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Geotechnical stability analysis, fragility of structures and velocity of movement to assess landslides vulnerability

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Abstract

Landslides are geohazards that can be potential risks to life and property; these phenomena usually cause disasters when they occur in densely populated communities as those that inhabit mountainous and steep regions.

Hazard and vulnerability are parameters determined by probability mathematical analysis with values between 0 and 1. When there are no records or enough information regards historical events on the phenomenon in study, that have occurred in a specific area (as in several mountainous regions of Mexico inhabited by ethnic groups), it has the disadvantage of not being able to perform a statistical analysis to properly evaluate the hazard nor the vulnerability.

To solve the problem, this paper presents a proposal for evaluating the physical and functional vulnerability of the elements at risk, from two fundamental aspects: (a) the exposure level (EL), and (b) the expected damage degree (EDD). First of these factors is determined by the severity index (SI) and the safety factor from geotechnical stability analysis (SFgeo); the second one from the construction type (degree of fragility of structures) and the velocity that may have the landslide. For evaluating the parameters aforementioned, included tables, graphs and equations proposed by the authors.

1 Introduction

The Mexican territory is mainly a mountainous country, created by tectonic activity (the convergence of Cocos Plate with the North America and the Caribbean Plates). The slopes formed by this process are morphologically and structurally prone to landslide processes. Triggering factors actively shift the state of stability to an unstable condition are rainstorms and seismic shaking.

The most vulnerable communities to natural hazards are ethnic groups settled on steep slopes or in areas prone to flooding, adjacent to rivers (Veracruz, Chiapas, Oaxaca, Guerrero, Hidalgo, Puebla, Michoacan, among others).

On October 1999, landslides had a big impact on the social and economic structure of Puebla, the economic damage was around USD 246 million and 250 human lives were lost. When the landslide occurred, information of historical events was not enough to perform a statistical analysis to properly evaluate the hazard.

Definitions

Landslide is the mass movement of rock, soil or debris material forming a slope (Varnes, 1978). Landslides phenomena occur along a surface that exceed the shear strength of the material, characterized by the movement of the ground, which may include blocks, rock fragments, debris and/or soils that fall down by gravity forces. When a landslide occurs on a densely populated area, it causes disasters in most cases (Alcántara, 2002; Cardona, 2004; Cuanalo et al., 2004; Wisner et al., 2004; Crozier, 2005; Petley, 2010).

Hazard is the probability of occurrence of a potentially damaging landslide occurring within a given period of time, a predefine area and for specific magnitude (Glade, 2006).

Vulnerability is defined as the intrinsic predisposition or susceptibility of a community to risk elements which produce damage or loss, due to the occurrence of a phenomenon with some intensity (Alexander, 2005).

To properly assess the vulnerability of a community to a potential hazard by a natural phenomenon, we must take into account the different elements exposed, these include people, community infrastructure, the geographical and natural resources, activities for normal operation as transport, communications, power supplies, utilities, economy, finance, trade, etc., all belonging to the physical and functional vulnerability (Leone et al., 1996; Douglas, 2007).

It is also important to take into account the social aspects of the various strategies and measures of the community and its institutions for prevention, reduction, disaster mitigation and management, organizational capacity and response contingency, etc.; all of these aspects from social vulnerability (Wisner, 1993).

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The vulnerability can be classified in three different aspects: physics, serviceable and social (Table 1).

Risk is defined as the potential loss caused by a natural phenomenon. It is evaluated as a function of fatalities and economic losses, including those caused by the temporary suspension of the normal activities in the affected community.

Risk is the level of expected losses or damages resulting from the interaction between the natural hazard or probability of an extreme natural event, and the vulnerability of the elements exposed to the natural phenomenon, expressed by Eq. (1) (Hollenstein, 2005; Crozier and Glade, 2010):

$$R = H \cdot V \cdot C \quad (1)$$

where,
R = risk (fatalities in human lives or economic losses)
H = Hazard (dimensionless)
V = vulnerability (dimensionless)
C = damage cost or expected losses of the exposed elements (human lives or economic losses).

Figure 1 shows the different components of each parameter that should be evaluated to assess the risk properly (Calcaterra et al., 2003; Chung and Fabbri, 2003; Fell, 2008), including those factors proposed in this paper: exposure level and expected damage degree, in order to develop the hazard, vulnerability and risk maps to landslides.

2 Puebla, the region of study (structure and geomorphology)

The state of Puebla is located in the center of Mexico, with some its elevations reaching up to 3200 m a.s.l. belonging to the Eastern Ridge (Fig. 2). Mountains are formed by marine sedimentary rocks that were intensely folded and lifted by compression forces during the Cretaceous–Tertiaryperiods (Paleocene), which originated the Eastern Range.

Geologic events produced great failures, intense cracking and layers inclination; a volcanic eruption covered the folded rocks with ashes and pyroclastic materials that are vulnerable to fast erosive processes. The volcanic activity ended up with abrupt collapses of the volcano surroundings and generated another regional failure system where the rivers have formed their channels.

