceleration). Spectral characterization of the terrain (allows to estimate the most realistic response depending on the geotechnical condition of the site: dense or hard soils versus hard or compact soils). One way to characterize the spectral shape of the terrain is through the correlation with field tests, (SPT, CPT, RQD).
Presence of groundwater level and/or groundwater	Identification of the depth of the water in soundings (noting that these levels are in date and determined meteorological condition). It helps to make design recommendations in the foundation, and open-pit excavations help identify liquefaction patterns and affects the terrain from bearing capacity.
Analysis of field and laboratory results	With the results obtained in the field and laboratory, a qualitative and quantitative analysis is issued that will allow building a matrix of the geotechnical behavior of the site
Evaluation of the bearing capacity of the terrain depending on the selected foundation system (design by resistance)	Depending on the bearing capacity of the land, the responsible engineer must have an estimate of the building loads to select the most appropriate foundation system and consider geometric, and depth variations for the range of loads are acting.
Calculation of expected settlements (design due to rigidity)	Determine the settlement or expected deformation of the terrain as a function of the acting force and the geometry of the selected foundation system.
Conclusions	They must be clear and precise. The conclusion of each aspect observed in the previous points must be reported.
Recommendations	Of geotechnical type and constructive method, recommendations for excavations, control of deformations, techniques of improvement or stabilization of soils and rocks, etc.
Annexes	Sketch of location of soundings, the probable profile of the terrain, stratigraphic profile used in the design of foundations, field registration of the drilling carried out, type floor of the building, template of the laboratory tests, other complementary information that helps the report.

Source: Own elaboration based on March 2016

Next, an example of the Geological-Geotechnical content applied in the Republic of El Salvador is presented in the project named: **"IMPROVEMENT OF THE ROAD NETWORK OF THE NORTHERN AREA OF EL SALVADOR "**

INTRODUCTION

Generalities

Description of the section

STUDY AREAS

Roads

- Geological Description
- Prospecting and testing
- Field Work
- Laboratory work
- Geological Characterization - Geotechnical
- Analysis of soils with plastic and undesirable characteristics
- Conclusions
- Recommendations

Slopes

- Geological Description
- Prospecting and Testing
- Field Tests
- Laboratory work
- Geological and Geotechnical Characterization
- Characterization of Existing and Generated Cut Slopes
- Analysis of the results of seismic refraction soundings carried out
- Characterization of Slopes in Hillside
- Slopes Generated in the Accesses to the Roads
- Stability Analysis
- Slopes in court (generated and existing)
- Conclusions
- Recommendations, Protection and Mitigation works

Embankments

- General Description of the Embankments
- Prospecting and Testing
- Geological and Geotechnical Characterization
- Stability Analysis
- Recommendations

Retention structures

- Geological Description
- Prospecting and Testing
- Field Work
- Laboratory work
- Geotechnical Characterization
- Stability analysis
- Conclusions
- Recommendations.

Banks of Materials

- General Characteristics
- Prospecting and Testing
- Field Work
- Laboratory work
- Geological Characterization - Geotechnical
- Conclusions and Recommendations

Dumps

Appendix



CHAPTER 4

SLOPES STABILITY ANALYSIS AND STABILIZATION METHODS

CA-06. Tegucigalpa, Honduras

4.1 Stability analysis

It is essential for the analysis of stability, initially, the knowledge of the movement mechanisms in the different geological materials; establish criteria for the collection of information and the interpretation of results to identify slopes instability.

This chapter lists different methodologies that may be applicable depending on the case that occurs in a slope, whether in soil or rock and the methods of analysis for the evaluation of the stability of slopes and hillsides in the case of seismic events, are detailed.

The conditioning and triggering factors that may influence and produce instability are described, the minimum safety factors are presented both to resist static and seismic movements. In any geotechnical study, it is sought to obtain a geotechnical and geophysical model; the steps to be followed for this modeling were incorporated.

The methodology to detect and prevent possible problems in areas prone to landslides is through:

- The identification of the most common failure mechanisms in the different types of geological materials.
- The establishment of criteria for the collection of information
- The search and interpretation of key effects to identify the possible instability of the slopes

4.1.1 Types of movement in mass.

Hunt (1984) proposes a classification of types of movements in mass based on the recognition of the geological factors that condition the movements. Slope landslides occur in many ways, and there is still some degree of uncertainty in predictability, rapidity of occurrence, and affected area. However, there are certain patterns that help identify and recognize potential areas of mass movements, which allows the treatment of the slope to eliminate or reduce to a minimum the risk of movement, Table 4.1.

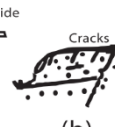
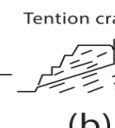
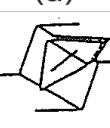
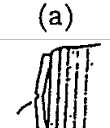
Table 4. 1 Classification of mass movement types based on the recognition of the geological factors that condition mass movements.

Type of movements in mass.	Type	Definition
Detachments	Freefall.	Sudden detachment of one or more blocks of soil or rock that descend in free fall.
	Rollover	Fall of a block of rock concerning a pivot located below its center of gravity.
Collapses	Planar	Slow or rapid movement of a block of soil or rock along a flat fault surface
	Rotational	Relatively slow movement of a mass of soil, rock or a combination of the two along a well-defined curved fault surface
	Lateral spreading.	Movement of different soil blocks with different displacements
	Debris slide.	Mixture of soils and pieces of rock moving along a planar rocky surface.
Avalanches	Of rock or debris	Rapid movement of an incoherent mass of rock or soil-rock where the original structure of the material is not distinguished.
Flow	Of debris	Soil or rock-soil is moving like a viscous fluid, usually moving at much greater distances from the fault. Usually caused by excess pore pressures.
Reptación		Slow and imperceptible movement downslope of a soil mass or soil-bedrock

Source: Hunt, 1984

A summary is shown in Table 4.2 of the forms of collapse in rock strata and their applicable numerical analysis methods.

Table 4. 2 Forms of collapses of rock strata and numerical analysis methods, GENSAI 2018.

Form of collapse.		Diagram of the pattern.	Assigned analysis.						
			Limit equilibrium method.	Block theory	Limited elements method.	Individual elements method.	Discontinuous deformation method.	RBSM method	
Collapses	Small scale	 (a)  (b)	IV	III	IV	II	I	III	With the method of discontinuous deformation, when introducing viscous terms, the situation can be considered up to the generation of the collapse and the situation after the beginning of the fall.
	Large scale	 (a)  (b)	IV	III	IV	II	I	III	
Landslides	Arch / complex landslides.	 (a)  (b)	II	II	I	II	III	II	For landslides, the limited element method with joint elements is widely used to follow the process until collapse due to landslides, the rigid body spring model (RBSM method) can be used. In recent years, there are cases in which the collapse process is studied with the collector method (Manifold). For collapses in which a 3-dimensional study is necessary, as in wedge collapses, the 3-dimensional individual element (DEM) method is effective.
	Flat landslides	 (a)  (b)	II	II	II	II	II	II	
	Wedge destruction.	 (a)  (b)	II	II	II	I	III	III	
Top segment	Deviation of the upper segment.	 (a)  (b)	III	III	III	II	I	III	Cracks are modeled in blocks to see their stability about the friction force between the blocks. It is widely used that discontinuous deformation method (DDA) and the individual element method (DEM). It is widely used that discontinuous deformation method (DDA) and the individual element method (DEM). Therefore, the collector method (Manifold) is proposed, however in Japan there are few cases.
	Upper segment in blocks.	 (a)  (b)	II	II	III	I	I	III	
	Buckling.	 (a)  (b)	IV	III	III	I	I	III	

Form of collapse.	Diagram of the pattern.	Assigned analysis.						
		Limit equilibrium method.	Block theory	Limited elements method.	Individual elements method.	Discontinuous deformation method.	RBSM method	
								Therefore, the collector method (Manifold) is proposed, however in Japan there are few cases.

I: Very Suitable, II: Suitable, III: Moderately adequate, IV: Not Suitable

Source: Own elaboration based on The Association of Roads of Japan (JAEA), 2009. Guidelines for cuts and earthworks on roads and slope stability. ISBN 978-4-89950-415-6

4.1.2 Geological and geotechnical model

Geological model

It consists of the two-dimensional or three-dimensional representation of a volume of rocks and the topography of a certain area. It can represent that the lithology, lithological structures, alteration, mineralization, and other types of the geological feature of the rock massif.

The creation of a geological model is one of the first stages of appreciation of a slope and requires a thorough knowledge of lithology, structures, geohydrology, among other characteristics.

It starts with the collection of surface-available geological information, channel sampling followed by exploration drill holes. Purpose of making a geological model:

- Increase knowledge of the morphology of the studied zone and represent it as close to reality as possible;
- Relate the units that have been affected by structural movements;
- Define soil/rock volumes in which the variable to be estimated has a homogeneous behavior.

Basics for a geological model:

- Valid database that contains the fields to represent

- b) Thorough knowledge of the geology of the area to represent
- c) Software

Basic steps to develop the model:

- a) Define the units to be modeled.
- b) Determine the orientation of the model, the distance, and the number of sets of two-dimensional sections to be interpreted.
- c) Build three-dimensional solids.
- d) Validate the model.

Geotechnical model

The geotechnical code of slopes and hillsides of Costa Rica defines the geotechnical model and details the criteria and methods that the geotechnics' can use to evaluate a slope in soil or rock and conforms to what is described in chapters 3 and 4 of this manual.

- a) The geotechnical method for the stability analysis of the slope must include at least the following:
 - The stratigraphy of the subsoil.
 - The depth (or position) of the water Table and its temporal variations
 - The position of the rupture surface (in case of analyzing a slope or hillside that shows evidence of landslide or where a fault has already occurred)
 - The physical-mechanical properties of the different types of materials found. Its determination must consider the conditions of the interstitial pressure regime and its relationship with the parameters of shearing strength, that is, under long-term drained conditions, conditions of partial drainage (intermediate-term) and undrained conditions (short term) as appropriate
 - The reciprocal effects between the ground and proposed stabilization measures
- b) The geotechnical method for slope analysis or design must define the failure criterion that best fits the physical and mechanical properties obtained in the resistance tests carried out in the field and laboratory
- c) The failure criteria commonly used in slope stability analysis in soils are the following: Mohr-Coulomb, Cam Clay, Hyperbolic, and Hardening Soil, among others. It is the responsibility of the professional responsible for selecting the failure criterion that best fits the characteristics of the soil and the analyzed ground, based on the geological and geotechnical investigations carried out.

- d) In the case of rocky slopes, the following failure criteria can be used for intact rock: Hoek and Brown, Mohr-Coulomb, Bieniawski, Fairhurst, Hobb, Johnston, Barton, among others. On the other hand, the criteria of failure used to calculate the resistance of the discontinuities of the rock mass is Mohr-Coulomb, Barton-Bandis and Hoek and Brown.

In Table 4.3, a guide of rupture criteria used to analyze the stability of rock massifs and the data necessary for its application is shown.

Table 4. 3 Criteria of rupture in rocky massifs and data necessary for its application

Characteristics of the rock massif.	Rupture along discontinuity planes.	Rupture through the intact rock.
Massive rock massif without discontinuities	It's not possible	Hoek –Brown (m for intact rock and s=1) Mohr-Coulomb (c and ϕ for intact rock)
Rocky massif with one or two families of discontinuities	Mohr-Coulomb (c and ϕ for the discontinuity) Barton-Bandis (JCS, JRC, and ϕ for the discontinuity)	Hoek –Brown (m for intact rock and s=1) Mohr-Coulomb (c and ϕ for intact rock)
Rocky massif with one or two families of discontinuities	Hoek –Brown (GSI, m, s and a for rocky massif) Mohr-Coulomb (c and ϕ for rocky massif)	It's not possible

Source: Own elaboration based on González et al., 2002

4.1.3 Methods of stability analysis of a slope

Regardless of the method used, the purpose sought in the stability of a cut or excavation is the safety factor, which consists in comparing the acting forces (gravity, the weight of the mass) versus resistant forces. If the acting forces exceed the resistant forces, the soil is stable, and if the acting forces are less than the resisting forces, the soil is unstable and may tend to slip. In soils, a fault surface should be assumed where the shear stress is a function of the cohesion, the density of the material, and the angle of the failure surface. The safety factor varies according to the scenario we present: normal or static condition, pseudo-static condition, and dynamic condition. Under pseudo static conditions, the normal condition plus seismic acceleration is considered, in these conditions if the safety factor is equal to or greater than 1.20 the material does not slip and safety factor less than 1.20 will slip. The dynamic condition will be equal to the normal condition adding the pseudo-static condition and the weight of the water

that is in pores of the soil; the safety factor will approach 1.04. The retaining wall must also be designed about the safety factor of the slope, ensuring that the wall is not oversized about the safety factor of the slope.

In the case of rock excavations, it is initially convenient to analyze the parameters contained in the RMR classification proposed by Bieniawski in 1989 and modified by Romana in 1985, Robertson (1988). They propose an appropriate method for slopes from the RMR, which becomes SMR and gives us a division into classes of slopes: the risk of instability that runs in each possible way of failure whether flat or wedge, toppling of mass; also suggests recommendations for support methods and/or correction. The Q-Slope system, which is a variant of the Q system developed by Nick Barton and others in 1974 to be used in the design of slopes, should also be considered. Barton, in his system, also characterizes the rock massif and adds the seismic component (pseudo-static) and through simple formulas, can be compared to the proposal of Bieniawski and Abbot.

The calculation methods are divided into two large groups: the exact ones which are the numerical methods and the limit equilibrium methods figure 4.1. In practical considerations, simple methods such as the abacus of Hoek and Bray provide adequate results when you do not have a program for the calculation of numerical and exact methods.

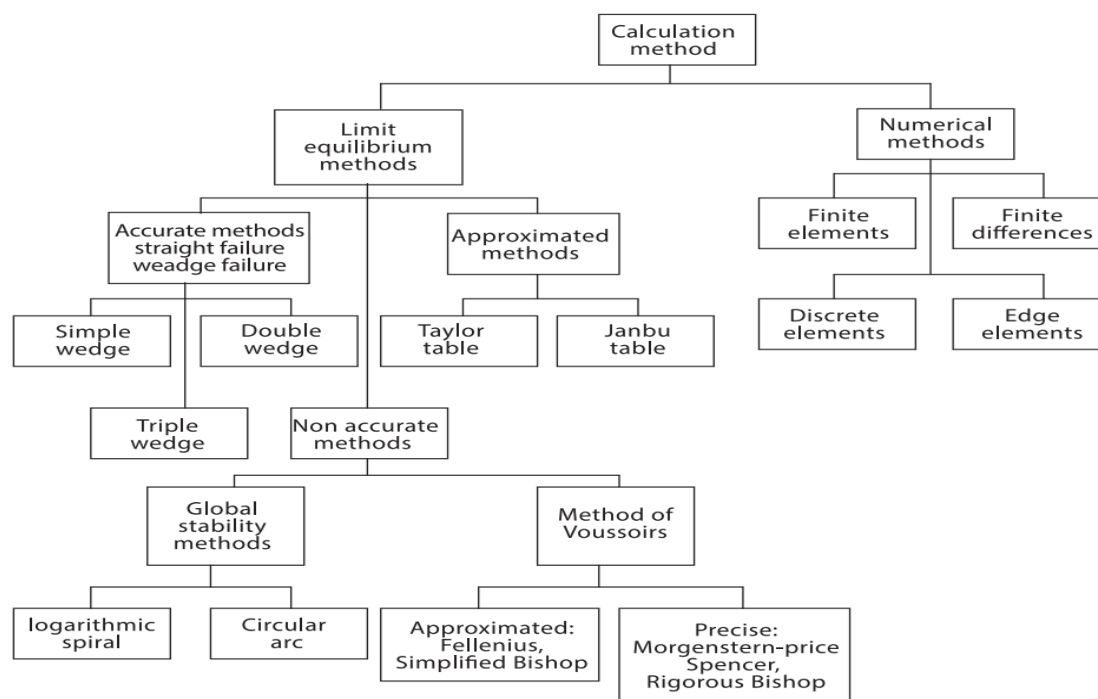


Figure 4. 1 Calculation methods for slope stability analysis.

Source: Own elaboration based on Suarez, J.

The methodologies for stability analysis of slopes, in soils and rock mass, are based on field evaluations, mechanical exploration, seismic survey and interpretation, rock mass geomechanics classification, stability modeling by limit equilibrium analysis among other methods.

After having geologically and geotechnically recognized the terrain affected by the excavation and identified the processes of instability that may affect a slope, the professional responsible for the study must consider the method of analysis considered most appropriate to estimate their degree of safety. Here it is presented as a guide, a brief description of the methods for estimating the best practice of the slopes and hillsides.

As far as possible, the most intuitive approximate methods (Taylor, Janbú Tables) should be applied and later contrasted with other more sophisticated methods (numerical methods). The use of more complex numerical methods does not necessarily mean that they will have better results.

Limit equilibrium methods.

In the book "Geological Engineering" by González de Vallejo, Luis, et al., 2002. Describes the methods of limit equilibrium (most used), analyzes the equilibrium of a potentially unstable mass, and consists of comparing the forces tending to movement with the resistant forces that oppose it along a certain surface of rupture. They are based on:

- The selection of a theoretical failure surface in the slope.
- The Mohr-Coulomb failure criterion.
- The definition of "Stability index or safety factor."

The problems of stability are statically indeterminate, and for its resolution, it is necessary to consider a series of different starting hypotheses according to the methods. Also, the following conditions are listed:

- The failure surface must be postulated with a geometry that allows the sliding to occur; that is, it will be a kinematically possible surface.
- The distribution of the forces acting on the braking surface can be computed using known data (specific weight of the material, water pressure, etc.)
- The resistance is mobilized simultaneously along the entire failure plane.

With these conditions, equilibrium equations are established between the forces that induce slip and resistant forces. The analyzes provide the safety factor value of the slope for the analyzed surface.

The limit equilibrium analysis assumes that the safety factor is the same across the entire slickenside. A value of the safety factor greater than 1.0 indicates that the capacity exceeds the demand and that the slope is stable to the slip concerning the failure surface analyzed. A value of safety factor less than 1.0 indicates that the slope is unstable.

There are several methods for calculating the safety coefficient by limit equilibrium, complex, developed primarily for application in soil type materials. The analytical methods provide the safety coefficient from the immediate resolution of simple equations (Taylor's method, from Fellenius), while the numerical methods need, for their resolution, systems of equations and iterative calculation processes; in this category are the methods of Morgenstern and Price, of Spencer, etc.

The limit equilibrium methods are classified as:

- Methods that consider the analysis of the block or total mass
- Methods that consider the mass divided into slices or voussoirs (wedge-shaped element), as shown in Figure 4.2.

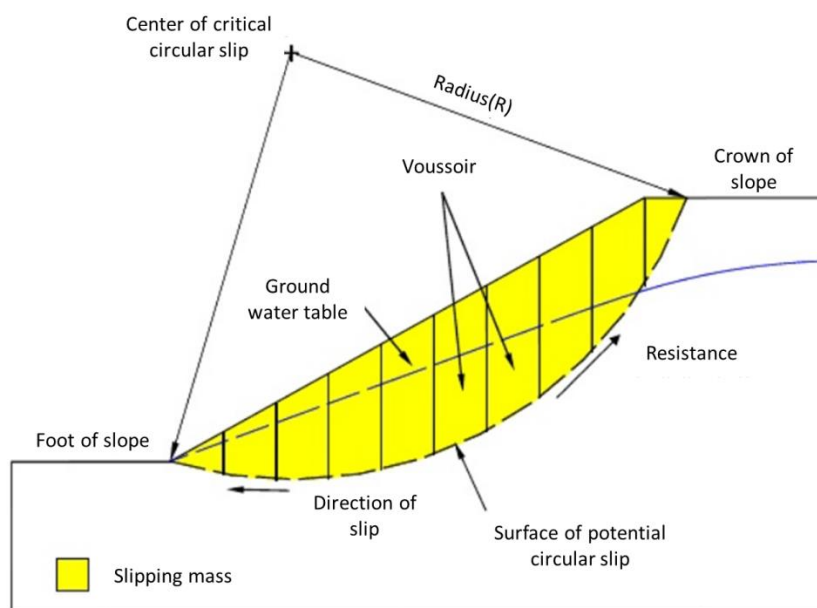


Figure 4. 2 Mass divided into slices or vertical stripes on a slope.

Source: <http://www.aimecuador.org>

The method of block or total mass is valid for homogeneous materials, and only performs the computation and comparison of forces at a point on the braking surface. The method of vertical slices or strips may consider inhomogeneous materials and

carries a series of own hypotheses about the location, position, and distribution of the forces that act on the slices; the calculation of the acting forces is made for each of the slices in which the slope has been divided, finally integrating the results obtained. The most common slicing methods are modified-Bishop's and Jambu's, valid for the analysis of curved, flat, and polygonal failures.

For failure in rocks, the methods are also based on the equilibrium equations between the acting forces, established based on the geometry of each type of failure.

Retrospective analysis

The retrospective analysis method is a practical method used in Japan to determine the real resistance should be to monitor the displacements of the mass and determine the location of the fault surface. The retrospective method can estimate the resistance of the slickenside by replicating in a model the situation found in the field, thus trying to replicate the current safety factor assumed from the conditions of the moving soil mass.

In the case of landslide control work, it is considered that in conditions of a moving mass, the safety factor is in the range of 0.95 to 1.00. The safety factor of 0.95 is used for active landslides. The design safety factor, however, is between 1.10 and 1.20, considering the importance of the objects to be protected.

However, for emergency responses that are taken to ensure temporary safety, the proposed safety factor can be set at 1.05 or higher.

It should be considered that the safety factor proposed here is a value for determining the scale of the landslide prevention works and not the value that indicates the stability of the slope after the works.

In the case of using the stability calculation using the retrospective analysis method, this is done using the procedures mentioned below.

- To determine the cohesion (c') is often estimated through a laboratory test. You can also use Table 4.4, which relates the cohesion with the maximum thickness of the mass of an active slip.

Table 4.4 Maximum thickness of the slipped mass

Maximum thickness of the slipped mass (m)	Cohesion C (kN/m ²)
5	5
10	10
15	15
20	20
25	25

Source: "Guidelines for Landslide Prevention Technologies," Draft: ISSN 0386-5878 o PWRI Technical Note No.4077

- When the maximum thickness of the vertical layer is greater than 25 m, it is established that c' is 25 kN / m². However, we must also determine not only the value of c' , but also the value of ϕ' . A separate evaluation is necessary for the value of c' when the thickness of the vertical layer is less than 5 meters.
- The internal friction angle (ϕ') can be determined using the retrospective analysis itself substituting the values of the assumed current safety factor and the cohesion determined by test or by Table 4.4 (c') in the stability analysis equation. Then, replace the cohesion (c') and the internal friction angle (ϕ') in the stability analysis equation, and examine the alternative landslide prevention works that will be required to achieve the design safety factor or desired control.

For more information on this method, you can consult the publication of Public Works Research Institute (PWRI), Japan 2007: "Guidelines for Landslide Prevention Technologies," Draft: ISSN 0386-5878 o PWRI Technical Note No.4077.

Slopes in soils

Infinite slope, the method is based on the hypothesis that the length of a superficial flat failure parallels to the slope can be considered infinite concerning the thickness slid. This method is generally used for stability analysis of natural hillsides. Example: colluviums on rock massif, figure 4.3.

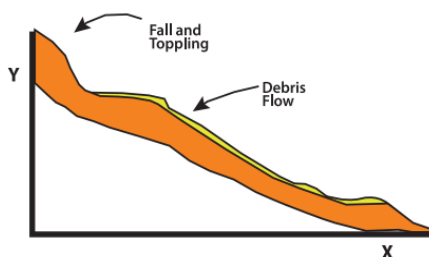


Figure 4. 3 Infinite slope, colluvium (yellow color) that slides on rocky massif (orange color).

Source: Own elaboration based on: Suárez Días, Jaime

Wedge method, although it has no relationship with the wedge-type fracture in fractured rock masses, the sliding hammer is divided into several blocks by vertical lines, for which the balance of vertical and horizontal forces is established. The safety coefficient is the ratio between the available tangential resistance and that required for equilibrium.

Total mass method or Taylor method (1948). It is based on the use of circular failure surfaces in two dimensions is a hypothesis very used in practice and represents the real problem in slopes of finite height, when there are no areas of land that clearly define the development of braking surfaces. The following actions are carried out on the failure surface:

- The own weight, W , of the soil mass.
- The interstitial pressure of water distributed along the braking surface, with the resultant U
- Tangential force distributed over the braking surface, resulting in T ($R_c + R \phi$) (where T = the tangential stress, R_c = resulting from the cohesion and $R \phi$ = resulting from the friction angle)
- Normal stress distributed on said surface, of resultant N .

Abacus of Hoek and Bray, (1981). It allows the calculation of the safety coefficient of slopes in soils with circular failure at the foot of the slope from the geometric data of the slope and the resistant parameters of the soil. Hypotheses are assumed:

- The material of the slope is homogeneous.
- The existence of a traction crack is considered.
- The normal tension is concentrated in a single point of the braking surface.

Five cases are considered concerning the location of the water Table on the slope (1. Slope completely drained, 2. Surface water by the height of the slope 3. Surface water by the height of the slope, 4. Surface water by the height of the slope and 5. Completely saturated) with the flow parallel to the slope. Depending about the water Table, one of the five calculation abacuses is chosen to determine the safety factor (the difference between the abacuses is the inclination angle of the slope about the water Table).

It is desired to obtain the safety coefficient of a partially saturated excavated slope.

Example of calculating the safety coefficient of a slope in soils with Hoek and Bray abacus. In González and others, 2002

Data:

Height of the soil, $H = 12 \text{ m}$

Inclination, $\psi = 35^\circ$

Resistant parameters of the soil., $c' = 1.5 \text{ t/m}^2$, $\phi' = 25^\circ$ and $\gamma = 1.8 \text{ t/m}^3$

The following steps are followed to obtain the safety coefficient:

- The corresponding abacus is selected according to the position of the water level in slope; in this case, the surface is like that of Figure 4.4, which corresponds to the abacus no. 3 figure 4.5
- Calculate the value of the expression $c' / (\gamma H \tan \phi')$, and set the abacus with this value
- The cut-off points of the line corresponding to the previous value with the curve corresponding to the angle of the slope allows to read in the ordinate and abscissa axes the values of the expressions $\tan \phi' / F$ y $c' / (\gamma H F)$, from which it to solve for F .

For the example data:

$$c' / (\gamma H \tan \phi') = 1.5 / (1.8 \times 12 \times 0.466) = 0.149$$

$$\tan \phi' / F = 0.425$$

$$c' / (\gamma H F) = 0.063$$

From where the value of $F = 1.1$ is solved.

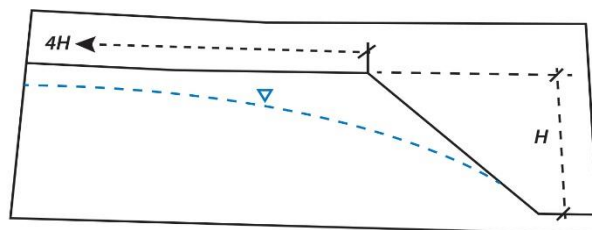


Figure 4. 4 Hypothesis n°. 3 for the location of the water Table on the slope; corresponding to the outcrop of the same at a distance $4H$ from the coronation of the slope.

Source: Hoek y Bray, 1981

The abacuses also allow obtaining the corresponding values of c' and ϕ' for a certain safety factor F and a slope angle.

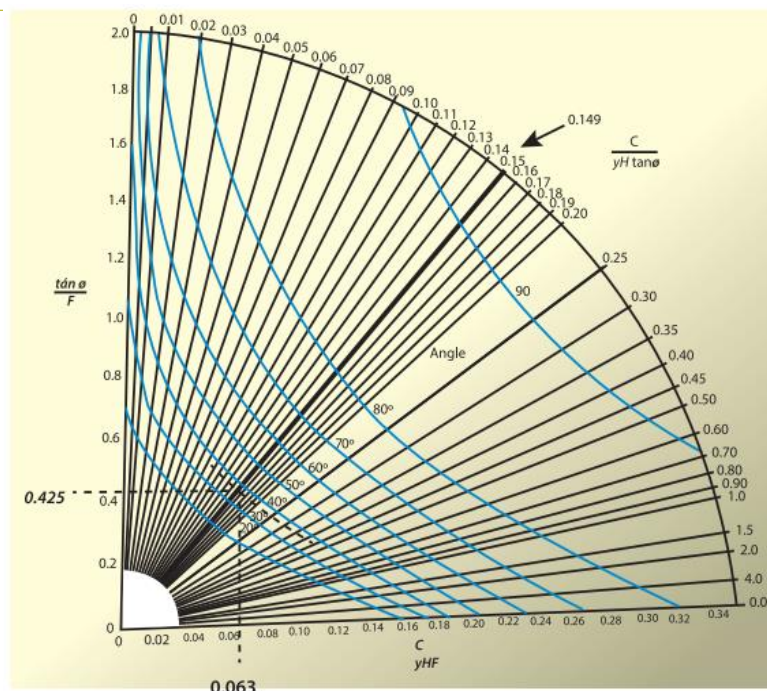


Figure 4.5 Abacus n.º 3 of Hoek and Bray for circular failure in soils.

Source: Own elaboration based on Hoek and Bray, 1981

Methods of slices. Bishop's method. The Taylor hypothesis assumes that the normal stresses at the braking surface are concentrated at a single point, which implies a certain error, although, in general, it remains on the side of safety. Also, the Taylor abacus only allows the introduction of water in the case of homogeneous soil and horizontal water Table. To avoid these inconveniences, Bishop developed in 1955 a method of slices, the method of Bishop, with the following hypotheses:

- A circular failure surface is assumed.
- The sliding mass is divided into "n" slices or vertical strips.
- The equilibrium of moments of the current forces in each slice is established with respect to the center of the circle.
- From the equilibrium condition of vertical forces in each slice, the N forces (normal to the braking surface) are obtained and substituted in the resulting equilibrium equation of moments.
- The simplified method of Bishop (the best known and used) also assumes that the contact forces before every two slices do not influence to be balanced.
- Thus, the expression of safety coefficient, F, of the surface considered is obtained.

Rock slopes

Quality index classification RMR (Rock Mass Rating) developed by Bieniawski 1989

In the RMR classification (Rock Mass Rating), the rock massif is divided into zones or sections that have uniform geological characteristics according to the observations made in the field, in which the data collection and measurements are carried out, referring to the properties and characteristics of the rock matrix and discontinuities.

To calculate the RMR index corresponding to each of the discontinuities, follow the procedure in Table 4.5. At the same time, a value is assigned depending on the characteristic that it presents, the sum of the values gives us the class of the rock mass; The procedure to calculate the RQD is in section 3.3.6 of this manual. Once the RMR classification is obtained, the correction suggested by Romana is made to obtain the slope class and the support method.

Once the scores resulting from applying the five classification parameters are obtained, the correction is made by the orientation of discontinuities, and a numerical value is obtained with which the rock massif is finally classified. Each class of massif is assigned a quality and geotechnical characteristic. Thus, a rocky massif classified as very good (Class I) will be a hard-rocky massif, little fractured, without significant filtration and little weathered, presenting very few problems in front of its stability and resistance. It can be deduced that it will have a high bearing capacity, will allow the excavation of slopes with steep slopes and will not require stabilization measures.

In this section, we propose the use of the SMR methodology (Slope Mass Rating), which corresponds to a method to determine the correct correction factors to apply the RMR classification to slopes.

Table 4.5 Geotechnical Classification RMR (Rock Mass Rating)
Corrections for orientation of discontinuities and classification.

1	Resistance of the rocky matrix. (Mpa)	Point load test	> 10	10-4	4-2	2-1	Simple compression (Mpa)		
		Simple compression	> 250	250-100	100-50	50-25	25-5	5-1	< 1
	Rating		15	12	7	4	2	1	0
2	RQD		90%-100%	75%-90%	50%-75%	25%-50%	< 25%		
	Rating		20	17	13	6	3		
3	Separation between joints.		> 2 m	0.60-2 m	0.2-0.6 m	0.06-0.2 m	< 0.06 m		
	Rating		20	15	10	8	5		
4	State of discontinuities.	Length of the discontinuity.	< 1 m	1-3 m	3-10 m	10-20 m	> 20 m		
		Rating	6	4	2	1	0		
		Opening	Nothing	< 0.1 mm	0.1-1.0 mm	1-5 mm	> 5 mm		

	Rating	6	5	3	1	0	
	Roughness	Very rough	Rough	Slightly rough.	Wavy	Soft	
	Rating	6	5	3	1	0	
	Backfilling	Nothing	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5 mm	
	Rating	6	4	2	2	0	
	Disturbance	Unaltered	Slightly altered	Moderately altered	Very altered	Decomposed.	
	Rating	6	5	3	1	0	
5	Groundwater.	Flow for 10 m of tunnel	Null	< 10 lts/min	10-25 lts/min	25-125 lts/min	> 125 lts/ min
		Ratio: water pressure / major principal stress.	0	0-0.1	0.1-0.2	0.2-0.5	> 0.5
		Overall status	Dry	Slightly damp	Damp	Dripping	Flowing water
		Rating	15	10	7	4	0
Correction for the orientation of the discontinuities							
Direction and dip		Very favorable	Favorable	Medium	Unfavorable	Very unfavorable	
Rating	Tunnels	0	-2	-5	-10	-12	
	Foundations	0	-2	-7	-15	-25	
	Slopes	0	-5	-25	-50	-60	
Classification							
Class	I	II	III	IV	V		
Quality	Very good	Good	Medium	Bad	Very bad		
Rating	100-81	80-61	60-41	40-21	< 20		

Source: Bieniawski 1989

The SMR classification (Slope Mass Rating) gives us:

- A division into slope classes
- The risk of instability that runs in each possible way of failure: flat or wedge, overturning, or mass
- Suggests recommendations for support methods and/or correction

The relation that Romana suggests for this classification includes an "adjustment factor" that works from the orientation of the joints and (product of three subfactors) and an "excavation factor" that depends on the method used.

$$SMR = RMR + (f1 + f2 + f3) + f4$$

The following Tables contain the modifications of the RMR (Rock Mass Rating) to obtain the SMR (Slope Mass Rating). The adjustment factor of the joints is the product of three subfactors, see Table 4.6; The adjustment factor according to the excavation method is shown in Table 4.7, and Table 4.8 describes the classes of the SMR, Table 4.9 contains the frequency of possible instabilities according to Romana and Table 4.10 correction measures proposed by the SMR.

