Landslides: Methodology to Select Stabilizing Construction Works

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Additional information is available at the end of the chapter

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Abstract

In landslide areas, after assessing the risk level, the obligatory questions from government authorities, communities, civil protection managers, and researchers are: What can we do? What should we do? What must we do? There are different strategies to reduce the vulnerability and risk: (a) increasing the knowledge of the population, (b) establishing an early warning system, and (c) selecting and constructing structures. The aim of this chapter is to present the methodology to select stabilizing construction works to avoid a landslide, through the "valuation factors," which are parameters to assess the intrinsic and trigger instability factors (morphology, geology, hydrogeology, vegetation, rainfall, earthquake, erosion, human activity, etc.). The *valuation factors* are presented in graphs, equations, and tables; based upon them, the different construction works are selected, including (a) geometric adjusting for reducing destabilizing forces; (b) reinforcement elements, anchors, and pile barriers to increase the resistive forces; (c) drainage for eliminating surface runoff water or lowering the hydrostatic pressure; (d) retaining walls to support the horizontal pressure; and (e) surface protection to prevent rock falls and reduce erosion and infiltration. The methodology has been used successfully in several mountainous regions: Puebla, Hidalgo, Chiapas, Baja California in México, and Ocaña in Colombia.

Keywords: landslides, construction works, valuation factors

1. Introduction

The landslides often cause disasters and damage to people and their properties at the mountainous areas around the world; these disasters cause casualties and economic losses, such as housing, infrastructure, public services, roads, bridges, hospitals, etc., and the interruption of the normal activities of the region, such as agriculture, livestock, commerce, tourism, financial transactions, etc. A fundamental problem to solve is to make the investments for reconstructing and rehabilitating the destroyed places, which must be obtained from other social investment programs, donations from other countries, and/or sources of external financing that lead to indebtedness and impoverishment of communities, regions, or countries [1].

The first step to establish adequate strategies for prevention, reduction, management, and risk mitigation is to assess landslide hazard, vulnerability, and risk, the latter in terms of casualties and economic losses. The rational solution to landslide problem is to relocate exposed and vulnerable people to secure sites, but acquiring land in mountainous regions is very difficult; besides the majority of population is rooted to its origin place, and it cannot be relocated so easily.

1.1. The landslide problem

Landslide is a failure through a surface in which shear resistance has been exceeded; it is featured by the movement of slope materials that slide downhill.

Landslides can occur due to natural and human factors (intrinsic and trigger factors); although many landslides are triggered by natural phenomena (heavy rains, earthquakes, volcanism, freezing and thawing, erosion and scouring, etc.), it can be estimated that many of those that have caused deaths and injuries can be attributed to human activity impact.

The landslide material may include from a simple rock that falls to a great slide of several hundreds or thousands of cubic meters of material dragged in an avalanche or in a debris flow. They also range in extent some affect only a very small area while others entire regions. The distance that the material travels during movement can also differ significantly, with displacements ranging from a few cm to many km in length, depending on the volume of material, its water content, and the slope inclination. The velocity of a landslide may range from a slow, almost undetectable, gradual movement that remains active for a long period of time (displacements of a few cm per year), to sudden rapid collapse.

1.2. The landslide disasters

Landslides are increasingly affecting our planet, like earthquakes, volcanic eruptions, hurricanes, floods, avalanches, etc., amplifying their intensity by different human activities that modify the delicate balance in nature.

In some mountainous regions at Central and South America, there are many communities belonging to ethnic groups that inhabit areas classified as high and very high poverty, whose features, among others, include localities of less than 2500 inhabitants, illiterate population in a large percentage, very low income, precarious social infrastructure, and houses built with fragile materials such as plastic, cardboard, and/or wood. In other places, there also are displaced populations due to social conflict, forcing them to move and take refuge in very vulnerable areas. In all these places, usually natural phenomena cause real disasters to impact on highly vulnerable communities [2].

2. Landslide instability factors

Landslide instability factors can be divided into two large groups—*intrinsic and triggers*—the first ones depend on the internal properties of slopes material and have a close relation with the type of failure and the susceptibility of the slope to a specific movement. The second ones, known also as external factors, are directly influenced by the climatic conditions, by extreme events such as earthquakes and volcanism, and the impact by human activities [3, 4].

3. Risk analysis

In order to assess the risk, a detailed analysis of the landslide hazard and the vulnerability of exposed people is required. **Figure 1** shows a sequential scheme that summarizes the different steps to be taken into account; a brief description is given below [5].

3.1. Hazard

Historical records of landslides in the study area, including their geographical location, magnitude, intensity, degree of affectation or damage, and their frequency, must be investigated. From these data, a catalog or inventory of landslides that includes the type of movement and the intrinsic and trigger factors of the instability is elaborated [6].

3.2. Vulnerability

The authors of this chapter propose to evaluate the population vulnerability from the exposure level (EL) and the expected damage degree (EDD): the first value according to the height of the slope and the safety factor obtained from the geotechnical stability analysis and the second based on the type of structures constructed (degree of fragility) and velocity of landslide [7, 8].

3.3. Risk

The risk assessment should result in the number of people affected and the cost of damages caused by the occurrence of the phenomenon under study [9].

4. Slope stability analysis

The landslides and slope instability are among the most common failure of earth masses or rocks. The weight of the land mass and their water content is the main force that produces the failure, while the shear strength of the terrain, diminished by the water pressure, is the main strength. Analysis of the slope stability is a problem of plastic equilibrium; when the mass is about to fail, the forces that produce the movement have become equal to the resistance that opposes the mass to be moved. A slight increase in forces is sufficient to produce a continuous deformation that can end in the general failure.