Brittle sedimentary rocks as shales and siltstones, which weathering into clayey and silty soils (CH and MH, unified soil classification system) were part of the stratigraphic sequence.

Also is common to find an alternating layer of limestone blocks, sandstones, shales and siltstones

2.1 Landslides phenomenon

Types of landslide in the study area:

2.1.1 Rotational and translational failures

Rotational slide can be defined as a slide in which the surface of rupture is a concave curve. When the surface of rupture is plane, the slide is called translational (Fig. 3).

Many rotational and translational landslides recorded at the study area, were originated where a cut had been made previously for building a road or a terrace.

2.1.2 Earth flow and debris flow

Earth flow is a rapid or slower, intermittent flow-like movement of plastic, clayey mud and debris flow is a very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel (Hungr et al., 2001).

Siltstones are highly weathered with thicknesses of soil up to 6 m. When these soils are saturated, they change their mechanical properties due to strength reduction, causing earth flow and debris flow.

2.1.3 Fallen rock

A fall starts with the detachment of soil or rock from a steep slope along a surface on which little or no shear displacement takes place. The material then descends mainly through the air by falling, bouncing, or rolling (Varnes, 1996).The intensely fractured rocks such as limestone and sandstones frequently collapse (Fig. 4).

2.1.4 Erosion

Another type of failure in volcanic soils like silts and sands is erosion by surface water runoff

3 Landslides data

Landslides phenomena occur frequently in Mexico, due to climate change and the role of human activity: cuts, excavation, mining, overloads, deforestation, water discharge, among other things.

3.1 Relationship between rainfalls and landslides

3.1.1 Tropical depression Eleven (September–October 1999)

Tropical depression Eleven of the 1999 Atlantic hurricane season caused torrential rainfall in Mexico for several days, resulting in at least 636 deaths and USD 1 billion in damages. Tables 2 and 3 shows landslides occurred at the mountainous region of Puebla and the cost of damages in different sectors, respectively.

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3.1.2 Hurricanes Stan and Wilma (October 2005)

As a tropical storm, Stan brought torrential rainfall and gusty winds on 1 October, affected several states of Mexico: Chiapas, Hidalgo, Oaxaca, Puebla, and Veracruz. According to Mexican president Vicente Fox, Hurricane Stan wrought roughly 20 billion pesos (USD 1.9 billion) in damage throughout the country. Some areas in the North ridge of Puebla were also flooded. Three people died in a mudslide at Xochiapulco Hill (Northern ridge).

After Stan had passed, Wilma surged from tropical storm to Category 5 hurricane in record time at 21 October. Winds around the eye wall of the storm were raging at 280 $km\,h^{-1}$, making it the most intense hurricane ever observed in the Atlantic basin.

3.1.3 Hurricanes Felix and Lorenzo (August–September 2007)

On 11 August, a tropical wave moved off the west coast of Africa, and, encountering favorable conditions, quickly spawned Tropical Depression Four, roughly 520 miles (835 km) west-southwest of Cape Verde. The depression was upgraded to Tropical Storm Dean on 14 August and became the first hurricane of the season just two days after. Dean reached a maximum intensity as Category 5 on the Saffir–Simpson Hurricane Scale – the strongest Atlantic hurricane since Hurricane Wilma – and it was tied for the seventh most intense Atlantic storm of all time. The hurricane made landfall on the Yucatán Peninsula on 21 August, causing severe damage and at least 44 deaths.

A tropical wave emerged off the coast of Africa on 11 September and traversed the Atlantic, crossing the Yucatan Peninsula on 21 September. On 25 September an associated low organized into a tropical depression in the southwest Gulf of Mexico. Further organization took place, and the depression was upgraded to Tropical Storm Lorenzo. Lorenzo peaked with winds of 80 mph a minimal hurricane – and made landfall near Tecolutla, Veracruz

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Table 4 shows landslides at mountainous region of Puebla in the period 1999–2013, and Figs. 5 and 6 presents location of Weather Stations and some graphics of monthly rainfall, respectively.

4 Vulnerability evaluation

The vulnerability study aims to determine the exposure level of the risk elements and their expected degree of damage, or susceptibility to loss as a result of the occurrence of a specific event defined as a potential hazard. That is to say, different vulnerability of the exposed elements involves different severity of the effects of the phenomenon on them (Glade, 2003; Van Westen, 2008).

When there are no records or enough relevant historical information that have occurred in a specific area, phenomenon in study (as in several mountainous regions of Mexico inhabited by ethnic groups, who build their houses with cardboard, wood or plastic and any natural phenomenon can be a major disaster, Fig. 7), it has the disadvantage of not being able to perform a statistical analysis to properly evaluate the hazard nor the vulnerability (Malamud et al., 2004). So that to establish the physical and functional vulnerability, the authors developed the concept of Exposure Level (EL) and Expected Damage Degree (EDD) of elements at risk at the mountainous region of Puebla, both will be describe below:

4.1 Exposure Level (EL)

The exposure level (EL) could be established from slope height (H) and the minimum safety factor (SF_{geo}) from geotechnical stability analysis. Then, for defined suitably the EL, it is necessary establish the concept of severity index.