- **F1** depends on the parallelism between the course of the joints and the face of the slope. It varies between 1.00 (when both courses are parallel) and 0.15 (when the angle between both courses is greater than 30 °, and the probability of fracture is very low). These empirically established values fit roughly to the following equation:
 - o $F1 = (1 - \sin aj - as)^2$
 - o Where aj and as are the dip values (aj) and the slope (as)
- **F2** depends on the dip of the joint in the flat failure. In a sense, it is a measure of the probability of the shear strength of the joint. It varies between 1.00 (for joints with dipping greater than 45 °) and 0.15 (for joints less than 20 °). It was established empirically, but can be adjusted as simplified as follows:
 - o $F2 = (\tan^2 bj)^2$
 - o Where bj is the dip of the board, F2 is worth 1,00 for rollover failures.
- **F3** reflects the relationship between the dips of the board and the slope. The values proposed by Bieniawski in 1976 have been maintained, which are always negative.

Table 4. 6 Adjustment factor for joints (F1, F2, F3) for SMR proposed by Romana (1985)

Case		Very favorable	Favorable	Fair	Unfavorable	Very unfavorable
P	aj-as	> 30°	30° - 20°	20° – 10°	10° - 5°	< 5°
T	aj-as-180°					
Value F1 (P/T)		0.15	0.40	0.70	0.85	1.00
P	bj	< 20°	20° - 30°	30° - 35°	35° - 45°	> 45°
Value F2 P		0.15	0.40	0.70	0.85	1.00
Value F2 T		1.00	1.00	1.00	1.00	1.00
P	bj – bs	>10°	10° - 0°	0°	0°-(-10°)	<-10°
T	bj + bs	<110°	110° - 120°	>120°		--
Value F3 (P/T)		0	-6	-25	-50	-60

Source: Bieniawski 1989

Where:

P = Plan failure

T = Joint by toppling

as = dip direction of the slope.

bs = dip of the slope

aj = dip direction of the joints.

bj = Dip of the joints

Table 4. 7 Adjustment factor according to Excavation method

Method	Natural slope	Precut	Soft blasting	Blasting or mechanical	Deficient blasting
F4	+15	+10	+8	0	-8

Source: Romana (1985)

Table 4. 8 Description of the SMR classes.

Case No.	V	IV	III	II	I
SMR	0 – 20	21 – 40	41 – 60	60- 80	81 – 100
Description	Very bad	Bad	Fair	Good	Very good
Stability	Completely unstable	Unstable	Partially stable	Stable	Completely stable
Failures	Big planar or soil-like	Planar or big wedges	Some joints or many wedges	Some blocks	None
Support	Reexcavation	Important /corrective	Systematic	Occasional	None

Fuente: Romana (1985)

Associated with the SMR classification and the type of failure of the rock mass, Romana 1985, suggests a frequency of possible instabilities that are shown in Table 4.9.

Table 4. 9 Frequency of possible instabilities

Type of failure.	SMR intervals	Frequency
Plane failure	SMR > 60 60>SMR>40 40>SMR>15	None Important Very large
Wedge failure	SMR >75 75 >SMR>49 49>SMR>40	Very few Some Many.
Toppling	SMR>65 65>SMR>50 50>SMR>30	None Minors Importantes
Mass failure	SMR>30 30>SMR>10	None Possible

Source: Romana (1985)

Romana presents a recommendation of countermeasures according to the estimated SMR value; the summary is shown in Table 4.10.

Table 4. 10 Suggested support method by the SMR

Type of support	SMR intervals	Support methods
Reexcavation	10 – 30	Reexcavation Walls
Drainage	10 – 40	Surface drainage Deep drainage
Concreting	20 – 60	Shotcrete Dental concrete Ribs and/or beams Toe Walls
Reinforcement	30 – 75	Bolts Anchors
Protection	45 – 70	Toe ditch Toe or slope fences Nets and/or meshes (on the surface of the slope)
No support	65 – 100	Scaling None

Source: Romana (1985)

Q-slope developed by Barton (2011)

The Q-slope method corresponds to a variation of the Q system developed by Barton et al. (1974), to be used in the design of slopes, in which:

$$Q_{\text{slope}} = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF_{\text{slope}}}$$

Where:

RQD = Rock Quality Designation

J_n = Joint set index that indicates the degree of fracturing of the rock mass.

J_r = Joint roughness index of discontinuities or joints.

J_a = Index that indicates the alteration of the discontinuities.

J_w = Reductive coefficient due to the presence of water adjusted to slopes.

SRF (Stress Reduction Factor) = Coefficient that considers the influence of the tensional state of the rock massif.

The three factors of the expression represent:

RQD/J_n: The size of the blocks.

J_r/J_a: The shear strength between blocks.

J_w/SRF: The influence of the tensional state.

Any of the following two correlations can be applied to relate Barton's Q to Bieniawski's RMR, following equations:

- Bieniawski (1976)

- $RMR = 9 \ln Q + 44$
- Abad and others (1983)
 - $RMR = 10.5 \ln Q + 42$

Barton developed Q_{slope} Index for slopes and reflects the potential of seismic refraction tests to exploit subsoil exploration for slope stability analysis adequately and suggests that it be a means to characterize all those properties that until now have been difficult to obtain.

Geotechnical strength index (GSI)

It is another option for the evaluation of the fractured rock mass, which depends on the properties of intact pieces of rock but also on the freedom, or contraction, that these pieces must slide or roll under different tension conditions. This index is based on the failure criterion of Hoek and Brown (1980) and updated to its latest version, Hoek and Brown (1997).

There are some uncertainties and inaccuracies that have created drawbacks in their implementation to numerical models and limit equilibrium computer programs. So, the method has been implemented in a program called "Roclab", includes Tables and graphs to estimate the compressive strength of the intact rock elements (σ_{ci}), the material constant (m_i) and the Geological Strength Index (GSI) that allow to define with more precision the parameters necessary for the modeling by limit equilibrium.

Plan Failure

Since it is considered one of the simplest cases of analysis, the procedure will be described. From the acting forces on the failure surface considered, the equation of the safety coefficient is established:

$$F = \frac{cA + (W \cos \alpha - U) \tan \Phi}{W \sin \alpha}$$

Where:

cA = force due to the cohesion in the slip plane.

$(W \cos \alpha - U) \tan \Phi$ = force due to friction in the plane.

$W \cos \alpha$ = stabilizing component of the weight (normal to the slickenside)

U = Total force due to the water pressure on the slickenside.

$W \sin \alpha$ = component of the weight tending to the sliding (parallel to the slickenside)

In the case of a water-filled traction crack, the following equation applies:

$$F = \frac{cA + (w \cos \alpha - U - V \sin \alpha) \tan \phi}{W \sin \alpha + C \cos \alpha}$$

V is the force exerted by the water on the traction crack.

The weight of the slope is calculated based on the unit volume of the sliding block and the specific weight of the material, and the force exerted by the water can be estimated:

$$U = \frac{1}{2} \gamma_w Z_w A; V = \frac{1}{2} \gamma_w Z_w^2$$

A being the length of the slickenside.

From this general formulation and depending on the characteristics and shape of the plan failure and the factors involved, the different acting forces are introduced into the equations. In the case of a strong external force applied on the slope, for example, an anchor, the expression of safety coefficient is:

$$F = \frac{cA + (w \cos \alpha - U - T \cos \delta) \tan \phi}{W \sin \alpha + T \sin \delta}$$

This equation allows calculating the total anchoring force necessary to achieve a certain safety coefficient.

Wedge Failure

For the analysis of the stability of a wedge, different procedures can be used. A procedure is a mathematical, analytical method (Hoek and Bray, 1981). There are computer programs for the deterministic and probabilistic analysis of wedge stability, which allow to include forces due to water pressure, external forces, seismic, etc.; as the Swedge program, based on the method of analysis proposed by the authors cited.

For the simple case of a wedge formed by two planes without cohesion and the presence of water, the abaci of Hoek and Bray (1981) allow obtaining the safety coefficient from the values of dip, the direction of dip and angle of friction of the planes.

The complete analysis of the stability of a wedge can be carried out by the method of John (1968) which is based on the stereographic representation of the directions of the forces acting on the wedge and the planes that form it, to know among the different resulting forces that allow to calculate the safety factor.

Toppling

The analysis for the toppling of blocks is carried out by studying the equilibrium conditions of each of the blocks that form the slope. The relations between them are established considering their mutual actions and the geometric relations of the blocks and the slope to perform the calculations. Goodman and Bray (1976) also Hoek and Bray (1981).

Mass failure

For the analysis of this type of mass failure, very altered or intensely fractured and of low resistance, the methods for circular failure in the soil can be used. Within the approximate methods, the most widespread is the simplified Bishop method.

Seismic analysis

Methods of seismic analysis in slopes

Four methods of analysis have been proposed for the evaluation of the stability of slopes and hillsides in the case of seismic events: (Houston 1987):

- **Pseudo static method** in which seismic loads are simulated as horizontal and vertical static loads.
- **Displacement method**, or the deformations, which is based on the concept that real accelerations can exceed the allowed limit acceleration, producing permanent displacements (Newmark 1965).
- **Stability method after the seismic**, which is calculated using the undrained resistances, in representative soil samples that have previously been subjected to cyclic forces comparable to those of the expected seismic. (Castro, 1985)
- **Method of dynamic analysis by finite elements**. Using analysis in two or three dimensions, using a specific model can obtain details related to stresses, cyclical or permanent deformations (Finn 1988, Prevost 1985)

The first two methods are the most used in the practice of geotechnics, especially due to their ease of implementation, and then each one is described.

Pseudo-static Analysis in Slopes.

The pseudo-static analysis is placed on all the elements analyzed in the slope, a horizontal force corresponding to a seismic coefficient K multiplied by the weight of the element. The location of force is an important point to consider in this analysis. Terzaghi (1950) suggested that force should be applied to the center of gravity on each slice. It is a reasonable and conservative criterion (Duncan and Wright, 2005).

The method uses the same general procedure of any of the limit equilibrium methods, with the difference that it includes horizontal and vertical pseudo static forces due to the seismic event. These seismic forces are assumed to be proportional to the weight of the potential slip mass and the seismic coefficients K_h and K_v , expressed in terms of times the acceleration g produced by the earthquake. It is generally recommended to analyze (with pseudo-static seismic load) only the most critical surface identified in the static analysis. Most analyzes only consider the horizontal seismic force, and K_v is assumed to be zero, which is not representative for landslides in the epicentral area where K_v is significant.

The magnitude of the seismic coefficient must simulate the nature of the force of the event that depends on the intensity or acceleration of the earthquake, duration of movement, and frequency. For a very conservative analysis, it can be assumed that the seismic coefficient K_h is equal to the maximum expected peak acceleration of a seismic event at the site. However, this conservative analysis can produce numerical difficulties for K_h greater than 0.4.

Coefficients for the Pseudo-static Analysis.

The quantification of a maximum acceleration value for slope stability must consider the following empirical criteria:

- If the mass considered for the slide is rigid, the acceleration induced on the mass must be equal to the expected maximum acceleration with its respective amplifications per site and topography.
- If the soil mass is not rigid, as is the case in most situations and if you consider that the peak acceleration only occurs in very short periods, not enough to produce a fault, you can use values between 0.1 and 0.2 g , depending on the intensity of the expected seismic.

Generally, the pseudo-static seismic coefficient corresponds to a horizontal acceleration, and usually vertical accelerations are not considered, and the seismic coefficient is represented as a horizontal force. It is recommended to use values between 30% and 50% of the maximum acceleration expected, with the respective amplification. In Table 4.11, the seismic coefficients most used in practice are shown.

Table 4. 11 Values of coefficient K recommended in the pseudo-static analysis.

Seismic coefficient K.	Remarks.
0.1	Important seismic, FS > 1.0
0.15	Seismic of great magnitude., FS > 1.0
0.15 a 0.25	Japan FS > 1.0
0.05 a 0.15	The state of California.
0.10 for $\mu = 6.5$ 0.15 for $\mu = 8.5$	(Seed, 1979) FS > 1.15
1/3 to 1/2 of the peak ground acceleration (PGA*).	(Marcuson and Franklin, 1983)
1/2 of the peak ground acceleration (PGA)	(Hynes, Griffin and Franklin, 1984) FS > 1.0 and a 20% reduction in resistance.
PGA/980 for (PGA < 200 gal) (PGA/980) ^{1/3} /3 for (200 gal < PGA)	Noda and Joubu 1975, Experience formula
0.5 a 0.65 *PGA/980 for (500 gal < PGA)	Torii 2015, Experience formula
0.6 of peak ground acceleration	GENSAI 2, integration and simplification of Noda and Joubu 1975 and Torii 201.

Source: Own elaboration based on Abramson and others, 2002 and GENSAI II Project

*PGA=Peak ground acceleration.

The reason for using the value of K less than the peak acceleration is that the seismic forces are of short duration and change direction many times in a second. Although the safety factor may be below 1.0, it is a short period, while the reverse force, these milliseconds are not enough to produce the fault (Federal Highway Administration, 1997).

Because seismic occurs in short periods, it is reasonable to assume that, except very thick gravels, the soil does not drain appreciably during the seismic. Therefore, in many cases, undrained resistors should be used for the pseudo-static analysis.

Table 4.12 shows the proposal of horizontal seismic coefficients for the pseudo-static method of slopes in Costa Rica and figure 4.6, the seismic zoning of Costa Rica.

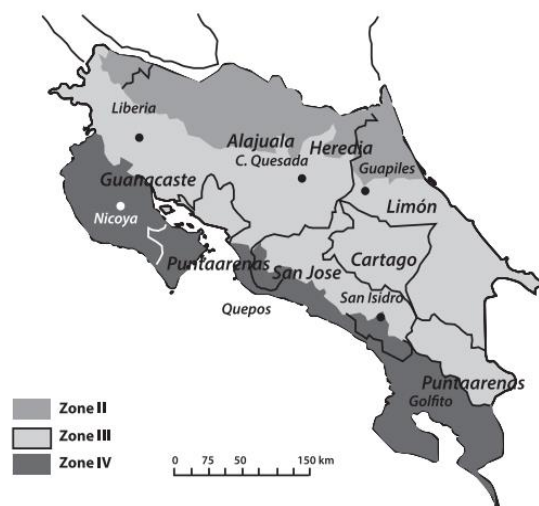


Figure 4. 6 Seismic location of Costa Rica.

Source: Seismic Code of Costa Rica, 2010.

Table 4. 12 Horizontal seismic coefficients for the pseudo-static method of slopes, Costa Rica

Type of site	Zone II.	Zone III	Zone IV
S1	0.15	0.15	0.20
S2	0.15	0.20	0.20
S3	0.15	0.20	0.25
S4	0.15	0.20	0.25

Source: Slope stability analysis according to the geometry of cuts in cohesive soils. Laporte, 2005

Table 4.13 describes the main characteristics of the four soil types (sites) proposed by the Seismic Code of Costa Rica, 2002.

Table 4. 13 Types of sites proposed by the Seismic Code of Costa Rica, 2010. (CSCR-2010)

Type of site	Description of the type of soil and rock that characterize each site.
S1	A profile of rock or rigid or dense soil with properties similar to a rock.
S2	A soil profile with conditions predominantly from moderately dense to dense or from moderately rigid to rigid.
S3	A soil profile with 6 m to 12 m of clay of consistency from soft to medium rigid or with more than 6 m of non-cohesive soils of low or medium density.
S4	A soil profile that contains a layer of more than 12m of soft clay

Source: Seismic Code of Costa Rica, 2010. (CSCR-2010)

The zoning and seismic values for El Salvador can be seen in Figure 4.7 and Table 4.14.

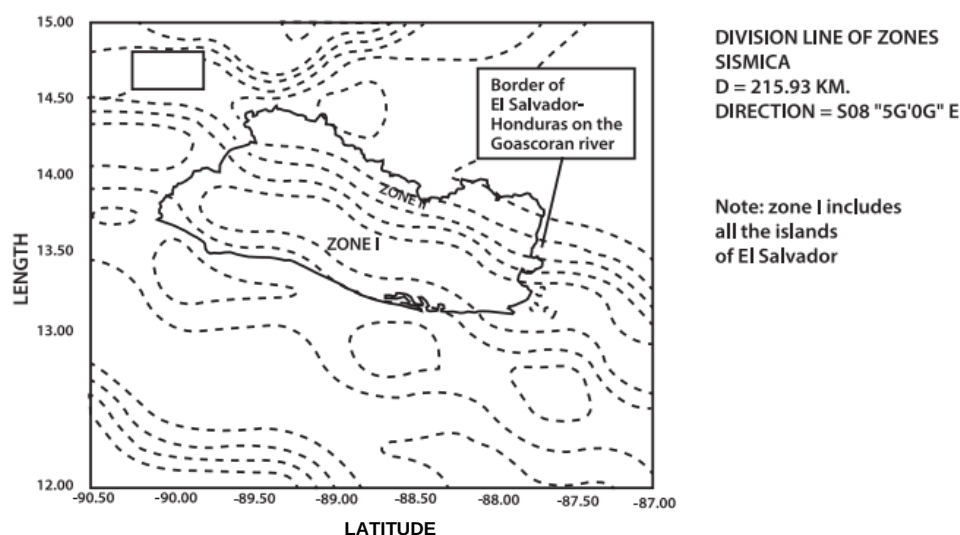


Figure 4. 7 Seismic zoning of the Republic of El Salvador, (MOP) 1997

Table 4. 14 Seismic coefficient by zones for El Salvador

	Zone I	Zone II
K_h	0.16	0.12

Source: MOP, 1997

The zoning and seismic values for Panama are presented in Table 4.15

Table 4. 15 Effective peak acceleration coefficients A_a and A_v for the Republic of Panama

City	A_a	A_v	City	A_a	A_v
Aguadulce	0.14	0.14	David	0.21	0.27
Aligandí	0.19	0.19	El Real	0.22	0.27
Almirante	0.21	0.22	El Valle	0.12	0.14
Bocas del Toro	0.21	0.21	Jaqué	0.22	0.28
Boquete	0.18	0.20	La Palma	0.21	0.27
Chanquinola	0.24	0.28	Las Tablas	0.17	0.20
Chepo	0.20	0.28	Panamá	0.15	0.20
Chiriquí Grande	0.18	0.20	Penonomé	0.11	0.14
Chitré	0.15	0.15	Portobelo	0.17	0.19
Chorrera	0.13	0.15	Puerto Armuelles	0.25	0.34
Colón	0.15	0.20	Puerto Obaldía	0.21	0.22
Concepción	0.22	0.28	Santiago	0.15	0.18
Coronado	0.12	0.15	Soná	0.17	0.19
			Tonosí	0.20	0.20

Source: Panamanian Structural Regulation, (REP) 2014

Where:

A_a = specific values of effective peak accelerations.

A_v = Effective peak accelerations related to speed.

The zoning and seismic values for Guatemala can be seen in Figure 4.8 and Table 4.16.

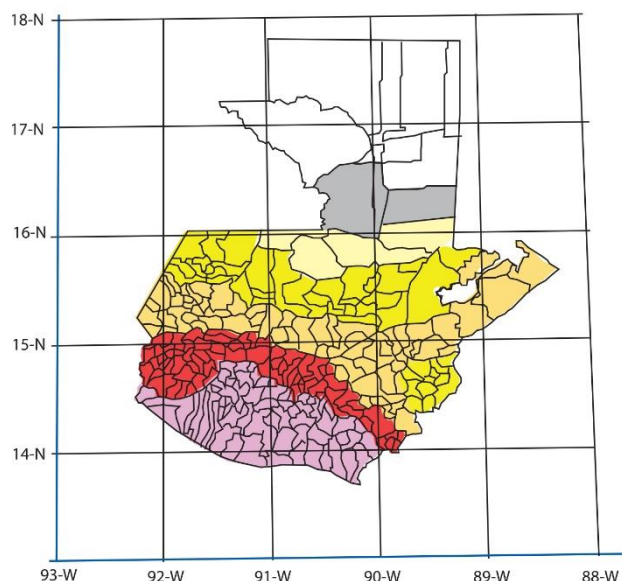


Figure 4. 8 Seismic zoning of the Republic of Guatemala, (AGIES) 2010

Table 4. 16 Seismicity index for the Republic of Guatemala.

Seismicity index. (I_0)	Scr	S1r
2a	0.50	0.20
2b	0.70	0.27
3a	0.90	0.35
3b	1.10	0.43
4	1.30	0.50
4	1.50	0.55
4	1.65	0.60

Source: Guatemalan Association of structural and seismic engineering (AGIES) 2010

Figure 4.8 is related to Table 4.16.

Where:

I_0 = Seismicity index is a relative measure of the expected severity of the seismic in a locality.

Scr = ordinate spectral of the short period of the extreme seismic considered in the rock base at the site of interest.

S1r = ordinate spectral of period 1 second of the same spectrum considered in the rock base at the site of interest.

The zoning and seismic values for Nicaragua can be seen in Figure 4.9 and Table 4.17.

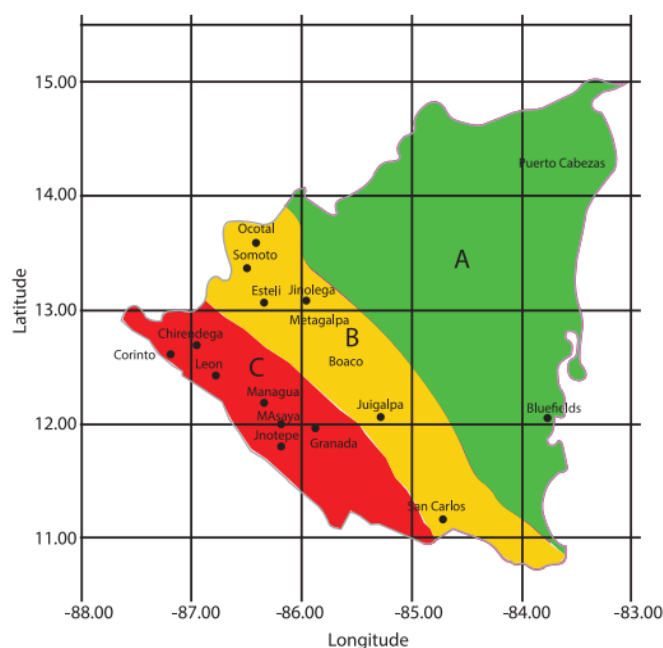


Figure 4. 9 Seismic zoning of the Republic of Nicaragua.

Source: National Construction Regulation, (RNC-7)

Table 4. 17 Amplification factors by soil type for Nicaragua, RNC-7

Seismic zone	Type of soil		
	I	II	II
A	1.0	1.8	2.4
B	1.0	1.7	2.2
C	1.0	1.5	2.0

Source: National Construction Regulation, (RNC-7)

For very soft Type IV soils, it is necessary to construct spectra of specific sites.

Los suelos propensos a la licuefacción no están incluidos en ningún caso. La tabla 4.17 debe estar relacionada con la figura 4.9.

Where:

Type I: Rocky outcrop with $V_s > 750$ m/s,

Type II: Firm soil with $360 < V_s \leq 750$ m/s,

Type III: Moderately white soil, with $180 \leq V_s \leq 360$ m/s,

Type IV: Very soft soil, with $V_s < 180$ m/s.

V_s is the average speed of shear waves calculated at a depth of not less than 10 m, which will be determined as:

$$V_s = \frac{\sum_{n=1}^N h_n}{\sum_{n=1}^N \frac{h_n}{v_n}}$$

Where:

h_n = thickness of the 'n'th stratum

v_n = shear waves velocity of the 'n'th stratum.

N = number of the stratum.

The zoning and seismic values for Honduras are shown in Figure 4.10 and Table 4.18.

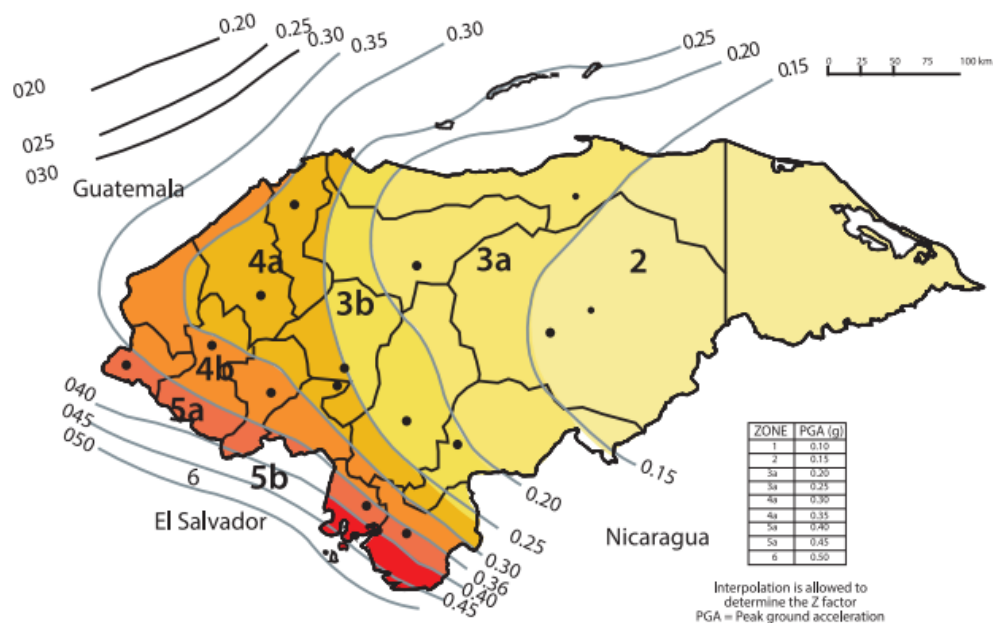


Figure 4. 10 seismic zones of the Republic of Honduras.

Source: Honduran Construction Code, 2008

Table 4.18 Factor de zona sísmica para Honduras

Seismic zone.	1	2	3a	3b	4a	4b	5a	5b	6
APS ¹	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50

¹ Peak Ground Acceleration

Source: Honduran Construction Code, 2008

You must relate Table 4.18 with Figure 4.10

Newmark displacement method

The displacement analysis proposed by Newmark (1965) assumes a block that slides on an inclined surface, which is subject to basal acceleration, as shown in Figure 4.11 and Figure 4.12.

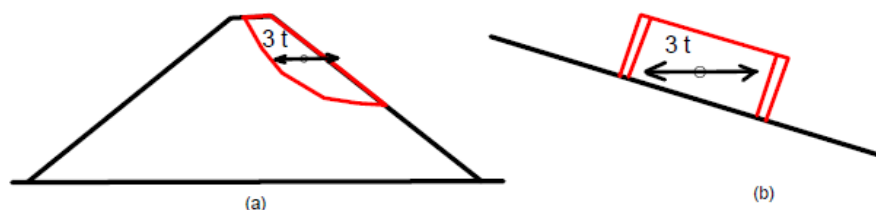


Figure 4. 11 Schematic representation of a sliding block.

Source: Newmark, 1965

Failure acceleration (A_R) is defined, as that limit acceleration, over which the block slip will occur, or, in other words, the minimum acceleration of the ground required to overcome the maximum resistance of the sliding block.



Figure 4. 12 Sliding block in a fault plane

Source: Own elaboration, Roatán, Honduras

In Newmark's method, the acceleration of rupture is calculated as a function of a static safety factor and the geometry of the slope. When the acceleration of the seismic wave exceeds the value of A_R , the block moves; the rest of the time the block remains at rest. In this way, the accumulated deformation during the whole seismic is calculated. By integrating the accelerations that exceed the critical acceleration, the speeds are determined first and with the double integration, the displacements.

General considerations of the method

- It is considered that well-defined planes of weakness exist in the slope, and the movement will occur along specific surfaces or planes.
- There will be permanent deformations only if the dynamic stress exceeds the shear resistance of the slope.
- Landslides occur "downhill." The "uphill" resistance is considered infinite, and the block will not move even if the critical acceleration is exceeded in the opposite direction.
- The critical acceleration is calculated by the limit equilibrium method.

Slip resistance of the block

The slip resistance of a soil or rock block is a function of shear strength under conditions applicable in a seismic. The magnitude of such resistance depends on the amount of displacement to occur; however, to mobilize the shear strength as a slope, a large displacement is not necessary. In the Newmark method, this resistance is established in terms of a coefficient N multiplied by the weight of the sliding mass. The quantity $N \cdot g$ where g is the acceleration of gravity corresponds to the constant acceleration acting in the appropriate direction, which exceeds the sliding resistance of the element in the direction in which the resistance has its smallest value. This acceleration is defined as failure acceleration A_R .

4.1.4 Determination of the type of the instability process: conditioning factors and triggers

- **Influential factors in slope instability.**

The stability of a slope is determined by geometric factors (height and inclination), geological factors (which condition the presence of planes and zones of weakness and anisotropy in the slope), hydrogeological factors (presence of water) and geotechnical factors or related to the mechanical behavior of the terrain (resistance and deformability). Table 4.19 summarizes the conditioning factors and slope triggers.

Table 4.19 Conditioning factors and triggers of slopes

Conditioning factors.	Triggers factors
- Stratigraphy and lithology. - Geological structure. - Hydrogeological conditions and hydrogeological performance. - Physical, resistant, and deformational properties. - Natural tensions and tense-deformational state.	- Static overload. - Dynamic loads. - Changes in hydrogeological conditions. - Climatic factors. - Variations in geometry. - Reduction of resistant parameters.

Source: González and others, 2002

■ **Stratigraphy and lithology.**

The physical and resistant properties of each type of material, together with the presence of water, represent its tensodeformational behavior and, therefore, its stability. Aspects such as the alternation of materials of different lithology, competition and degree of alteration, or the presence of layers of soft material or hard strata, control the types and disposition of the failure surface. In soils, which can generally be considered homogeneous in comparison with rocky materials, the difference in the degree of compaction, cementation or granulometry predisposes areas of weakness and water circulation that can generate instabilities. In the rocky massifs, the existence of layers or strata of different competition also implies a different degree of fracturing in the materials.

■ **Geological structure and discontinuities.**

The geological structure is a definitive parameter in the stability conditions of the slopes in the rocky massifs. The combination of the structural elements with the geometric parameters of the slope, height, and inclination, and their orientation define the problems of stability.

■ **Hydrogeological conditions.**

Most failures occur by the effect of water on the ground, as the generation of pore pressures, or flows and erosion, surface or internal, of the materials forming the slope. In general, it can be said that water is the greatest enemy of the slope stability (in addition to anthropic actions, when inadequate excavations are carried out without geotechnical criteria).

The presence of water in a slope reduces its stability by decreasing its terrain resistance and increasing the forces tending to instability. Its most important effects are:

- Reduction of the shear strength in the planes of failure when diminishing the effective normal tension.
- The pressure exerted on the tensile cracks increases the forces that tend to the slip.
- Increase in material weight due to saturation.
- Internal erosion by subsurface or underground flow
- Weathering and changes in the mineralogical composition of the materials

The shape of the water Table in a slope depends on different factors, which are the permeability of the materials, the geometry or shape of the slope, and the environmental conditions. In the rock mass, the geological structure has a great influence on the arrangement of the water Table and therefore the distribution of pore pressures over any potential slickenside at a slope and alternating permeable and impermeable materials.

■ **Geotechnical properties of the soils and rocky massifs**

In soils

The failure of a slope depends on the shear strength. In the first instance, this resistance depends on the resistant parameters of the material: cohesion and internal friction. Then, the influence of the nature of the soils on their mechanical properties implies that the selection of representative strength parameters of shear strength should be made, considering the geological history of the material.

In rocky massifs

It is the resistant properties of the discontinuities and the rock matrix that control the mechanical behavior: failure network, failure length, opening, filling in the failure, weathering, resistance, roughness, hydrology, etc.

■ **Natural stresses.**

Tectonic type stresses, the excavations give rise to liberation and redistribution of energy; this modification of the previous tensional state contributes to the loss of resistance of the material. Discontinuities and areas with compressive structures (for example, folds) can become areas of weakness by the appearance of extensional stresses.

Due to changes in geometry, the stress state of a slope depends on its geometrical configuration and the stress state of the rocky massif before excavation. In deep

excavations, the high stresses that are generated in singular areas such as at the foot of the slope can give rise to conditions of imbalance. Stress states that cause vertical cracks are also generated at the head of the slope.

■ Other factors which cause instability of slopes

Static overloads are the weight of buildings, landfills, dumps, heavy equipment passage, retaining walls, etc. When exerted on the head of the slopes, they provide an additional burden that can contribute to the destabilizing forces.

Dynamic overload, Dynamic loads are mainly due to seismic, natural or induced movements; and to the vibrations produced by blasting near the slope. The main effect of fractured rock massifs is the opening of pre-existing discontinuities, the reduction of their resistance to shear strength and fall of rock blocks. In cases of strong seismic movements, the forces applied instantaneously can produce the general failure of the slope if there are favorable conditions for instability.

Precipitation and the climate regime influence the stability of the slope by modifying the water content of the land. The alternation of periods of drought and rain produces changes in the structure of the soils that give rise to losses of resistance.

Weathering processes, in a certain type of soil or soft rocky massifs the weathering processes play an important role in the resistant properties, giving rise to alteration and intense degradation when the materials are exposed to environmental conditions because of an excavation. These resistance losses can lead to the fall of the surface material and, if it affects critical areas of the slope, such as your foot, can generate general failures, especially in conditions of water presence.

■ Types of failures

Soil slopes

The failure in soil slopes failure is generally curved **surfaces**, with a diverse shape conditioned by the morphology and stratigraphy of the ground.

- It can be approximately circular (the most frequent), with its lower end at the foot of the slope, (foot slip) when it is formed by homogeneous terrain or by several strata of homogeneous geotechnical properties.
- It can be almost circular but passing under the foot of the slope (deep slide).

If certain conditions exist in the slope as the existence of strata or layers of different competence, a failure may occur in favor of a **flat surface** or a **polygonal surface** formed by several flat sections. The **"infinite" slope** model, (its length can be considered infinite with respect to the thickness of the failure mass) can be adopted on many natural slopes where the contact defines the failure surface, practically parallel to the slope between the surface ground (colluvial or residual soil) and the underlying rock.

Rock slopes

Flat failure occurs in favor of a pre-existing structure, which can be stratification, a tectonic joint, a fault, etc. The basic condition is the presence of discontinuities dipping in favor of the slope and with its same direction. In slopes excavated parallel to the stratification, flat failures can occur by sliding of the strata; This type of failure is typical in litotic or slate massifs, generating failure planes in favor of schistocyte.

Wedge failure corresponds to the sliding of a wedge-shaped block, formed by two planes of discontinuity in favor of its line of intersection. For this type of failure to occur, the two planes must appear on the surface of the slope. This type of failure usually occurs in massif with several families of discontinuities, whose orientation, spacing, and continuity determine the shape and volume of the wedge.

Stratus overturning, they occur in slopes of rocky massifs where the strata present dip opposite the inclination of the slope and direction parallel or subparallel to it. In general, the strata appear fractured in blocks in favor of systems of discontinuities orthogonal to each other. This type of failure involves a rotational movement of the blocks, and the stability thereof is not solely conditioned by its sliding resistance.