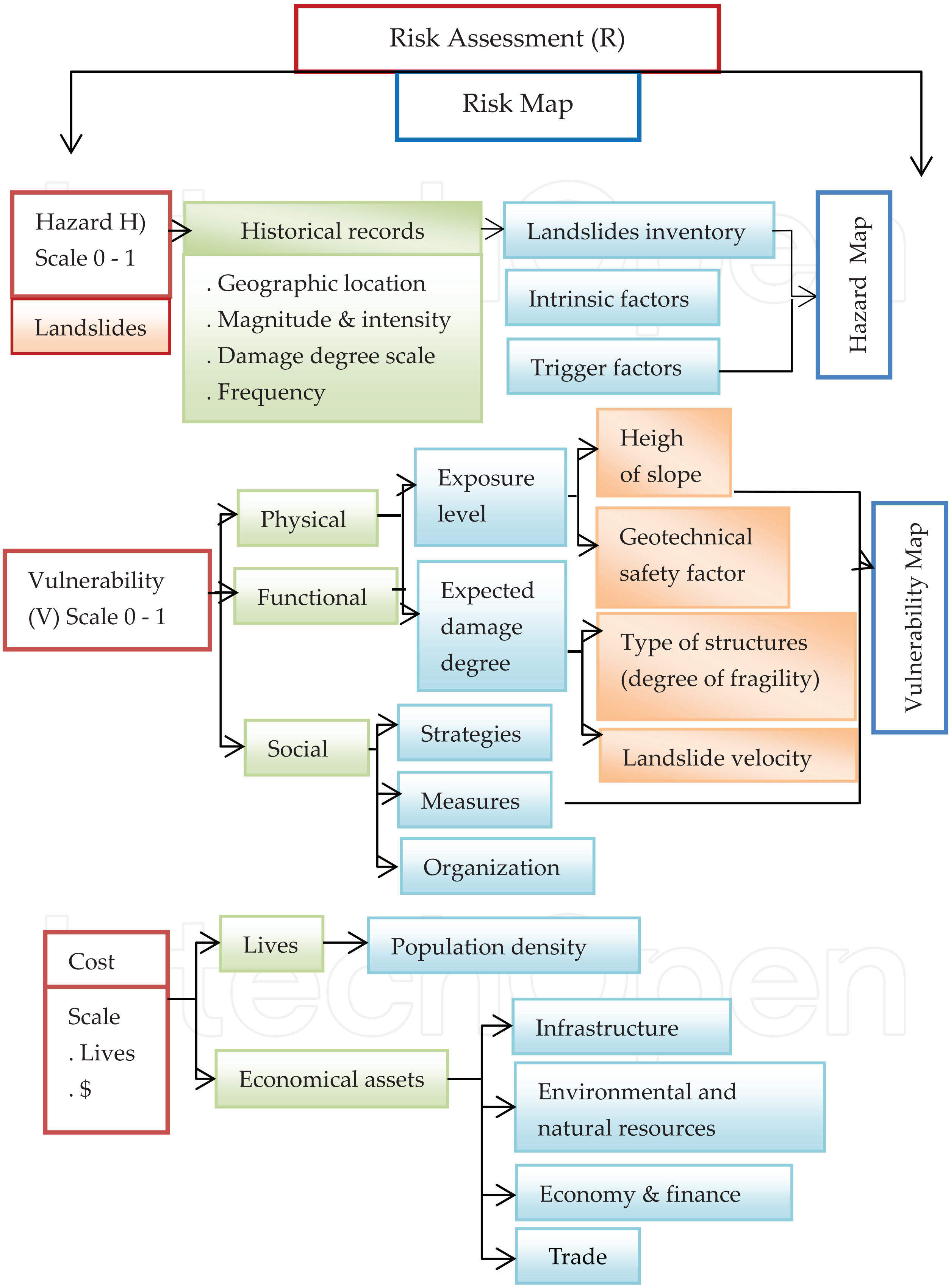

Figure 1. Sequential scheme to assess landslide hazard, vulnerability, and risk [5].

4.1. Quantitative stability assessment

The classical quantitative analysis of slope stability gives the safety factor and the location and geometry of the failure surface, using the parameters related to the intrinsic characteristics of the hill that depend mainly on its origin and geological formation, including topography, geology, soil mechanics, and groundwater.

4.1.1. Limit equilibrium methods

They rely exclusively on the laws of static to determine the state of equilibrium of a potentially unstable slope. They do not take into account the deformations of the land and assume that the shear strength is fully and simultaneously mobilized along the failure surface. The most commonly used limit equilibrium methods by computer programs are the following: Fellenius, Bishop, Janbu, Bell, Sarma, Spencer, and Morgenstern and Price [10].

4.1.2. Failure surface

The failure surface is the interface zones between the potentially unstable or moving ground or rock mass and the stable or static ground mass of the slope. These surfaces have very variable geometric shapes, but in the particular case of landslides, two main groups can be considered: the curvilinear and concave surfaces characteristic of the rotational landslides and flat or undulating surfaces, typical of translational landslides.

4.1.3. Safety factor

The safety factor (SF) is used to evaluate if a slope is stable under conditions at a given site. The acceptable value of safety factor is selected taking into account the consequences or damages that could cause the slide. In geotechnical slope stability, the values range from 1.2 to 1.5 or higher, depending on the confidence in the geotechnical data (exploration, soil sampling, and laboratory testing), as well as the available information on the intrinsic and trigger factors of instability. Overall the safety factor can be defined as the ratio of natural shear strength to destabilizing forces.

4.2. Qualitative stability assessment

The calculation methods described in Section 4.1.1 allow us to take into account the influence of some of instability factors, and there are powerful calculation programs to stability analysis. In order to take into account most instability factors, a qualitative analysis is necessary through the *valuation factors* that will be described below.

4.2.1. Valuation factors

The valuation factors are a set of parameters that allow to evaluate the influence of intrinsic and trigger factors (**Table 1**). The characteristics of each factor should be adequately analyzed to involve its effect on the behavior; one way of doing this is by assigning them a range of weighted values indicating their effect on the slope stability.