Puebla's landslides in 1999, show that slopes with more than 10 m of height produced more damages on infrastructure and human lives losses. Therefore, the authors defined the severity index (SI) like a unit if the slope height is 10 m (Fig. 8).

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Consequently, if the height of the slope is more than 10 m, the severity unit was more than one, because the damage will affect more elements than the failure of a slope 10 m high.

Severity Index was obtained from the mathematical modeling of a fault block, which volume mobilized by landslides varies exponentially with the height of slope. The values of Fig. 8 were normalized to a volume corresponding to fault block 10 m high; that is to say, the failure volume of a slope 50 m in height is 25.6 times greater than the volume of a failure slope 10 m high; also, a fault block 5 m high is about 0.25 of one of 10 m.

Equation which roughly fits the curve of Fig. 8 is as follows:

$$\mathrm{SI} = 0.0215\, e^{\sqrt{H}} \tag{2}$$

where

SI: severity index (dimensionless)

H: slope height (m).

And now, the exposure level (EL) can be evaluated, as follows:

$$\mathrm{EL} = \left(\frac{\mathrm{SF}_{\mathrm{proy}} - \mathrm{SF}_{\mathrm{geo}}}{\mathrm{SF}_{\mathrm{proy}} - 1}\right)^{\frac{1}{\mathrm{SI}}} \tag{3}$$

where EL = Exposure level (dimensionless)

$\mathrm{SF}_{\mathrm{proy}}$ = Safety factor of project (dimensionless)

$\mathrm{SF}_{\mathrm{geo}}$ = Minimum safety factor obtained from geotechnical stability analysis

SI = Severity index as a function of height of slope (H), Fig. 8.

Figure 9 was proposed to determine the exposure level (EL) of the mountainous region of Puebla, after 1999. The safety factor of project ($\mathrm{SF}_{\mathrm{proy}}$) in this case was 1.7 and the geotechnical safety factor ($\mathrm{SF}_{\mathrm{geo}}$) can vary with values less than 1 (unstable condition), between 1 a 1.7 (critical stability) and greater than 1.7 (stable).

If the minimum geotechnical safety factor ($\mathrm{SF}_{\mathrm{geo}}$) is equal to or greater than the safety factor of project ($\mathrm{SF}_{\mathrm{pro}}$), the slope is stable and there is no possibility of a landslide, so the exposure level (EL) will be zero. On the other hand, if the minimum geotechnical safety factor (SF_{geo}) is near unity or less, the slope is unstable and there is a big possibility that a landslide causes damage to all elements within the failure block: top, slope and lower parts, as shown in Fig. 10; in this case the exposure level (EL) is the highest with a value equal to unity. If the minimum geotechnical safety factor (SF_{geo}) is between 1 and the value of the safety factor of project (SF_{pro}), it will have a critical stability and exposure level (EL) will be between one and zero.

4.2 Expected damage degree (EDD)

The expected damage degree (EDD) of the exposed elements should be based on the type and characteristics of buildings or structures; that is, the degree of fragility and the landslide velocity, Tables 5 and 6.

If the expected landslide is fast to very fast, it will cause damage to all structures within the failure block, independently if they are made of wood, masonry, steel, concrete, etc. Overall the velocity of landslide depends on the inclination of slope, the ground materials (soils and/or rocks) and the degree of saturation, all of them belonging to the determinants factors (Cuanalo et al., 2005). On the other hand, if landslide is slow or very slow, we can preserve lives and economic assets; for the latter when we use stability construction works properly.

Fast landslides occur frequently in saturated materials, where the water contained in the soil plays a critical role in the instability, so they are associated with places with heavy rainfall or where rains are often the triggering factor. In contrast, slow landslides occur in regions with low rainfall and where the triggering agent can be an earthquake or a volcanic eruption (Cuanalo et al., 2006). Regardless of the velocity of the landslide, many problems are associated with the influence of human activity such as cuts, excavations, deforestation, overloads, waste water, mining and filling materials, land use change, filled in loose condition, etc.

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Figure 11 is proposed to determine the expected damage degree (EDD) caused by a landslide as a function of the type of construction (degree of fragility) and the velocity of the movement.

The latter graph is adequate for evaluating the expected damage degree (EDD), it is stated that if the velocity of movement is fast, all constructions on the slope will collapse; on the other hand, if the velocity is low, then the steel reinforcement structures will be the only ones to resist deformation and can be preserved if stabilization construction works are placed properly: geometric rectification, drainage elements, barrier piles, anchors, retaining walls and surface protection (Cuanalo, 2004; Cuanalo et al., 2012).

It is important to mention that it requires collecting more information about the parameters that define the velocity of a landslide: slope inclination, degree of saturation and type of ground materials, and the characteristics of structures: fragility and stiffness in order to develop a more accurate mathematical model for adjusting the curves at Fig. 11.