Mass failure can occur in soft rocky massifs that are not very competent and in very altered or intensely fractured massifs, which present anisotropic behavior and where the planes of discontinuity do not control the mechanical behavior.

Use of software

Currently, commercial computer software programs are known, such as **SLOPE/W**, **STABLE**, **SLIDE**, **TALREN**, **Road Geohazard Management Tool: GeoMT (Calculation Sheet)**² and **EXSSA**³ (**Excel Based Slope Stability Analysis Tool, Calculation Tool**). They allow in a fast and simple way to obtain the safety factors of slopes or hillsides with a certain degree of complexity and by any of the methods of analysis. Some methods use finite

² JICA, GENSAI 2 developed Excel spreadsheet tools (available on the DACGER website, El Salvador)

³ Same as 2 above

elements with very little success in the stability of specific slopes, and others use equilibrium analysis by interaction, the latter being widely used universally.

JICA GENSAI II developed spreadsheet tools (available on the website of DACGER, El Salvador) EXSSA: Tool for Analysis of Slope Stability, based on Excel, whose analysis analyzes the equivalence method of the equivalent limit in the seismic coefficient.

Numerical methods

The finite element method solves many of the shortcomings of limit equilibrium methods. This method was introduced by Clough and Woodward (1967). The method essentially divides the soil mass into discrete units that are called finite elements. These elements are interconnected in their nodes and predefined edges. The method typically used is that of the displacement formulation, which presents the results in the form of stresses and displacements to the nodal points. The failure condition obtained is that of a progressive phenomenon where not all the elements fail simultaneously. Although it is a very powerful tool, its use is very complex, and its use is very limited to solve practical problems. Wong (1984) mentions the difficulty of obtaining safety factors to the fault.

Although its use is not very expanded, there are some programs of slope stability analysis using numerical methods. These programs are known: **FLAC**, **UDEC** (Benko-Stead-1993), **PLAXIS**, among others. In the **FLAC method**, the materials are represented by zones to form a mesh according to the geometry, and a variety of stress/strain relations can be selected. In the **UDEC method**, the slope is divided into blocks according to the system of joints or cracks, which can be rigid or deformable.

4.2 Stabilization methods.

Before beginning a stabilization method, it is always advisable to analyze the conditions of the slope. The positioning of the water Table that caused the landslide, the type of geological formation, the geometry and some geotechnical data as cohesion and friction values, geometry of the failure surface, the influence of the seismic activity and with the data must be considered. Determine a safety factor that approaches 1.0.

Subsequently, the stabilizing measures are considered, which may consist of: modification of the slope geometry, drainages, increase of the resistance of the ground by introducing resistant structural elements into the slope, construction of walls or other containment elements.

Or, through superficial protection measures that help eliminate the problems of falling rocks, avoid or reduce erosion and weathering, infiltration of runoff water.

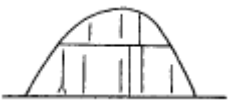
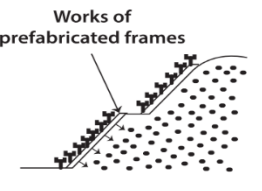
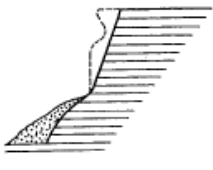
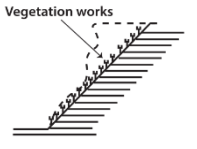
It is common to observe in the road lines installation of metallic meshes, facing walls, installation of geotextiles materials, and plantings of species that contribute to reinforce the ground.

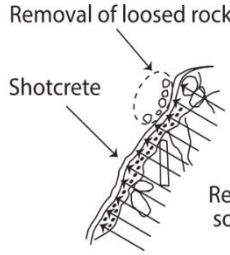
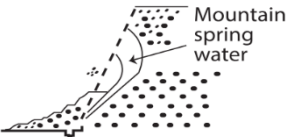
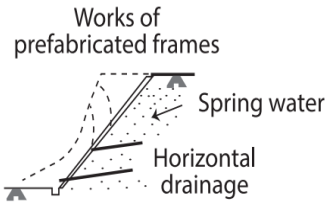
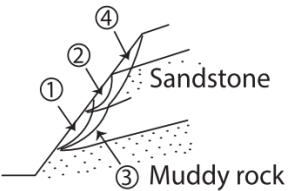
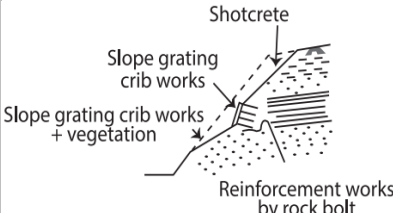
4.3 Slope protection and stabilization work

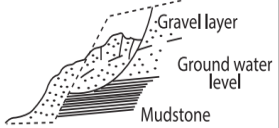
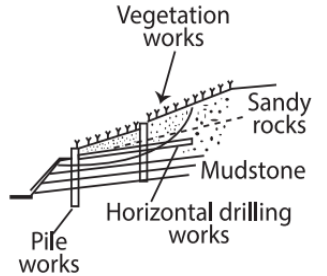
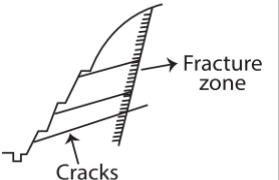
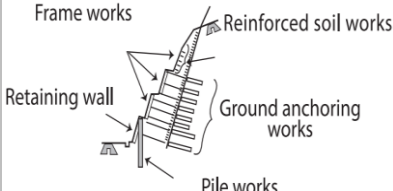
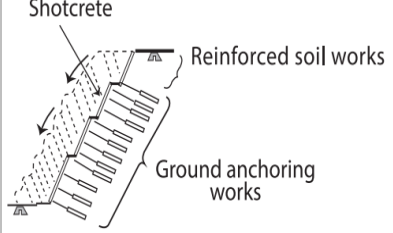
A distinction must be made between structural and non-structural protection measures as structural measures are considered those are protecting the slope surface as shotcrete, cement coating. Modification of the topography: intermediate terraces or berms, lowering of the slope grade, removal of the material at the head of the slope. Control of surface and groundwater. Containment and anchoring structures, Table 4.20 classifies, explains, presents the form of collapse and proposes a method to stabilize it. Table 4.21 contains the main works of slope protection with structure and purpose.

Non-structural measures are those that include non-physical actions aimed at educating, preventing, mitigating, or preventing current and future risks. They can be considered equal or more efficient than structural measures.

Table 4.20 Classification of landslides, presenting form and stabilization method

Classification	Explanation	Landslide form	Example of strategic work method
Erosion, collapse	Type I. Desquamations of the surface layer or furrows occur due to drought and humidity, freezing and rain, among others. When left without intervening, this can turn into deep landslides.	 Erosion by water in superficial layers/appearance of furrows.	 Works of prefabricated frames Works with meshes + vegetation works / Works of prefabricated frames + vegetation works
	Type II The projection of the upper part of the slope collapses		 Vegetation works Profiling + vegetation works

Classification	Explanation	Landslide form	Example of strategic work method
	Type III. The rocks collapse due to the numerous cracks and joints	 Detachment of loose rocks	 Removal of loose rocks Shotcrete Reinforced soil works Mortal spraying + reinforced soil works + anchorage of rocks
Sliding surface layers	Type I. Surface landslides occur including the rock layers with high erosion of the lower layers. In most cases, spring water is the trigger.	 Mountain spring water	 Works of prefabricated frames Spring water Horizontal drainage Profiling + Works of prefabricated frames + Horizontal drainage
	Type II. A rockfall occurs due to weathering.	 Sandstone Muddy rock Landslide due to the process of weathering	 Shotcrete Slope grating crib works Slope grating crib works + vegetation Reinforcement works by rock bolt Works with Shotcrete / works with frames + bolts in rock / Works with frames + vegetation
	Type III. There is a fall of rocks on the slope, and there are cracks in the rocks (joints, small rupture, and thin layers). In the second case, there are also many cases of falls in the form of wedges	 Desplomes a lo largo de las grietas de las rocas Crashes along the cracks of the rocks	 Removal of unstable rocks Mortar spraying Reinforced soil works Mortar spraying + reinforcement works with rock anchoring

Classification	Explanation	Landslide form	Example of strategic work method
Collapses or large-scale landslides	a. The slope is composed of layers of weak and poorly consolidated soil. The slope has unstable geological elements and collapses when the groundwater level rises	 Discontinuous surface slip in high permeability formation	 Profiling + piles / lateral drilling works + vegetation works
	b. Rocks that have geological structures with inclined strata, faults, and fractured zones create large-scale landslides	 Fault in the fracture zone as the sliding surface	 Work of beams + work of powdered beams + works of anchorage to the ground + works of ground with reinforced soil + winding concrete
	c. Slopes that have inclined strata in the opposite direction to the inclination of the slope and that contain faults can collapse or rotate forward	 Rotation, the collapse of inclined layers (Toppling)	 Shotcrete + groundwork with reinforced soil + ground anchoring work

Source Own elaboration based on "Slopes Protection Works Manual" of GENSAI Project, Ministry of Public Works, Transportation and Housing and Urban Development of El Salvador, 2018, Modified from the Association of Roads of Japan (JAEA), 2009. Guidelines for cuts and earthworks on roads and slope stability. ISBN 978-4-89950-415-6.

Table 4.21 Main works of slope protection with structure and purpose

Item	Purpose
Vegetation base net	To hold the soil for the vegetation base To prevent erosion due to surface water flow
Woodpile Cylinder wire	To control the erosion of the surface and the sediment yield due to spring water
Precast concrete block	To hold the filling material and prevent erosion
Shotcrete Stone pitting Block pitting	To prevent erosion, weathering, and infiltration of surface water
Concrete pitting Slope grating crib works (precast or cast-in place concrete)	To prevent the slope surface failure and the weathering and stripping of the rocks Ground retention works for small soil pressures
Masonry retaining wall Gabion works Concrete retaining wall Reinforced soil of cutting slope with polypropylene fibers	To prevent slope failure due to ground pressure
Rock bolts Ground anchors Piles works	To prevent slope failure due to sliding slope subsurface
Sheet piling	To formulate the impervious wall to protect piers and river abutment structures
Mechanically stabilized earth	Increase the cohesion of the soil, improving the mechanical properties

Source Own elaboration based on "Slopes Protection Works Manual" of GENSAI Project, Ministry of Public Works, Transportation and Housing and Urban Development of El Salvador, 2018. Modified of the Association of Roads of Japan (JAEA), 2009. Guidelines for Earth Works for Road Slope Stability. ISBN 978-4-89950-415-6.

■ Modification of the geometry

The most frequent actions are:

- Decrease the inclination of the slope.
- Remove weight from the head of the slope.
- Increase the weight at the foot of the slope (counterweight fill).
- Construct slopes and berms (steps in the slope)

Conversely, when the slope gradient becomes smooth, the area exposed to direct rain will increase, so it is necessary to preserve it from erosion by drainage and vegetation. Table 4.22 shows critical angles in rock slopes.

Table 4.22 Critical angles in important slopes in rocks

Predominant rock	Stratification or preferential direction of joints	Height (m)	Critical angle of the slope	The radius of curvature in plan (m)	Life of the slope	Reference
Shale		95	27.3° (18°-36°)	≥300 (pie)	70 years	Piteau (1970)
Shale		95	39.5° (23°-56°)	60 (pie)	70 years	Jennings (1970)
Shale	Parallel to the slope	90	42° (35°-60°)		Recent	Patton and Deere (1970)
Porphyry shale		150	58°	400 (medio)		Broadbent and Rippere (1970)
Very altered rhyolite		52	60°	-75 (pie)		Hamel (1971)
Granodiorite with altered areas	Parallel to the slope in a part	248	42°-46.5°		Very long	Keonedy and Niermeyer (1970)
Healthy porphyry		100-200	>60°		Many years	Pryor (1970)
Frayed or weathered porphyry		100-200	>50°		Many years	Pryor (1970)
Slate	Parallel to the slope	100-200	37°-40°		Many years	Pryor (1970)
Slate	Parallel to the slope	100-200	40°-45°		Many years	Pryor (1970)
Decomposed slate		100-200	≈33°		Many years	Pryor (1970)
Pyrite		100-200	≈45°		Many years	Pryor (1970)
Mineral waste		100-200	≈33°		Many years	Pryor (1970)
Sandstone with partially clayey cement	Horizontal	70	Almost vertical		Hundreds of years	

Source: Geotechnics and foundations II, mechanics of soil and rocks. Second edition. José A. Jiménez Salas and others

The Road Association of Japan (JAEA), contemplates guidelines for cuts and earth movements in roads and stability of slopes, which establishes the standard gradient for

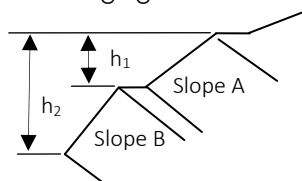
cuts in slopes. According to this code, the design for a cut Slope will depend on the type of soil or rock, as indicated in Table 4.23, the values are determined empirically according to the geological conditions, because in practice it is not easy to perform stability analysis on slopes with heights less than 10 m for a section of several meters in length.

Table 4.23 Geometric standards of cuts in small slopes according to the type of soil and rock

Characteristics of the soil and rock		Height of the slope (m)	Horizontal: vertical gradient
Hard rock			0.3:1 - 0.8:1
Soft rock			0.5:1 - 1.2:1
Sand	Loose and poor distribution of particles.		1.5:1 or softer
Sandy ground	Dense	Less than 5 m	0.8:1 -1.0:1
		5-10 m	1.0:1 - 1.2:1
	Loose	Less than 5 m	1.0:1 - 1.2:1
		5-10 m	1.2:1 - 1.5:1
Sandy soil with gravel and rocks	Dense and good distribution of particles.	Less than 10 m	0.8:1- 1.0:1
		10-15 m	1.0:1 – 1.2:1
	Poor and bad distribution of particles	Less than 10 m	1.0:1 – 1.2:1
		10-15 m	1.0:1 – 1.2:1
Fine-grained soils (cohesive soils or silt)		Less than 10 m	1.0:1 – 1.2:1
Fine-grained soil with gravel and rocks		Less than 5 m	1.0:1 – 1.2:1
		5-10 m	1.2:1 – 1.5:1

Source: The Road Association of Japan, 1984

Notes: (1) Except for the properties of the soils and rocks shown in the Table, for slopes greater than 10 m, it must be studied individually. (2) The vertical cutting height must be determined, as shown in the following figure:



h_1 : height of the slope to determine slope gradient A.

h_2 : height of the slope to determine the gradient of the slope B = the height from the base of slope B (road surface) to the upper part of slope A.

The erosion control works with vegetation and drainage on the inclination of the slope are required to stabilize the slope in the long term.

Berms and banks on slopes

Berms are generally built from one to two meters wide for every 5 to 7 meters in height with the following purpose:

- Reduce the speed of water flow on the bank surface, decreasing the erosive force.
- Provide a space for drainage ditches, and

- As a sidewalk for inspection or scaffolding for repair.

A wider berm is recommended when the slope is long and high where it is necessary to install screens or protection fences for falling rocks.

■ **Resistant structural elements**

The purpose is to increase the shear strength through some of the following systems:

- Introduce elements that improve the resistance of the ground on the failure surface (for example, piles or micro-piles).
- Introduce elements that increase the tangential forces of friction on the failure surface (for example, anchors and bolts).

The sheet piles are alignments of these elements spaced apart from each other, in such a way that they constitute a relatively continuous structure, crossing the slid area and embedding in the stable zone. The distribution and length of the piles must be studied in detail, as well as their resistance to the stresses to which they will be subjected. The diameters of the piles vary from 0.65 to 2 m, often being braced on the surface using a beam.

Similarly, micropile sheets can be used that pass through the slipped area and enter the stable zone. The micro-piles usually have a diameter between 12 and 15 cm and lengths that reach 15 and 20 m; They are armed with a steel tube that is filled by cement injection.

Jet-grouting columns are often used to stabilize slopes in granular soils, even in cohesive soils, by cutting the slip surface and creating areas with greater shear strength. The procedure consists of drilling the ground, generally between 0.40 and 1.0 m in diameter, injecting cement at high pressure (between 30 and 60 MPa) through a grid that rotates at high speed, penetrating and its failures the surrounding terrain. This results in a high strength column formed by the soil and the injection.

The anchors are elements formed by cables or steel bars that are anchored to stable areas of the massif, work by traction and provide a force contrary to the movement and an increase in the normal stresses on the failure surface.

Depending on the way they work, they are classified as passive (the anchor begins to work when the block or terrain movement occurs), active (the anchor is stretched after installation until its admissible load) and mixed (the anchor is stretched) with a load lower than its admissible load.

Walls and containment elements. The construction of walls is used to reinforce the standing area of the slopes, avoiding, also, the degradation in this critical area against stability. The walls are built at the foot of the slope as resistant, containment or support elements, being effective against surface instabilities. The retaining walls present the disadvantage that the foot of the slope must be excavated for its construction, which favors the instability. The support walls are built separately from the foot of the slope, filling later the backbone (space between the wall and the slope). The purpose of the revetment ones is to protect the soil from erosion and provide a stabilizing weight at the foot of the slope. Gabion walls are flexible walls consisting of fillings of rock fragments, contained in a steel mesh, work by gravity and can be built with stepping towards the interior or exterior of the slope. They have the advantage of allowing the circulation of water from the slope. The slurry walls are reinforced concrete elements built in situ, in ditches dug below the surface of the land, which can be constructed using cast concrete or cast in place concrete. They have placed rows of anchors at various levels. Reinforced earth walls are formed by a prefabricated exterior wall of concrete or metal sheets and a floor-filling, reinforced by metal or plastic bands or braces, which are anchored to the wall or the slope. The anchored walls are walls reinforced with anchors to improve the resistance to overturning and the sliding of the structure. They can be classified as gravity structures, semi-gravity, or slurry walls. The gravity or semi-gravity walls are reinforced concrete walls, to which are added pre-tensioned anchors at various height levels. Sheet piling is thin structures buried, metallic or reinforced concrete, anchored in its upper part. A variant of the system is the tangent/secant piles. The steps in the design of walls for the stabilization of landslides are presented in Table 4.24.

Table 4.24 Steps to follow in the design of retaining walls to stabilize landslides

Step 1	Determine the feasibility of using containment structures Analyze right-of-way restrictions, materials, equipment, existing structures, environmental aspects, aesthetics, sensitivity, earth movements, costs, etc.
Step 2	Geotechnical information of the landslide or slope Topography, lateral extension, soil profile, groundwater levels, parameters for the analysis, fault surface, seismicity, etc. Ensure that the topography of the slip and the depth of the actual or expected fault surface, and the groundwater level conditions are known clearly and precisely.
Step 3	Evaluate the safety factor of the existing slope Calculate the safety factor using a limit equilibrium software. Perform a conventional slope stability calculation and adjust the conditions in such a way that the model is as close as possible to reality. It is designed for the minimum safety factor.
Step 4	Select the type of wall and its location The type of wall depends on the space, the available materials, the required magnitude, the possibility or not of carrying out excavations, the time available. The location of the wall depends on the specific objective and the characteristics of the slide.

Step 5	Resize the wall and calculate the safety factor of the slope or global fault with the wall A trial and error with slope stability software by limit balance modify the dimensions and location of the wall to achieve the desired safety factor.
Step 6	Evaluate safety factors for slip, rollover and support capacity Calculate the safety factors and modify the dimensions of the wall until obtaining the specified factors. If the wall is modified, it is required to check the safety factor to the total failure of the slope.
Step 7	Design the internal structure of the wall and special details Calculate reinforcements, subdrains, drains, facade elements, etc.

Source: Suárez J., 2001. Erosion Control in Tropical Areas. Chapter 3. Page 147

Drainage is an aspect that should be considered in the construction of walls, since it can produce saturation of the ground in its backbone, generating high interstitial pressures and thrusts on the structure.

■ Surface protection measures

These measures are aimed at:

- Eliminate the problems of falling rock
- Increase security against surface fractures
- Avoid or reduce erosion and weathering on the sloping surface
- Prevent the entry of runoff water (geosynthetics and bioengineering)

The most frequent actions consist of:

- Installation of metal mesh
- Shotcrete on slopes
- Construction of revetment walls on foot of the slope
- Installation of geosynthetic materials
- Waterproofing
- Sowing of species that contribute to reinforce the surface terrain in slopes excavated in soils

Shotcrete in slope stabilization consists of covering the surface of the slope, releasing the mixture pneumatically through a hose. Normally several layers are thrown on the slope, with a total thickness of 5 to 8 cm. The shotcrete can be reinforced by fixing a metal mesh to the slope on which the mixture is sprayed. The saturation of soil using drainages should be considered.

This practice must comply with the standards applicable to the quality of materials:

Cement: The cement must meet the ASTM C1157 specification.

Aggregates: Aggregates must comply with the ASTM C33 or ASTM C330-05 specification if lightweight concrete is specified by the buyer, except that the granulometry of the total aggregate that constitutes the shotcrete must be by the Table. 4.25 for the specified number of granulometry.

Water: The mixing water must comply with the ASTM C1602 / C1602M-06 specification.

Additives: Cement supplementary materials and chemical additives must comply with the ASTM C1141 / C1141M specification.

Table 4.25 Granulometric limits for aggregate combination for shotcrete

Percentage of mass passing in a single sieve		
Sieve size ^A	Granulometry No. 1 ^B	Granulometry No. 2 ^B
12.5 mm (1/2 inch)	-	100
9.5 mm (3/8 inch)	100	90-100
4.75 mm (No. 4)	95-100	70-85
2.36 mm (No. 8)	80-98	50-70
1.18 mm (No. 16)	50-85	35-55
600 µm (No. 30)	25-60	20-35
300 µm (No. 50)	10-30	8-20
150 µm (No. 100)	2-10	2-10

^A The sieve size shown in parentheses is for reference only; The only standard sieve sizes are those established in the ASTM E-11 specification.

^B The ranges shown in this Table are extensive so that they can be adapted to the conditions of each country. Or, develop an average granulometry for specific projects.

Source: Guatemalan Standards Commission (COGUANOR), 1962

Shotcrete is a mortar or concrete that is released at high speeds pneumatically on a surface, which can be concrete, rock, natural terrain, masonry, wood, etc. The projection at high speeds allows not only the action of placing but also compacting the concrete.

Measures that could be taken to reduce the dangers of falling rocks

The slopes excavated in fractured rock masses usually present problems of **block detachments** in favor of the network of discontinuities. Rock mechanics is currently used to determine the stability or possible instability of rock fragments. When it comes to boulders at the top of the slope, the dangers of falling rocks are obvious. However, types of faults occur in rocks that represent greater danger, and this is due to a block that is suddenly released by deformations of the surrounding rock mass. It can occur when the forces acting through planes of discontinuity, which isolate a block of the adjacent ones, change because of water pressures in the discontinuities or a reduction

of the shear strength of these planes due to weathering, causing landslides of significant or large-scale blocks.

Among the actions for the stabilization of unstable rock blocks are:

- Installation of bolts for fixing rock blocks; When the blocks to be stabilized have large dimensions; their fixation must be done through anchors.
- Installation of cables and meshes to stabilize very fractural areas of the slope; consists of the placement of a metal mesh, which is superimposed on a series of cables forming a grid, anchored to the rock at its ends and stressed.
- Elimination of blocks by controlled blasting, expansive cement, fragmentation by chopper hammer, manual removal by levers, etc. Only the appropriate blocks must be removed. Otherwise, the effect may be detrimental to the stabilization of other blocks in contact
- A method to reduce rock fall detachment is to eliminate the excavation by blasting; the vibrations destabilize the blocks with a tendency to fall.
- If it is accepted that it is not possible to detect or prevent all rockfalls, then the construction of berms, ditches, fillings, construction of fences or metal mesh covers should be considered as possible measures to reduce damage. Hoek Rockscience, 2000.

Possibly in the system of protection against permanent falling of rocks, the most effective system in most roads is the construction of a trench of capture at the end of the slope. The base of this trench should be covered by a layer of gravel to absorb the energy of the falling rocks. Between the road and the trench, a resistant barrier or mesh must be built, the location can be calculated using a rockfall analysis. It must be considered that the rocks do not impact the barrier; the rocks must dissolve the kinetic energy in the gravel of the trench. The design criteria for rock blockage ditches are shown in Table 4.26.

Table 4.26 Design criteria for rock block trap trench

Inclination of the slope	Height of the slope (m)	Width of trench (m)	Depth of trench (m)
Almost vertical	5 to 10	3.7	1.0
	10 to 20	4.6	1.2
	> 20	6.1	1.2
0.25 H 0.3H:1V	5 to 10	3.7	1.0
	10 to 20	4.6	1.2
	20 to 30	6.1	1.8
	>30	7.6	1.8
0.5H:1V	5 to 10	3.7	1.2
	10 to 20	4.6	1.8
	20 to 30	6.1	1.8
	>30	7.6	2.7

0.75H:1V	0 to 10	3.7	1.0
	10 to 20	4.6	1.2
	>20	4.6	1.8

Source: Ritchie, 1963

In terms of rockfall hazards evaluation, an accepted classification is the Rockfall Risk Classification System (RHRS) developed on the Oregon State Highway, Pierson, and others 1990. See Table 4.27. Hoek Rockscience, 2000

Table 4.27 Rockfall Risk Classification System (RHRS)

Category			Rating criteria			
Slope height			25 ft	50 ft	75 ft	100 ft
Effectiveness in the trench			Good catchment	Moderated catchment	Limited catchment	No catchment
Average vehicle risk			25% of the time	50% of the time	75% of the time	100% of the time
Percentage of visible distance decision			Appropriate visible distance, 100% below the design value.	Moderated visible distance, 80% below design value	Limited visible distance, 60% below design value	Very limited visible distance, 40% below design value
Road width including shoulder paving			44 ft	36 ft	28 ft	20 ft
Geological characteristics	Case 1	Structural condition	Discontinuity of joints, favorable orientation	Discontinuity of joints, random orientation	Discontinuity of joints, adverse orientation	Continuity of joints, adverse orientation
		Friction angle	Rugged, Irregular	Wavy	Planar	Clay fill
	Case 2	Structural condition	Erosion characteristics poorly differentiated	Occasional erosion characteristics.	Many erosion characteristics	Important erosion characteristics
		Differences in erosion rates	Small difference	Moderated difference	Big difference	Extreme difference
	Block size			1 ft	2 ft	3 ft
Amount of material slipped			3 cubic yards	6 cubic yards	9 cubic yards	12 cubic yards
Climate and presence of water in the slope			Low to moderate precipitation without water on the slope	Moderate precipitation, intermittent water in the slope	High precipitation, water flow in the slope	High precipitation and continuous water flow in the slope

Source: Own elaboration based on Chapter 9 of Hoek Rockscience, 2000

Slope height represents the vertical height of the slope, not the distance of the slope. Rocks on the upper part of the slopes have more potential energy than rocks on lower parts, so they represent a greater hazard and receive a higher rating. The measurement is at the highest point from where a rockfall is expected.

Effectiveness in the trench, the effectiveness of a trench is measured by its ability to prevent the fallen rock from reaching the road. When estimating the effectiveness of the trench several factors must be qualified: 1) Height and angle of the slope, 2) width, depth, and shape of the trench, 3) expected block sizes and amount of fall, 4) impact of irregularities of the slope (fall characteristics) of the falling rocks. It is especially important for the evaluator to evaluate the impact of irregularities on the slope because a fall feature can cancel the expected benefits in a fall area. The evaluator must first consider whether the slope is natural or man-made, then drop rocks onto the paved road. Based on the fall characteristics, it determines which rocks are captured by the trench and which pass to the road. The rating points must be assigned as follows:

3 points, **good catchment**. All or almost all the rocks that fall are retained by the captured trench.

9 points, **moderate catchment**. The fallen rocks occasionally reach the road.

27 points, **limited catchment**. The fallen rocks frequently reach the road.

81 points, **without catchment**. All or almost all the falling rocks hit the road.

Average Vehicle Risk (AVR)

This category measures the percentage of time a vehicle will be present in the danger zone of falling rocks. The percentage is obtained by using a formula (shown below) based on the length of the slope, the average daily traffic (ADT) and the posted speed limit on the site. A rating of 100% means that, on average, you can expect a car to be in danger 100% of the time. Care must be taken to measure only the length of a slope where falling rocks are a problem. Excessive estimated lengths will strongly bias the formula and results. When there are high ADT values, values higher than 100%, it means that at a certain moment, there is more than one car present within the measured section. The formula used is:

$$\frac{ADT \text{ (vehicles per hour)} \times \text{Length of the slope (milles)} \times 100\%}{\text{Posted speed limit}} = \text{AVR}$$

Percentage of the Decision Sight Distance

The Decision Sight Distance (DSD) is used to determine the length of the road in feet where the driver must make a complex or instantaneous decision. DSD is critical when obstacles along the way are difficult to perceive or when unexpected maneuvers must

be made. The sight distance is the shortest distance along a road from where a given height object is continuously visible to the driver, Table 95. Along a section with rockfall, the sight distance can change appreciably. Horizontal and vertical curves on the road, rocky outcrops or vegetation on the edges of the road can hinder the driver from defining a rock on the road. To determine where these impacts are most severe, walk through the sector with rockfalls in both directions. Then decide which direction of the road has the shortest sight. The horizontal and vertical curves must be evaluated. Normally an object will be darker after a curve. Place a 6-inch object on the edge of the road at the curve location and walk away from the traffic flow to determine how far the object is visible when the height of the view is 3.5 feet above the surface of the road. Table 4.28 can be applied to measure this distance. The distances represent the lowest design value, and the posted speed limit must be used on the damaged road section.

Table 4.28 Distances that represent the lowest design value using the posted speed limit on the damaged road section.

Posted speed limit (mph)	Sight distance (pies)
30	450
40	600
50	750
60	1,000
70	1,100

Source: Taken from chapter 9 of Hoek Rockscience, 2000

These values can be changed in the following formula to calculate the percentage of the Decision Sight Distance.

$$\frac{\text{Actual distance of the site} \times 100\%}{\text{Decision Sight Distance}} = \%$$

Road width

This dimension is measured perpendicular to the centerline of the road from edge to edge of the pavement. This measure represents the space required to make a maneuver and prevent the fall of a rock. When the width of the road is not consistent, this must be the minimum width.

Geological characteristics

The geological conditions of the slope are evaluated, considering this category.

Case 1 is for slopes where contacts, stratification planes, or other discontinuity are the dominant structural features on a slope with rock mass. **Case 2** is for slopes where differential erosion or excessively steep slopes are the dominant conditions of rockfall. The professional should use the case that best suits the evaluation. If both cases are present, both are evaluated, but the highest score is taken.

Case 1

If the structures dip or bend in the direction of the road, you should consider the friction angle of the rocks, the filling of the joints and the presence of water. Adverse conditions are those that cause failures by a detachment of blocks, wedge blocks, or landslides. For joints larger than 10 m in length:

Three points, discontinuous joints, favorable orientation, consolidated rock without planes of inclined joints in favor of the road, stratification planes with favorable inclination to the road, etc.

Nine points are discontinuous joints, random orientation, slope rocks with randomly oriented joints creating a three-dimensional pattern. This type of pattern may have some scattered blocks, with joints oriented opposite the slope, but are not favorable to the slope.

Twenty-seven points, discontinuous joints, adverse orientation, slope exhibit a prominent fracture pattern, stratification planes, and other discontinuities with adverse orientation, with continuous length less than 10 feet.

Eighty-one points, continuous joints, adverse orientation, the dominant pattern of joints are exposed in slope. The stratification or other discontinuity adverse to the slope and with a length greater than 10 feet.

Friction angle

This parameter directly affects one block to move about another. IN the angle of friction in joints, stratifications, or other discontinuity is defined by macro and micro-roughness of the surface. The roughness is the degree of the waviness of the joints; the micro-roughness is the texture of the joints. In areas where the joints are weathered or degraded by hydrothermal alteration, open joints, with the presence of water, the potential for falling rocks is greater. Characterizing the joints and orientation about the slope, you can determine the angle of friction.

Three points, the surfaces of the joints are rough and irregular. This macro and micro-roughness provide optimal mooring.

Nine points, wavy surface and high roughness, but without optimal mooring. Twenty-seven points, flat structures, the surfaces do not contain undulations. The friction is strictly derived from the roughness of the surface of the rock.

Eighty-one points are fractures with clay filler, separate or open joints, altered or weathering joints, etc. They represent a low angle of friction.

Case 2

Structural condition

It is applied to slopes where differential erosion or seismicity is the dominant condition of falling rocks. For erosion to occur requires high slopes, unsupported rocks, or hard rocks that may eventually fall off. Rockfall is caused by a lack of local support or the entire slope. The common slopes susceptible to these conditions are Strata with weathered rocks where the erosion undermines, and the resistant rock falls off; slopes with various materials such as conglomerates and mudflows, etc. Where the climate influences to weaken the matrix and makes the rock fragments by gravity detach.

Three points, few characteristics of differential erosion distributed along the slope.

Nine points, occasional erosion characteristics distributed along the slope. **Twenty-seven points**, many features of differential erosion along the slope.

Eighty-one points, severe cases of erosion as dangerous overhangs produced by erosion.

The difference in erosion rates

It is related to the future potential of falling rocks. As erosion progresses, there is no support, and slope conditions develop. The impact of physical erosion, chemical processes, human activities should be considered. The degree of danger produced by erosion is related to the size of the blocks that are detached, frequency of fall and amount of material slipped.

Three points, the difference in the rate of erosion is such that the characteristics are appreciated over many years.

Nine points, the difference in the rate of erosion is such that the characteristics are appreciated over a few years.

Twenty-seven points, the difference in the rate of erosion is such that the characteristics are appreciated annually.

Eighty-one points, difference in the rate of erosion is such that the characteristics develop quickly.

Block size or number of rocks slid by event

The most probable type of rocks that occur in the fall should be represented. If the individual blocks are the most typical that fall, the size of the blocks should be the reference. If a mass of blocks is the reference, then the number of events must be taken or estimated when there is no maintenance history. Very useful to apply corrective measures.

Climate and presence of water in the slope

The periods of water help the weathering and movement of the rocky material. If it is known that water flows continuously or intermittently on the slope, it is classified as follows: areas that receive less than 20 inches per year are considered low rainfall areas, areas that receive more than 50 inches per year they are considered high precipitation areas. The responsible professional must consider that areas with precipitation or areas where water flows freely have a category of 27 points. Eighty-one points are reserved for areas with extreme water presence.

4.4 Drainage and sub-drainage work on slopes

Its purpose is to eliminate or reduce the water present in the slope and, therefore, the interstitial pressures that act as a destabilizing factor in the fracture surfaces and traction cracks. These measures are generally the most effective, since water is the main agent that triggers problems of slope instability, increasing the weight of the unstable mass, raising the water Table and interstitial pressures, creating hydrostatic thrusts, softening the ground, eroding the foot of the slope, etc.