Valuation factor	Concept		Function of
Intrinsic features	Morphology and topography		Shape and inclination of slope
	Geology*		Folding
			Fracture
			Weather
			Physical and mechanical properties
	Soil mechanics	Coarse soils	Slope inclination, friction angle "φ"
		Fine soils	Inclination of slope, height, volumetric weight, and undrained strength
	Hydrogeology*		Slope inclination, saturation degree
			Soil thickness
	Vegetation*		Types of vegetation
			Density of foliage
			Covered area
			Root type
Trigger factors	Rain		Average annual precipitation
	Earthquake		Seismic coefficient
	Volcanism		Volcanic activity
	Erosion and scouring*		Superficial soil characteristics
			Basin area
			Drainage grid features
	Human activities*		Cuts and excavations
			Overloads
			Deforestation
Geotechnical slope stability	Failure surface		Depth
	Safety factor		Quantitative value

*Average value.

Table 1. Summary of valuation factors proposed by author.

The author proposes valuation factor values between 0 and 1 (arbitrarily selected but with common and logical sense); the first corresponds to a null or minimal effect on stability (not influenced or very little) and the second the one with the greatest impact on it (influences significantly). Non-extreme effects are evaluated with intermediate values [11].

4.2.1.1. Morphology and topography valuation factor (Fmt)

The "Fmt" takes into account the morphology and maximum inclination of the slope; its height, although importantly influences stability, is considered in the soil mechanics valuation factors described later. The gravitational effect of a unit weight of the ground (W = 1) is divided into two forces, normal and parallel components to slope inclination (β). The latter component represents the weight of soils or rocks that slide and whose value is proposed as a valuation factor (Eq. (1)):

$$Fmt = sen\,\beta. \tag{1}$$

4.2.1.2. Geology valuation factor (Fg)

The rock geological structure defined by its folding and discontinuities is taken into account because it causes an anisotropic behavior that affects the type of failure and its magnitude. Another important aspect is the material weathering caused by the climatic conditions (temperature, humidity, rain, wind, solar radiation, etc.) that produce physical and chemical alterations of rocks and their minerals, causing a wide range of variation in the geotechnical properties that origin a mixed behavior between soil and rock.

The geology valuation factor (Fg) is presented in **Tables 2** and **3** and **Figures 2** and **3**, in which values include (a) the fold inclination "α" determined from Eq. (2), (b) the fracture of the rock from the rock quality designation (RQD), (c) the chemical and physical weathering from the adequacy of data between weather and weathering processes proposed by Emblenton and Thurner [12], and (d) the physical and mechanical properties of the rock:

$$Fg_{folds} = sen\,\alpha \tag{2}$$

The final valuation factor is obtained as an average of the aforementioned.

Characteristic	Intrinsic details/geology valuation factor (Fg)				
Folds	(Eq. (2))				
Fractured rock	Fractures in dense grid	Fractures each 20–30 cm	Closed fractures, few joints	Microcrack	Monolithic rock
	Very poor: RQD < 25%	Poor RQD: 25–50%	Fair RQD: 50–75%	Good RQD: 75–90%	Excellent: RQD 90–100%
	1–0.88	0.88–0.75	0.75–0.50	0.50–0.20	0.20–0
Chemical weathering*	Very intense	Intense	Moderate	Low	Very low
	1	0.75–1	0.50–0.75	0.25–0.50	<0.25
Physics weathering*	Very intense	Intense	Moderate	Low	Very low
	1	0.75–1	0.50–0.75	0.25–0.50	<0.25
Physical properties		Fg = 1−(Ds/De)			
Mechanical properties		Fg = 1−(Ds/De)			

*Adaptation of graphs between climate and the weathering processes proposed by Emblenton and Thurner [12].
RQD: rock quality designation.
Ds: rock properties from laboratory test (volumetric weight for physical properties and simple compression strength for mechanical properties).
De: reference value considering massive rock (**Table 3**).

Table 2. Geology valuation factor (Fg).

Rock origin	Type	Classification	Volumetric weight (KN/m^3)	Compression resistant (MN/m^2)
Igneous	Extrusive volcanic	Andesite	21.6–23.0	206–314
		Basalt	26.5–28.4	147–211
		Rhyolite	23.5–25.5	–
		Tuff	18.6–22.5	10–45
	Intrusive volcanic	Diorite	26.5–27.9	177–240
		Gabbro	29.4–30.4	206–275
		Granite	25.5–26.5	167–226
Sedimentary	Detritical	Quartzite	25.5–26.5	196–314
		Sandstone	22.5–25.5	54–137
		Shale	21.6–25.5	29–69
		Siltstone	–	–
		Conglomerate	–	–
	Chemical	Dolomite	24.5–25.5	88–245
	Organic	Limestone	22.5–25.5	78–137
		Choral	22.5–25.5	78–137
Metamorphic	Massive	Quartzite	25.5–26.5	196–314
		Marble	25.5–27.5	118–196
	Foliated	Phyllite	24.5–26.5	98–177
		Schist	24.5–27.5	49–59
		Gneiss	26.5–29.4	157–196

Table 3. Physical and mechanical properties of sound rocks.

4.2.1.3. Soil mechanics valuation factor (Fsm)

Soil mechanics valuation factors (Fsm) take into account the type of soil, coarse and fine, according to the Unified Soil Classification System. For coarse soils, their relative compactness defined by internal friction angle φ is the main factor governing their behavior, while for fine soils, the height, the slope inclination, the volumetric weight, and the cohesion as a function of water content are the factors that control their behavior.

4.2.1.3.1. Coarse soils

The stability of a slope formed by coarse soils depends fundamentally on its strength (internal friction angle "φ") and the slope inclination "β." The geotechnical safety factor "SF" is determined by the Eq. (3):

$$SF = \frac{\tan \varphi}{\tan \beta} \tag{3}$$

Critical stability occurs when the slope angle (β) is equal to the internal friction angle (ϕ); in this case the safety factor SF = 1 and the slope will be in a critical equilibrium condition, so that

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the soil mechanics valuation factor “Fsm” will also be unitary. When the safety factor (SF) is equal to 1.5 (proposed value as the lower limit), the behavior will be stable, and then the valuation factor is equal to zero (Fsm = 0) (**Table 4**).