4.3 Vulnerability assessment

Equation (4) is proposed to determine physical and serviceable vulnerability from exposure level (EL) and the expected damage degree (EDD). The first factor evaluated from the geotechnical safety factor (SF_{geo}) and the slope height (H); the second one as a function of the type of constructions (degree of fragility) and of the velocity of landslide, Figs. 9 and 11, respectively.

$$V = \mathrm{EL} \cdot \mathrm{EDD} \tag{4}$$

where

V = vulnerability; (dimensionless)

EL = exposure level; (dimensionless)

EDD = expected damage degree (from 0 to 1).

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5 Discussion and conclusion

Landslides are geohazards that can be potential risks to life and property; these phenomena usually cause disasters when they occur in densely populated communities as those that inhabit mountainous and steep regions.

To assess the landslides risk, it must be determined the probability of occurrence of the hazard phenomenon (H) and the vulnerability of the exposed elements (V): population and its economic assets, Fig. 1.

When there are no records or enough information regards historical events that have occurred in a specific area, on the phenomenon in study (as in several mountainous regions of Mexico inhabited by ethnic groups), it has the disadvantage of not being able to perform a statistical analysis to properly evaluate the hazard nor the vulnerability.

This article aims to assess the physical and functional vulnerability from two characteristic parameters: (a) The exposure level (EL) and (b) The expected damage degree (EDD).

The exposure level (EL) proposed determine from the height of slope (H) and the safety factor obtained by geotechnical stability analysis (SF_{geo}), Fig. 9 and Eq. (3).

The expected damage degree (EDD) is determined from the types of constructions or structures (degree of fragility) and the velocity of landslides, Fig. 11 and Table 6. At this moment it requires collecting more information about the parameters that define the velocity of a landslide: slope inclination, degree of saturation and type of ground materials, and the characteristics of structures: fragility and stiffness in order to develop a more accurate mathematical model for adjusting the curves at Fig. 11.

Graphs and equations proposed for assessing vulnerability are based on characteristic factors that define the slope behavior; they are determined from engineering-geological studies and quantitative geotechnical stability analysis; these last using computer programs for everyday use in geotechnical engineering.

Equation (4) allows assessing vulnerability adequately from a range 0 and 1, which is technically acceptable and rational from an engineering point of view. Besides it

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solves the problem of lack of information or historical data to do probabilistic analysis of this important parameter, which is a major limitation to assess adequately the risk in mountainous regions of Mexico inhabited by ethnic groups.

The main advantage of the proposal contained in this article, to determine the level of physical and functional vulnerability of a community at risk by landslides phenomenon at the mountainous regions of Mexico, is that it takes into account the different factors that directly influence risk, namely: (a) the exposure of its elements evaluated from factor geotechnical safety that is universally used in the stability analysis of a slope, and (b) the degree of expected damage of elements from type of construction and the speed of the movement.

Another important concern of landslides at mountainous regions inhabited by ethnic Mexicans groups (Nahuas, Totonacas, Otomis, Tepehuanos, Zapotecos, Mazahuas, Mixtecos, Lacandones, Chontales, Quiches, etc.), which generally does not take into account is the social aspect of our communities that directly affect their vulnerability, including their high degree of marginalization, their low level of education, low level of income, poor diet, disease, housing, etc.

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Table 1. Aspects of the vulnerability.

Vulnerability	Risk elements
Physics	People
	Infrastructure
	Geographical and natural resources
Serviceable	Transport
	Communications
	Power supplies
	Utilities
	Economy
	Trade
Social	Strategies and measures for the prevention, reduction, and disaster mitigation
	Organization and community response to a contingency

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Table 2. Landslides in Puebla (1999) (Cuanalo et al., 2012).