Drains can be superficial, deep drains, "California" drains, vertical wells, draining sheets or a combination of them.

4.4.1 Surface drainage

This section has been taken from the "Manual of Slope Protection Works" Chapter 2, this manual has been prepared by the GENSAI Project in conjunction with the Ministry of Public Works, Transportation and Housing and Urban Development of El Salvador with the support of JICA, Japan International Cooperation Agency in 2018.

Classification of surface drainage facilities

The classification of the relevant surface drainage facilities for road cutting slopes is as follows, and as shown schematically in Figure 4.13.

- a. Drainage channel of the upper part of the slope
- b. Berm drainage channel or horizontal drainage trench
- c. Side drainage channel
- d. Longitudinal drainage channels

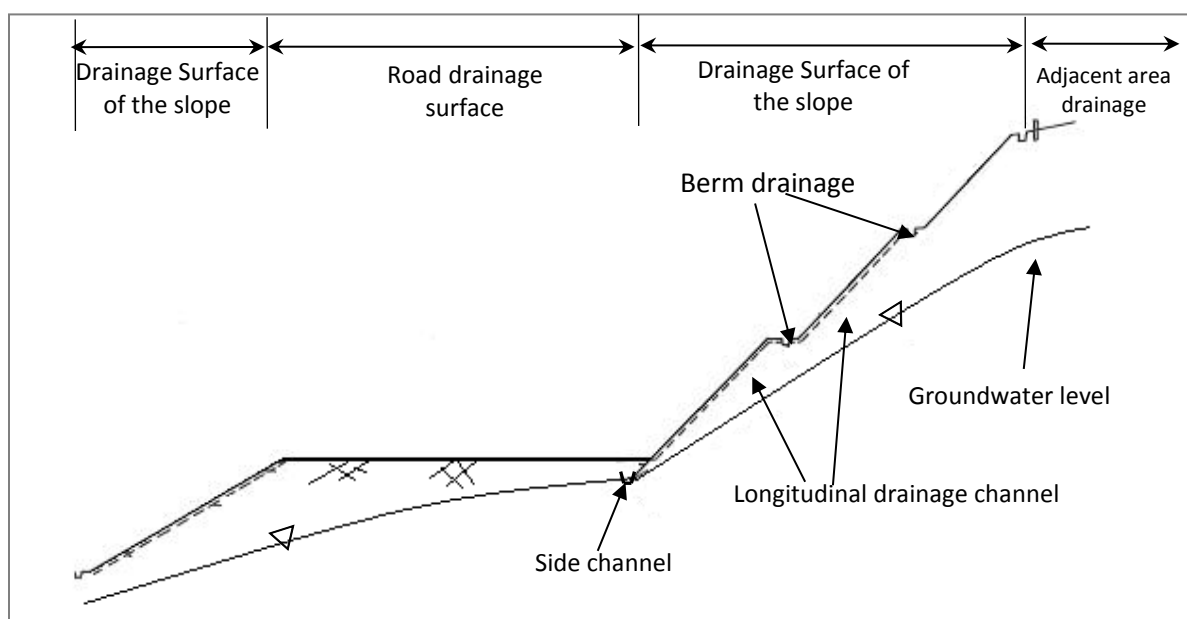


Figure 4. 13 Classification of Surface Drainage Installations, GENSAI, 2018

Each drainage installation is detailed below:

a) Drainage channel in the upper part of the slope

Drainage channels will be installed for the upper part of the slope along the entire part of the crown of the slope to avoid the flow of surface runoff from the areas adjacent to the slope.

The size of the ditch along the top of the slope will be determined according to the amount of runoff due to precipitation. The ditches will be built using soil-cement mixture, stone masonry, etc. Figure 4.14 gives a structural image of a drainage ditch made with a cement mixture for floors, JICA, 2018.

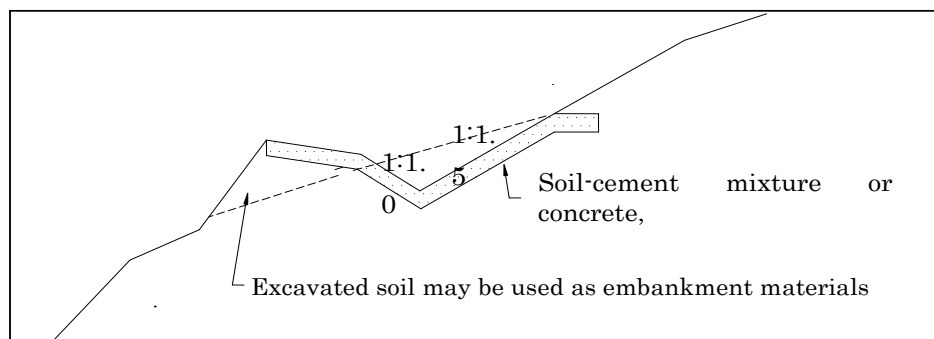


Figure 4. 14 Drainage channel with soil-cement mixture, GENSAI, 2018

These channels will be installed near the tip of the slope to prevent water flow in the back or side of the ditch.

b) Berms or horizontal drainage ditches

The horizontal drainage channels or drainage ditches of the berms should be designed to avoid surface erosion of the slope caused by rainfall or spring water. The drainage channels will be constructed using cement mixtures for soils, reinforced concrete U-shaped gutters, stone pitching, or they will be of unsupported types. Figure 4.15 shows the structural image of a horizontal drainage channel or berm.

When berm drains are provided, the width of the berm should be greater than 1.5 m.

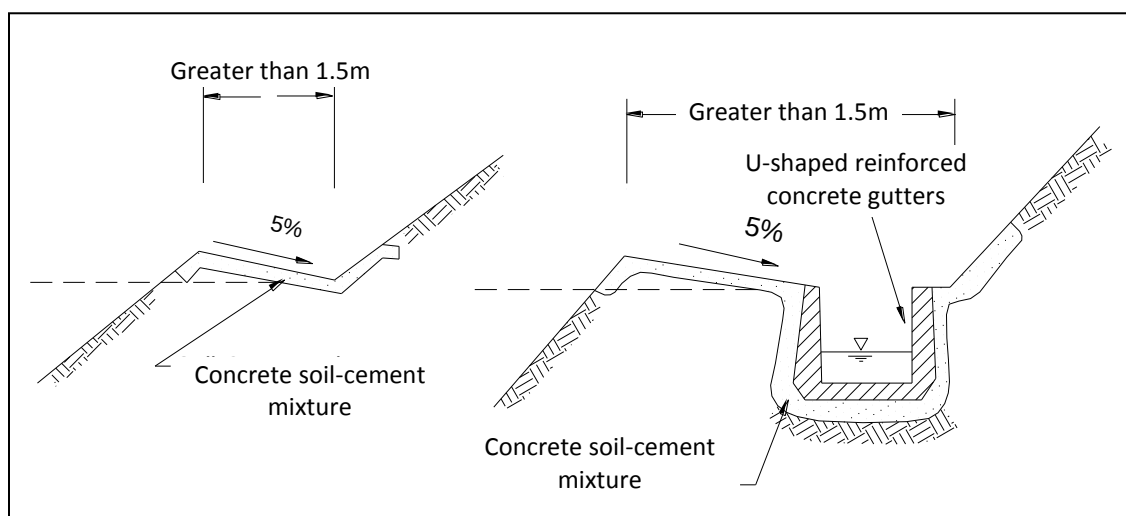


Figure 4. 15 Details of the drainage channel of Berm, GENSAI, 2018.

Source: Prepared by the authors based on the Association of Roads of Japan (JAEA), 2009. Guidelines for cuts and earth movements in roads and stability of slopes. ISBN 978-4-89950-415-6

c) Side drainage channel

The lateral drainage channels should be designed to cope with the maximum amount of runoff from the slope and its adjacent.

The following types of channels are generally used:

- a. Gravel channel - Can be used where the discharge is less, and there is enough space available.
- b. Stone or rock channel - The bottom of the channel is protected with stone or rocks. This type is adoptable when the speed of running water is a little faster.
- c. Stone masonry channel - The channel is covered with river stones on one or both sides, sometimes even at the bottom. This type is recommended for mountainous areas.
- d. Cast concrete channel in situ - Especially where the discharge is quite large, and the speed of the running water is fast, a concrete channel is recommended. Due to its larger section, the cast concrete channel in place is often used covered.

d) Longitudinal drainage channel

Longitudinal drainage channels should be designed to guide water from a trench at the top of a slope or berm to an appropriate channel at the bottom of the slope.

Longitudinal drainage channels are usually constructed with channels in U shape of reinforced concrete, reinforced concrete pipes, or are stone channels (ladder type). An example is shown in Figure 4.16.

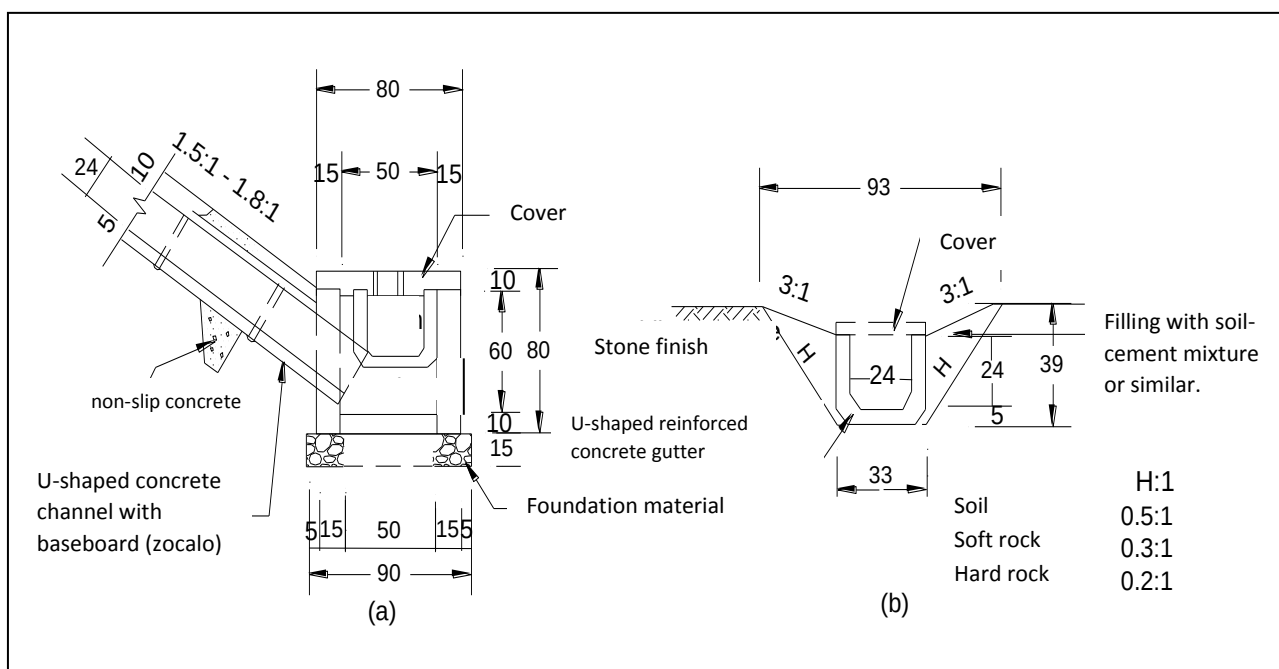


Figure 4. 16 Structural image of the drainage channel, JICA, 2018

In places where the flow direction changes drastically or where the longitudinal drainage channel meets other waterways, a collection basin with covers and simple sediment pit should be installed to reduce the power of the running water. In principle, the longitudinal drainage channels are installed under the following conditions Figure 4.17;

- The slopes are wider than 100 meters; Y
- On the valley slope, it is expected that rainwater will flow from the upper slope.

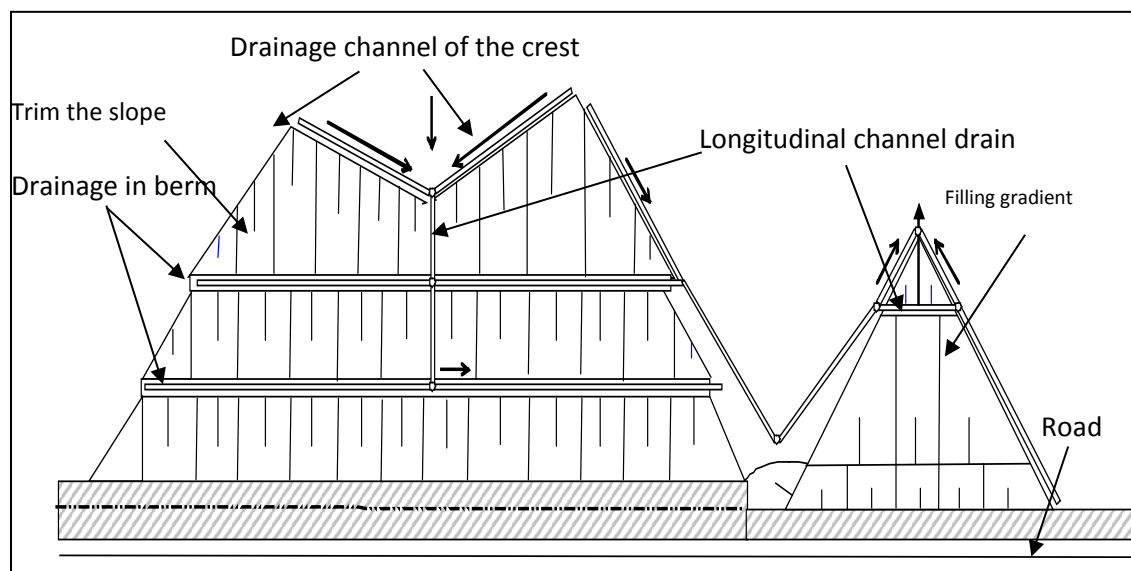


Figure 4. 17 Drainage channel design example, JICA, 2018

4.4.2 Underground drainage

This section 4.4.2 up to the subtopic "Design Consideration" has been taken from the "Manual of Slope Protection Works" Chapter 2 this manual has been prepared by the GENSAI Project in conjunction with the Ministry of Public Works, Transportation and Housing and Urban Development of El Salvador with the support of JICA, Japan International Cooperation Agency in 2018.

Groundwater is generally divided into two types, superficial and deep. Shallow groundwater, 0 to 5 meters below the surface of the soil, is mainly due to accumulated short-term rainfall. Shallow groundwater often causes surface failure or failure at the foot of a slope creating a large-scale landslide. In such cases, the sewers and horizontal drainage holes are effective.

The drainage system must be designed in such a way that it anticipates capturing the water before it affects the wall. In addition to the sub-drains, drainage holes must be installed to prevent hydrostatic pressure, which is normally from 2 to 6 inches in diameter (due to the difficulty of maintenance it is advisable to use a diameter greater than four inches) spaced no more than 1.5 meters horizontally and 1.0 meter vertically, the columns should be interspersed. The sub-drains should be placed from a minimum height of 30 centimeters above the level of the foot of the wall. Reference: Manual for Design for Slope Protection. JICA, 2018.

The horizontal drainage holes are used to drain surface and deep underground water, to stabilize the landslide by decreasing the pore pressure that is responsible for

activating the sliding surface. The works are useful as a temporary measure to diminish the progress of an active landslide.

Stability analysis of the effectiveness of subsurface drainage

The horizontal drainage drilling works are one of the best cost-effective methods of controlling a landslide. The amount of reduction in pore water pressure must be achieved by constructing the horizontal drainage hole, to satisfy the proposed safety factor is obtained using the following equation, and as schematically shown in Figure 4.18.

$$\Delta U = \frac{1}{\tan \phi} (PF_s \times \sum T - \sum (N - U) \tan \phi - C \times \sum L)$$

Where,

ΔU (kN/m) = Assumed reduction in pore water pressure.

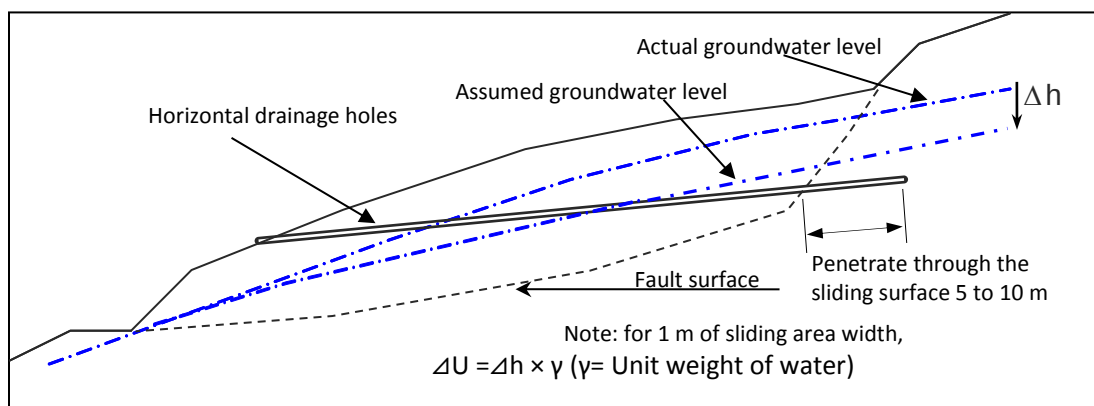


Figure 4. 18 Schematic diagram of horizontal drainage efficiency, JICA, 2018

In the case of a standard scale landslide with a landslide depth of 20 m, it can be expected that the reduction of the groundwater level by installing the horizontal drain is from 1 to 3 meters.

Design consideration

Horizontal holes are constructed for the drainage of shallow and deep groundwaters. If the topography prevents the drainage of groundwater in a smooth gradient, drainage wells, or tunnels with horizontal drainage holes will be used to achieve drainage, Figure 4.19.

When designing horizontal drains, the following points should be carefully considered:

Horizontal drainage is used to discharge groundwater flowing into a landslide and to discharge the groundwater flowing from the landslide and, therefore, work should be planned to locate the groundwater passage and thus to take underground water before or just after the fault surface. In general, the upper part of the slope of the sliding area tends to be placed for better results.

The interval of the horizontal drainage holes should be 5 to 10 meters at the end of the hole.

The horizontal drainage holes must be designed to cross the aquifer or penetrate through the sliding surface from 5 to 10 meters deep.

Horizontal drainage holes, usually 20 to 50 meters in length, should be excavated in a gradient of 5 to 10 degrees upwards to quickly remove the collected groundwater.

Hard polyvinyl chloride (PVC) pipes or gas pipes with an internal diameter of more than 40 mm are used as casing pipes. The parts of the casing pipes that run through the aquifer or the entire length of the pipeline are drilled to collect the groundwater. Rigid pipes should not be used in a landslide or unstable area because a rigid pipe does not accommodate the landslide movement that is occurring in an area without separating at joints.

Groundwater that is collected by horizontal drainage should be removed from a landslide or unstable areas using drainage channels or some similar structure. Do not allow the collected water to be discharged back into the slip area. Otherwise, erosion or an increase in the water Table could happen again.

The protection of the outlet of the horizontal drainage holes must be made with gabions or concrete. Without exit protection, erosion due to collected water would be active and would cause the collapse of the outlet.

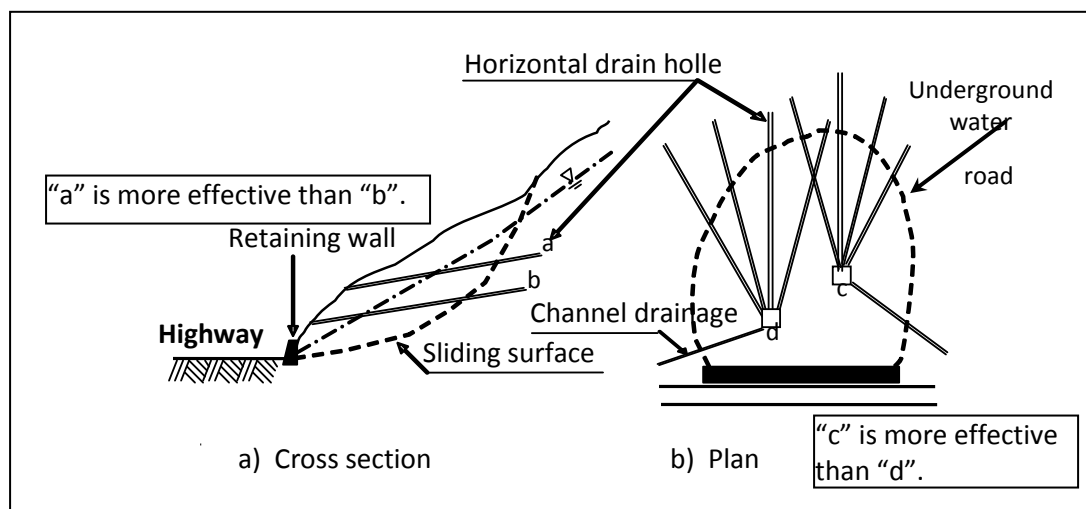


Figure 4. 19 Effective disposal of horizontal drainage holes, JICA, 2018

Table 4.29 presents methods for eliminating water according to the granulometry of the soil / rock. It can be deduced that the most effective drainage method is horizontal drains.

Table 4.29 Presents methods for water removal according to the granulometry of the soil / rock

Conditions	Wells Points Systems	Suction wells	Deep wells	Systems with ejectors	Horizontal drains
Soils					
Silty and clayey sands	Good	Deficient	Deficient to regular	Good	Good
Clean gravels and sands	Good	Good	Good	Deficient	Good
Stratified soils	Good	Deficient	Deficient to regular	Good	Good
Clay or rock in the subgrade	Regular to good	Deficient	Deficient	Regular to Good	Good
Hydrology					
High permeability	Good	Good	Good	Deficient	Good
Low permeability	Good	Deficient	Deficient a regular	Good	Good
Close recharge	Good	Deficient	Deficient	Regular to good	Good
Far recharge	Good	Good	Good	Good	Good
Program					
Need for a fast descent	Suitable	Suitable	Unsatisfactory	Apt	Suitable
Slow allowable descent	Suitable	Suitable	Suitable	Suitable	Suitable

Conditions	Wells Points Systems	Suction wells	Deep wells	Systems with ejectors	Horizontal drains
Excavation					
Shallow (<6m)	Suitable	Suitable	Suitable	Suitable	Suitable
	Requires multiple stages	Requires multiple stages	Suitable	Suitable	Special equipment
Characteristics					
Normal spacing	1.5 a 3.0 m	6.0 a 12.0 m	15.0 m	3.0 a 6.0 m	
Capacity range					
Per unit	0.4 - 95 l/min	190 - 2270 l/min	0.4 - 11350 l/min	0.4 - 150 l/min	
The whole system	Low – 19000 l/min	7500 – 95000 l/min	Low- 222500 l/min	Low– 3800 l/min	Low – 7500 l/min
Efficiency with correct design	Good	Good	Regular	Deficient	Good

Source: Powers J.P 1992

As a general guide, the drainage material must have a permeability at least 100 times greater than that of the soil or rock to be drained. The filter material must be thick and granular to ensure its effectiveness.

The thickness of the drainage layers is determined by construction criteria rather than by drainage capacity. Drains can be used in geotextile or composite materials, according to the design criteria of the soil mechanics.

Subdrainage drilling

The objective is to lower the water Table and decrease the pore pressures on the potential fault surfaces. In rocky massifs, the most used drainage system is drilling or penetration subdrains. Subdrains are designed behind potential fault surfaces. The direction of the perforations depends essentially on the location of the main discontinuities. The optimum drain is the one that intercepts the greatest number of discontinuities per longitudinal meter of subdrain, Simons et al., 2001.

The effectiveness of the subdrains depends on the size, permeability and orientation of the discontinuities. The effectiveness should be evaluated by the decrease in pore pressures and not by the water flows collected. The subdrains are generally constructed with a slope of 5 ° with the horizontal.

Typical spacings vary from 10 to 15 meters. It is common to install fan-shaped drain batteries to minimize the movements of the drilling equipment.

The subdrains should be internally cleaned to prevent that the presence of mud or clay decrease their effectiveness. Generally, in rocky massifs, the subdrains are only coated

at the exit; however, erodible materials may require the placement of perforated pipe over the entire length of the subgrade.

Other systems for subdividing rock masses include galleries or filter tunnels, pumping wells and ditch subdrains.

4.5 RMR application example

Example taken from a slope of Cerro La Potra, in the Bajo Frío hydroelectric project, Republic of Panama. The field research in the study is extensive and characterizes several families of fractures, the procedure being similar for each case, so only the steps followed for a discontinuity family are presented.

Description for a discontinuity (S) in a slope, it must be done for each of the families of present joints and then averaging the values to establish the quality, in Table 4.5 is the score and values of RMR.

Weathered alluvial material on weathered sandstone rock.

Favorable stratification joint with a 22 ° dip, dip direction of an azimuth of 61 °.

The filling of the openings is calcite and iron oxides.

The thickness of the openings is from 10 to 100 mm, so it is classified as very wide.

Rippled roughness with slightly rough texture (Classified with Barton's comb).

No water friction

Average spacing of the joints 62 cm.

Moderate continuity from 3 to 10 m.

Uniaxial strength of the 21Mpa compression rock matrix (resistance obtained from the sclerometer) is classified as a soft rock.

The RQD index can be determined in the rock mass by means of empirical correlations, Palmstrom, 1975, (in ISMR, 1981).

$$RQD = 115 - 3.3J_v \text{ for } J_v > 4.5$$

$$RQD = 100 \text{ para } J_v \leq 4.5$$

$$\text{Where } J_v = \sum \frac{\text{N}^\circ \text{ of discontinuities}}{\text{Measurement length}}$$

For this example, the obtained J_v was 7, applying the empirical correction of Palmstrom, the index of Rock Quality Designation (RQD) is 91.9%

$$RQD = 115 - 3.3J_v$$

$$RQD = 115 - (3.3 \times 7) = 91.9 \%$$

Where J_v = is the total number of discontinuities per cubic meter. (Palmstrom, 1975).

Table 4.30 RMR geotechnical classification example

RMR geotechnical classification	Value	Score
Resistance of the rocky matrix (MPa)	21.00	2
Rock Quality Designation (RQD)	91.90	20
Separation between joints (m)	0.62	15
Length of the discontinuity (m)	4.00	2
Opening (mm)	25.00	0
Roughness	Slightly rough	3
Filling	Soft fill less than 5 mm	2
Disturbance	Very altered	1
Groundwater	Dry	15
Correction for the orientation of the discontinuities	Medium	-5
Total score		55
RMR		III
Quality		medium



Source: Bajo Frío hydroelectric project, Panamá

Conclusion

The established in the RMR geotechnical classification of the slope, suggests that for its stabilization and protection it is: **shotcrete**.



CHAPTER 5

HIGHWAY SLOPE COUNTERMEASURES MAINTENANCE AND CONTROL

CA-1. Los Chorrros, Colón, La Libertad, El Salvador

This chapter contains information for the maintenance and control of slopes in road works. It is intended to be a tool applicable by the ministries of public works of the Central American countries to follow up on existing slopes or in fill cuts of any order of roads.

The main objective is to provide criteria to the field professional in the delimitation of maintenance areas, control of active landslides and stabilization through the different techniques; after the traditional techniques described in chapter IV, treatments are presented for slope restoration by soil erosion using cover systems (biotechnical) and, erosion control for stabilization of slopes through bioengineering. Visual inspection forms for the periodic control of slopes are made available.

Being able to determine the external signs that present the different types of faults, the stable parts that surround the sliding and the moving parts is determinant to establish the control of the movement.

SIECA in the "Central American Manual of Environmental Standards for the Design, Construction and Maintenance of Roads" addresses in C.1.6 the related to slopes as follows: *"Prior to the start of excavation activities, the recommendations established in the designs must be verified in relation to the works that will guarantee the stability of the cut slopes and embankment of the road"*.

With the provisions of the previous paragraph, it is worth mentioning the need to decree legalities for compliance with geotechnical studies after the designs and construction of the works to maintain control and maintenance of the slopes.

5.1 Delimitation of the maintenance area in situ.

In a concise manner, the most common external signs in the different types of failure are presented in Table 5.1. Characterizes the stable parts that surround the landslide at the initiation of the failed zone or crest, behind the fault zone, and on the flanks. It also defines the features presented by the moving parts in the head, body and base of the slope.

Table 5.1 Most common exterior signs of the different types of faults.

Movement type.	Material class	Stable parts that surround the landslide.			Parties that have moved.			
Falls and collapses.	Rock	Crest or initiation of the fault zone.	Main slope (behind the failed area)	Limbs	Head	Body	Base	Foot
		Loose rock, probable cracks behind the fault line, irregular appearance	Normally almost vertical, irregular, smooth, rock with a fresh appearance, rock with joints.	In general, clean rock edges.	Generally, it is not well defined. The fallen material forms a pile of rocks near the escarpment.	Irregular surface with rock fragments. If it is very large and if it has trees or material of contrasting colors, the material can	The base commonly buried. If it is visible, it usually presents fault features, such as weak underlying rock or strata	If the fallen one is small, it has an irregular slope of detritus. If the rock fall is large the foot can have a round outline.
Soil falls	Soils	Cracks behind the fault line.	Almost vertical, soil. Superficially very cracked.	Often almost vertical.	Generally, it is not well defined. The fallen material forms a pile of rocks near the escarpment.	Irregular	Like the one above	Irregular
	Landslide	Numerous cracks, most of them concave towards the landslide.	Inclined, clean, concave towards the landslide, commonly high. It can present striae and ditches on the surface, ranging from the crest to the head. The upper part of the slope after the fault can be vertical.	The striae of the limbs of the escarpment have large vertical components near the head and remarkable horizontal components near the base. The height of the limbs decreases toward the base. The limb of the landslide can be higher than the original terrain surfaces between the base and the foot. Step cracks surround the landslide in the early stages.	The top of the failed material preserves parts of the natural terrain before failing. Waterlogged occurs at the foot of the main slope. The entire fault head is furrowed by cracks and the trees in the fallen area point uphill.	The part of the ground that moves that moves failures and disintegrates. Longitudinal cracks, dip. Generally, waterlogged develop just above the base.	Transverse dips and cracks are usually developed on the base. Survey area, absence of large individual blocks. The trees tilted downhill.	Frequently a lobulated earth flow area, material rolled over and buried. The trees are laid or at various angles mixed with the material of the foot.
Circular	Soil							
	Rock	Cracks tend to follow fractures in the original rock.	Like the one above.	Like the one above.	Like the one above.	Like the one above, but the material does not failure so much or deform	Like the one above.	Little or no flow of land. The foot is often almost straight and close to the base. It can have an abrupt front.

Movement type	Material class	Stable parts that surround the landslide.				Parties that have moved.			
Translational	Rock or soil.	Crest or initiation of the failed zone.	Main slope (behind the failed area)	Limbs	Head	Body	Base	Foot	
		Most cracks are almost vertical and tend to follow the contour of the slope.	Almost vertical at the top; in the lower part almost flat and with a gradual transition.	The side flanks are very low, vertical cracks. Cracks generally diverse downhill.	Relatively unaltered. There is no rotation.	Generally composed of one or more unchanged units except for stress cracks. The cracks present little or no vertical	Neither base nor lifting zone.	Sliding on the surface of the ground.	
Rock slide	Rock	Loose rock, cracks between the blocks.	generally staggered according to the spreading of joints or stratification planes. Irregular surface in the upper part and slightly inclined in the lower part; It can be almost flat or composed of rock spills.	Irregular.	Many blocks of rock.	Rugged surface with many blocks. Some blocks may be in their original position, but lower if the movement was slow to move.	Generally, there is no real basis.	Accumulation of rock fragments.	
Dry material flow.	Rock	As in the rock falls	As in the rock falls.	As in the rock falls.	There is no head.	Irregular surface of mixed rock fragments spilled downwards in fan. It shows valleys and transverse lobes.	There is no base.	Composed of tongues. It can slide along natural river lines.	
Flows of rock fragments.									
Sand flows.	Soil	No cracks	Funnel shape when it reaches the angle of repose.	It is developed in a continuous curve from the crest.	Generally without a head	Conical mound of sand equal in volume to the part emptied of the head.	There is no base.	There is no foot, or this is a wide fan that is not perceptible.	

Movement type	Material class	Stable parts that surround the landslide.			Parties that have moved.			
Of wet material	Soil	Crest or initiation of the failed zone.	Main slope (behind the failed area)	Limbs	Head	Body	Base	Foot
Sludge flow		Few cracks.	La The upper part in a serrated or V shape, long and narrow, smooth and commonly grooved.	Inclined, irregular at the top. Stacking of material in the lower part of the limbs.	There may be no head.	From wet to very humid; it can have large blocks packed in fine material matrix. Flow lines. Follow the drain line and you can make sharp turns. Very long compared to the width.	Absence of base or buried in debris.	Laterally extended in lobes. When the foot dies, it may have a low height front step.
Soil flow	Soil	There may be some cracks.	Concave towards the slip. In some cases, it is almost circular. Slipping occurs through a narrowing.	Curved, steep sides.	It commonly consists of a sunken block.	Broken into many small pieces. Wet, shows the structure of the flow.	There is no base.	Extended in lobes.
Sand or silt flow		Few cracks.	Inclined, concave towards the slide, there may be varieties of shapes in the contour (almost straight, circular arc tendency or bottle shape).	Frequently the limbs converge in the direction of movement.	Generally, under water.	The body extends as fluid.	There is no base.	Extended in lobes.

Source: Soil Engineering in the Land Roads, Volume 1, Rico and del Castillo, 2010

5.2 Monitoring of active landslides.

Once the area with evidence of displacement is identified, it will be necessary to monitor it. Monitoring has different objectives:

- a) Quantify the progression of movement, in speed and direction.
- b) Characterize the fault surface.
- c) Determine the water Table.
- d) Evaluate the effectiveness of the control works once executed.

For this it is necessary to make use of certain tools and procedures that facilitate and optimize this task. A correct characterization of the slip allows a better selection and planning of the control work to be carried out.

Active landslide monitoring can also include the periodic measurement of variables that could affect the stability of the slip mass, such as rainfall or seismic registration in place.

Monitoring can be done in real time using specialized automated equipment, such as telemetric stations or ground radars for displacement monitoring; or by traditional equipment specially configured for that purpose. This document delves into traditional options.

For the determination of the landslide movement we have:

Topographic monitoring:

The control points survey is performed when the direction of movement of the slide is not clear or when the movement is intense.

The control points (piles) are installed inside and outside the assumed sliding area. The movements are measured once over several days or weeks using geodetic equipment such as the theodolite, aerial photographs of drone for photogrammetry or GPS devices. The movement speed is obtained as a function of the change of position over time. The survey can control the direction and speed of movement. In general, the control points are arranged in a straight line so that they are orthogonal to the assumed horizontal direction of sliding at intervals of 5-10 m. Both ends of the line extend to the assumed stable terrain, Figure 5.1.