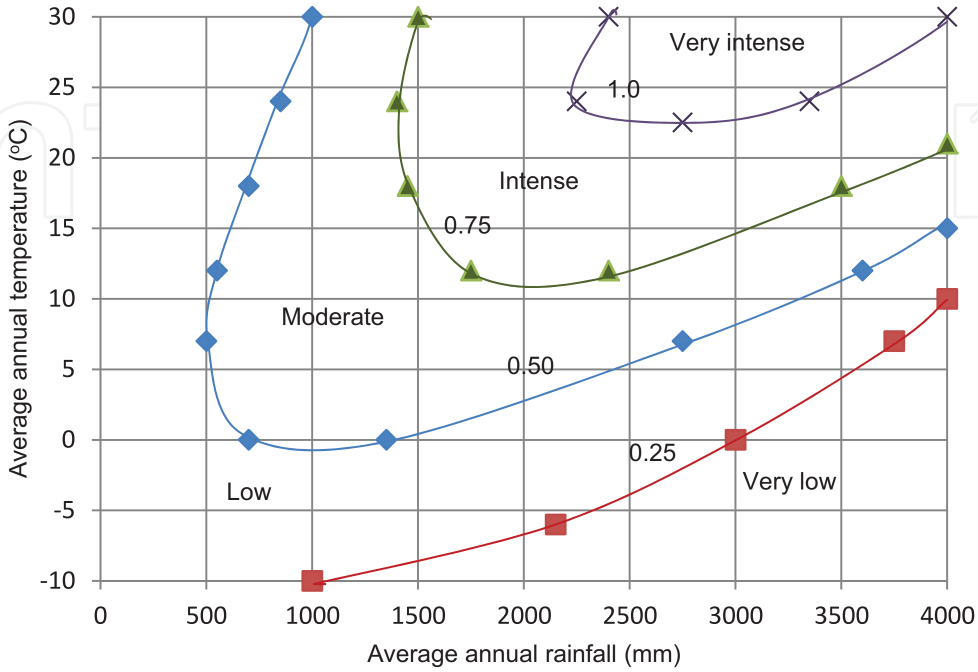

Figure 2. Geology valuation factor by chemical weathering (Fg).

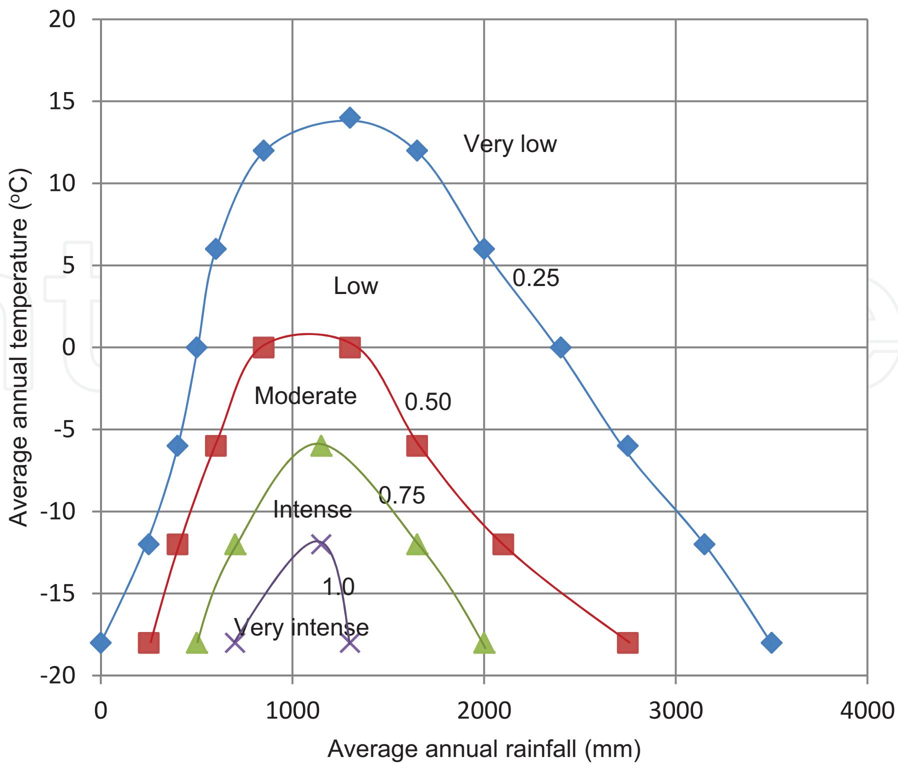

Figure 3. Geology valuation factor by physical weathering (Fg).

Internal friction angle "ϕ"	SF = 1.5	SF = 1.4	SF = 1.3	SF = 1.2	SF = 1.1	SF = 1
	Fsm = 0	Fsm = 0.2	Fsm = 0.4	Fsm = 0.6	Fsm = 0.8	Fsm = 1
	Slope inclination "β"					
26°	18°	19.3°	26.7°	22.2°	24°	26°
28°	19.5°	20.8°	22.2°	23.9°	25.8°	28°
30°	21°	22.4°	23.9°	25.7°	27.7°	30°
36°	25.8°	27.4°	29.2°	31.2°	33.5°	36°
41°	30°	31.8°	33.8°	35.9°	38.3°	41°
46°	34.6°	36.5°	38.5°	40.8°	43.3°	46°

SF: safety factor from Eq. (3).

Table 4. Soil mechanics valuation factor for coarse soil (Fsm).

4.2.1.3.2. Cohesive and friction-cohesive soils

For a slope of cohesive or friction-cohesive soils, both of them homogeneous, the stability depends on its height, inclination, and resistant properties. All these variables are presented in a simple way in equations by the Taylor method for slope stability analysis (Eqs. (4) and (5)):

$$\mathrm{SF} = \frac{Hc}{H} \tag{4}$$

$$\mathrm{Hc} = \frac{Ns^{*}\,C}{\gamma} \tag{5}$$

where SF = safety factor, Hc = critical height, H = slope height, Ns = stability number (as a function of internal friction angle "φ" and slope inclination "β") (**Figure 4**), C = soil cohesion, and γ = natural volumetric weight.