Municipality	Community	Movement/material	H/β (m deg^{-1})	A (m^2)	D (m)	V (m^3)
Teziutlán	La Aurora	Flows/fine volcanic soils	63/31°	7700	8	3610
	Valle Dorado	Rotational/fine volcanic soils	32/22°	450	6	134
	Montes de Oca school	Erosion/fine volcanic soils	48/18°	–	–	–
	Juan Acateno	Rotational/fine volcanic soils	19/21°	2750	11	1690
	Ixtlahuaca	Rotational/fine volcanic soils	23/18°	1370	8	767
	Mexcalcuautla	Fallen rocks/sandstone	12/55°	–	–	1240
	Coahuixco	Erosion/fine volcanic soils	15/11°	–	–	–
	Cuautepehuac	Rotational/weathered shales	8/36°	360	8	360
	Aire libre	Rotational/weathered shales	27/43°	1300	12	650
	Apullco	Fallen rocks/weathered sandstones	19/70°	–	–	225 000
Tlatlauquitepec	Reforma street	Rotational/fine volcanic soils	18/17°	210	5.5	94
	Independencia street	Erosion/fine volcanic soils	6/8°	–	–	–
	Elvira Cabañez school	Erosion/silty sand	56/15°	–	–	–
	Reforma Oriente	Traslational/weathered tuff	32/13°	690	7	230
	Venustiano Carranza street	Flows/fine volcanic soils	16/11°	180	5	90
	Reforma Norte	Rotational/fine volcanic soils	18/19°	760	7	372
	Las Bugambilias	Flows/silty sand	40/12°	2735	9	2 465
	Tatauzoquico	Erosion/sandy silts	22/23°	–	–	–
Zacapoaxtla	La concordia	Rotational/fine volcanic soils	14/17°	21 000	11.5	19 320
	Libramiento Oriente	Rotational/fine volcanic soils	9/56°	893	6	520
	Zacapoaxtlaschool	Traslational/fine volcanic soils	14/60°	180	2.5	38
	Zaragoza road	Erosion/fine volcanic soils	–	–	–	–
	El Fortin	Flows/fine volcanic soils	41/23°	945	3.5	355
	Teacalco bridge	Flows/Sandy clays	7/60°	270	3	73
	Betancourt street	Rotational/weathered shales	5/43°	1276	2	245
	Barranca Independencia	Erosion/fine volcanic soils	27/64°	–	–	–
	Federal 35 school	Rotational/fine volcanic soils	12/48°	570	4	185
	Independencia street	Flows/fine volcanic soils	7/11°	2550	3.5	892
	Nexticapan	Flows/fine volcanic soils	22/90°	1830	5	4 570
Zaragoza	Acuacostream	Erosion/fine volcanic soils	6/60°	–	–	–
	San Martin	Rotational/fine volcanic soils	–	–	–	–
Juan Galindo	Necaxaltepetl	Rotational/weathered shales	33/35°	430	6.5	250
	Mexico–Tuxpan road (km 126)	Fallen rocks/limestones	23/90°	348	–	174
Chignautla	Chignautla	Flows/fine volcanic soils	8/90°	250	2	470
Yaonahuac	Atotocoyan	Fallen rocks/sandstones	120/65°	–	–	30 000
Zapotitlan	Zapotitlan de Mendez	Rotational/weathered shales	62/35°	2700	6	460
Tetela	Tetela de Ocampo	Rotational/weathered shales	5/90°	24	1	12
Pahuatlan	Pahuatlan de Valle	Rotational/weathered shales	43/29°	80 000	9	146 080

H: height; β = inclination; A: area; D: depth of failure surface; V: approximate volume.

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Table 3. Cost of damages in Puebla (1999).

Actions (1999)	Morales M, 2001	Bitran D. and Reyes C., 2000
1. Emergency Actions Secretary of Health SEDENA IMSS DICONSA	USD 3.29 MD	USD 0.49 MD USD 1.17 MD USD 2.32 MD USD 0.67 MD USD 4.2 MD
2. Housing program	USD 33.12 MD (15 960 houses)	USD 39.58 MD (16 511 houses)
3. Educational sector	USD 7.44 MD (269 schools) include 27 new buildings	USD 3.06 MD (570 schools)
4. Health sector		USD 0.243 MD (3 centers of Health)
5. Hydraulic infrastructure program	USD 8.42 MD (404 communities)	USD 8.42 MD (377 communities)
6. Electricity		USD 46.89 MD (916 populations) (192 000 people)
7. Highways and bridges	USD 84.69 MD (2947 km)	USD 94.9 MD (2685.8 km)
8. Agricultural Sector	USD 4.73 MD (64 854 product)	USD 16.33 MD USD 1.5 MD
9. Forest and fishing sector	USD 1.61 MD (7170 ha of forest) (240 ha of soil)	USD 3.41 MD USD 7.6 MD
TOTAL	*USD 153.3 MD*	*USD 223.94 MD*

Note: MD: million dollars
1 USD = 10.26 Mexican pesos (December 2000).

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Table 4. Landslides at mountainous region of Puebla (period 1999–2013).

Date	Place	Coordinates	Type of movement	Trigger factor Rain	Damages	
					Lives	USD
Oct 1999	Teziutlán and Huauchinango regions (70 municipalities)	19°49′07″ N 97°21′25″ O; 20°11′03″ N 98°03′12″ O	Rotational, traslational flows, erosion, fallen rocks	Cold fronts 11 and 14; 750 mm/ 3 days	> 250	> 200 million
Oct 2005	Teziutlán, Huauchinango and Tehuacán regions (114 municipalities)	19°49′07″ N 97°21′25″ O; 20°11′03″ N 98°03′12″ O 18°23′20″ N 97°14′17″ O	Rotational, traslational flows, fallen rocks	Stan hurricane; > 140 mm day^{-1}	3	90 million
Aug Sep 2007	Teziutlán, Huauchinango and Tehuacan regions (92 municipalities)	19°49′07″ N 97°21′25″ O; 20°11′03″ N 98°03′12″ O 18°23′20″ N 97°14′17″ O	Rotational, traslational flows, erosion, fallen rocks	Dean hurricane, Lorenzo tropical cyclone	16	120 million
Sep 2010	Teziutlán, Huauchinango and Tehuacan regions (113 municipalities)	19°49′07″ N 97°21′25″ O; 20°11′03″ N 98°03′12″ O 18°23′20″ N 97°14′17″ O	Rotational, traslational flows, fallen rocks	Karl hurricane; 250 mm day^{-1}	2	21 million
2013	Teziutlán and Huauchinango regions (31 municipalities)	19°49′07″ N 97°21′25″ O; 20°11′03″ N 98°03′12″ O	Rotational, traslational flows, fallen rocks	Ingrid hurricane and Manuel tropical storms	3	56 million

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Table 5. Degree of fragility of structures.