This method allows the determination of the range and speed of movement for direct (D), components of horizontal direction of two rectangles (X, Y) and vertical (Z).

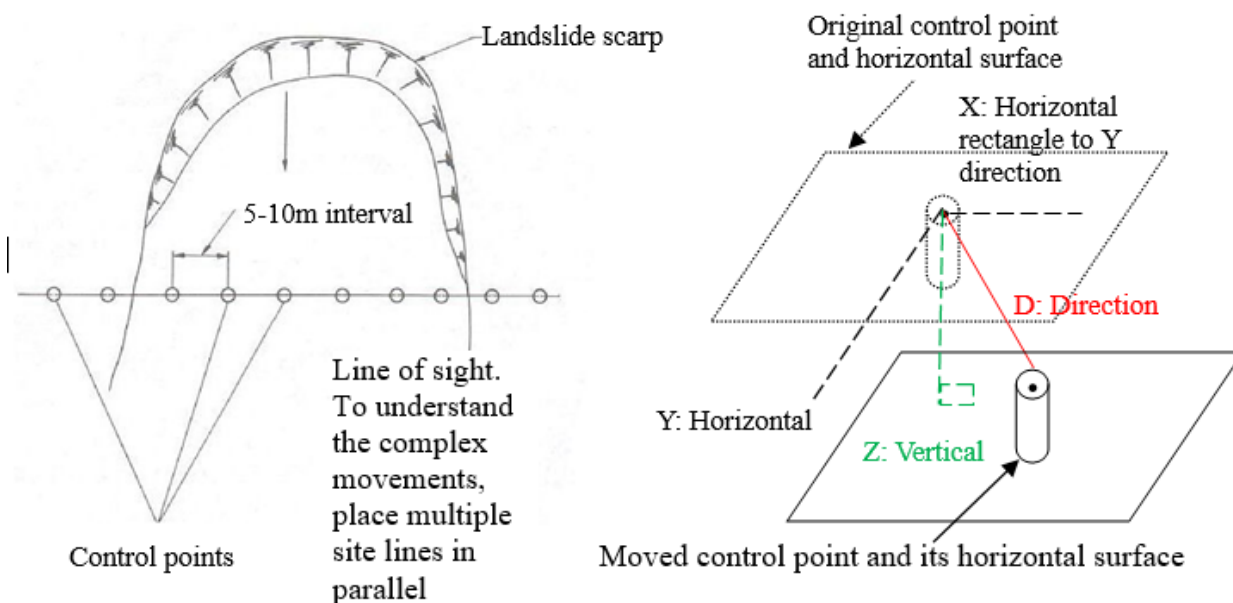


Figure 5.1 Design of control points for the monitoring of the movement of landslide.
Source: GENSAI II project contribution.

The periodicity of the reading of the distances will be given by the magnitude of the displacement found, being able to be daily, weekly or fortnightly, figure 5.2.

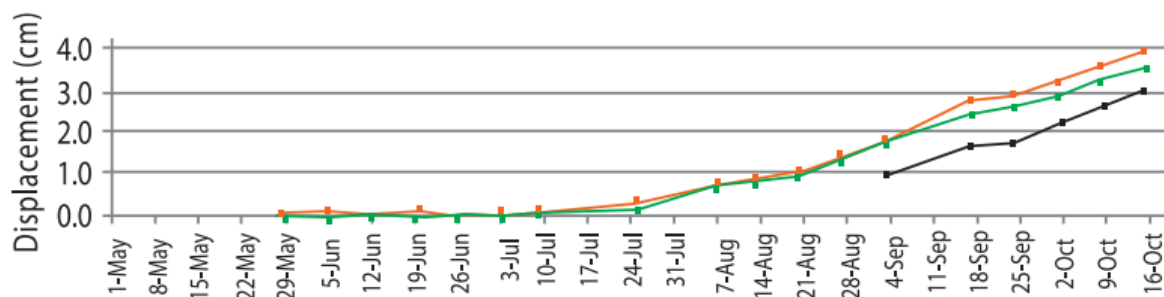


Figure 5.2 Direction displacement of control points in km 18.5.
Source: DACGER 2012

Permanent measurement between two points by extensometer:

An extensometer is a meter that is installed on opposite sides of cracks or dislocations to measure the relative movement between both sides by measuring the accumulated tension in a cable that joins said points, generally of invar, metallic alloy of low coefficient of thermal expansion, figure 5.3.

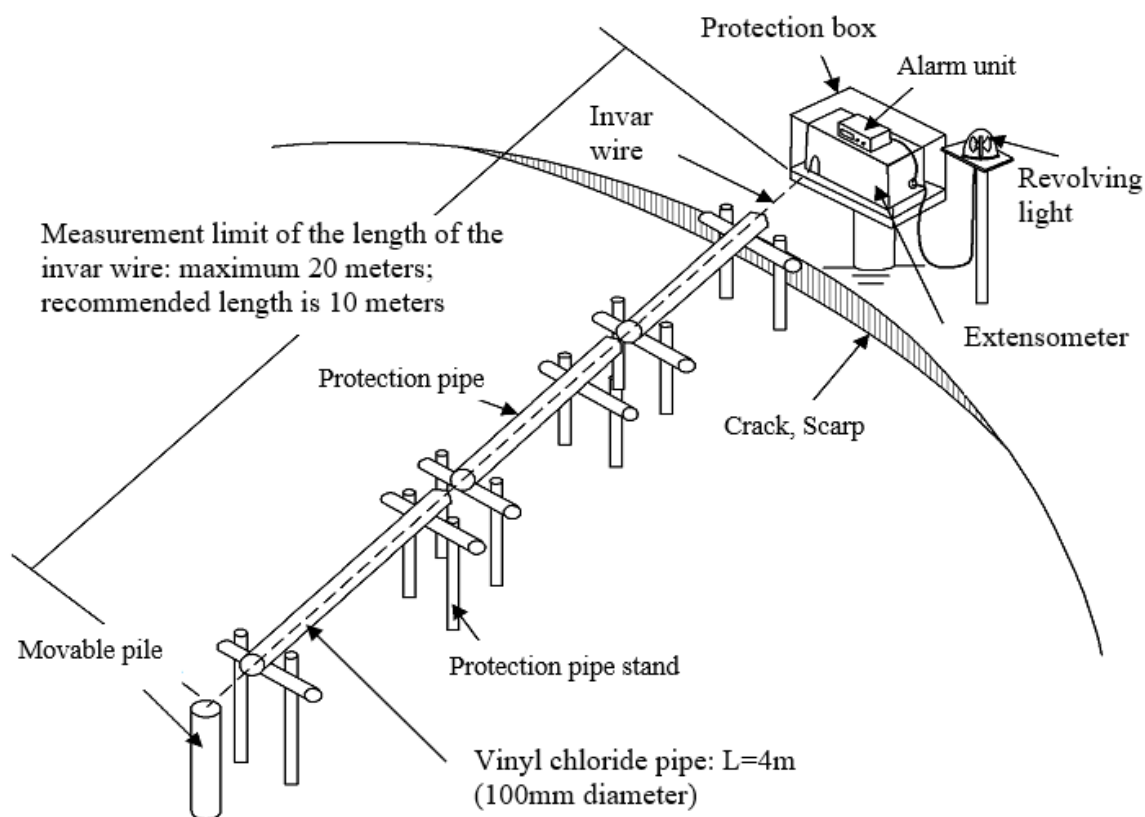


Figure 5.3 Scheme of extensometer.
Source: GENSAI Project/ DACGER, 2018

The results of extensometer measurements are expressed as cumulative data as shown in the figure 5.4. The rainfall data should be compared with the results, since the movement of landslides could be related to the behavior of the rain. They must be shown together to evaluate the characteristics of the landslide.

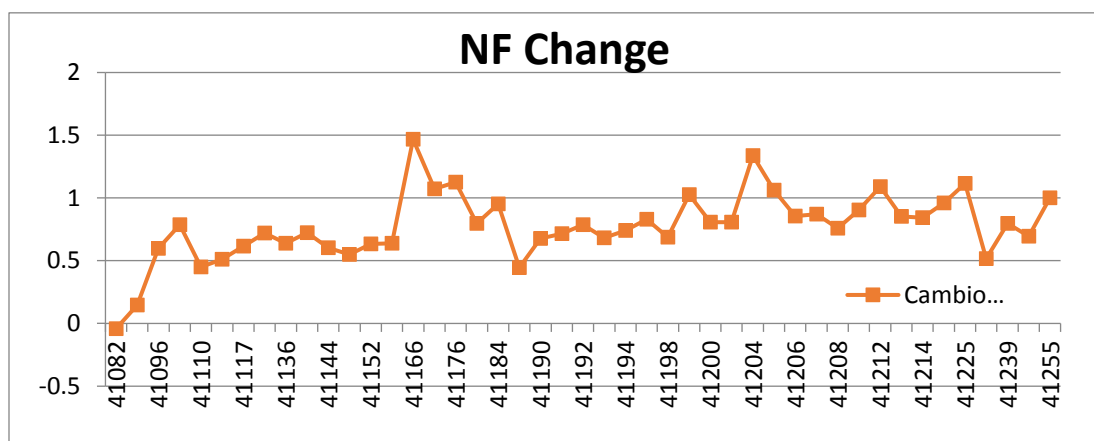


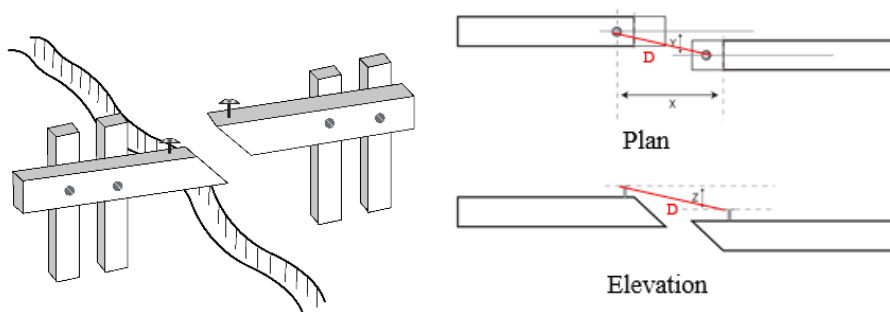
Figure 5.4 Example of extensometer fixed data set (GENSAI project/DACGER 2018)

The monitoring method for the simple deformation detection plate is shown in the figure 5.5 and figure 5.6.



Figure 5.5 An example of a simple deformation detection plate with an artisan extensometer.
(DACGER 2012)

Measure the distance of the nails as soon as the plate has been installed. Then the distance of the nails is measured. A measuring tape or ruler is used. The measurement point is outside of the nail to determine the specific points. A surveyor measures the direct distance (D). Measures the horizontal component along the plate's long side on top (X), the horizontal component orthogonal to the plate's long side on top (Y), and the vertical component (Z). A simple way is to install the piles on both sides of the crack and drive a nail on top of both piles. The distance of the nails is measured after installation.



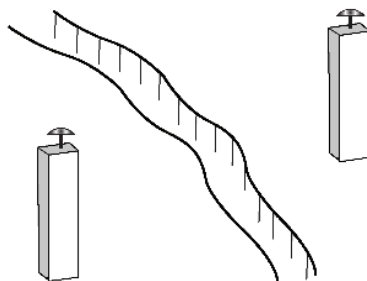


Figure 5.6 Monitoring procedure of the simple deformation detection plate through an artisan extensometer (GENSAI Project/ DACGER, 2018)

For the characterization of the fault surface:

Pipe equipped with strain gauges.

This procedure involves embedding an instrumented PVC tube with strain gauges on the slid surface to a depth enough to intercept the intended failure surface. Once installed, the periodic measurement of the deformations of the gauges is made, figure 5.7. The interpretation of the deformation data may determine the location of the fault surface in terms of depth; To determine the fault surface better, it is necessary to place at least two tubes in two independent perforations.

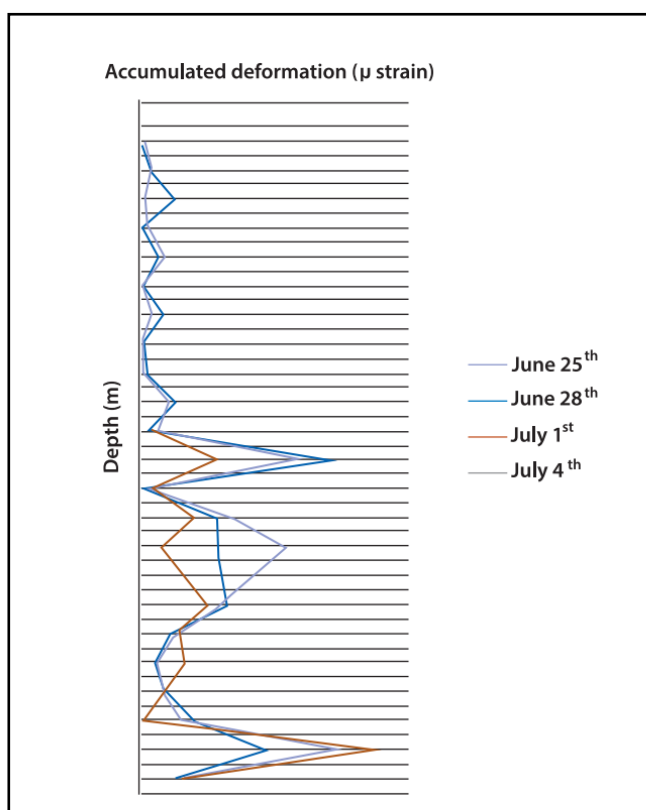


Figure 5.7 Deformations in S1 (DACGER 2012)

For the instrumentation of the PVC tube, it is necessary to place the gauges in opposite transverse ends, at a constant longitudinal distance (no more than one meter). The measurement of the deformation of the tube will be given by the differential of electrical resistance between an end that contracts and the opposite that extends, figure 5.8 and 5.9. An example of the casing of the borehole inclinometer is shown in Figure 5.10.

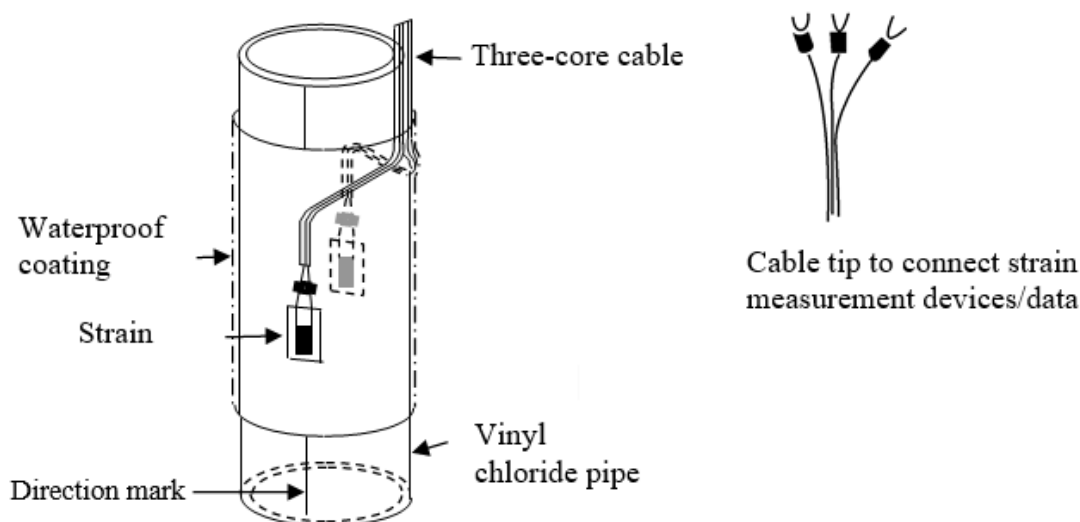


Figure 5.8 Pipe with strain gauges. (GENSAI Project/ DACGER, 2018).

Source: Own elaboration based on the Association of Roads of Japan (JAEA), Modified of Japan Landslide Society, National Conference of Landslide Control 2002, Landslide in Japan.

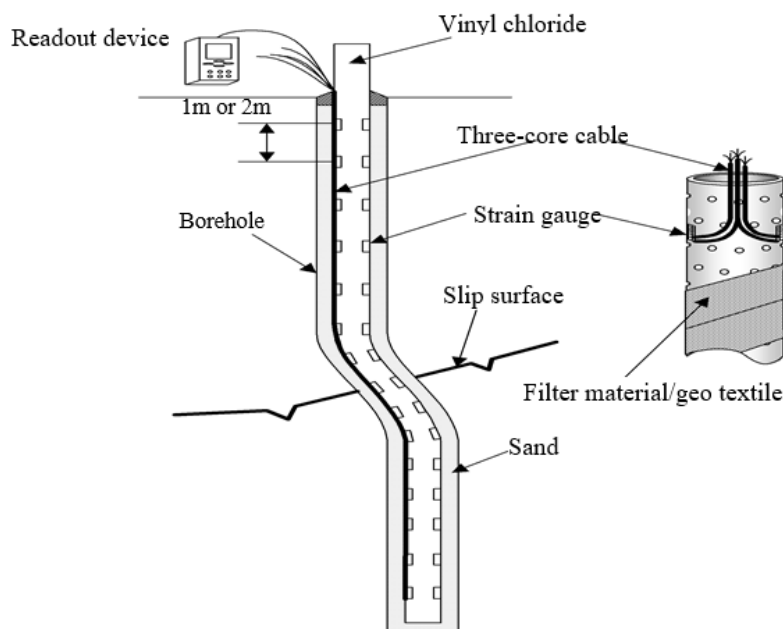


Figure 5.9 Installation of the pipe meter with strain gauges with groundwater level monitoring. (GENSAI Project/ DACGER, 2018)

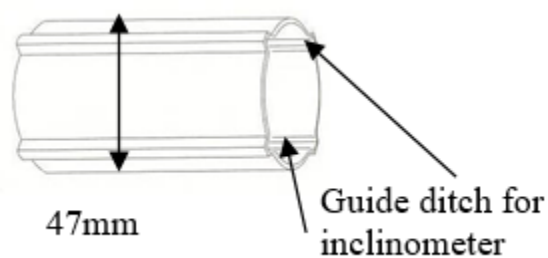


Figure 5.10 An example of the guide pipe for the borehole inclinometer (GENSAI Project/ DACGER,2018)

Monitoring is done by inserting a probe into the borehole, as shown in Figure 5.11.

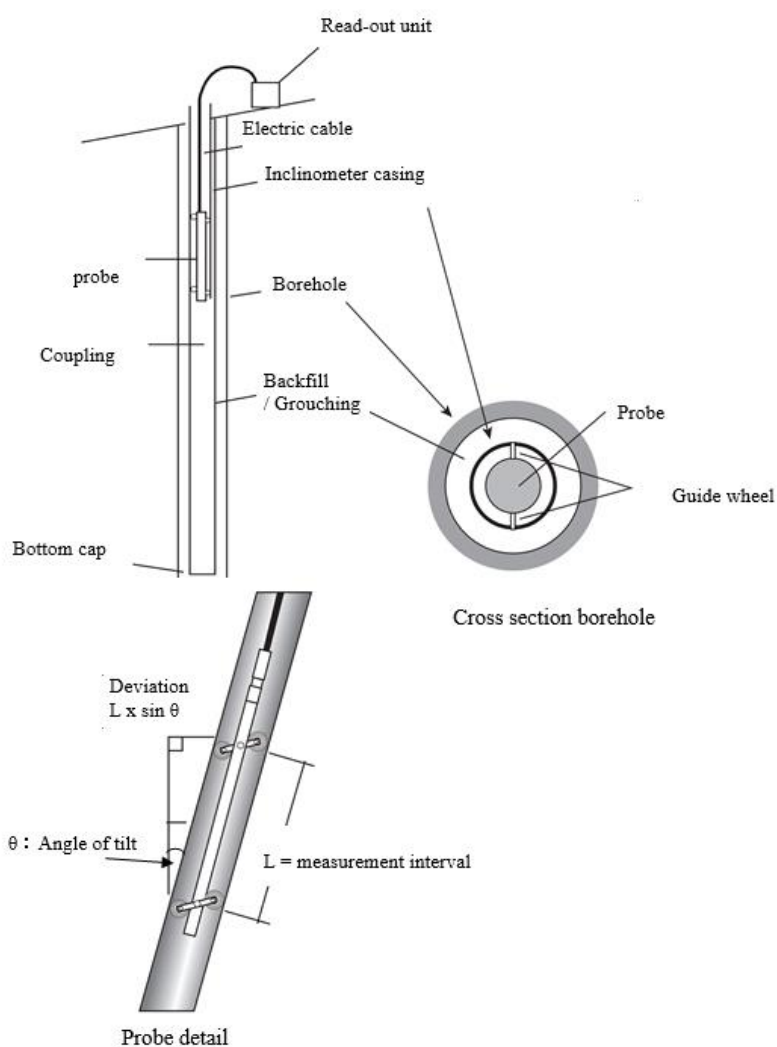


Figure 5.11 Monitoring of the Borehole Inclinometer (GENSAI Project/ DACGER, 2018)

The data from the borehole inclinometer should be processed as shown in figure 5.12. The point with the highest amount of gradient change is estimated as the slip surface of the landslide. Rainfall data should be compared with the results because the movement of landslides could be linked to rainfall performance.

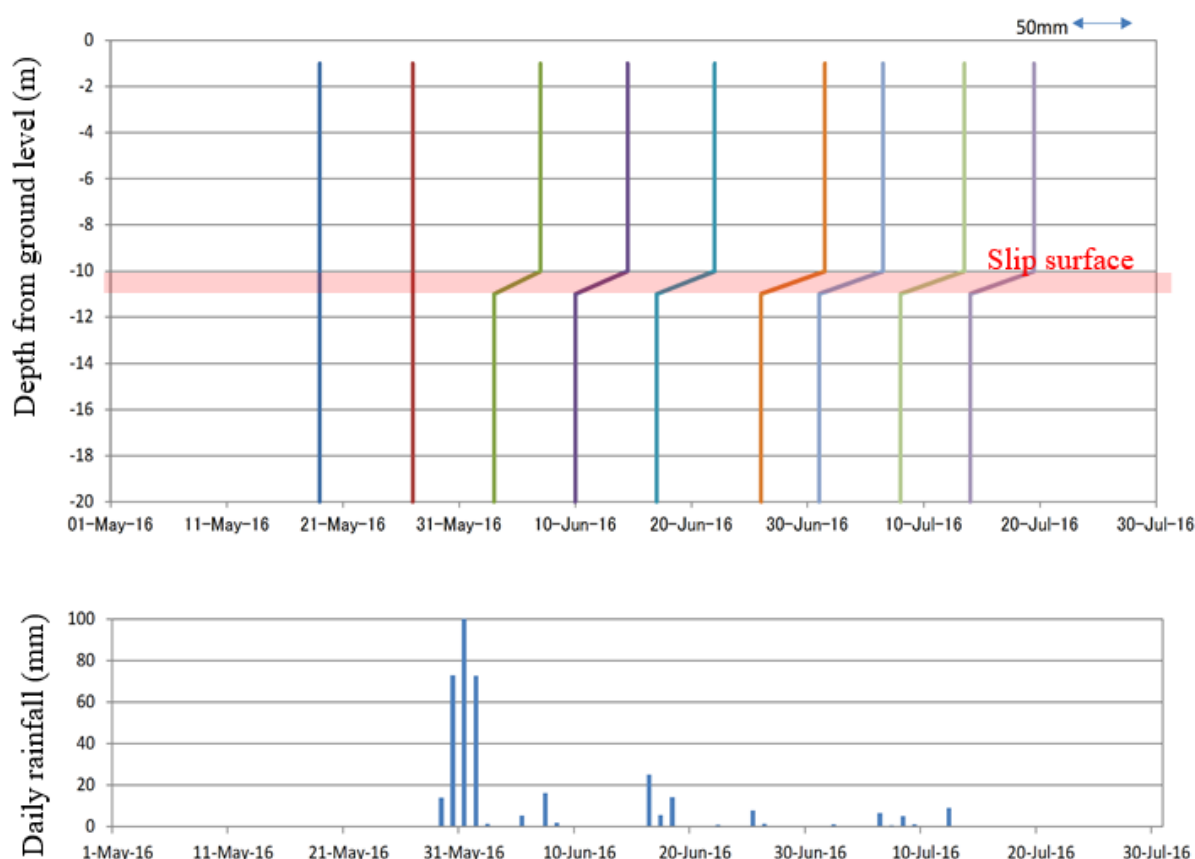


Figure 5.12 Example of borehole inclinometer monitoring

Source: GENSAI Project Contribution / DACGER, 2018

Determination of the water Table.

Direct measurement

The direct measurement consists in introducing in a borehole of Suitable diameter a volumetric measuring instrument that allows marking the distance at which the water Table is located from the surface.

Automated measurement

Automated measurement is achieved by the permanent installation of a sensor at the bottom of a vertical borehole. This type of sensors records the difference in height from the bottom (where it is located) to the surface of the water. To interpret the depth of the water table, it is necessary to know in advance the depth of the sensor to interpret the. These sensors have recording equipment, so they present a continuous measurement over time and is the best method when determining the performance of the local water Table in the event of rain.

5.3 Control of active landslides.

Sometimes it is necessary the combination of methods to maintain the balance of the sliding masses, Jaime Suárez presents four methods for the control of masses in movement: berms, trenches, retention structure, and protective covers, Table 5.2; each with its advantages and disadvantages. In addition, it classifies the stabilization systems into five categories: 1) conformation of the slope or hillside that tends to achieve mass balance, Table 5.3; 2) surface coating, Table 5.4; 3) control of surface and ground water, Table 5.5; 4) Containment structures, Table 5.6 y 5) Soil improvement, Table 5.7.

Rico and del Castillo consider that to maintain control of the movements, it is necessary to know the agents that provide the landslides, the processes and how they act in others, Table 5.8. But in cases of bad planning practice and not foresee the occurrence of these movements, Schuster and Kockelman provide some engineering practices to solve the movements, cataloging them into four categories, See Table 5.9.

Table 5.2 Control structures in mass movements.

Methods	Advantages	Disadvantages
Berms	They are generally economics, quick to build.	A large space is required in the middle of the slope.
Trench	They serve at the same time to control the rainwater.	Los cantos fácilmente pasan por encima.
Retention structure	Retain the moving mass.	Se pueden requerir estructuras algo costosas.
Protective covers	They are one of the most effective methods to reduce road risk.	They are very expensive.

Source: landslides and slope stability in tropical zones, Jaime Suárez 1998

The detail of the stabilization systems, using the Jaime Suárez classification, is presented below:

- 1) Conformation of the slope or hillside.

This system tends to achieve a mass balance, reducing the forces that produce movement, Table 5.3.

Tabla 5.3 Sistemas que tienden a lograr un equilibrio de masas

Methods	Advantages	Disadvantages
Removal of materials in the head of the slope.	Very effective in the stabilization of rotational landslides.	In very large movements the masses to be removed would have a great magnitude.
Abatement of the slope.	Effective especially on friction soils.	It is not economically viable in high altitude slope.
surface terraced.	In addition to sliding stability, it allows building works to control erosion.	Each terraced must be stable independently.

Source: landslides and slope stability in tropical zones, Jaime Suárez 1998

2) Surface coating.

They are the methods that try to prevent the infiltration or the occurrence of superficial phenomena of erosion, or that reinforce the most superficial soil. The coating may consist of waterproofing elements such as concrete or elements that strengthen the surface structure of the soil such as vegetation cover.

Table 5.4 Methods that attempt to prevent infiltration and erosion.

Methods	Advantages	Disadvantages
Coating the surface of the slope.	The coating helps control erosion.	The stability of the coating must be guaranteed.
Conformation of the surface.	It can improve the conditions of surface drainage and facilitate the erosion control.	Its direct effect on stability is generally limited.
Sealing surface cracks.	Decreases water infiltration.	Cracks can open again and require maintenance for important periods of time.
Sealing joints and discontinuities.	It decreases the water infiltration and pore pressures in the discontinuities.	There may be many discontinuities that are required to be sealed.
Vegetation cover: trees, shrubs and pastures.	They represent an environmentally excellent alternative.	It may require maintenance for its establishment.

Source: landslides and slope stability in tropical zones, Jaime Suárez 1998

3) Control of surface and ground water.

Systems tending to control water and its effects, decreasing forces that produce movements or increasing resistant forces.

Table 5.5 Systems tending to control water and its effects.

Methods	Advantages	Disadvantages
Surface channels for runoff control.	It is recommended to build them with complementary works in most cases. Generally, ditches are built above the crown of the slope.	Structures must be built for water delivery and energy dissipation.
Subdrains of the trench.	Very effective to stabilize shallow landslides in superficial saturated soils.	Little effective to stabilize deep landslides or landslides with deep water Table.
Horizontal subdrains of penetration.	Very effective for intercepting and controlling relatively deep groundwater.	Special drilling equipment is required, and its cost can be high.
Galleries or tunnels of subdrains.	Effective to stabilize deep landslides in formations with significant permeability and groundwater.	Very expensive.
deep wells of subdrains.	Useful in deep landslides in formations with groundwater.	Its use is limited due to the need for permanent operation and maintenance.

Source: landslides and slope stability in tropical zones, Jaime Suárez 1998

4) Containment structures.

They are the methods in which external forces are placed to the movement, increasing the resistant forces, without diminishing the acting ones.

The containment structures are generally massive works, in which the weight of the structure is an important factor and it is common to place anchored structures in which the force is transmitted to the sliding by means of a cable or steel rod.

Table 5.6 Containment structures.

Methods	Advantages	Disadvantages
Fill or berm of rock or soil at the base of the landslide.	Effective in not very large landslides, especially in the rotational ones acting as a counterweight.	A competent foundation is required to place the filling.
Conventional reinforced earth retaining walls.	Useful to stabilize relatively small masses.	Good foundation quality is required. They are less effective in high-rise walls.
Piles.	They are effective in shallow landslides, in which there is soil below the fault plane that is competent to allow the driving and support of the piles.	They are not effective in deep landslides or when rock or very hard ground appears below the surface of the fault.
Anchors or bolts.	Effective in rock, especially when it is stratified.	Special equipment is required and are usually expensive.

Methods	Advantages	Disadvantages
Anchored screens.	Useful as small to medium-sized mass containment structures.	There are some uncertainties about its effectiveness in some cases, especially when there is groundwater.

Source: landslides and stability of slopes in tropical zones, Jaime Suárez 1998

5) Soil improvement.

These processes seek to increase consolidation and reduce possible settlements. Suarez describes it as methods that increase the resistance of the soil, including physical and chemical processes, which increase the cohesion or friction of the soil-stabilizer product mix or modified soil. Suárez 1998.

Table 5. 7 Soil improvement.

Methods	Advantages	Disadvantages
Injection or uses of chemicals	Hardens the soil and can cement the failure surface.	The decrease in permeability can be a negative effect.
Explosives	Fragments the fault surface.	Its effect is limited and can have negative effects.
Solidification	Convert the soil into rock using special rays developed by special industry.	Its use today is only for experimental use.
Freezing	Hardens the ground by freezing it.	Non-permanent effects.
Electro-osmosis	They reduce the water content.	Use for non-permanent stabilization.

Source: Landslides and slope stability in tropical zones, Jaime Suárez 1998

The actor agents that provide the landslides, the processes, and means by which they act in others, Table 5.8.

Table 5.8 Actors that produce mass movements.

Agent	Process that puts the agent in action.	Means by which the agent acts.	Materials more sensitive to the action of the agent.	Physical nature of the action of the agent.	Effects on stability.
Erosion and transport	Constructive processes or erosions.	1. Increases the height or inclination of the slope.	All the materials.	Changes in the state of stress.	Increased shear stress.
			Rigid or fissured clays. Shales.	Changes in stress state and crack opening.	Increased shear stress. the capillary pressures are reduced.
Tectonic stress	Tectonic movements.	2. Large deformities of the earth's crust.	All the materials.	Increase the angle of the slope.	Increased shear stress.

Agent	Process that puts the agent in action.	Means by which the agent acts.	Materials more sensitive to the action of the agent.	Physical nature of the action of the agent.	Effects on stability.
Tectonic stress or use of explosives.	Tremors or exploitation with explosives.	3. High frequency vibrations.	All the materials	Changes of transitory stress.	Increased shear stress.
			Loess, lightly cemented sands and gravel.	Alteración de los nexos interparticulares.	Decreased cohesion and increased shear stress.
			Fine or medium sand, loose and saturated.	Rearrangement of grains.	Liquefaction.
Weight of the material that forms the slope.	Construction of the slope.	4. Superficial landslide.	Hard or fissured clay. Remnants of old landslides.	Opening of closed fissures and production of new fissures.	Decrease in cohesion. Increase of capillary pressures.
		5. Landslide in weak strata at the foot of the slope.	Hard materials on soft strata.		
Water	Rain or fusion of snow	6. Displacement of air in the voids.	Wet sand.	Increased pore pressure in the water.	Decrease in resistance.
		7. Displacement of air in open joints.	Rock with joints. Shales.		
		8. Reduction of capillary pressures associated with expansion.	Clay hard and fissured. Some shales.	Expansion.	Decrease in expansion.
		9. Chemical decomposition.	Any rock.	Weakening of interparticular nexuses.	
	Ground freezing.	10. Water expansion by freezing.	Rock with joints.	Opening of closed fissures and production of new fissures.	Decrease in cohesion.
		11. Formation of ice lenses in the soil.	Limes and silty sands.	Increase in water content of frozen soil	Decreased frictional resistance,
	Period of drought.	12. Contraction.	Clay	Cracking by contraction.	Decrease in cohesion.
	Quick emptying.	13. Flow towards the foot of the	Limes and fine sands.	Increased pore pressure in the water.	Decrease in friction resistance.

Agent	Process that puts the agent in action.	Means by which the agent acts.	Materials more sensitive to the action of the agent.	Physical nature of the action of the agent.	Effects on stability.
		slope.			
	Fluctuations in the elevation of the level.	14. Rearrangement of grains.	Medium to fine sand, loose, saturated.	Increased pore pressure in the water.	Liquefaction
	Ascent of the water Table in a distant aquifer.	15. Elevation of the piezometric level in the material that forms the slope.	Strata of sand or slime between or under clay.	Increased pore pressure in the water.	Decrease in friction resistance.
	Internal flow of water.	16. Flow towards the slope.	Saturated slime.	Increased pore pressure in the water.	Decrease in friction resistance.
		17. Displacement of air in the voids.	Fine sand wet.	Dissipation of surface tension.	Decrease in cohesion.
		18. Removal of soluble cementitious.	Loess	Weakening of interparticular nexuses.	
		19. Internal erosion.	Slime or fine sand	Tubing	Increased shear stress.