For a stratified soil profile, authors recommend to use only the properties of the poor quality stratum.

From the above equations, the soil mechanics valuation factors for cohesive and friction-cohesive soils were obtained taking into account the following:

- When SF = 1, there is a limit equilibrium, and therefore the height of the slope "H" is equal to the critical height "Hc." In this case, you will have a valuation factor Fsm = 1 which represents a potential risk condition.
- As the safety factor increases, stability improves and the Fsm decreases. When SF = 1.5, which is the minimum acceptable value, there will be a null valuation factor (Fsm = 0).

- Therefore, safety factor values between 1 and 1.5 correspond to intermediate values between 1 and 0, respectively, for the valuation factor Fsm.

The soil mechanics valuation factor proposed for cohesive and friction-cohesive soils are presented in **Figure 5**.

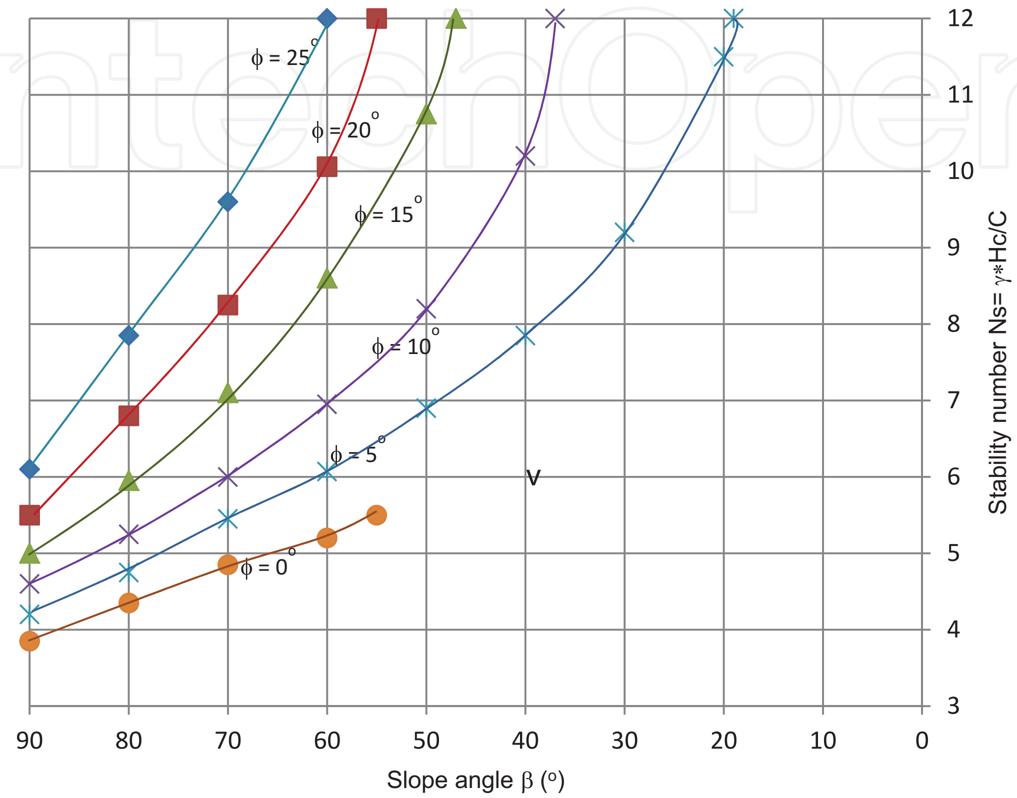

Figure 4. Stability number "Ns."

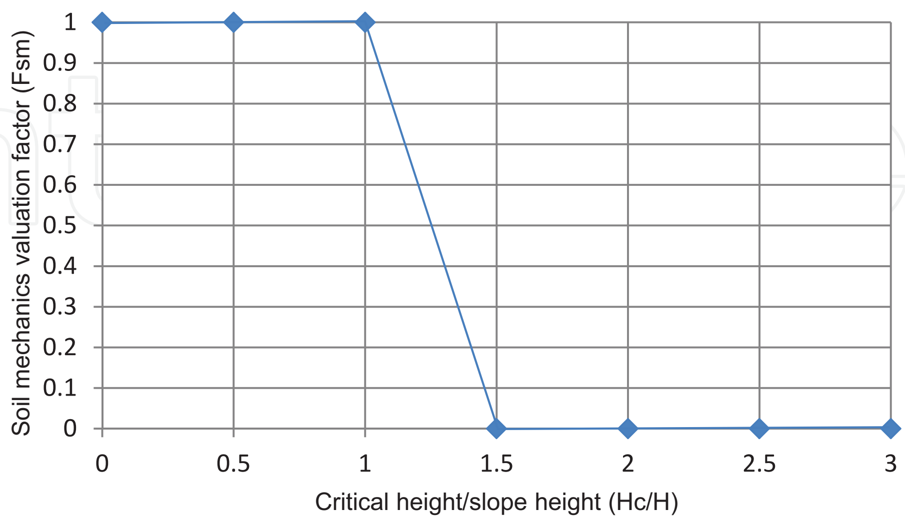

Figure 5. Soil mechanics valuation factor for cohesive and friction-cohesive soils (Fms).

4.2.1.4. Hydrogeological valuation factor (Fh)

The water content has a significant influence on slope stability due to [13] (a) reduction of shear strength of the ground by decreasing the effective tension, (b) increased pressure on traction cracks with corresponding increase of destabilizing forces, (c) increased volumetric weight by saturation, (d) internal erosion by underground flow, (e) weathering and changes in the mineralogical composition of the material, and (f) opening of discontinuities by frozen water.

The hydrogeological valuation factor proposed (Fh) is obtained as a function of the soil saturation degree (Gw), the slope angle (β), and the soil stratum thickness (e), as explained below.

4.2.1.4.1. Soil saturation degree and slope angle

Figure 6 shows "Fh" as a function of saturation degree "Gw" and slope angle "*β*."