Type	Structures	Degree of fragility
1	Mud and timber houses	Very high
2	Stone wall structures	High
3	Brick with reinforcement concrete	Medium
4	Steel structures	Low
5	Reinforcement concrete structures	Very low

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Table 6. Velocity of landslide.

Movement	Velocity	
Fast–very fast	0.005–0.0005 $m\,s^{-1}$	0.3 $m\,min^{-1}$–1.8 $m\,h^{-1}$
Moderate	0.0005–0.00005 $m\,s^{-1}$	1.8 $m\,h^{-1}$–4.3 $m\,day^{-1}$
Slow	0.00005–0.000005 $m\,s^{-1}$	4.3 $m\,day^{-1}$–3 $m\,week^{-1}$

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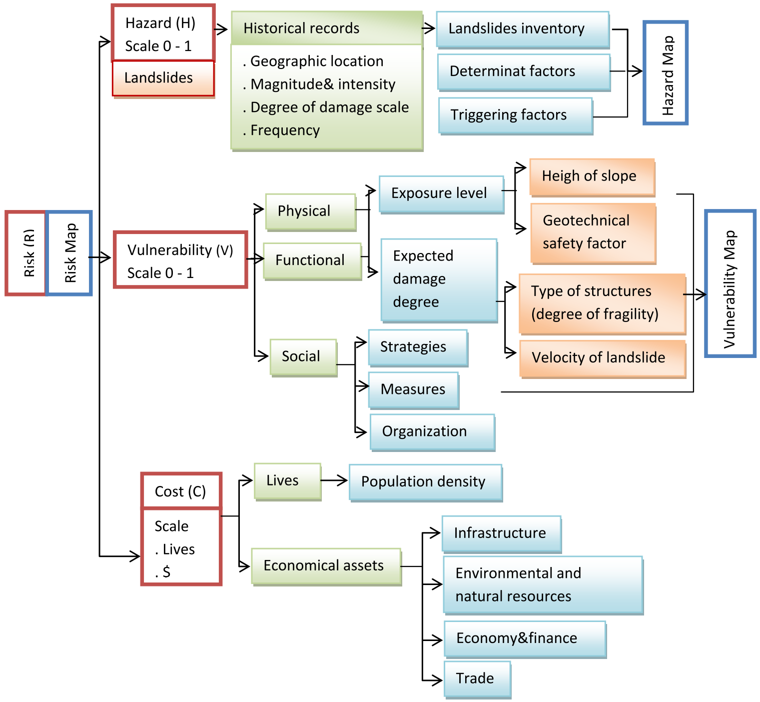

Figure 1. Parameters defining hazard, vulnerability and risk to landslide.

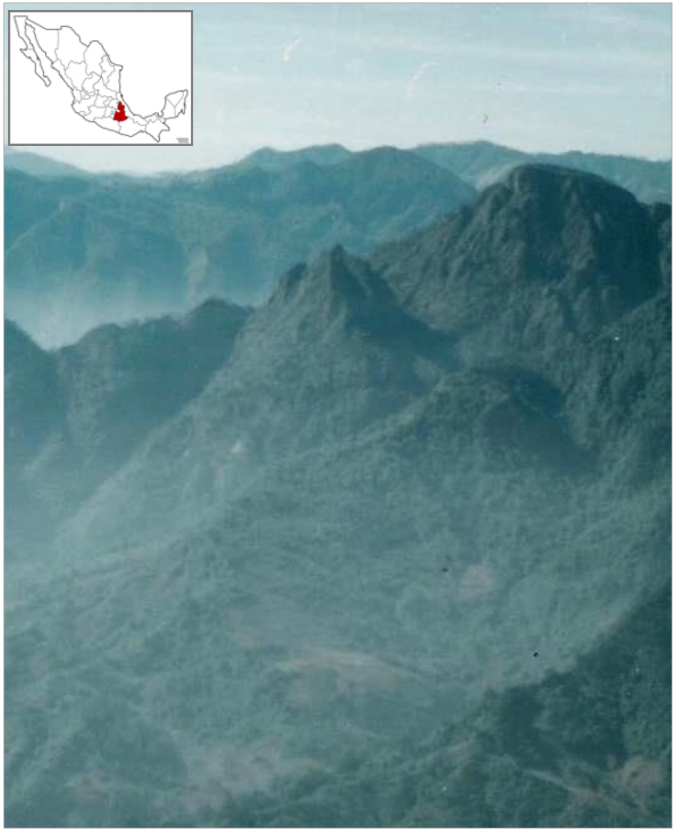

Figure 2. Morphology of Puebla, México (Eastern Ridge).