Source: Land Engineering in the Roads, Volume 1, Rico y del Castillo, 2010

Evasion of movement.

After having exhausted the technical and economic possibilities of stabilization and improvement of a landslide, circumvention methods are applied. While this should be avoided through a good planning phase, these are practices that should be considered. Some engineering practices are mentioned to solve them, Schuster and Kockelman (1996), Table 5.9.

Table 5.9 Options for movement evasion.

Options for movement evasion.	Descripción
Construction of variants	By recognizing and quantifying a landslide, it may be more advantageous for the project to modify it to avoid the problem zone. It requires a very complete geological and geotechnical knowledge of the area that determines that it is not technically or economically the use of a stabilization method and the alternative is to avoid the problem. Modifying the project or building a variant.
Total removal of the mass of landslides or unstable materials.	When the construction of a variant is not possible, it may be considered to move totally or partially the materials of the old movements or with the risk of activation.

Options for movement evasion.	Descripción
Construction of bridges.	These bridges should generally be supported by deep piles on rock or competent soil below the unstable materials. Very thorough studies must be carried out to be sure of the depth and the foundation system is enough to guarantee the stability of the bridge. Piers should be designed to withstand lateral loads, which are difficult to predict.
Modification of the level of the subgrade, project elevation or alignment.	At the design stage, the modification of the level of the subgrade of an unstable road section can be more stable and cheaper than building a stabilization work. At this stage, both the designed and geotechnical engineer should work together to achieve a balance between stability and project characteristics.

Source: Prevention, stabilization and slope design. Schuster and Kockelman 1996

5.4 Erosive processes.

The control of water, modification of the slope and destruction of the vegetation cover are some of the main causes of erosion, several authors have addressed the issue, including Fournier believes that the bases to avoid erosion by water runoff is to facilitate the infiltration, limit the length of the slopes to fragment the volume of the water, preventing it from reaching an erosive velocity and ensuring the circulation of the controlled waters towards the outlets in specially consolidated and conditioned collectors. Suarez defines the typical gradient that the slope must have depending on the type of material and height to avoid slope collapse, Table 5.10. In the Manual for the Control of Erosion and Afforestation of Watersheds in the Semi-Arid Zone, Santiago, Chile (JICA, 1998, makes a classification of general and specific treatments in erosion treatment, see the Table 5.11. Gray and Sotir present the advantages and disadvantages of using different types of plants in the control of erosive processes, see Table 5.12. Caltrans classifies and describes the types of erosion, also proposes the treatment for soil slope protection, Tables 5.13 and 5.14. Another alternative for erosion control, which is friendly to the environment and relatively economical, is the technique of slope stabilization and erosion control through bioengineering, Table 5.15 defines the different techniques, uses in engineering and construction procedures.

Principle of soil and water conservation.

Among the main causes of erosion in roads and specifically slopes are the following, FAO, 1986 cited by Marín 1992.

- Elimination or reduction of protective cover.
- Destruction or deterioration of the structure and natural fertility of the soil.
- Increase in slope conditions (cutting and filling of material)
- Decrease in the infiltration rate because of compaction by grading.
- Interception of surface flows by the cuts of the gradient.

- Decrease in shearing strength due to cutting effect.

In general, the bases on which the control of water is supported, to avoid erosion by runoff are the following, Fournier, 1975.

- Facilitate water infiltration.
- Limit the length of the gradients to fragment the volume of the water, preventing it from reaching an erosive speed.
- Ensure the circulation of controlled water to the exits in specially consolidated and conditioned collectors.

Thus, it has as guidelines for water control:

- The variation of the length and inclination of the gradient
- The capture and conduction of waters.
- The covering with vegetation.

The main problem of slope collapse has its origin in the characteristics of the layout and design of slopes. Suárez, 1992.

Table 5.10 Typical gradient for cutting slopes.

Material	Slope height	Gradient (V:H)
Hard rock		1:0.3 a 1:0.8
Soft rock		1:0.5 a 1:1.2
Badly graded sand.		1:1.5
Dense sandy soil.	< 5 m	1:0.8 a 1:1.0
	5-10 m	1:1.0 a 1:1.2
Dense sandy soil.	< 5 m	1:1.0 a 1:1.2
	5-10 m	1:1.2 a 1:1.5
Sand with gravel and dense pebbles.	< 10 m	1:0.8 a 1:1.0
	10-15 m	1:1.0 a 1:1.2
Sand with gravel and not dense pebbles.	< 10 m	1:1.0 a 1:1.2
	10-15 m	1:1.2 a 1:1.5
Cohesive soil.	0-10	1:0.8 a 1:1.2
Cohesive soil with pebbles.	< 5 m	1:1.0 a 1:1.2
	5-10 m	1:1.2 a 1:1.5

Source: Suárez, 1992

Table 5.11 Classification of erosion control treatments.

Erosion control treatments.	General treatments.	Specific treatments
	Regulation of hydric flows.	Water diversion channel.
		Longitudinal channel
		Simple transversal channel.
		Composite transversal channel.
	Increase in infiltration.	Infiltration trench
		Forestry terrace.
	Linear works of hillsides and slopes.	Wooden poles
		vine shoot fascines.
		branches fascines.
		Filled sacks.
		Tire coatings.
	Surface covers.	Mats of species.
		Eucalyptus branches
		Corn canes
	Regulation of hydric flows in channels.	Dykes of wood poles.
		Gabion structures dam.
		Dispersers
	Control and slope stabilization.	Structures of wooden pole.
		Shade cloth
		Wall with filled sacks.
		Wall of tires.
		Wall of wooden posts.
	Biological	Hydroseeding

Source: JICA and others 1998

Table 5.12 Advantages and disadvantages through various types of plants.

Type	Advantages	Disadvantages
Pastures	Versatile and cheap; varieties to choose from with different tolerances; easy to establish, good coverage.	Shallow roots and permanent maintenance are required.
Reeds	They grow easily and are easy to establish on riverbanks.	Difficult to obtain and the planting system is not easy.
Hierbas	Raíz relativamente profunda.	Sometimes they are difficult to establish, and roots are not obtained.
Shrubbery	Varieties to choose. There are species that reproduce by stake. Deep root, good coverage, low maintenance.	Sometimes they are difficult to establish.
Trees	Deep roots do not require maintenance.	Their establishment is delayed, and they are generally more expensive.

Source: Gray y Sotir, 1996

Table 5.13 Types of erosion that develop on the surface of a slope.

Type of erosion	Description.	Image
Erosion by splash.	It is produced by the direct impact of raindrops on bare ground. The resulting sediments can be transported later by water or wind.	
Laminar erosion	It consists of pulling up and transporting particles of the soil by a thin layer of water on the smooth and uniform surfaces. It occurs when the soil is not able to infiltrate the rainwater in the subsoil and flows to lower levels.	
Erosion by irrigation ditch.	It is produced by the concentration of laminar surface flows. The laminar concentration tends to concentrate in the lower levels of the surface due to the irregularities of the surface, forming furrows in favor of the slope. They are indicative of high erosion rate.	
Erosion in gullies.	They are ground splits, deep, caused by repeated scouring on the ground, due to the concentrated flow of runoff downhill. The presence of gullies is related to a very advanced degree of ground degradation. It can be 100 times greater than the rills.	
Mass movement.	They are prevented with geotechnical studies (this classification is not included), however mass movements are triggered by the rupture of hydrological instability prior to construction, and by the removal of the structured edaphic soil that retained, and in part infiltrated, the humidity in the different horizons of the soil.	

Source: Caltrans, 2010

Slope protection using biotechnical coverage systems.

Table 5.14 presents the various techniques for covering soil slopes by soil erosion and describes the treatments for restoration.

Table 5. 14 Treatments for the restoration of slopes by soil erosion.

Techniques	Description	Image.
Decompaction of the surface.	The decompaction on slopes consists of failure, through mechanical operations, a smooth and compacted surface. It is used on the surface of newly built clearings or very compacted embankments. The depth of the application is variable and will depend on the depth of the root of the coverage to be established. It is recommended on slopes with a gradient less than or equal to 18 ° and can be done with a backhoe or bulldozer.	
Increase in the roughness of the soil.	The increase of rugosity in slopes is a practice of temporary erosion control of frequent use in conjunction with the grade of gradients. It can be carried out with heavy machinery that makes furrows in the ground or with the placement on the surface of elements that increase the roughness, for example, the placement of small rocks or isolated plant remains. It is recommended to increase the roughness to slopes less than 33 °. Caltrans, 2011.	
Direct sowing	In slopes, direct sowing consists of the distribution of seeds, usually herbaceous, directly on the ground, treated by means of minimum tillage and/or fertilizers when the soil is not suitable for vegetation. It can be applied by manual methods or by mechanical methods. Manual direct seeding is not recommended on slopes greater than 19 ° and mechanical seeding greater than 17 °.	
Hydroseeding	Mechanical sowing consisting of the application of a mixture composed of seeds, fixers, fertilizers and additives on the surface of the slopes. Its objective is to establish a vegetative cover over dirt that is difficult to access or has a steep gradient. Despite being a well-extended technique, it does not ensure mechanical stabilization on slopes, nor the control of erosive processes, especially in areas with not very rainy weather. Bautista et al., 1997.	

Techniques	Description	Image.
Management of soil nutrients.	The nutrients in slopes can be managed through a variety of treatments, which include topsoil, mulch or organic mulch, compost, and organic and commercial fertilizers. Materials with slow nitrogen release are required for the development of vegetation.	
Use of topsoil.	In the restoration of slopes favors plant establishment and improves soil properties, filtration and moisture retention. In addition to seed growth of native species present in the soil before earthworks. Depending on the plant species, a thickness between 0.50 to 1 m thick can be considered.	
Use of Composting or Compost	It is an organic soil conditioner created by the decomposition of organic matter under controlled conditions. Like the topsoil, it favors the establishment of the vegetation and improves the properties of the soil.	
Mulch use or organic coverage	They are used to temporarily control bare soils, increase filtration and improve soil conditions. It simulates the fallen leaves layer, protects from the impact of rain and decreases the speed of surface runoff. It generates vegetation growth, increases vegetation and moisture content. It should be applied between 5 to 10 cm.	
Organic blankets.	Related to the geotextiles formed by a sewing of meshes and natural fibers (coconut fiber, jute, straw, others) or synthetic. It is used for the control of the superficial erosion, like support of soils, of sowing or hydroseeding, helping to improve the establishment and plant rooting. There are organic blankets in the market with reinforced, three-dimensional meshes, sewn to other geotextiles or geogrids, and even with incorporated seeds.	
Geocells	They are a cellular confinement system of three-dimensional geosynthetic elements formed by an alveolar structure of perforated high-density polyester, polyethylene or polypropylene strips to facilitate the lateral movement of soil particles or aggregates.	

Techniques	Description	Image.
	The system of cavities or alveoli allows to retain materials or incorporate soil depending on the height of the cells.	
Volumetric geogrids.	Three-dimensional systems formed by several thermo-welded meshes to which treatments are applied to resist ultraviolet radiation. They can be used on large slopes, so it is indicated for clearing, where it is not possible to provide soil to improve the substrate. They are also adopted in combination with other bioengineering techniques such as living stakes or branch beds (branches).	
Combination of treatments in slope restoration.	The combination of topsoil with some surface finish that improves the soil and promotes vegetation, Caltrans 2010.	

Source: Caltrans, 2010 in Barbero, 2013.

The benefits of finished slopes to prevent erosion after intense precipitation according to Dully & Hatzell, 1988.

- Reduces the volume and speed of runoff.
- Improves the infiltration rate.
- Improves soil moisture retention capacity.
- Improves the likelihood of achieving a durable plant cover.
- Decompaction improves the structural properties of the soil: porosity where the roots can penetrate.

Slope stabilization and erosion control through bioengineering.

Bioengineering is the inclusion of grasses, shrubs, trees and other vegetation in engineering design to improve and protect hillsides, embankments and structures from problems related to erosion and other types of surface instabilities on hillsides.

It uses the beneficial mechanical and hydraulic effects of a set of plants to fulfill a function in engineering:

- Vegetation can increase soil resistance to cracking.
- Protect laminar erosion from an exposed floor surface and
- Catch soil particles that slide down the slope.

Biotechnical stabilization and soil bioengineering are concepts where their main characteristics are given by the association of the materials and their types used to recover the soils of slopes or slopes, from the degradation processes that affect them.

Table 5.15 presents the techniques of slope stabilization and erosion control through bioengineering.

There are two approaches to this problem, figure 5.13.

- "Hard" or "conventional" approach: those that through structures such as cemented surfaces, gabions, wire meshes, others, give solution to the problem.
- "Soft" or "green" approach that, with vegetation, also provides a solution to the problem.

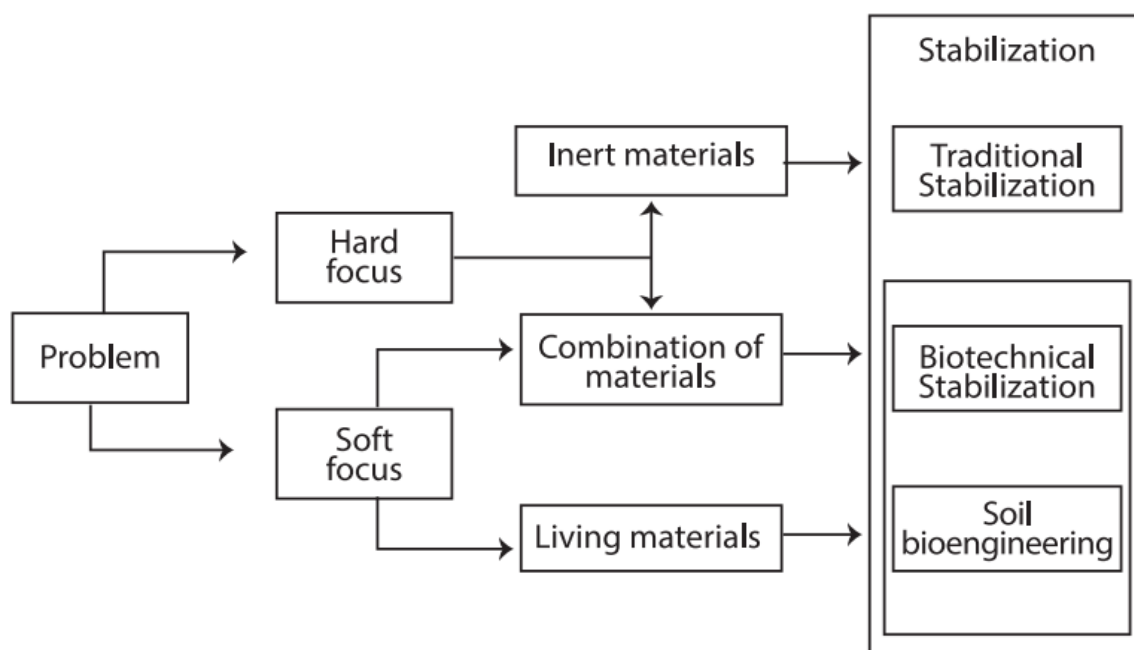
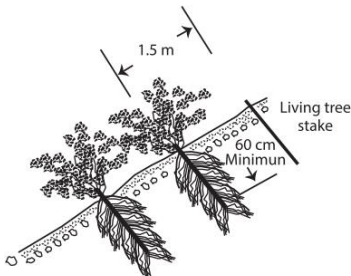
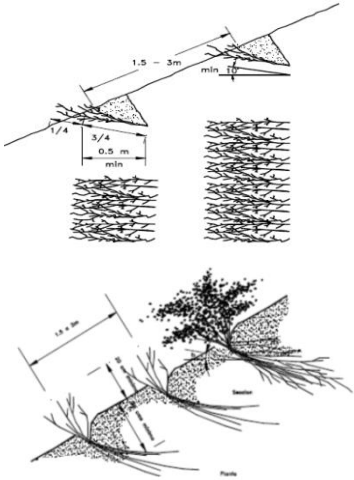


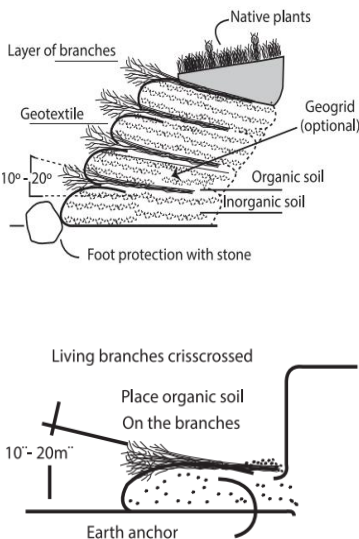
Figure 5.13 Approaches to tackle the problem of slope erosion.

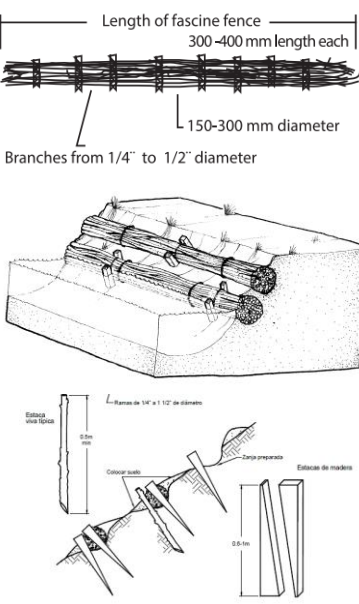
Source: Bioengineering manual

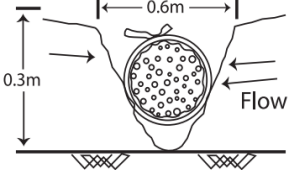
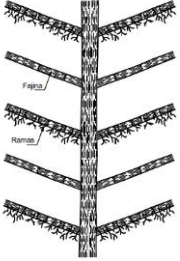
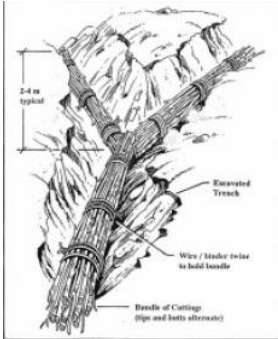
Table 5.15 Techniques of slope stabilization and erosion control through bioengineering.

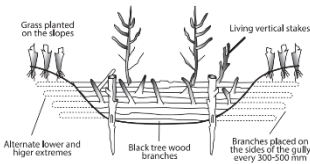
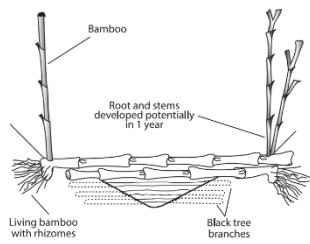
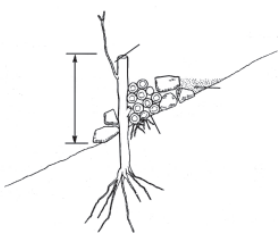
Technique	Description	Use in engineering	Materials	Process
Living stakes. 	They are portions of stems of trees and shrubs that are buried in the ground to sprout trees.	As a primary treatment where they fulfill the objective of anchoring other elements such as vegetal trinkets or mantles, which later	Stakes 1 to 3 cm in diameter and 0.60 to 1 m in length, from trees 2 to 3 years old and thin rind.	Cut the top of the stake normal to the shaft and the bottom in the form of a tip to facilitate insertion. Nail the stake at a right angle, normal to the slope surface.

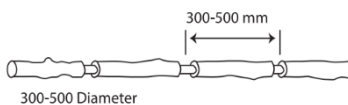
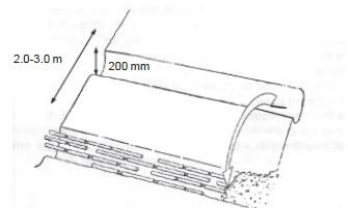
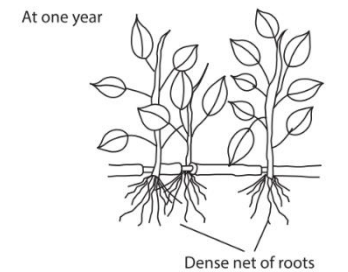
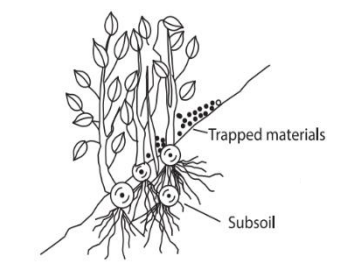
Technique	Description	Use in engineering	Materials	Process
		turn into trees or shrubs.		With the buds up. You can also make a hole with a bar. The density should be between 3 to 4 stakes per square meter. Between each stake there must be at least 1.5 m distance. Two thirds (60 cm) of the stake must be buried. Compact the dirt around.
Scrub steps / layers of branches.  Variations: with compacted soil layer in each layer of branches.	They are branches of woody species, with the capacity to root, arranged in small ditches or between successive layers of earth arranged along the slope of the slope, so that they form steps. is also called the entwined branches layer. It differs from the fascines in the orientation of the branches and the depth of the ditches. Here the branches are oriented perpendicular to	Reinforce the soil and increase resistance to landslides. It helps to retain sediments and improve the infiltration of water in dry soils. Drains very wet soils. Decreases the effective length of the gradient. It acts as horizontal drains. It acts as a sediment	Branches of 1 to 2.5 m in length and 25 to 50 mm in diameter (black log or willow). Yute. Stakes. Shovel.	Ditches are dug by hand from the foot of the slope to the headland according to the level lines of the slope. In very humid slopes it can be placed following the gradient to facilitate drainage. The ditches slightly inclined in reverse gradient (10 to 20 °) towards the slope are excavated until a depth of 50 cm and with a width between

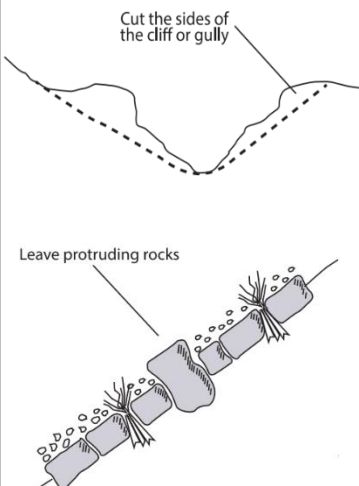
Technique	Description	Use in engineering	Materials	Process
 With compacted soil and covered with geotextile or jute.	the profile of the slope and are introduced up to 2 m into it. The perpendicular orientation is more effective for soil reinforcement and stability of the slope against mass movements.	barrier and flow retarders. Reinforces the slope in a similar way to geosynthetics. When it germinates, the reinforcement increases due to the roots.		0,50 to 1m. Between each ditch there must be between 1.5 and 3 m distance according to the gradient of the slope. The branches are placed perpendicular to the surface of the slope, with the growth buds outward, buried to $\frac{3}{4}$ of their length, remaining outside $\frac{1}{4}$. (about 30 cm) The branches are placed crisscross with a thickness between 75 to 200 mm.
Fascines	They are semi-cylindrical bundles of masses or herbs of diameter 0.20 and 0.40 m and lengths between 2 and 9 m, tied with wire or ropes of organic fiber or polypropylene every 0.20 or 0.30 m.	It captures and retains the surface layers of soil. It supports the slope that is immediately above the fascines. Drain the slope and reduce surface runoff. It decreases the runoff speed.	Long, straight and flexible branches, and provided with growth buds, from trees between 1 to 4 years of age. Shovel, machete, rope, stakes 1 meter long,	A ditch is built to an approximate depth of 20 cm in the contour of the slope, following the level lines, with a small slope to facilitate drainage. Place the half-buried fascines in the ditches. Fasten the fascines to the ground with

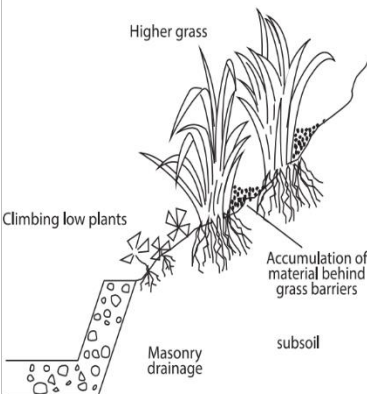
Technique	Description	Use in engineering	Materials	Process
		It improves the site by stabilizing the areas and avoiding the formation of gullies and ravines. They reduce the length of the gradient.	hammer.	wooden stakes. The stake is driven in such a way that it exceeds the upper level of the fascine. After the fascines are secured with stakes, the ditch is filled with mixed soil.

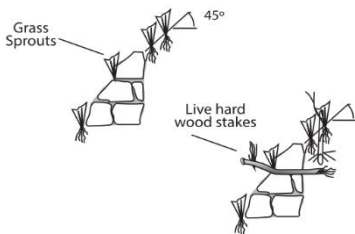
Technique	Description	Use in engineering	Materials	Process
Drain fascines.  Dig trench   Fascines combined.	They are semi-cylindrical bunches of branches or herbs with a diameter of 0.20 to 0.40 m and lengths between 2 and 9 m tied with wire or ropes of organic fiber or polypropylene every 0.20 or 0.30 m.	They can be used as surface subdrains to control runoff water.		It consists of digging ditches in the shape of a fishbone. A main ditch with arms that contain secondary ditches with lateral angles between 20 ° and 45 °. The main ditch has a depth of 50 cm, the secondary ditches have depth between 20 and 30 cm, 60 cm wide. The spacing between ditches varies between 1 to 2.5 m in parallel and with lengths between 3 and 8 m. The ditches are filled with living fascines all along. Fix the fascines with stakes. Fill the ditches with soil around the fascines.

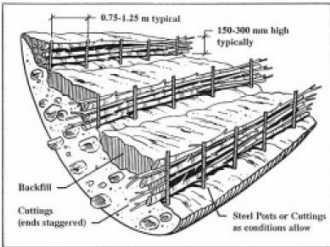
Technique	Description	Use in engineering	Materials	Process
Mini living control barriers.   Bamboo and blackwood control dam Side view.  Variations or combinations 	A living mini erosion control dam is built with live plants and local materials. A control dam of this type is porous, and its main objective is to reduce the effective slope in a fissure or gully and thus decrease the speed of water.	Prevents cracks from becoming large gullies. Repair small gullies with a maximum depth of 1m and maximum width of 2m. It reduces eroded material from fissures and gullies that reach a debris disposal site and that would otherwise enter natural drainage channels. Strengthen natural drainage channels in culverts and dump sites in the ditches.	Stakes of hard wood from 1 to 2 m long and 60 to 120 mm in diameter from, for example: Gliricidia sepium (Black wood) and Erythrina corallodendrum (Elequeme). Long stems of Pennisetum purpureum (elephant grass) for light and small control prey. <i>Bambusa vulgaris</i> (Bamboo) stems of 2 - 3 years. Robust grasses, such as Vetiver zizanioides (vetiver), with fibrous roots to reinforce the sides of the gullies. Weeds and angular	Trim the slopes of the gully if they are too steep. Any excess loose material that remains, throw it upstream of the control dam. Prepare bales of 4 or 5 hardwood stakes. Place the bale of stakes on the side of the gully at a depth of 300-500 mm and compact the material around the bale. Fill the area behind the dam with local weeds and angular rocks. Sow shoots or cuttings upstream from the sides of the gully.

Technique	Description	Use in engineering	Materials	Process
Dense barrier living.  300-500 mm 300-500 Diameter Prepare black tree branches with annular cuts in the bark at intervals 300-500  2.0-3.0 m 200 mm Use material excavado de arriba para cubrir la barrera desde abajo. At one year  Dense net of roots  Trapped materials Subsoil	It forms a dense environment that is established along the slope using material that can propagate from stakes of horizontally placed hardwoods or grasses. Dense barriers can withstand small surface movements of the slope and are strong in tension across the slope.	Strengthens the sides of the gullies and vulnerable areas below the discharge sites of the sewers. They protect the drainages so that they do not block with small rocks from the top of the slope. Rehabilitate waste disposal sites. Control surface movements of <300 mm depth in cut slopes in soft material.	stones to fill. Stakes of Gliricidia sepium (black wood) with a diameter of 60-12 mm and between 1 to 2 m long, with annular cuts in the head in intervals of 300-500 mm. It takes 4 m of black wood stakes per meter of ditch.	Establish an environment along the slope. Prepare black wood stakes. Make an annular cut in the bark of the cuttings at intervals of 300 to 500 mm to stimulate the growth of roots along the trunk. Prepare bunches from 4 to 5 and keep them in a cool, shady place until you use them. Prepare a ditch 200 mm deep in the contour of the slope. Place stakes bundles in the trench making sure there is overlap between them. Cover the stakes with a maximum of 100 mm of dirt.

Technique	Description	Use in engineering	Materials	Process
Stone barrier interspersed with vegetation. 	A layer of stones, boulders and small rocks carefully placed to prevent erosion and scouring of the surface.	Reinforce to a depth of 300 mm below the rip rap (vegetation component- rip rap-geotextile (may be jute or twine)) and stone to prevent erosion. Protects the surface of the soil preventing surface erosion (stone component). Protect the base of a slope from erosion. Protect the base of a ravine from scour. Protect the sewer discharge site from scour. Protect the elevated shoulders of the roads from surface erosion.	Corner stone or sub rounded of good quality with a size approx. 100 mm deep x 300 mm x 300 mm. Grass, seeds or shoots, example: Panicum maximum (shoots of guinea grass) or Vetiver zizanioides (vetiver). Stakes of hard wood of 400 to 900 mm long (including at least 2 knots in each cut) and with a diameter of 80 mm, for example: Gliricidia sepium (black wood). Species Vetiver zizanioides (Vetiver), Panicum maximum (guinea	Prepare the surface of the slope, the bed of the ravine or the shoulder of the road, to create a flat surface. I do not ground any rock that protrudes from the surface. Place a 100 mm layer of granular material with free drainage on the slope. Carefully place the rocks in the area to be protected. Lay down the rocks well and minimize spaces between them. Fill the spaces between the rocks with soil and sow grass at 150 mm between plants. You can also use living stakes between rocks at intervals of 1.5 m. Be sure to plant the grass and living stakes deep enough so that the roots penetrate

Technique	Description	Use in engineering	Materials	Process
			grass), <i>Gliricidia sepium</i> (Black tree).	below the rip rap layer.
Grass barrier to trap sedimentation. 	It is an effective method to prevent material coming down the slope from reaching a drainage or a channel.	Above the lateral drains. Above the drains. Around the sewers or gutters. Retain small rocks or small dirt fall	Robust grass that forms a barrier and recovers after partial burial, such as elephant grass stems and vetiver shoots. It requires 12 plants approximately per square meter. Species <i>Vetiver zizanioides</i> (Vetiver), <i>Panicum maximum</i> (guinea grass), <i>Pennisetum purpureum</i> (elephant grass), grass to cover the ground as for example <i>Pueraria thunbergiana</i> (kudzu grass), <i>Gliricidia sepium</i> (black tree).	Establish a guide for sowing parallel to the drain or side of the road. Plant a double row of grass with a space of 150 mm between plants in the row and 200 mm between the rows. Depending on the severity of the erosion and space, a denser barrier may be planted that includes wood vegetation. Fill the area behind the dam with brush and cornerstones that are in place. Sow suckers or grass stems on the sides upstream of the hollow.
Control of surface erosion with vetiver grass	Sow vetiver grass densely on the entire slope. This reinforces and	Protect the slopes at the edge of the road.	Vetiver pastures of good quality	Prepare enough plant shoots for a day's work.

Technique	Description	Use in engineering	Materials	Process
 Forma y distancia de siembra de vetiver. 	protects the slope against damage caused by surface erosion or the shallow collapse of the surface.	Rehabilitate collapsed cutting slopes. Cover up again the fill slopes with vegetation. Protect the shoulders of the roads on elevated pavements. Effective use in the splicing of an engineering structure on edges such as masonry dams. Retaining wall, or in the connection of gabions with the ground.	from a nursery or natural areas.	Keep the suckers prepared in the shade until they are sown. Do not allow the suckers to dry with the sun or with the wind. If the vetiver grass was grown in polyethylene bags, remove the polyethylene before planting. Prepare a hole for sowing about 70 to 100 mm deep and 50 mm wide. The hole should be of enough size to place the vetiver shoot without bending the roots. Fill the hole and compact the soil firmly around the grass shoot.
Stone floor with vegetation. 	Strengthens the base of the slope to prevent erosion and scour that can lead to a gradual withdrawal of the slope.	At the base of cut slopes or consolidated fill slopes. It is not suitable for slopes in loose and unconsolidated fillings. Protect	Natural rocks or boulders. Grass plants. Hardwood stakes of Gliricidia sepium (black wood), (if stakes are	Select hard and angular rocks to build the base of the stone wall. Clean the base of the slope of any waste and make a slight cut at the base of the slope to place the

Technique	Description	Use in engineering	Materials	Process
		natural drainage from erosion or from the collapse of debris.	required). Plants of small trees and shrubs if it is necessary to sow. Level and rope. Species <i>Vetiver zizanioides</i> (Vetiver), <i>Pennisetum purpureum</i> (elephant grass) y <i>Gliricidia sepium</i> (black wood).	angular rocks. Build a stone tread of about 300 to 500 mm high with a base of 300 mm. Place the stone on the back of the slope at an angle of 5 ° from the vertical. As the rock floor is being built, place grass shoots in the spaces, ensuring that the root penetrates the ground.
Retention fences. 	Erosion control structures and sediments constructed from stems and / or trunks of live shrubs that can continue to grow once placed in the ground or non-germinal stakes.	Stabilize the production of sediments and stop the erosion of the hillsides. Avoid erosion of its physical structure until established plants can provide protection against permanent erosion.	Black wood stakes. Wooden stakes. Cords and strings. Vegetal material.	It is constructed from the base of the gradient to the top of the hillside. Prepare hardwood stakes, which will be placed every 0.75 to 1.25 m. Place the stakes using a hand level across the width of the slope following the contour lines, insert them to a depth of 50 cm and compact the material around
Stabilization terraces.		Reduce the effective gradient. They reinforce		

Technique	Description	Use in engineering	Materials	Process
		inclined gradient areas and fill slopes where excess moisture could cause rotational landslides.		the stake. Place logs of black wood and attach to the posts with ropes or wire. You can also use braided branches of bamboo or other species. Fill the area behind the fence with local weeds and cornerstones. Plant shoots and stems upstream. Calculate the distance between fences, when the erosion is severe, the fences can be built in intervals from 2 to 3 m.

Source: Compilation of several authors by Miriam Downs, Swiss Cooperation in Honduras.

5.5 Maintenance plan

Considering that the protection works gradually deteriorate over time, the types of structures related to slopes have been classified, inventing the possible defects that they may contain and annotations that the professional could consider the visual inspection of the state of the structures in the field, Table 5.16.

Based on the information in Table 5.16, Table 5.17 and Table 5.18 have been constructed to record the damage in slope works; It contains initially compilation of general data: region, date of inspection, name of inspector and the number of sheets for the survey.