4.2.1.4.2. Soil stratum thickness

Authors consider that when the soil thickness is small, it is anchored to the deepest strata by the trees roots. Conversely, for greater soil thicknesses, the sliding surface will be deeper, increasing the risk of failure. **Table 5** gives "Fh" as a function of the soil stratum thickness "e."

4.2.1.5. Vegetation valuation factor (Fv)

There is evidence of the positive effect on vegetation on slope stability. The vegetation valuation factors (Fv) depend on the type of vegetation, the density of foliage which dampens the impact of raindrops, the covered vegetation area, and the depth of the roots that absorb subsoil

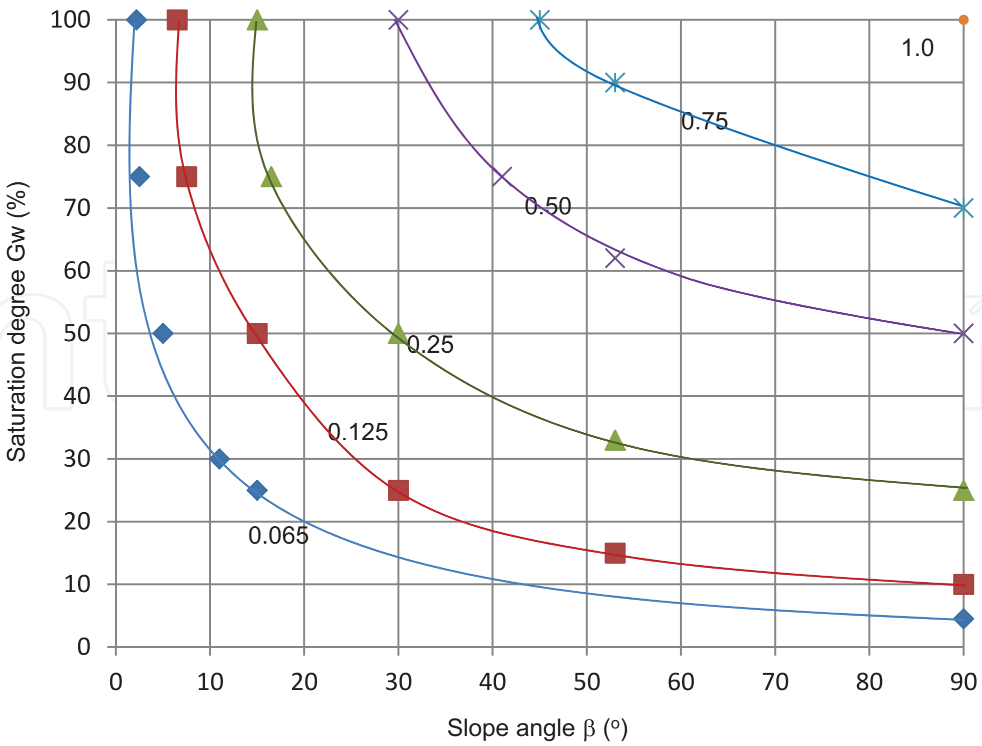

Figure 6. Hydrogeological valuation factor by saturation degree (Fh).

Soil thickness (e)	Failure surface	Fh
<1.5 m	Shallow	0–0.075
1.5–5 m	Somera	0.075–0.25
5–12.5 m	Deep	0.25–0.625
12.5–20 m	Very deep	0.625–1

Table 5. Hydrogeology valuation factor for soil thickness (Fh).

Characteristics	Vegetation valuation factor (Fv)				
Type of vegetation	Tree	Shrub	Grass or scrub		Grass
	0	0.33	0.66		1
Density of foliage*	Null or low	Little bit	Medium	Thick	Very thick
	1	0.75	0.5	0.25	0
Covered area	Null	¼ area	½ area	¾ area	Total
	1	0.75	0.5	0.25	0
Depth of roots	Somera	Shallow	Median	Deep	Very deep
	<0.3 m	0.3–0.5 m	0.5–1.5 m	1.5–3.0 m	>3.0 m
	1–0.92	0.92–0.85	0.85–0.52	0.52–0	0

*The density of foliage is evaluated as the percentage of sun that passes through the leaves in the area that projects the tree in summer.

Table 6. Vegetation valuation factor (Fv).

water and anchorage the superficial soil to the rock; all of them were obtained from a linear interpolation considering zero value for minimum effect on stability and one for significant effect (**Table 6**). The final valuation factor is obtained as an average of the aforementioned.

4.2.1.6. Rainfall valuation factor (Fr)

Rain is one of the main factors affecting the slope stability; many landslides occur during or after rainy periods, and areas with higher annual rainfall present more stability problems, due to the groundwater with higher flow and more weathered materials. The shallow landslides due to torrential rainfall depend on the combined effect of infiltration and loss of apparent cohesion, which are influenced by the amount of rainfall and the duration of the storm [14]. Rainfall valuation factors (Fr) are determined by linear interpolation from the average annual rainfall data (**Table 7**).

4.2.1.7. Earthquake valuation factor (Fe)

Earthquakes are trigger agents that cause deformations and cracks on slopes. Seismic shaking can lead to landslides, flows, and avalanches depending on the intrinsic characteristics of the

Characteristics	Rainfall valuation factor (Fr)				
Average annual rainfall	<400 mm	400–800 mm	800–1500 mm	1500–3000 mm	3000–4500 mm
Classification	Very low	Low	Medium	High	Very high
Valuation factor (Fr)	<0.09	0.09–0.18	0.18–0.33	0.33–0.67	0.67–1

Table 7. Rainfall valuation factor (Fr).

ground and the magnitude and distance to the epicenter [15]. The earthquake valuation factors (Fe) are determined from a linear correlation with the seismic design coefficients (Cs); these latter are obtained from municipal building codes as a function of the terrain type (hard, medium, or soft), the frequency which the event occurs, and the ground acceleration, the latter depending on the magnitude and intensity of the movement (**Table 8**).