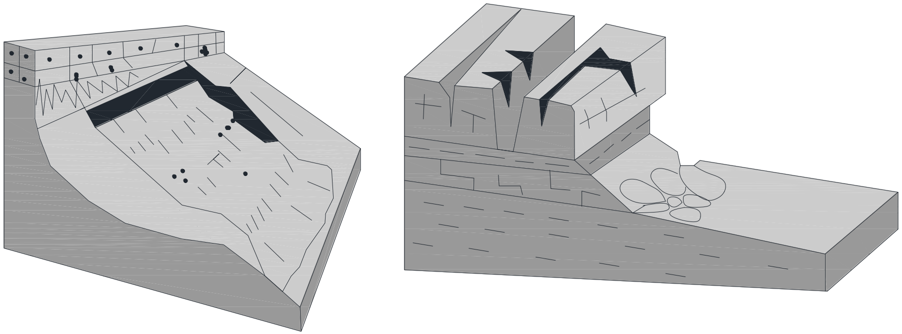

Figure 3. Schematics types of rotational and translational landslides (Varnes, 1978).

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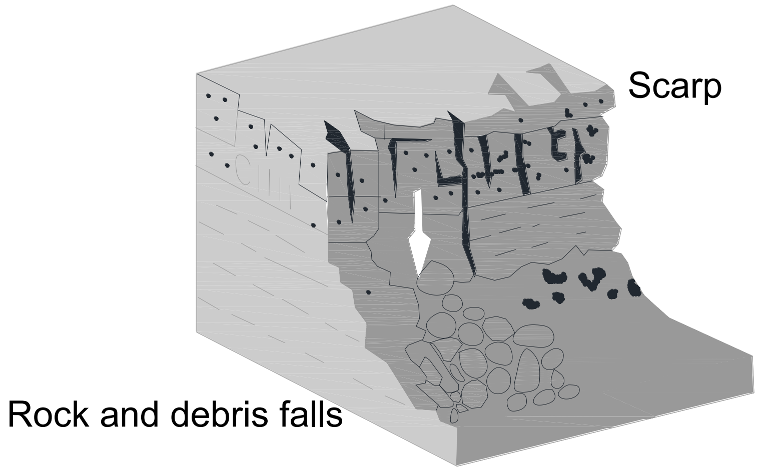

Figure 4. Schematics types of fallen rocks (Varnes, 1978).

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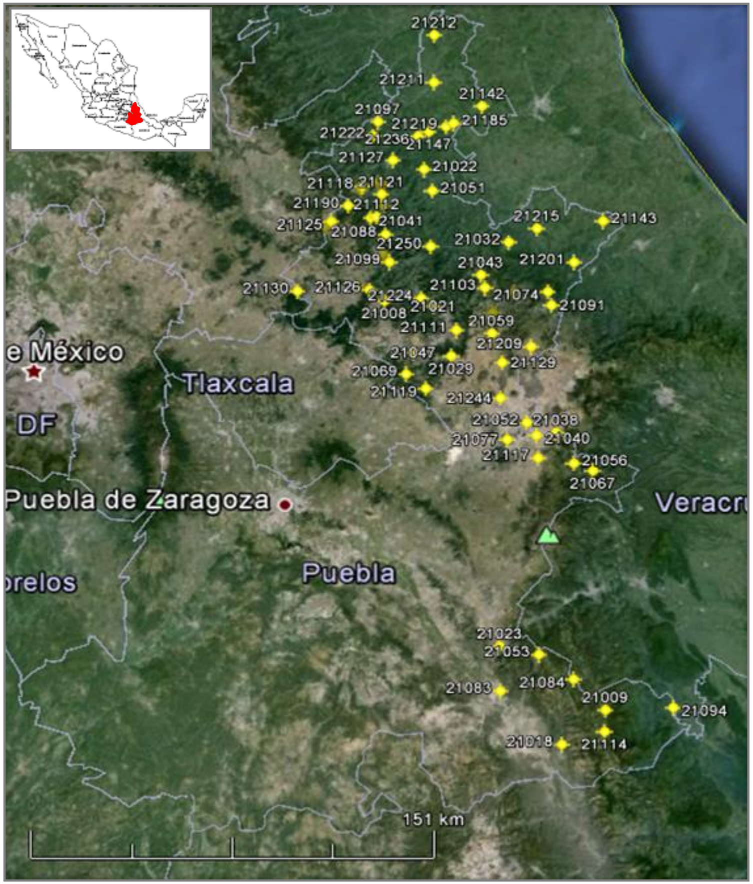

Figure 5. Locations of Weather Stations at mountainous regions of Puebla.