Then the name of the road, name of the sector, contract (number and year), road code, location of the work in UTM WGS84 coordinates or the one used in the country where the data collection and the characteristics of the work.

It also included the types of movements, landslides or flows that could affect the stability of the slope. The possible damages in the containment works are listed, leaving space for annotations of dimensions, number of photo and observations.

Finally, Table 5.18 (sheet 2 of 2) presents the typology of the work with a small box next to it to indicate which one is manifested, a space for the sketch and additional observations that the format does not specify.

Table 5.16 Inspections of structures on slopes.

Structure	Defects	Annotations in the inspection.
Containment structures.	Scouring	The depth, width and depth affected must be recorded. If there is a possibility of knowing the foundation material, write down the type of material, regarding apparent gradation.
	Settlements	They are not easy to establish, unless there is a reference point that allows obtaining a measurement of them. However, differential settlements are easy to observe, when you notice an inclination of the surface of the containment structure. The magnitude of the settlement should be noted, if it is differential, the length should also be noted. In the observations should be noted any additional information to establish possible causes of settlement: soft material, soil / rock moisture difference, other.
	Dumps	It is important to define the angle of inclination. If you do not have a compass with inclinometer, you can use a plumb line to establish the legs that form the angle, that is, the height and the horizontal difference.
	Gyre	They are rotations with respect to a vertical axis. They can be easily appreciated, since they generally produce surface undulations, and cracks in gravity or reinforced walls. The turn does not necessarily have to be of the whole structure, it can be only a portion of it. Note the length of the structure that presents the turn, the angle of rotation, or, failing that, the maximum displacement occurred.
	Cracks or fissures.	They are generally produced by bending stresses in gravity and reinforced walls. Of these damages report the length, depth and opening. Characteristics of the filling, in addition, exhibitions of iron in case of reinforced walls. It is important to record in a diagram the orientation and location of the cracks in the structure and in relation to the slope.
	Fractures	Corresponds to the detachment of fragments of the containment structure, product of the impact of an object with the wall, or the union of two or more cracks forming individual blocks. The height, depth and length should be noted to establish the wall volume that presents fracturing, in addition to drawing the relative location of the damage with respect to the wall and any influential feature of the slope (e.g. Rocks that have impacted).
	Leaks	Any type of outcrop of water on the slope, either through holes or cracks, should be noted. It must be quantified if the filtration moistens, drips and if flow estimates flow. Note the coloration of the structure in the outcrop.
	Vegetation	The characteristics of slope coverage in terms of vegetation are fundamental to establish patterns of erosion and infiltration as a general complement of the slope. Record the percentage of vegetation cover of the slope and make observations of the

Structure	Defects	Annotations in the inspection.
Gabion walls		coloration of the vegetation (light green, dark green, intense green) and type of vegetation (grass, shrub, trees).
	Drainage	To establish the possibility that the slope must eliminate surface water, filters are constructed, which deliver the water to sewers or weirs. The only observation is regarding operation. If there is no flow delivery, the slope being humid, observations should be made.
	Corrosion	After having noted the characteristics of the mesh (hexagonal triple twist, hexagonal double twist or electrowelded mesh) the defects are noted. The dimensions of corrosion are measured in area. It is recorded if the corrosion is partial or total, and the corrosive agent that precipitated the damage (environmental humidity, corrosive fluids, others).
	Failure of the mesh.	The dimensions are measured in area of the affected mesh. It is noted if there are important deformations that prevent "sewing" the mesh, or if the repair requires a reshaping of the gabion. Record the number of gabions involved and, in the diagram, draw the shape how the mesh failure is located.
	Coating loss.	In case the gabions are partially or totally coated, the type of coating and the area affected by the detachment should be noted.
	Weathering	In relation to the aggregates of the gabion, a qualitative annotation of the quality of the aggregate must be made, and its susceptibility to erosion. It is noted by the presence of residual dust or flakes in the aggregate.
Concrete gravity walls and reinforced concrete walls.	Inadequate size	The minimum size of the aggregate must, in any case, be greater than the opening of the mesh. Similar or lower sizes should be reported and note if the behavior is general or the number of gabions that present this deficiency.
	Cold joints.	They are generated by the emptying of concrete in different stages and when they are not treated correctly, they allow the entry of water and harmful agents for the concrete and for the reinforcing steel in case of existing. It is reported that this damage is done in linear meters of the affected length, specifying as much as possible if the reinforcing steel is exposed or may be affected by the damage. If there are several cold joints, the report must be made for each one separately, indicating the mentioned aspects.
	Exposed reinforcement.	This damage is generated by the loss of the concrete coating of the reinforcing steel; steel is exposed to the environment and corrosion problems arise. The report must be made in area (m ²). It should be noted in the outline.
	Segregation	Este daño consiste en la distribución inadecuada de los componentes de la mezcla. El reporte debe realizarse cuantificando el área afectada (m ²), y mencionar en lo posible si el acero de refuerzo se encuentra expuesto o con corrosión derivada de este daño. Señalarse en el esquema de registro.
	Anthill	They are generated by several causes in which the lack of vibration is highlighted, the improper practice in the placement of concrete in areas with high density of reinforcement and the inadequate dosage of concrete mixtures. The report must be made by consigning the affected area (m ²) and indicate it in the registration scheme.
	Efflorescence	They are deposits of salts on the surface of the concrete. Report the affected area (m ²).
	Carbonation	It is the reaction that occurs between carbon dioxide (CO ₂) from

Structure	Defects	Annotations in the inspection.
		atmospheric air or soil with the alkaline components of the concrete $\text{Ca}(\text{OH})_2$. It can generate corrosion of the reinforcing steel. The report of this damage must be done consigning the affected area (m^2).
	Concrete pollution.	They are affections of concrete due to chemical attacks of substances produced by the presence of microorganisms or vegetation on the surface of structures. These chemical attacks can increase the permeability of the concrete, generate color changes in the concrete, and others. Damages are reported by quantifying the area of damage in (m^2) and should be noted in the diagram.
Mechanically stabilized dirt (reinforced)	Panels	They must verify if they are fractured or detached, and in any case, place the number of affected panels. Record the characteristics of the exposed material in observations.
	Settlement	The filling may have compressibility drawbacks, particularly when it is part of the bank. Any type of settlement manifests on the surface. The magnitude of the settlement should be noted in case of having a reference point, and the area where it is presented, accompanied in the damage scheme. Note if there is possibility of evolution.
	Exposure of reinforcement.	In case the geotextile is visible, or the basket of electro welded steel if it exists, it should be noted the area affected by this damage and the oxidation conditions of the steel.
Anclajes	Punching	It is the concentration of the charges on the anchor side and in a small area around it. It is characterized by the appearance of fissures in the side and its surrounding area. In the report the opening, depth and length of the fissures and depth of penetration of the die in the surface should be recorded; in the diagram, the distribution of these within the die and around it should be illustrated.
	Loss of bolts.	This situation occurs in the press-cables that hold the tension of the anchor. The number of bolts lost relative to the total must be entered (e.g. 1/3 to indicate that a bolt of three required bolts has been lost).
	Plate cracking	A fissure pattern in the plate that holds the anchor. Illustrate the distribution of cracks in relation to the plate.

Source: Manual for the visual inspection of stabilization works, Ministry of Transport of the Republic of Colombia, 2006.

Table 5.17 Damage record (page 1 of 2)

Logo 1	STUDY AND INVESTIGATION OF THE CURRENT STATE OF SLOPES.				Logo 2
	Region:	Date:			
	Surveyed by: _____	Sheet of			
INSPECTION OF SLOPES AND CONTAINMENT WORKS. CONTRACT _____					
Name of the road: _____ Name of the sector: _____					
Road code.: _____ Concession.: Integral maintenance: Road Administration Sector N°					
ID 1) Location: _____ 2) Characteristics of the work.: _____ Coordinates X: _____ Type of work N°. _____ Other _____ Y: _____ Length: _____ m Height: _____ m Width: _____					
SLOPES STABILITY a) Movement type Fall <input style="width: 30px;" type="checkbox"/> Overturn <input style="width: 30px;" type="checkbox"/> Landslides: Rotational <input style="width: 30px;" type="checkbox"/> Translational <input style="width: 30px;" type="checkbox"/> Flows: Flujo plástico <input style="width: 30px;" type="checkbox"/> Flujos de detritos <input style="width: 30px;" type="checkbox"/> Flujos de lodos <input style="width: 30px;" type="checkbox"/>					
b) Longitud de calzada afectada: _____ m					
WORKS OF CONTAINMENT.					
Works	Type of damage	Dimensions	N°. photo	Remarks	
General	Scouring				
	Gyres				
	Collapse				
	Overturn				
	Fissures				
	Cracks				
	Fracturing				
	Leaks				
	Vegetation				
	Insufficient drains.				
	Clogged drains.				
	Reconfor mation	Clogged berms.			
Flows					
Ground instability					
Concrete walls	Cold joints				
	Exposed reinforcement				
	Segregation				
	Anthill				
	Efflorescence				
	Carbonation				
Anchor s	Punching				
	Loss of bolts				
	Plate cracking				
Reinfor ced earth wall.	Panels				
	Settlement				
	Exposure of reinforcement.				
Gabions	Mesh				
	Corrosion				
	Mesh failure.				
	Coating loss				
	Aggregates				
	Weathering				
	Inadequate size				

Source: Manual for the visual inspection of stabilization works, Bogotá D. C. 2006

Table 5. 18 Damage registration study (sheets 2 of 2)

[illegible]

Source: Manual for the visual inspection of stabilization works, Bogotá D. C. 2006

Maintaining the slope lawn is essential for growth and propagation which can last for a while depending on the type of soil where it lies, Table 5.19, contains maintenance information according to the type of soil and Table 5.20, shows a summary of maintenance after executing seeding work.

Table 5.19 Maintenance classified by soil type on slopes with planned vegetation cover.

Methods and soft soil cutting.	Sandy ground	It is planned for poor germination. The surface should be covered as soon as possible. An erosion forecasting agent should be used if the seeds are not ready for the heavy rain season.	Any broken coverage is dangerous. Additional fertilizer is immediately needed if you find bare portions of the ground.
	Clay floor	Slow growth	Maintenance is almost unnecessary. Additional fertilizer is required according to growth.
Hard ground cutting		Shortage of water immediately after work or lack of fertilizer occurs quickly. Sufficient water spray and additional fertilizer is necessary.	It takes a long time for the stabilization of the seed. The additional fertilizer must be continued for several years.

Complement of the inspection of structures developed in Table 5.17 and 5.18, it was considered necessary to present two more Tables for the inspection, Table 5.20 and 5.21; the first one for raising formed slopes and natural slopes where civil works do not exist, only drainage works and a second where civil works exist.

Table 5.20 Summary of maintenance after executing seeding work (maintenance classified by method of execution)

LOGO 1	MINISTERIO DE OBRAS PÚBLICAS (EJEMPLO DE COSTA RICA)										LOGO 2
FORMULARIO PARA INSPECCIÓN VISUAL (TALUDES Y LADERAS)											
ZONA:	Día	mes	año	Hoja	de	Estruc.	Ruta	Sentid	Lado	Km	
REGIÓN:											
RUTA:	EMPRESA:										
SELECCIÓN DE CONTROL:	RESPONSABLE:										
DATOS GENERALES											
Ubicación		Dimensiones		Definición		Esquema					
Km. Inicial	Sentido	Longitud (m)		Ladera natural		FOTOGRAFÍA					
Km. final	Lado	pendiente promedio (°)		Talud artificial (corte)							
Coordenadas X	Coordenadas Y	Altura máxima (m)		Terraplén (relleno)							
ESTADO DEL TALUD											
Movimientos											
Tipo de movimiento				Magnitud				Tipo de material			
De caída		Volcamiento		< 20 m3				Roca			
Flujos		Deslizamiento		entre 20 m3 y 100 m3				Coluviales (detritos)			
detritos y tierra		Rotacional		>100 m3				Tierra			

de lodos	Traslacional	Especificar:		Especificar:		
Plástico (reptación)	Movimiento complejo					
SEÑALES DE MOVIMIENTO						
Patología		Dimensiones	Fotos	Anotaciones		
Erosión superficial						
<10 (%) superficie						
10 -30 (%) Superficie						
>30 (%) superficie						
Agrietamiento						
Cuerpo del talud						
Corona del talud						
Pie del talud						
Carretera (grietas de tracción)						
Caída de material suelto						
Hundimiento de corona de talud						
Hundimiento de subrasante en terraplén						
Levantamiento de pie de talud						
Socavación de pie de talud						
Deformación de estructuras adyacentes						
DEFICIENCIA DE DRENAJE Y SUBDRENAJE						
Patología		Severidad			Fotos	Anotaciones
		Baja	Medi a	Alta		
Taponamiento de drenajes profundos						
Obstrucciones en drenajes						
Agrietamiento en drenajes						
Rotura en drenajes						
Inexistencia de drenaje						
Observaciones:						

Source: Final graduation project "Model of prioritization of geotechnical works for the intervention and maintenance of road infrastructure works of CONAVI", Calvo Vargas, 2013

Table 5.21 For visual inspection (structures)

LOGO 1	MINISTERIO DE OBRAS PÚBLICAS										LOGO 2
	FORMULARIO PARA INSPECCIÓN VISUAL (ESTRUCTURAS)										
ZONA:	Día	mes	año	Hoja	de	Estruc.	Ruta	Sentido	Lado	Km	
REGIÓN:											
RUTA:	EMPRESA:										
SELECCIÓN DE CONTROL:	RESPONSABLE:										
ESTRUCTURAS											
De contención						Otras					
Dique de contención en tierra		Muro de concreto reforzado				Pantallas y anclajes					
Muro de gaviones		Muro anclado				obras de drenaje y subdrenaje					
Muro de gravedad en concreto (ciclópeo)		Muro de encofrado o cribas									
Muro de tierra armada											
DATOS GENERALES DE LA ESTRUCTURA											
Ubicación		Dimensiones		Anotaciones		Esquema					
Km. Inicial:	Sentido:										
Km. final:	Lado:										
Coordenadas X:	Coordenadas Y:										
PATOLOGÍAS DE OBRAS DE CONTENCIÓN											
Falla parcial o total por:		Daño por impacto (fractura miento)				Erosión de juntas					
Volteo		Erosión, no grietas				Longitud afectada:					
Deslizamiento		Erosión y grietas				Vegetación:					
Capacidad portante		Rotura				% área afectada					
Deflexión excesiva		% área afectada				Corrosión:					
Abombamiento		Agrietamiento				% de área afectada					
Asentamiento		< 3 mm				Rotura o expansión de refuerzo (concreto ref.), malla (gaviones), geotextil (tierra armada)					
Otros		3 a 5 mm				% área afectada					
Erosión de la superficie de la estructura		>5 mm				Otra:					
< 2 cm		% área afectada				FOTOGRAFÍA					
>2 cm, <10% superficie		Desplazamiento de juntas									
>2 cm, >10% superficie		Pérdida de sello <20%, sin infiltración									
% área afectada		Pérdida de sello entre 20-40%, sin infiltración									
Observación:		Pérdida de sello >20%, hay infiltración									
Dimensiones:		Longitud afectada:									
PATOLOGÍA EN PANTALLAS Y ANCLAJES											
Daños o pérdidas en cabezales		Desprendimiento de cobertura rígida				FOTOGRAFÍA					
Corrosión		Fisuramiento de pantalla									
% área afectada		Otros:									
PATOLOGÍA DE DRENAJES Y SUBDRENAJES											
Patología		Medición		Severidad		Anotaciones		FOTOGRAFÍA			

			Baja	Media	Alta		
Taponamiento drenajes profundos							
Obstrucciones en drenajes							
Agrietamiento en drenajes							
Rotura drenajes							
Inexistencia drenajes							
Observaciones							

Source: Final graduation project "Model of prioritization of geotechnical works for the intervention and maintenance of road infrastructure works of CONAVI", Calvo Vargas, 2013



CHAPTER 6

RISK MANAGEMENT

6.1 Risk analysis

The risk, according to the Economic Commission for Latin America and the Caribbean (ECLAC), an organization of the United Nations, is defined as "the result of the interaction of three factors: Threat, vulnerability and exposure"⁴. The risk can also be defined according to ECLAC as "the probability of harmful consequences or expected losses (deaths, injuries, damage to public or private property, interruption of economic activities)⁵" and at present the environmental part and its deterioration, but it is being integrated as an implicit term in the exhibition.

Derived from the above concepts, we can say that the disaster risk is made up of two parts:

- The threat
- The vulnerability

This is expressed as follows:

$$\text{Disaster risk} = f(\text{threat, vulnerability})$$

To better understand the issue of Risks some basic concepts and terminology are explained which have been taken from the publication "Terminology on Disaster Risk Reduction. International Strategy for Disaster Reduction "of the United Nations in 2009 and of the" Basic Guide for the elaboration of the state and municipal atlas of hazards and risks "of CENAPRED in 2014.

Risk, in a technical context, emphasizes the consequences or in terms of "possible losses" related to a cause, place and time. This should be taken as the concept of probability or the possibility of something, such as the "risk of an accident"

Vulnerability is defined as the internal disposition to be affected by a threat; so that without vulnerability there is no loss, damage or destruction. It is also defined as "the characteristics and circumstances of a community, system or good that make them susceptible to the harmful effects of a threat".

⁴ The impact of natural disasters on development: Basic methodological document for national case studies. ECLAC. December 14, 2005.

⁵ Public policies for reducing vulnerability to natural and socio-natural disasters. Jorge Enrique Vargas. Environment and Development Series. ECLAC. UN Chile. April 2002

For sliding slopes or hillsides, there are no methodologies to determine the damage functions; the difficulty is in the different phenomena that can attack them, for example, in the seismic case, velocities or maximum acceleration should be taken as a single parameter. The problems of landslides are given depending on several parameters that depend on each type of movement considered, the parameter or the physical parameters that define the vulnerability, are different.

The degree of loss of a given element or of a set of elements within the area affected by the landslide(s). It is expressed on a scale of 0 (no loss) to 1 (total loss). In the case of a property, the loss will be the value of the property; for the case of people, it will be the probability that a life (the element at risk) is a loss, given the person (s) affected by the landslide.

Danger: A condition with the potential to cause an undesirable consequence. Descriptions of landslide dangers, particularly for zoning purposes, should include the characteristics of landslides. These may include the volumes or areas of the landslides and the probability of their occurrence. The description of the sliding speeds can also be valuable. Alternatively, danger can be understood as the probability with which a landslide occurs within a given lapse.

Hazard: A phenomenon, substance, human activity or dangerous condition that can cause death, injury or other health impacts, as well as damage to property, loss of livelihoods and services, social and economic disruption, or environmental damage.

Risk assessment: A methodology to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm people, property, services and media exposed livelihood, as well as the environment on which they depend. Table 6.1 and Figure 6.1 show some geological and meteorological processes that cause risks.

Table 6. 1 Geological and meteorological processes that can cause risks.

Phenomenon	Potential risks.
External geodynamic processes	-Landslides and loosening -Sinking and subsidence - Erosion - Expansibility and collapsibility of soils
Internal geodynamic processes	- Earthquakes and tsunamis - Volcanism - Diapirism
Weather processes	- Torrential rains and intense rainfall. - Floods. -Rivulets processes. -Hurricanes. -Tornadoes.

Source: González and others 2002.

The criteria that allow to establish the degree of slip hazard that the slopes can present, are shown in Table 6.2.

Table 6.2 Hazard scales to landslide*

Hazard	Type of Slope
Very high	Slope/Hillsides with cracks, escarpments or ledges. Very disturbed soils (see Fig. 6.1), loose and/or saturated. Presence of unfavorable discontinuities. History of landslides in the area or site. Slope/Hillside deforested.
High	Slope/Hillsides that exhibit fault zones. Weathering from moderate to high. It has unfavorable discontinuities, where landslides have occurred. Slope / Hillside deforested.
Moderate	Slope/Hillsides with some fault zones. Rock formations with alteration and moderate cracking. No history of landslides in the site or region.
Low	Slope/Hillsides in rock formations with low to moderate alteration. Discontinuities planes are less favorable to the landslide. Hillside without deforestation. A layer of compact soils of little thickness.
Very low	Slope/Hillsides in rock formations not altered, little cracked or fissured. Without discontinuity planes that favors the landslide. Slope/Hillsides without deforestation.

* Source: Basic guide for the elaboration of the state and municipal atlases of dangers and risks "of the CENAPRED, page 234.

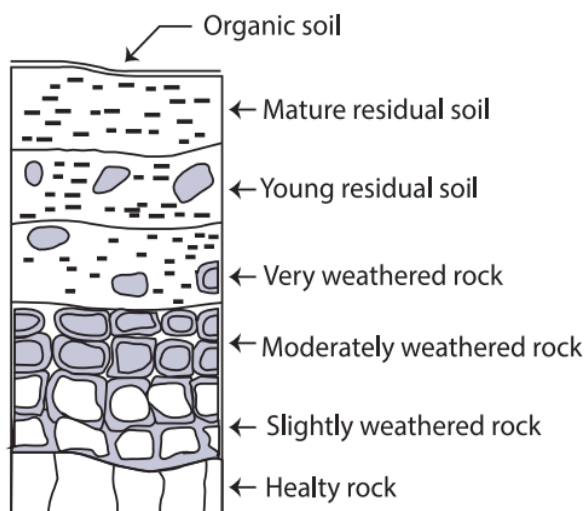


Figure 6. 1 Alteration profile of residual soil and basal rock.

* Source: Basic guide for the elaboration of the state and municipal atlases of dangers and risks "of the CENAPRED

To determine or estimate the danger of landslide on a slope/hillside, Table 6.3 should be considered, and each factor should be evaluated to later add the given score and review Table 6.4 to know the scale of danger of the slope/hillside.

Table 6.3 Factors to estimate the landslide danger of a slope/hillside.

Topographical and historical factors.					
Factor	Intervals or categories	Score	Remarks	Score	
				1	2
Slopes dip.	More than 45°	2.00	Estimate the average value. Use clinometer.		
	35° to 45°	1.80			
	25° to 35°	1.40			
	15° to 25°	1.00			
	Less than 15°	0.50			
Height	Less than 50 m	0.60	Unevenness between the crown and the valley or bottom of the glen. Use leveling, plans or topographic charts. Doubtful levels with GPS.		
	50 to 100 m	1.20			
	100 to 200 m	1.60			
	More than 200 m	2.00			
History of landslides in the site, area or region.	It is not known.	0.30	Plausible reviews of locals.		
	Some briefly	0.40			
	Yes, even with dates.	0.60			
Geotechnical factors					
Types of soils and rocks.	Slightly compacted granular soils to loosen. Soils that soften with the absorption of water. Unconsolidated formations.	1.5 to 2.5	Vulnerable to erosion; or soils of soft consistency.		
	Metamorphic rocks (shales, slates and schist.) from low to very weathered.	1.2 to 2.0			

	Consistent clay soils or compacted silty sand.		0.5 to 1.0	Multiply by 1.3 if it is cracked.		
	Sedimentary rocks (sandstones, conglomerates, etc.) and competent tuffs.		0.3 to 0.6	Multiply by 1.2 to 1.5, depending on the scale of weathering.		
	Healthy igneous rocks (granite, basalt, rhyolite, etc.)		0.2 to 0.4	Multiply by 2 to 4, depending on the scale of weathering.		
	Thickness of the soil layer	Less than 5 m	0.50	Check cuts and ravines; or, recur to manual exploration.		
5 to 10 m		1.40				
15 m to 20 m		1.80				
Structural aspects in rock formations.	Dip of discontinuity.	Less than 15°	0.30	Consider contact planes between formations, cracks, joints and planes of weakness. (Figure 6.2)		
		25 to 35°	0.60			
		More than 45°	0.90			
	Angle between the dip of the discontinuities and the inclination of the slope.	More than 10°	0.30	Positive differential angle if the dip is greater than the inclination of the slope. (Figure 6.3)		
		0 to 10°	0.50			
		0°	0.70			
		0° to 10°	0.80			
		Less than - 10°	1.00			
	Angle between the course of the discontinuities and the course of the direction of the slope.	More than 30°	0.20	Consider the direction of the most representative discontinuities.		
		10° to 20°	0.30			
Less than 5 °		0.50				
Geomorphological and environmental factors						
Geomorphological evidence of "holes" in contiguous hillsides	Nonexistent		0.00	Forms of shells or funnel (flows)		
	Moderate volumes		0.50			
	Large missing volumes		1.00			
Vegetation and ground use.	Urban zone		2.00	Consider not only the slope, but also the platform at the top.		
	Annual crops		1.50			
	Intense vegetation		0.00			
	Rocks with roots of bushes in their fractures.		2.00			
	Moderate vegetation		0.80			
	Área deforestada		2.00			
Water regime in the hillside	Surface water Table		1.00	Detect possible emanations of water in the slope.		
	Non-existent water Table		0.00			
	Ditches or depressions where water accumulates on the slope or platform.		1.00			
Summation					0	0

* Source: Basic guide for the elaboration of the state and municipal atlas of dangers and risks "of the CENAPRED.

Table 6.4 Landslide hazard estimation of slope/hillside.

Landslide hazard estimation.		
Grade	Description	Sum of the scores.
1	Very low danger	Less than 5
2	Low danger	5 to 7
3	Moderate danger	7 to 8.5
4	High danger	8.5 to 10
5	Very high danger	More than 10

* Source: Basic guide for the elaboration of the state and municipal atlas of dangers and risks "of the CENAPRED.

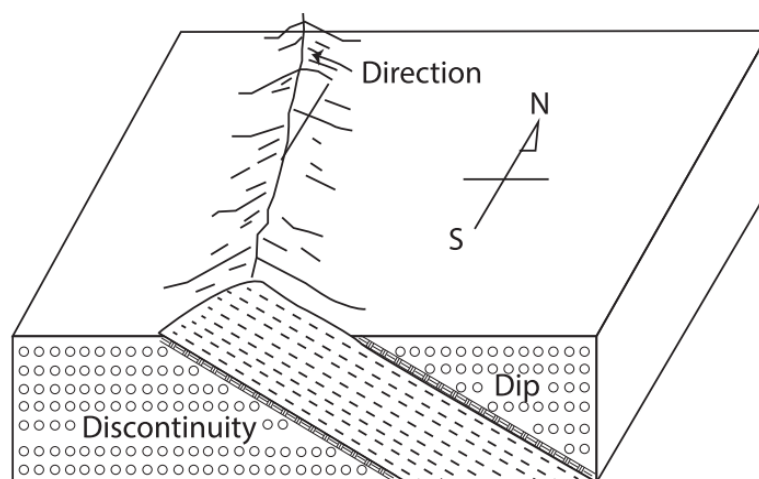


Figure 6.2 Course and dip of a geological formation.

Source: Basic guide for the elaboration of the state and municipal atlas of dangers and risks "of the CENAPRED.

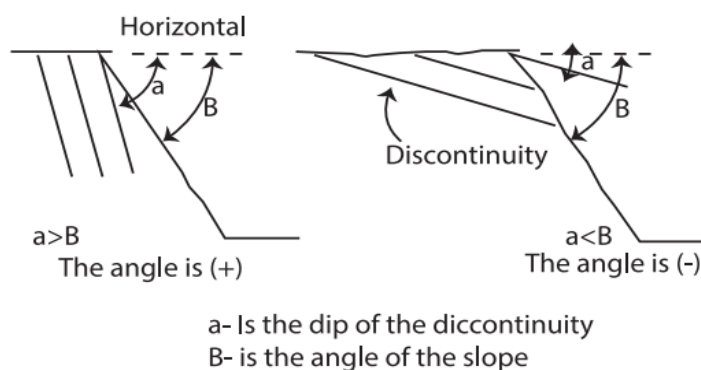


Figure 6.3 Relation between the dip of discontinuities and the inclination of the slope.

Source: Basic guide for the elaboration of the state and municipal atlas of dangers and risks "of the CENAPRED

Determination of the elements at risk.

The objective is to determine the distribution of probability for the number, nature and characteristics of the elements at risk (people, infrastructure, properties), which may be affected by the danger. This involves determining the number and nature of the elements. Some relevant characteristics that need to be considered are the location of the element in relation to the hazard and its size; for example, if it is located on the slope/hillside, its top, at the foot or at a certain distance from the foot. Also, if the item has a fixed position, for example a house; or if it is a mobile element, such as a person or a car.

A summary of the "HGGeoA Road Geomatics Management Tool Manual" is presented in Annex I. This tool was developed through the GENSAI project for the Department of Adaptation to Climate Change and Strategic Risk Management (DACGER) of the Ministry of Public Works of El Salvador, to determine and evaluate the risk, the "HGGeoA" tool allows road management planners to analyze and assess road geological hazard risks and thus promote and carry out efficient investments in reducing the risk of road geohazard. HGGeoA is a tool developed in Excel to facilitate its use by any geohazard road management planner.

6.2 Geological hazards or geohazards.

In 2005, Solheim, A., R. Bhasin, F. V. D. Blasio, L. H. Blikra, S. Boyle, A. Braathen, J. Dehls, et al. in its publication in the International Centre for Geohazards (ICG): Assessment, prevention and mitigation of geohazards. Norwegian Journal of Geology. 85. 45-62, they defined the Geohazard as "events caused by geological, geomorphological and climatic conditions or processes that represent serious threats to human life, property and the natural and built environment".

Geohazards on roads cover almost all hazards that affect road infrastructures, such as landslides, collapses, earth flows, debris flows, floods and erosion. Most geohazards are related to climate activity, such as rain, snowmelt or snow. In recent years, climate change has increased the intensity of rain and the average temperature, increasing the geological risk events of the flow type, such as debris or earth flows and floods. Geological risks damage road infrastructure threatens lives and livelihoods, and cause secondary impacts, disrupting traffic and services, such as water and energy supplies in some cases.

There are several types of geohazards that affect roads, and these can be classified according to their location and types of movement (i.e., fall or collapse of the

mountain, collapse of the side of the valley or erosion of the river, landslide and flow); and the dominant material involved (i.e., bedrock, soil and water).

Regarding the location of the geohazards on the road, these can be on the gradient of the mountain hillside or on the gradient of the valley side, this refers to a cut gradient or gradient of the embankment or a natural gradient on the surface of the road, in addition to the case in which the point in question is at a point of intersection with a river.

The most relevant risks for road systems are addressed below, such as floods, geological processes in volcanoes, earthquakes, landslides and slope collapses, debris flows, land flows.

6.2.1 Floods

Floods can occur when rainfall in a region exceeds the capacity of the soil and vegetation to absorb all the water that arrives and runs off into the ground. They also occur due to the overflowing of rivers, failure of embankments, dikes and dams, obstruction of pipes, the rise in sea level, or the discharges of water from reservoirs.

Floods damage roads, property, cause soil erosion and deposit sediments. They also affect crops and wildlife (Figure 6.4). Among the important factors that condition the floods are the spatial distribution of the rain, the topography, the physical characteristics of the streams and rivers, the forms and lengths of the channels, the type of soil, the gradient of the ground, the vegetation cover, the use of soil, the location of dams and the elevations of river banks.



Figure 6.4 Flood due to channel change due to storm 12E, Usulután Salinas Sisiguayo, El Salvador 2012 (MOP El Salvador)

6.2.2 Volcanoes (pyroclastic flows, lahars, lavas ash)

■ Volcanoes

Volcanoes are dangerous, but their location is punctual, so delimiting an area of possible disaster is easier, unlike other natural disasters. It is practically impossible to have a history with all the eruptions of a volcano so to be able to predict the behavior is difficult.

Having knowledge of the volcanic hazards that may occur in a given volcano, will result in a reduction in human and economic losses, figure 6.5. In addition, it will allow an improvement in building techniques for housing and buildings in general, implementation of restrictive measures for construction in hazardous areas and the development of better evacuation and disaster mitigation plans.



Figure 6.5 San Miguel volcano in El Salvador. (MOP El Salvador)

■ Pyroclastic flows.

Pyroclastic flows can receive various names: pyroclastic flows, burning clouds, hot ash flows; It is one of the most destructive phenomena of an active volcano. In the eruptions, pyroclastic flows can be created that consist of a hot mixture of gases, ashes and fragments of rock that descend through the volcano at great speed. These gases travel to the bottom of ravines and valleys, as well as rise above high reliefs. It is impossible for anything in its path to be saved whether they are constructions or living beings. The flow can destroy well-built buildings and even entire forests, leaving nothing standing, and can travel distances ranging from meters to hundreds of meters.

■ Lahars

The lahars comprise a mixture of volcanic materials deposited on the slopes (rocks, ash, pumice, slag), mostly ashes which are mobilized by the action of water or rain that erode the deposited material. The water mixes with the loose volcanic material that is in its path and quickly becomes a flow with characteristics like fresh concrete. Due to its density, this flow can transport rocks, bridges, trees, houses and anything in its path. It can also travel very long distances (figure 6.6), so its destructive power is equally great.



Figure 6.6 View of the lahars from the Volcano of Guatemala (General Directorate of roads, Guatemala.)

6.2.3 Earthquake

Seismic are phenomena that shake the earth, these are produced by the internal and proper interaction of the earth's crust. This phenomenon in which accumulated energy is released in the form of a jolt can be produced by geological faults (Figure 6.7) or by friction at the edges of the tectonic plates or by some volcanic process. There may be other non-geological factors that produce earthquakes such as nuclear detonations or the impact of an asteroid. There is no reliable way to predict earthquakes, but these can have a great impact on road structures notably.



Figure 6.7 Landslide induced by earthquake in "La Leona" Curve CA-01. 2001. El Salvador (MOP El Salvador)

6.2.4 Landslides and rock falls.

Fall: a rapid downward movement of a mass of rock or soil that travels mainly through the air by free fall, jump or sway, with little or no interaction between one moving unit and another.

Collapse: a gradual or rapid downward movement of soil or rock under gravitational stress, often because of artificial factors, such as the removal of foot material from a slope. (Figure 6.8).

Landslide: a massive movement of earth, snow or rock in shear mode along one or more sliding surfaces. (Figure 6.9)



Figure 6.8 Collapse of rocks induced by rains on the national route RN-15. June 2018. (MOP El Salvador)



Figure 6.9 Road landslide to the turns, Chalatenango 2016. (MOP El Salvador)

For more information on these topics see Chapter 4 section 4.1.1

6.2.5 Debris/Mud flows.

According to the CENAPRED document "Diagnosis of Hazards and Identification of Disaster Risks in Mexico" in the classification of landslides there is a group that is designated as flows, which are usually associated with extraordinary rainfall, with highly devastating consequences.

The extreme climatic conditions facilitate the rapid disintegration of rocks, in addition, the intense and sustained rains act as a very efficient transport agent. The mechanism with which the mud and debris flows are generated is the sudden and sustained saturation of the unconsolidated sediments that are found in the upper part of the areas of steep terrain, such as the mountain ranges.