4.2.1.8. Erosion and scouring valuation factor (Fes)

The erosion and scouring valuation factor (Fes) is obtained from the basin geometric characteristics (length and width), because the basin shape influences the stream hydrograph and the flow rate. The characteristics of the drainage density (Dd = sum of the tributary flows length between the total basin area) were also taken into account, considering that the higher drainage density will have higher flows in the stream [16]. Finally, the characteristics of the ground evaluated according to their infiltration capacity “If” are included. Eqs. (6)–(8) present the “Fes” as a function of the aforementioned:

Seismic zone	Soil type	Seismic coefficient (Cs)	Valuation factor Fe
A	Hard	0.08	0.09
	Medium	0.16	0.19
	Soft	0.2	0.23
B	Hard	0.14	0.16
	Medium	0.3	0.35
	Soft	0.36	0.42
C	Hard	0.36	0.42
	Medium	0.64	0.74
	Soft	0.64	0.74
D	Hard	0.5	0.58
	Medium	0.86	1
	Soft	0.86	1

Zone A: very low seismicity; no earthquake in the last 80 years, ground acceleration <10% gravity acceleration.
Zone B: low seismicity; earthquakes not so frequents, ground acceleration <70% gravity acceleration.
Zone C: medium seismicity; earthquakes not so frequents, ground acceleration <70% gravity acceleration.
Zone D: high seismicity; very frequent earthquakes, ground acceleration >70% gravity acceleration.

Table 8. Earthquake valuation factor (Fe).

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$$Fes_{basin\ characteristics} = 0.0625^* \left(\frac{L}{W}\right) \tag{6}$$

$$Fes_{drainage\ density} = 0.1^* Dd \tag{7}$$

$$Fes_{infiltration} = 1 - 0.033^* If \tag{8}$$

where L = basin length (km), W = basin width (km), Dd = drainage density (km/km^2), and If = infiltration rate (mm/h).

4.2.1.9. Human activity valuation factor (Fha)

The relationship between landslides and velocity of urbanization on slopes has been demonstrated; the worst cases have been registered in geotechnical susceptible areas with rapid and disordered urban development. Since human actions directly influence nature, this human activity valuation factor (Fha) is assessed by taking into account cuts or excavations, landfills, building overloads, and deforestation (**Table 9**).

The human activity valuation factor by overloads was obtained from the average loads or stresses transmitted by the building to the soil foundation and the population density, which both directly impact on the behavior and slope stability (**Figure 7**).

The final valuation factor is obtained as an average of the aforementioned.

4.2.1.10. Geotechnical slope stability valuation factor (Fgss)

The results of geotechnical slope stability analysis are the safety factor (SF) and the location of failure surface; these data are important to know a potential failure; furthermore we suggest taking them into account to obtain geotechnical slope stability factor (Fgss), as a function of the depth of failure surface (superficial, shallow, deep, and very deep) and the value of the safety factor (**Table 10**).

Human activity	**Human activity evaluation factor (Fha)**				
Cuts or excavations	Stabilized by efficient construction works				Not stabilized
	Fha = 0				Fha = 1
Overloads	One-floor building		Two-floor building	Three-floor building	Four-floor building
	W = 10 kN/m^2		W = 20 kN/m^2	W = 30 kN/m^2	W = 40 kN/m^2
	Fha (**Figure 7**)				
Deforestation	Null	Slight	Medium	High	Total
	0% area	25% area	50% area	75% area	100% area
	0	0.25	0.50	0.75	1

W = overload.

Table 9. Human activity valuation factor (Fha).

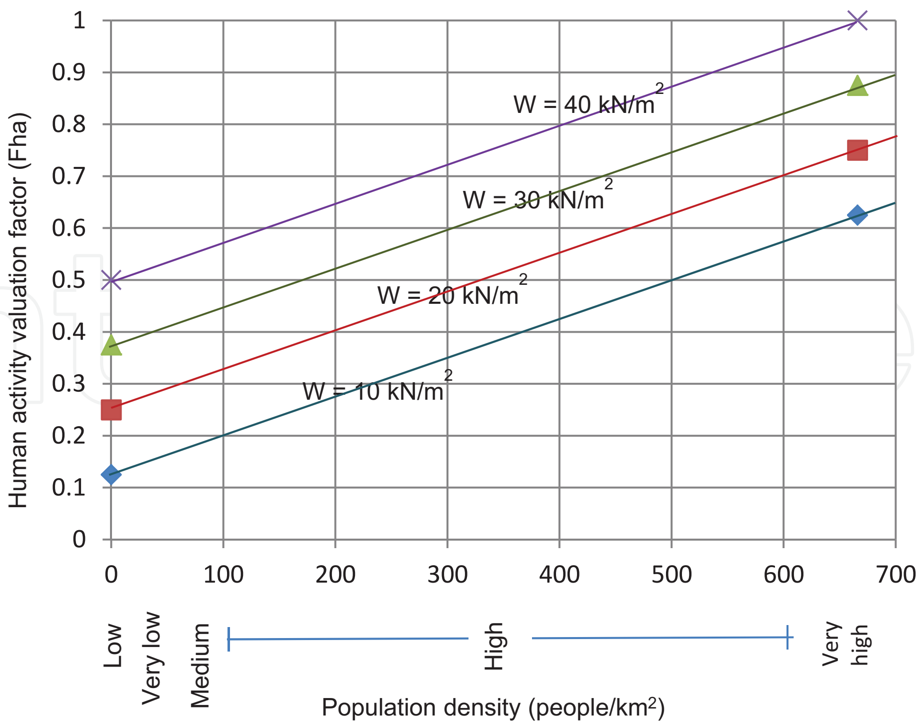

Figure 7. Human activity evaluation factor by overloads (Fha).

Slope stability analysis	Geotechnical slope stability valuation factor (Fgss)			
Failure surface	Superficial	Shallow	Deep	Very deep
	<1.5 m	1.5–5 m	5–12.5 m	12.5–20 m
	0.25	0.50	0.75	1
Safety factor (SF)	Unstable	Critical stability		Stable
	<1	1–1.5		>1.5
	1	0.75		0

Table 10. Geotechnical slope stability valuation factor (Fgss).

