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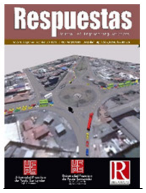

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Análisis y evaluación del riesgo por inestabilidad del terreno en proyectos de urbanización. Un estudio de caso en Tijuana, México

Analysis and assessment of the terrain instability in urbanization projects. A case study in Tijuana, Mexico

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ABSTRACT

This article explains aspects related to the risk produced by the terrain instability and its components (hazard and vulnerability), different methods to estimate it, its main conditioning and triggering factors, and the close link with urbanization processes in areas of rugged topography and complex geological - geotechnical conditions. A procedure is described that allows analyze and assessment this risk in urbanization projects, as an essential tool for making decisions about its feasibility and viability; and the results of its application in a case study in the metropolitan area of Tijuana, Mexico, are presented.

Keywords:

Hazard;
terrain instability;
urbanization projects;
risk;
vulnerability.

RESUMEN

En este artículo se explican aspectos relacionados con el riesgo producido por la inestabilidad del terreno y sus componentes (amenaza y vulnerabilidad), los diversos métodos y criterios para estimarlo, sus principales factores condicionantes y desencadenantes, y el estrecho vínculo con los procesos de urbanización en zonas de topografía accidentada y condiciones geológicas – geotécnicas complejas. Se describe un procedimiento que permite analizar y evaluar este riesgo en proyectos de urbanización, como herramienta esencial para la toma de decisiones sobre su factibilidad y viabilidad; y se presentan los resultados de su aplicación en un estudio de caso en la zona metropolitana de Tijuana, México.

Palabras clave:

Amenaza;
inestabilidad del terreno;
proyectos de urbanización;
riesgo;
vulnerabilidad.

Introduction

As a consequence of accelerated growth and insufficient territorial planning in some cities, many urban developments are built on land where topographic, geological and geotechnical conditions are not appropriate for supporting structures and infrastructure. In these scenarios, stresses and deformations in soil and rock masses are usually close to the admissible limit values, and anthropic processes during and after the execution of urbanization projects modify the equilibrium of the terrain and increase the risk of instability.

Risk due to terrain instability

This risk is defined as the probability of loss and damage to physical property and people, due to the occurrence of terrain instability phenomena that depend, to a large extent, on the geomorphological and geological-geotechnical conditions of the site; and the modification of these by geodynamic processes, land use, human activities, etc. [1-2]. Mathematically, risk is a function of hazard, understood as the probability of the occurrence of potentially destructive instability events; and vulnerability, defined as the degree of loss or damage that could occur in the exposed elements, if the threatening event were to occur [3].

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Successful risk estimation depends on the analysis and assessment stages being properly carried out [4]. The analysis consists of estimating the risk by quantifying the hazard and vulnerability, using all available information on the study area. While, in the assessment, it is determined whether the existing risk is acceptable (or not) and decisions are made on the control and mitigation measures to be implemented [5].

There are various methods and procedures for analyzing and assessing risk, but, in general, they can be grouped into three categories: qualitative, semi-quantitative and quantitative [6-7-8-9-10-11-12-13-14]. The first ones describe the risk in terms of high, moderate and low; while the quantitative methods express the quantity, cost and number of goods and people that could suffer damage or loss.

Urbanization vs. terrain instability

Many cities that have undergone accelerated and chaotic urbanization processes are located in mountainous areas where valleys and plains have been occupied by urban sprawl; and the areas available for new development present very complex topographic, geological and geotechnical conditions. In these cases, the analysis and evaluation of the risk of terrain instability is fundamental for making decisions on the feasibility of urbanization projects.

These projects are characterized by the generation of economic, financial, environmental, social and technical risks, which must be considered in the economic and financial structuring of their different stages. Soil instability is included among the technical risks that should be analyzed and evaluated at the study stage [15].

Urbanization and land instability in Tijuana: In Mexico, the increase in urbanization processes generated new patterns of population distribution and economic activities in certain territories called urban regions, among which the Northwest urban region, led by the metropolitan area of Tijuana, stands out for its growth and development [16].

This area has been characterized by an accelerated and chaotic expansion, with territorial growth rates of up to 3.5 hectares/day and population growth rates of over 6% per year [17]. By the 1970s, the urban sprawl had occupied practically all of the plains of the Tijuana River and the Alamar stream, and began to advance towards areas of hillsides characterized by the presence of ravines, canyons and steep slopes (Figure 1).

Figure 1. Tijuana's Metropolitan Area.
Source: Google Earth

Currently, there are very few areas available with good conditions for building urban works, so most urbanization projects are developed in hilly and geologically complex terrain, where instability phenomena are a constant danger. Consequently, the number and frequency of destructive events in urban developments built on hillsides has increased (Figure 2).

Figure 2. Damage caused by ground instability phenomena. a) Fraccionamiento Laderas de Monterrey (2010), b) Fraccionamiento El Palmar (2011), c) Fraccionamiento Terrazas de la Presa (2013), d) Fraccionamiento Valle Sur (2017).
Source: Municipal Directorate of Civil Protection, Tijuana

Materials and methods

This article describes and applies a procedure to analyze and evaluate the risk due to terrain instability, based on the characterization of the physical environment; it estimates the hazard based on the susceptibility and probability of occurrence of different phenomena; and determines the vulnerability considering characteristics and costs of the exposed threatened elements [1].