When the saturation of the material is generated, it increases its weight, which destabilizes the soil, increasing the destabilizing forces of the body of the slope; at the same time the internal pressure developed by the newly accumulated water, in addition to the one that runs downhill from the highest parts through the interior of the same mass of sediments, generates a significant reduction in the internal resistance of the earth material. Under these circumstances, the collapse of large volumes of materials, such as silts, clays, sand, gravels and rock fragments of various sizes, inevitably occurs.

In this way, the collapsed material falls like an avalanche, at high speed, until reaching an area of land with a lower slope, where there is a sudden reduction in the flow velocity, so the fragments of heavier material are deposited. (Refers to figure 6.10)



Figure 6.10 Debris flow in Joateca, El Salvador 2018. (MOP El Salvador)

6.2.6 Hurricanes

The document "Diagnosis of Hazards and Identification of Disaster Risks in Mexico" of CENAPRED describes that a hurricane or tropical cyclone consists of a large mass of warm and humid air with strong winds that rotate in a spiral around a central area of low pressure. Tropical cyclones generate heavy rain, strong winds, large swells and storm surges. Hurricanes / tropical cyclones present an almost circular area in the plant and have the lowest pressure in the center. The trajectories that describe the cyclones are a function of the existing climatological conditions and can enter or not to earth. Its average pattern is known, although in some cases there are cyclones with erratic trajectories. The forecast of the trajectory of the hurricanes / tropical cyclones serves as a guide for the decision making on the protection of the population, since one can have an idea of the positions that the cyclone will have in the immediate future and of the evolution of its intensity. From these, alert times are established and the eventual evacuation of the inhabitants in the risk areas is prepared.



GLOSSARY

GLOSSARY

Alluvium: Soil whose components were transported in suspension by a stream of water and subsequently deposited by sedimentation.

Altered sample: Part of the soil extracted for laboratory study, which does not require its conservation in its natural state.

Angle of internal friction: The angle between the axis of normal stresses and tangent to the Mohr envelope at a point representing a given condition of rupture strength of a solid material. The internal friction angle of a soil corresponds to the angle whose tangent is the average coefficient of friction between the particles of a soil.

Anticline: It is a fold of the earth's crust that has the oldest strata in its core. It is formed by the tectonic effects of terrestrial dynamics.

Block: Rock fragment, which may be rounded by abrasion, whose diameter is greater than 25 cm.

Cohesion: Shear strength of the ground when the effective normal pressure is zero.

Cohesive floor: When the proportion in the weight of fine content that has plasticity is equal to or greater than 35%.

Colluvium: A term applied to any soil mass deposited by runoff, which is usually found at the base of hills or hillsides of a moderate gradient. The colluviums or colluvial deposits are formed by poorly graded sands and gravels. In a broad sense, this concept has been used to generically designate hillsides deposits or gravitational deposits.

Cone test: Soil exploration method, consisting of the penetration of a penetrometer with the conical tip. The number of strokes for the advance for drilling in a certain depth allows the calculation of the shear strength of the soil.

Diaclases: (In Spanish) Surface of discontinuity of the rock mass caused by the tensions.

Dip: It is the angle that forms the line of the maximum gradient of a surface of a stratum, vein or fails with its projection with the horizontal plane.

Direction fault (course, transcurrent or tear): When the displacement is horizontal and parallel to the course of the fault, it can correspond to the direction of the blocks (referenced to the position of an observer located on one of the blocks), sinistral or left

direction: when the block opposite the one occupied by the observer moves to the left, dextral or right direction: when the block moves to the right. The fault plane can be inclined or vertical.

Discontinuity: Discontinuities in soil and rock masses include faults, joints, stratification planes, foliation planes, fractures and cracks, and fill material.

Discordant contact: Separates two materials that are not parallel to each other, that have no temporal continuity. (It is presented by a dashed line).

Fault with indication of sinking: Movement of the terrestrial surface in which the shallow descending sense predominates and that takes place in areas of different characteristics and gradients. It differs from subsidence by its much shorter temporal and spatial scales. It can be induced by different causes and can develop at very fast or very slow speeds depending on the mechanism that leads to such instability.

Geogrid: Net manufactured with synthetic materials to be used with soil, rock, earth or other material related to a project, structure or system. Normally geogrids are used as reinforcement elements in the construction of reinforced earth structures.

Geohazard: Events caused by geological, geomorphological and climatic conditions or processes that represent serious threats to human life, property and the natural and built environment. Geo-hazards on roads cover almost all hazards that affect road infrastructure, such as landslides, collapses, earth flows, debris flows, floods and erosion.

Geomembrane: Laminar element, manufactured with synthetic materials, whose waterproof characteristics allow it to be used as a coating or as a barrier to control the passage of fluids in a project, structure or system.

Geophysical methods: Exploration methods that are used to analyze physical phenomena, such as the gravity of the earth, seismic waves, resistivity and the magnetism of the earth.

Geotechnical unit: Each one of the superposed layers of the land that presents common physical and mechanical characteristics, relative to its origin, identification of the materials that compose it, state, resistance and deformability.

Geotechnics: Application of engineering principles to the generation, interpretation and use of knowledge of materials and processes that occur in the earth's crust for the solution of engineering problems. For a complete development, the application of

different fields of knowledge is required, especially; soil mechanics, rock mechanics, geology, geophysics, hydrology, hydrogeology and related sciences.

Geotextile: Permeable laminar element, manufactured from polymers. Geotextiles are commonly used as a drainage or protection element for drainage works; occasionally they are also used as reinforcement elements.

Granular soil: When the ratio in weight of sand and gravel content is greater than 65%.

Granulometric analysis: Determination of the relative amounts of particles in a granular material that is within defined ranges of diameter, by separating them on screens of different sizes of aperture, or by other processes suitable for the effect such as sedimentation or examination by optical means.

Groundwater: Which can move in the saturation zone of a mass of soil or rock by the effect of gravitational attraction.

Moisture content: Ratio of the weight of the water contained in a certain sample to its dry weight.

Interstitial pressure: Pressure (more than atmospheric pressure) of water in the voids of a saturated soil or rock.

Jet grouting: High pressure injections.

Joints: Discontinuity in a rocky mass. This generic term includes joints, faults and stratification planes as elements of discontinuity.

Landslide: Generic term that includes a wide variety of erosion processes in mass that includes the downhill transport of soil and rock masses. Normally the removed material moves along a surface or a restricted shear zone, and is preceded, accompanied and followed by a perceptible deformation along a sliding surface and inside the mass of soil affected by these processes.

Liquefaction: Cancellation of the capacity to resist shear stress of fine granular soil, saturated and with relatively low density, because of increased interstitial pressure caused by vibrations.

Liquid limit: Moisture content of remolded soil corresponding to the boundary between its liquid consistency and plastic states. Moisture content of which a mass of remolded and cut soil with a standard size router flows to join 13 mm under the impact of 25 blows in a standardized device for liquid limit determination.

Loan zone: Land intended for the extraction of materials for the construction of earth embankments and dams.

Loosening: Also called collapse; mass movement characterized by the fall of a mass of rock or soil controlled mainly by gravity, with minimal influence of water as a destabilizing factor.

Mechanical contact: The contact plane is a fault. (It is presented by a continuous line).

Mylonitized zone: When the deformation takes place in the ductile or fragile-ductile domain of the rocks, in conditions of metamorphism the mylonite are produced, which define the shear bands, with a characteristic rock swaying.

Normal fault: When the hanging of ceiling block moves downwards with respect to the adjacent or wall block. The fault plane is tilted.

Normal or concordant contact: Separate two materials parallel to each other, which can be assumed to be consecutive in geological time. (It is represented by a dotted line).

Normally consolidated soil: Consolidation of a soil is called a process of volume reduction of cohesive fine soils (clays and plastic silts), caused by loads on its mass and that takes place in a generally long time. This causes vertical subsidence and if this occur on a large scale in construction site, this can lead to considerable damage to buildings.

Percussion drilling: A technique that is practiced by inserting a tool in the field through successive blows.

Piezometric height: Height that reaches the water level when placing a piezometric tube at a point.

Piezometric level: Level that will reach the water in a hole in contact with the atmosphere.

Plastic limit: The moisture content of a remolded soil corresponding to the boundary between their states and rigid plastic consistency. Moisture content with which a soil begins to crumble when a cylinder of 3 mm in diameter is formed with it.

Plasticity index: Measurement of the plasticity of a soil given by the absolute value of the moisture interval in which the soil behaves as a plastic material, numerically the

plasticity index is equal to the difference between the liquid limit and the plastic limit. $PI = w_L - w_p$.

Reverse or rider fault: When the hanging block moves upwards relative to the lying one. They are denominated the reverse faults of low angle of dip. The fault plane is tilted.

Rivulets process: Geological processes carried out by the water that circulates on the surface without a fixed channel and gives rise to a high erosion giving rise to grooves, gullies and ravines.

Rock jumping: Trajectory of the movement of a rock slope down, depending on the geometry of the slope, the rock can reach high speeds and rebound along the route.

Rock mechanics: Theoretical and practical science that deals with the properties and mechanical performance of rocks.

Rock Quality Designation (RQD): Quality classification of a rock mass proposed by Deere based on the state of the drilling cores with diameter Nx. Numerically the RQD is defined as the percentage ratio of a) the sum of the lengths of the pieces of cores larger than 10 cm to b) the total length of the perforated section.

Rotary drilling: A technique that is practiced when advancing in the field a drill that rotates on its axis while applying a pressure on it.

Safety factor: 1. Numerical relation between a) the ultimate strength of a material, b) the admissible stress. 2. Numerical relation between a) the theoretical support capacity, b) the allowable support capacity, or, alternatively, the contact stress. 3. On hillsides stability, numerical relation between, a) the resistant forces or moments, and b) the forces or moments of a soil mass.

Sample unaltered: Soil sample whose structure has not been modified by manipulation through the sampling process and transport to the laboratory to perform special tests and determine the mechanical properties of the stratum studied.

Sample: Portion of material that is taken to determine the characteristics or properties of a part or of its totality. Soil or rock material taken for study in a soil mechanics laboratory.

Schistosity: Property of certain rocks and soils, shales or slates, which leads them to organize themselves into sheets or surfaces parallel to each other. It is linked to the

micro structure of the material, because in certain configurations the presence of a perpendicular force allows the reorientation of minerals that comprise it.

Scouring: Erosion of the land caused by the movement of water.

Seismicity: Degree of frequency or intensity of earthquakes that occurs in a certain area.

Soil mechanics: Application of the principles of mechanics and hydraulics to engineering problems that deal with the nature and behavior of soils, sediments and other accumulations of solid particles. Detailed and systematic study of the physical properties and the use of soils, especially in relation to road engineering, foundations, with the study of problems related to the stability of slopes and slopes.

Stability factor: A dimensionless factor, used in the analysis of slope stability, defined by Terzaghi, 1962 with the following equation: $N_s = H_c \gamma_e / c$, where, c = soil cohesion, H_c = critical height of the slope and γ_e = submerged unit weight of the soil.

Standard penetration test: Soil exploration method that consists of driving a penetrometer by hitting a pile driver, where the number of strokes is the main parameter to calculate the shear stress of the soils studied.

Stereographic projection: Two-dimensional representation of three-dimensional directions used in the solution of structural problems and in the stability analysis of rock slopes. In it the lines are represented by points that indicate their direction and the planes by maximum circles, or by points that represent the lines perpendicular to the planes. There are two types of network for stereographic representations; Wulf and Schmidt or Lambert. The first is used if you want to maintain the angular relations and the second if you want to maintain the relation of areas.

Stratigraphy: It defines the description of the component layers of the subsoil, its depth, thickness and some of its properties.

Stress: Force per unit area on which the force is applied. The stresses can be normal, sharp or torsional.

Syncline lying down: It is a fold of the Earth's crust that presents the most recent strata in its nucleus with the axial plane with an angle in relation to the vertical axis.

Syncline: It is a fold of the earth's crust that presents the most recent strata in its nucleus. It is formed by the tectonic effects of terrestrial dynamics.

Tilted anticline: It is a fold of the earth's crust that has the oldest layers in its core with the axial plane with an angle in relation to the vertical axis.

Tilting (in Spanish: basculamiento): Inclination of a geological block, in the manner of a scale or balance. Along with the folding, it is responsible for the inclination of the strata.

Varnes: It refers to hillside landslides based on the classification made by (Varnes, 1978) which includes: movements of a rock mass, soil or debris, of a hillside in a downward direction. Any type of mass movement is included, but erosion, subsidence and karstic subsidence are excluded.

Water Table: Height at which water is found in a hole; position of the upper surface of the water in an aquifer. In free aquifers, the water Table coincides with the piezometric level.

Weathering: Process of disintegration and decomposition of a material because of its exposure to the atmosphere, the action of chemical agents, water and temperature changes.



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List of primary sources of national consultation.

Country	GTR member	Institution
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Costa Rica	Antonio José Romero Castro	Ministry of Public Works and Transportation (MOPT)
Nicaragua	Marco Antonio Perez Lara	Ministry of Transport and Infrastructure (MTI)
Honduras	Hugo Fernando Martínez Silva	Ministry of Infrastructure and Public Services (INSEP)
El Salvador	Mónica Patricia Gutiérrez de Guevara	Ministry of Public Works, Transportation and Housing (MOP)
Guatemala	Juan Carlos Galindo	General Directorate of Roads. (MCIV)

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ANNEXES

Guadalupe, San Vicente, El Salvador

APPENDIX

APPENDIX I

Road Geohazard Management Tool, HGGeoA

According to the "GeoHMT Road Geohazards Management Tool Operation Manual", this tool allows road management planners to analyze and evaluate road geological geohazard risk and thus promote and carry out efficient investments in the risk reduction of road geohazards. GeoHMT has been developed as an Excel-based tool to facilitate its use by any road planner.

This tool can be downloaded from the website of the Ministry of Public Works, Transport, Housing and Urban Development (www.mop.gob.sv) by entering the Department of Adaptation to Climate Change and Strategic Risk Management (DACGER) to then search in the technical reports download center the name "GeoMT - Road Geohazards Management Tool" and proceed to download, the tool has its version in Spanish and English.

GeoMT is a road geohazard management tool that targets geohazard road events, both seismic and non-seismic. Non-seismic geohazard events on the road occur mainly or are induced by heavy rains or events that occur independently of earthquakes or storms. In this tool, the geohazards are classified according to a mass of rocks, soil (debris or earth) and water. In most cases, the material is a mixture of these, such as the mixture of soil and water. The types of movement of geohazards are classified as i) fall or collapse, ii) erosion, iii) landslide, and iv) flow or flood.

The GeoMT, evaluates the probability of occurrence of a geo-hazard event on the road, the potential loss of an event, the risk of potential annual loss of a risk-prone road location, the benefits of an investment in the risk reduction of road geohazard and cost-benefit indicators such as the net present value of the risk reduction investment. From these, we can determine the most efficient plan for a road location prone to geohazards risks, to reduce road geohazard risks and prioritize projects, using this tool.

The types of location to which GeoHMD should be applied are:

- Road location with mountainside slope (M) (falling risk, collapsing or landslide of mountainside slope);
- Location road with valley side slope (V) (collapse risk, landslide or erosion of the road foundations);
- Road location with stream crosses (S) (with geohazards risks of type flow such as flash flood and debris flow); and

- Road bridge (B) (with failure risk of the bridge superstructure or foundation).
- For the road location with stream crossings and bridge structures, it is required that both evaluation groups be carried out for the road location with stream crossings (S) and bridges (B).

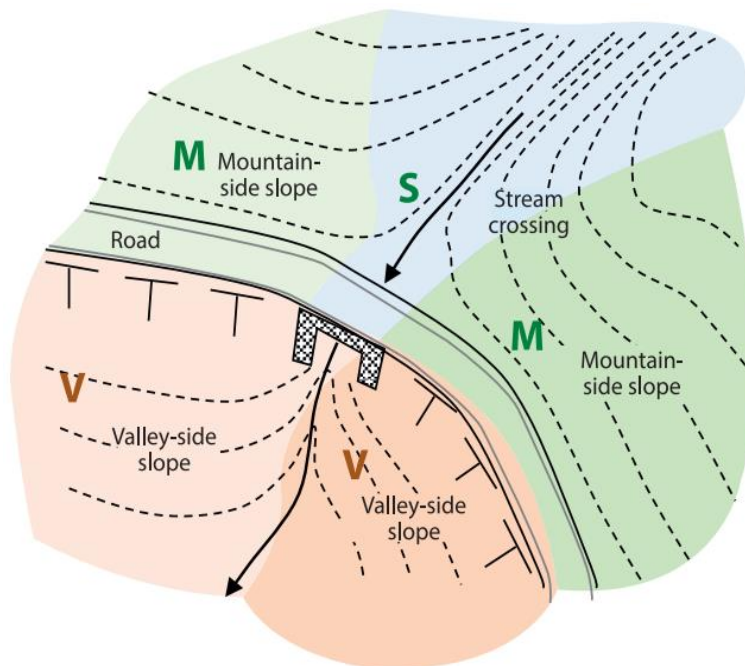
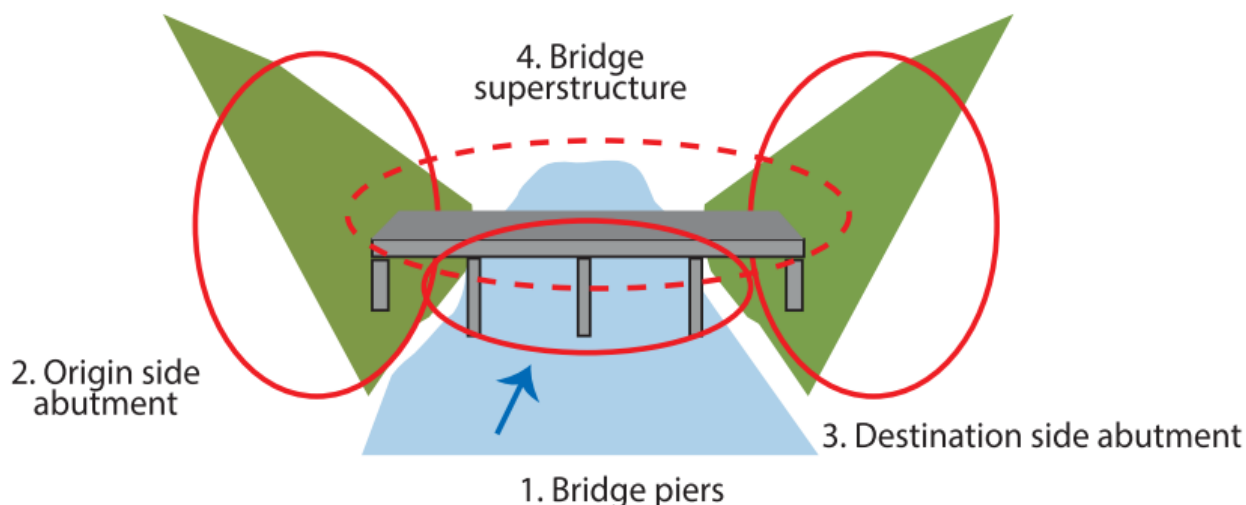


Figure 1. Type of Road Location for Geohazard Management

In the case of a bridge, its risks are evaluated separately for each part of it:

- i) Bridge piers,
- ii) Abutment on the origin side,
- iii) Abutment on the destination side y
- iv) Bridge Superstructure

These are added to calculate the total risk of a bridge.



The GeoMT is a set of files developed in Excel sheets, therefore, it is necessary to have Microsoft Excel, because the files are in "xlsx" format and facilitates the manipulation of data. GeoMT consists of eleven (11) worksheets which are explained in the "GeoMT Road Geohazard Management Tool Operation Manual".

N°.	Worksheet N°.	Purpose of Uses.
1	Spreadsheet 1-M	Estimation of the probability of occurrence of geo-hazard events, for a road location with Mountainside Slope.
2	Spreadsheet 1-V	Estimation of the Probability of Occurrence of Geo-Hazard Events for a Road Location with Valley-side Slope.
3	Spreadsheet 1-S	Estimation of the Probability of Occurrence of Geo-Hazard Events for a highway location with a Flow or Stream Crossing.
4	Spreadsheet 1-BP	Estimation of the Probability of Occurrence of Damage Events in Bridge (Bridge Pillars)
5	Spreadsheet 1-BA (O)	Estimation of the Probability of Occurrence of Bridge Damage Events (Bridge Abutment on the Origin Side)
6	Spreadsheet 1-BA (D)	Estimation of the Probability of Occurrence of Bridge Damage Events (Bridge Abutment on the Destination Side).
7	Spreadsheet 1-BS	Estimation of the Probability of Occurrence of Bridge Damage Events (Bridge superstructure)
8	Spreadsheet 2	Estimate of Monetary Losses due to road Geohazard events.
9	Spreadsheet 3-SS	Estimation of Annual Economic Loss and Benefit of the Risk Reduction for a Current Slope or Stream Crossing with Hazard Potential.
10	Spreadsheet 3-BR	Estimation of the Annual Economic Loss and Benefit of the Risk Reduction for a Bridge with Hazard Potential.
11	Spreadsheet 4	Cost-Benefit Analysis for a Location at Risk.

Table 1 shows each set of worksheets required by each type of location since it may not require the eight (8) spreadsheets, for example, if the selected road location is in a location with mountainside slope, the Worksheets 1-M, 2, 3-SS and 4 are necessary.

Table 1. Worksheets required for each type of location

Worksheet	Mountainside Slope	Valley-side Slope	Stream Crossing	Bridge
1-M	Yes			
1-V		Yes		
1-S			Yes	Yes
1-BP				Yes
1-BA(O)				Yes
1-BA(D)				Yes
1-BS				Yes
2	Yes	Yes	Yes	Yes
3-SS	Yes	Yes	Yes	
3-BR				Yes
4	Yes	Yes	Yes	Yes

Regarding a bridge, users should know that Spreadsheet 1-B is divided into three worksheets of 1-BP, 1-BA (divided into 1-BA (O) and 1-BA (D)), and 1-BS. Worksheets 1-BP, 1-BAs and 1-BS are for "group of pillars", "abutment" and "superstructure" respectively. Two worksheets 1-BA should be prepared because a bridge has two abutments.

Spreadsheet 1-M Estimation of the Probability of Occurrence of Geohazard Events, for a Road Location with Mountainside Slope, and Spreadsheet 1-V Estimation of the Probability of Occurrence of Geohazard Events for a Road Location with Valley-side Slope are showed as follows.

Worksheet 1-M: Rating Checklists for Probability for Geohazard damages for a road location with mountainside slope				GeoMT	
Users are allowed to enter data into white cells only.					
Date of Data Entry (MM/DD/YYYY)		MM	DD	2017	
I. General Data					
II-1) Location ID					
II-2) Road Name					
II-3) Station Origin					
II-4) Station Destination:					
II-5) Extension along the road: E		m			
II-6) Number of road lanes					
II-7) Total road width (m)		m			
II-8) Widths of road elements from the mountain-side (m)					
a) Mountain-side strip		m			
b) 1st lane		m			
c) Center divider between 1st and 2nd lanes		m			
d) 2nd lane		m			
e) Center divider between 2nd and 3rd lanes		m			
f) 3rd lane		m			
g) Center divider between 3rd and 4th lanes		m			
h) 4th lane		m			
i) Center divider between 4th and 5th lanes		m			
j) 5th lane		m			
k) The other lanes and center dividers		m			
l) Valley-side strip		m			
II. Observations					
III. Location Data					
Latitude and Longitude		Deg.	Min.	Sec.	
a) Latitude		0			
b) Longitude		0			
c) Elevation		m			
IV. Historical road damage events due to geohazards (Three Latest Events)					
a-1) Geohazard movement/material type					
b-1) Date of event		(MM/DD/YYYY)		MM	DD
c-1) Historical occurrence frequency period in years of a specific extent of a road damage event (unit: years)		Years			
d-1) Description					
a-2) Geohazard movement/material type					
b-2) Date of event		(MM/DD/YYYY)		MM	DD
c-2) Historical occurrence frequency period in years of a specific extent of a road damage event (unit: years)		Years			
d-2) Description					
a-3) Geohazard movement/material type					
b-3) Date of event		(MM/DD/YYYY)		MM	DD
c-3) Historical occurrence frequency period in years of a specific extent of a road damage event (unit: years)		Years			
d-3) Description					
V. Rating of safety degree of probability (SDP) in years		Safety degree of probability (SDP) in years			Critical PGA of seismic damage in gal
		Non-seismic damage level			
Checklist items	Categories	Roadside damage	One-lane closure	Tow-lanes closure	
[V-1] Extension (Length) of the hazardous location: E	a) $E \geq 300$ m	0.0	0.0	0.0	0.0
[V-2] Angle of the mountain-side slope up to the point of the inclination change: AS	a) $AS \geq 60^\circ$	0.0	0.0	0.0	0.0
[V-3] Height of the whole mountain-side slope: WH	a) $WH \geq 200$ m	0.0	0.0	0.0	0.0
[V-4] Height of the mountain-side slope up to the point of the inclination change: H	a) $H \geq 90$ m	0.0	0.0	0.0	0.0
[V-5] Offset from the toe of the mountain-side slope to the nearest vehicle lane: D	b) $4\text{ m} > D \geq 2\text{ m}$	0.1	0.3	0.4	7.9
[V-6] Type of the mountain-side slope up to the point of the inclination change	a) Valley type	0.0	0.0	0.0	0.0
[V-7] Dominant material of the mountain-side slope surface	c) Gravels	0.0	0.0	0.0	0.3
[V-8] Dominant geology of the mountain-side slope	f) Quaternary: Volcanic rock (Lava)	0.0	0.0	0.1	2.0
[V-9] Geometry of the dominant discontinuity against the mountain-side slope surface	b) The discontinuity extends vertically in the slope.	0.0	0.0	0.0	0.5
[V-10] Spring (groundwater) condition of the mountain-side slope	b) Spring water is recognized seasonally.	0.0	0.0	0.0	0.5
[V-11] Surface water of the mountain-side slope	b) Surface water is recognized seasonally.	0.0	0.0	0.0	0.5
[V-12] Dominant vegetation of the mountain-side slope	b) Sparse vegetation: vegetation covers 20% or less of the slope.	0.0	0.0	0.0	0.5
[V-13] Type of the mountain-side slope up to the point of the inclination change	b) Engineered slope of cutting	0.0	0.0	0.0	0.5
[V-14] Soil covers the impervious bedrock of the mountain-side slope.	a) Yes	0.0	0.0	0.0	0.0
[V-15] A hard rock layer lies on a soft rock layer	a) Yes	0.0	0.0	0.0	0.0
[V-16] Slope protection	c) There is no slope protection.	0.0	0.0	0.0	0.0
[V-17] Frequency of rockfalls by the slope	a) Once a year	0.0	0.0	0.0	0.0
[V-18] Distresses (predictable phenomena to road damages)					
a) Minor collapses/falls on the mountain-side slope of the road	Yes	0.0	0.0	0.0	0.0
b) Fallen/inclined trees on the mountain-side slope of the road	Yes	0.0	0.0	0.0	0.0
c) Open-cracks below an overhang on the mountain-side slope of the road	Yes	0.0	0.0	0.0	0.0
d) Open-cracks to cause wedge-shaped slide on the mountain-side slope of the road	Yes	0.0	0.0	0.0	0.0
e) Continuous cracks (more than 5 m long) of the road surface	Yes	0.0	0.0	0.0	0.0
f) Upheaval on the road	No	3.1	15.4	31.0	126.0
g) Rill erosion (10-100 cm deep) on the mountain-side slope of the road	Yes	0.0	0.0	0.0	0.0
h) Erosion as trenches or gullies (deeper than 1 meter)	Yes	0.0	0.0	0.0	0.0
i) Over 5-m-long continuous cracks in the slope	Yes	0.0	0.0	0.0	0.0
j) Apparent deformation due to land-sliding	Yes	0.0	0.0	0.0	0.0
k) Open-cracks by toppling	Yes	0.0	0.0	0.0	0.0
l) Open-cracks by sliding	Yes	0.0	0.0	0.0	0.0
m) Depression of the road surface	Yes	0.0	0.0	0.0	0.0
n) Surface erosion (1-10 cm deep)	Yes	0.0	0.0	0.0	0.0
o) Subsurface erosion of the slope due to piping.	No	3.1	15.4	31.0	126.0
[V-19] Average annual rainfall: AAR	a) $AAR < 500$	1.0	0.0	0.0	0.0
[V-20] Average annual maximum daily rainfall: AAMDR	b) $50 \leq AAMDR < 100$	2.0	0.0	0.0	0.5
[V-21] Average number of months with rainfall (more than 10mm of a month) of a year: ANMR	a) $ANMR < 2$	1.0	0.0	0.0	0.0
[V-22] Rated safety degree of probability (SDP) or critical peak ground acceleration (PGA) (when not considering existing measures)		10.6	31.1	62.5	265.6
VI. Safety degree of probability (SDP) considering existing measures					
[VI-1] Existing measures (specify in the white cells to the right)					
[VI-2] Design safety degree of probability (SDP) of existing measures (years)					
[VI-3] Design peak ground acceleration (PGA) of existing measures (gal)					
[VI-4] Safety degree of probability (SDP) or critical peak ground acceleration (PGA) considering existing measures		10.6	31.1	62.5	265.6
[VI-5] Safety degree of probability (SDP) considering existing measures for seismic damage		10.6	31.1	62.5	470.0

Worksheet 1-3: Estimation of Occurrence probability of damage events due to geohazards in a road location with a stream-crossing				GeoMT	
Users are allowed to enter data into white cells only.					
Date of Data Entry (MM/DD/YYYY)		MM	DD	2017	
I. General Data					
[I-1] Location ID					
[I-2] Road Name					
[I-3] Station Origin					
[I-4] Station Destination:					
[I-5] Extension along the road: E					
[I-6] Number of road lanes					
[I-7] Total road width (m)					
[I-8] Widths of road elements from the mountain-side (m)					
a) Mountain-side strip					
b) 1st lane					
c) Center divider between 1st and 2nd lanes					
d) 2nd lane					
e) Center divider between 2nd and 3rd lanes					
f) 3rd lane					
g) Center divider between 3rd and 4th lanes					
h) 4th lane					
i) Center divider between 4th and 5th lanes					
j) 5th lane					
k) The other lanes and center dividers					
l) Valley-side strip					
II. Observations					
III. Location Data					
Latitude and Longitude		Deg.	Min.	Sec.	
a) Latitude	0				
b) Longitude	0				
c) Elevation					
IV. Historical road damage events due to geohazards (Three Latest Events)					
a-1) Geohazard movement/material type					
b-1) Date of event		(MM/DD/YYYY)			
c-1) Historical occurrence frequency period in years of a specific magnitude of a road damage event (unit: years)		MM	DD	Years	
d-1) Description					
a-2) Geohazard movement/material type					
b-2) Date of event		(MM/DD/YYYY)			
c-2) Historical occurrence frequency period in years of a specific magnitude of a road damage event (unit: years)		MM	DD	Years	
d-2) Description					
a-3) Geohazard movement/material type					
b-3) Date of event		(MM/DD/YYYY)			
c-3) Historical occurrence frequency period in years of a specific magnitude of a road damage event (unit: years)		MM	DD	Years	
d-3) Description					
V. Rating Checklist of Occurrence Probability in years without Existing Measures		Score of occurrence probability of road damage			
		Whole width closing		Critical Peak Ground Acceleration (Gal)	
[V-1] Width of the stream crossing: W	d) $3\text{ m} > W$	55.1		223.6	
[V-2] Angle of the streambed at the road crossing: G	d) $10^\circ > G$	55.1		223.6	
[V-3] Area of the watershed of the stream at the road crossing point: A	d) $0.1\text{ km}^2 > A$	55.1		223.6	
[V-4] Height from the streambed to the road surface at the stream crossing: H	a) $H \geq 5\text{ m}$	55.1		223.6	
[V-5] Dominant material of the upstream bed surface	b) Hard intact rock	55.1		223.6	
[V-6] Dominant geology of the valley-side slope	k) Precambrian	55.1		223.6	
[V-7] Dominant vegetation of the valley-side slope	d) Intense vegetation: vegetation covers 80% and more of the slope.	55.1		223.6	
[V-8] Water flow at the stream crossing	d) No water flow is seen.	55.1		223.6	
[V-9] Geometry of the streambed at the stream crossing: DEG	d) The downstream bed is steeper than the upstream bed: $10^\circ \leq \text{DEG}$	55.1		223.6	
[V-10] Plan shape of the stream at the stream crossing section	a) Straight	55.1		223.6	
[V-11] Slope failures in the drainage area of the stream	d) Newly-formed collapses (bare/no vegetation) are not recognized.	55.1		223.6	
[V-12] Timing of the last deposit of volcanic ash	f) $160 \leq Y_s$	55.1		223.6	
[V-13] Timing of the latest pyroclastic flow or volcanic lava flow in the basin (Years ago: Ys)	f) $160 \leq Y_s$	55.1		223.6	
[V-14] Relation: Aa/Da					
	Aa	1 m			
	Da	10 m			
	θ	6°			
	c) $\tan(Aa/Da) = \theta$ [°]: $\theta < 3^\circ$	55.1		223.6	
[V-15] Relation: Ab/Db					
	Ab	1 m			
	Db	5 m			
	α	11°			
	c) $\tan(Ab/Db) = \alpha$ [°]: $\alpha < 3^\circ$	55.1		223.6	
[V-16] Abnormalities (predictable phenomena to road damages)					
At least one past debris flow deposit/trace is recognized on the road	Yes	0.0		0.1	
At least one past flood or debris flow event is recognized on the road	Yes	0.0		0.1	
Debris of trees is seen in the channel.	Yes	0.0		0.1	
[V-17] Average annual rainfall: AAR	a) $AAR < 500$	1.0		0.0	
[V-18] Average annual maximum daily rainfall: AAMDR	a) $AAMDR < 50$	1.0		0.0	
[V-19] Average number of months with rainfall (more than 10mm of a month) of a year: ANMR	a) $ANMR < 2$	1.0		0.0	
[V-20] Occurrence probability of (when not considering existing measures)	Whole width closing (years)	829.9			
[V-21] Critical horizontal peak ground acceleration (CPGA: gal)		3353.5			
VI. Occurrence Probability considering Existing Measures					
[VI-1] Existing measures, specify in the white cells to the right					
[VI-2] Effect of existing measures to the occurrence probability (years):	20				
[VI-3] Design P.G.A. of Existing Structural Measures (gal)	10				
[VI-4] Occurrence probability of (when considering existing measures)	W.W.C. (years)	829.9			
[VI-5] Horizontal peak ground acceleration by considering the effect of engineering improvement measures (gal)	3353.52				
[VI-6] Occurrence probability of the critical horizontal peak ground acceleration (years)					