5. Methodology to select stabilizing construction works

Most techniques and construction works to stabilize unstable slopes or active landslides can be included in the following classification groups: (a) geometric adjusting, (b) drainage, (c) reinforcing structural elements, (d) retaining walls, (e) surface protection, and (f) soil improvement.

The most effective and economical solution is a combination of two or more stabilization techniques [17]. At first glance it could be thought that the quantitative evaluation of stability by geotechnical analysis of equilibrium-limited methods (safety factor and the failure surface) is sufficient to propose and decide the types of construction works to be used. However, it must be taken in mind that many factors influencing stability and construction stabilization works are difficult to model and include in the analysis using the calculation methods and should be evaluated in a qualitative way.

5.1. Methodology description

The methodology uses both quantitative and qualitative analyses, organized in stages as described below:

5.1.1. Data collection from engineering: geological studies

In this stage, the following data are obtained: topography (height and slope inclination), geology (folding, fracturing, and weathering of rocks), soil mechanics (classification and physical-mechanical properties of soils and rocks, thickness of the soil strata, and saturation degree), seismology (classification and seismic coefficient according to local building codes), climatology (annual temperature and average annual rainfall), hydrology (drainage grid and its basin), studies of human activity impact (cuts or excavations, population density, overloads, type of constructions, number of floors of houses, and degree of deforestation), vegetation characteristics (type, foliage density, area covered, and depth of root), and volcanic activity.

5.1.2. Stability analysis before the construction of stabilization works

5.1.2.1. Quantitative analysis: safety factor (SF) and critical failure surface

Slope modeling and geotechnical stability analysis using some of the limit equilibrium methods: Fellenius, Bishop, Janbu, Bell, Sarma, Spencer, or Morgenstern and Price.

5.1.2.2. Qualitative analysis: valuation factors

If the safety factor (SF) obtained from geotechnical stability is lower than the minimum value required as an acceptable limit, it is necessary to use construction works to improve stability. The selection of these stabilizing construction works is made into qualitative way, through the *valuation factors* that consider the influence of intrinsic and trigger factors.

Once the valuation factors are obtained, it is necessary to establish the influence intervals to assess the level of care required as follows: (a) if valuation factor is <0.5, there will be no stability problems; (b) if the value is between 0.5 and 0.75, it requires attention; and (c) if the value is >0.75, it requires urgent solution.

5.1.3. Selection of construction works and stabilization proposals

In landslide problems, it is common to combine several factors that give rise to a critical behavior, so it is very likely that a combination of construction works is also required to address the problem and avoid a risk condition. **Table 11** summarizes the type of problem to be solved, the suitable construction work, and the aims of them.

Problem type	Applicable construction works	Specific objectives
Morphologic	Geometric adjustment	Decreasing acting forces
Geological	Reinforcement, wire mesh	Increasing resisting forces
Soil mechanics	Drainage, reinforcement, and superficial protection	Decreasing pore pressure, increase resistance, and prevent erosion
Hydrological	Drainage and surface protection	Reducing soil saturation and weathering
Vegetation	Surface protection	Avoid erosion and reinforce soil
Rain	Drainage	Decreasing pore pressure, avoid saturation and erosion
Earthquake	Reinforcement and retaining walls	Increasing resistance and retaining potentially unstable material
Vulcanism	Geometric adjustment and retaining walls	Remove unstable materials and contain soil masses
Erosion	Drainage, retaining walls and surface protection	Avoid erosion and protect the hillside foot
Human activity	Reinforcement, retaining walls, and surface protection	Increasing resistance, contain potentially unstable material, and reforest
Failure surface	Geometric adjustment, reinforcement, and retaining walls	Changing location
Safety factor	Geometric adjustment, reinforcement, and retaining walls	Increasing the value

Table 11. Instability factors and suitable construction works.

5.1.4. Checking over slope stability with the proposed construction works

The selected construction works should ensure that safety factor (SF) is equal to or greater than the required minimum factor, so it is necessary to check that condition, including the works selected in the quantitative stability analysis, which is performed with the same methods that are used to assess geotechnical stability in a quantitative way, but now including these construction works (or their influence) in the modeling stage.

6. Results

The equations, figures, and tables of *valuation factors* presented in this chapter to evaluate the influence of the intrinsic and trigger factors, as data previously needed to select the construction structures to avoid landslides, are important tools to help different specialists who face the phenomenon. In addition to the above, the following is also required:

6.1. Technical and economic assessment of stabilization proposals

Set up the necessary activities to carry out the stabilizing construction works: resources and their yields [18]. This is essential for the economic assessment of stabilization proposals where it is also important to include the direct costs of materials, labor, and equipment and indirect costs resulting from the expenses technical-administrative necessary for the correct execution of any construction work [19].

6.2. Selection of the stabilizing construction proposal

As shown in **Table 11**, it is very common that the most effective and even economic stabilization method corresponds to the simultaneous application of two or more stabilization construction works, and sometimes, in addition to the cost factor, esthetic and environmental factors have to be taken into account. It should be noted that the final decision on the construction works to a potentially unstable slope or an active landslide must be in the hands of experienced specialists with broad knowledge of the intrinsic properties of the slope and the specific conditions of the region where it is located.

Nomenclature

α	fold inclination
β	slope inclination
γ	volumetric weight
φ	internal friction angle
C	cohesion
Cs	seismic coefficient
Dd	drainage density
e	soil stratum thickness
EL	exposure level
EDD	expected damage degree
Fmt	morphology valuation factor
Fg	geology valuation factor
Fsm	soil mechanics valuation factor
Fh	hydrogeological valuation factor
Fv	vegetation valuation factor
Fr	rainfall valuation factor
Fe	earthquake valuation factor
Fes	erosion and scouring valuation factor
Fha	human activity valuation factor
Fgss	geotechnical slope stability valuation factor
Gw	soil saturation degree
Hc	critical height

H	slope height
If	infiltration rate
L	basin length
Ns	stability number
W	basin width
SF	safety factor
RQD	rock quality designation

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