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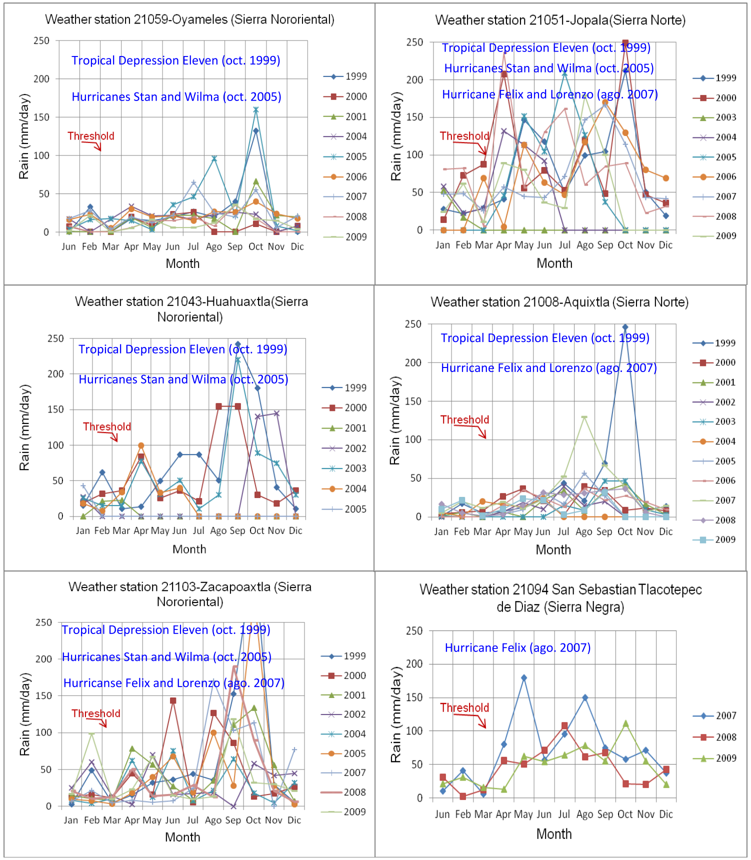

Figure 6. Graphics of monthly rainfall at mountainous regions of Puebla.

Figure 7. Vulnerable ethnic groups at the mountainous region of Puebla, México.

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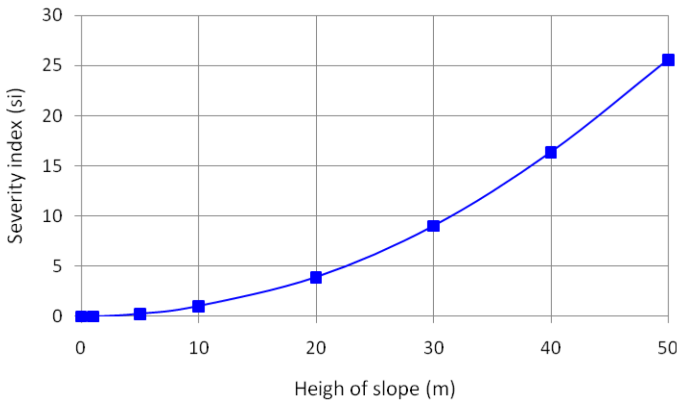

Figure 8. Height of slope vs. Severity Index.

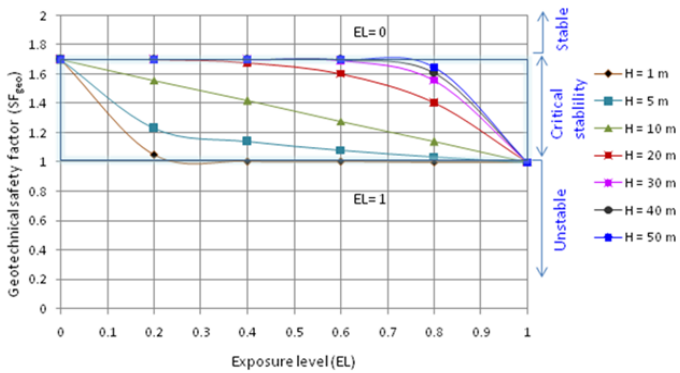

Figure 9. Exposure level vs. Geotechnical safety factor.

Figure 10. Elements at risk within the failure block (La Aurora landslide, Teziutlán Puebla, México).

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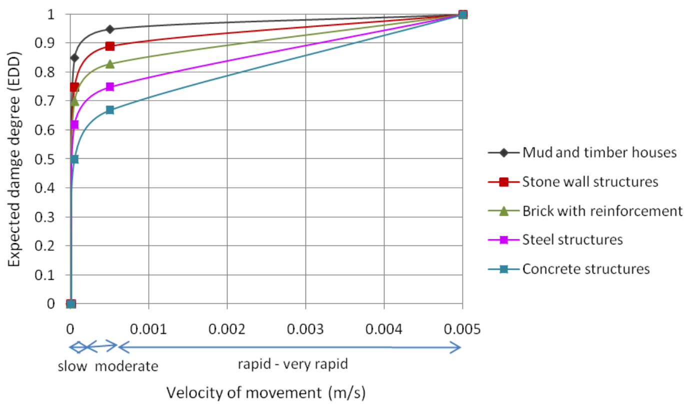

Figure 11. Velocity of movement vs. Expected damage degree.

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