Description of the procedure

The procedure used is a quantitative method and consists of the following stages:

I. Investigation and characterization of the study area

Studies are carried out to identify conditioning and triggering factors of instability [18], to elaborate the geological-geotechnical models used to estimate and quantify the hazard, and to characterize the elements exposed to damage. Studies of: topography and geomorphology; geology and geotechnics; tectonics and seismic activity; hydrology and hydrogeology; vegetation; erosion and scour; and anthropic processes and human activity are recommended.

II. Hazard analysis and assessment

They are carried out based on the susceptibility and probability of occurrence of instability events. Threat is determined through equation (1):

$$H_i = f(S,P)\,|_t \qquad (1)$$

Where:

Hi is the hazard of an event of intensity i, at time t.

S is the susceptibility of the terrain to instability

P is the probability of occurrence of the event

It is proposed to determine the susceptibility using the following methods: a) Method of valuation factors for mass movements [7]; b) Expert criteria for other instability phenomena.

The probability of occurrence of instability events is estimated by deterministic methods that allow obtaining potential rupture surfaces, safety factors and displacements.

III. Analysis and assessment of the vulnerability of exposed elements

It is performed following the following stages: identification, location and characterization of the exposed elements; evaluation of the expected types of damage and; calculation of vulnerability using equation (2) [6-10].

$$V = \begin{cases} \frac{1}{2}\left(\frac{I}{1-F}\right)^2 & I \leq 1-F \\ 1-\frac{1}{2}\left(\frac{1-I}{F}\right)^2 & I > 1-F \end{cases} \qquad (2)$$

Where:

V is the vulnerability of the element exposed to the hazard.

I is the intensity of the event

F is the fragility of the exposed element

IV. Risk analysis and evaluation

The specific risk is calculated using equation (3).

$$R_s = H_i \; V \; C \qquad (3)$$

Where:

Rs is the specific risk, which expresses the degree of expected losses due to the materialization of the hazard of intensity i.

Hi is the hazard of intensity i

V is the vulnerability of the elements exposed to the hazard, expressed on a scale between 0 and 1.

C is the quantification of the exposed elements. In economic terms, it is the cost of the elements threatened.

Losses in physical assets are evaluated through the approximate cost of damage, as a percentage of the commercial value of the exposed elements, obtained considering the value of the actions to restore normality in the affected area. The approximate cost of damage makes it possible to categorize the risk, evaluate its acceptability and determine actions for its control and mitigation (Table 1).

Table I. Categorization of risk to physical properties

Approximate cost of damage	Category	Description
Over 60%	HIGH	Unacceptable risk
60 – 20%	MEDIUM	Can be tolerated in certain circumstances, but requires detailed investigation and planning to prevent it from escalating
20 – 0%	LOW	Usually acceptable to decision makers

Source: [9]

Case Study

The described procedure was applied in an urbanization project planned to be developed in the metropolitan area of Tijuana.

- Description of the project site

The study area is located in the so-called southwestern elongated sierras, and occupies an area of approximately 24 hectares, of lomerío relief, with heights of up to 275 meters and slopes of more than 35% (Table 2, Figure 3).

Table II. Terrain slopes in the study area

Portion of total area (%)	Pending (%)
10.30	0.00 – 5.00
17.20	5.00 – 15.00
11.20	15.00 – 25.00
6.20	25.00 – 35.00
55.10	> 35.00

Source: Authors

Two lithological units predominate in the site, in which there are soils consisting of coarse alluvium, conglomerates, sandstones with scattered boleos, slope deposits, and tuffs with clayey and sandy facies in most of the area.

Before requesting the study described in this article, the company responsible for the project carried out earthworks (cut and fill) in the area to form six platforms that will house lots for single-family homes, apartment buildings, a school and stores, as well as the embankments that will serve as the base for the main road connecting the platforms and the secondary roads inside the lots.

Figure 3. Location and details of the study area.
Source: Google Earth

Results and Discussion

The results of the analysis and evaluation of the risk of ground instability in the existing platforms and embankments are presented.

Investigation and characterization of the study area

Geological, geophysical, hydrological and geotechnical studies carried out in the area were reviewed and interpreted in order to characterize the physical environment in the study area. In addition, reports and technical reports of nine ground instability events that occurred in nearby areas with similar geotechnical characteristics were studied.

Hazard analysis and evaluation

It was carried out considering the probability of occurrence of ground instability phenomena, as well as the susceptibility of the terrain to their occurrence.

- Terrain stability analysis

The topographic profiles shown in Figure 4 were used, and methods based on limit equilibrium of potentially unstable land masses, as well as stress-strain analysis [19-20].

Figure 4. Location of the profiles selected for stability analysis.
Source: Authors

Table 3 presents the results of the analysis performed using methods based on limit equilibrium.

Table III. Minimum safety factors (F.Smín.) and depths of the potential breaking surfaces.

Profile	($F.S_{min.}$)	depths of the breaking surfaces (m)
A – A	0.95 – 1.00	12.00
B – B (Lower zone)	0.94 – 1.00	9.00
B – B (High zone)	1.11 – 1.19	15.00
C – C	1.04 – 1.17	9.00
D – D	1.02 – 1.15	4.00
E – E	0.98 – 1.04	5.00
F – F	1.05 – 1.18	3.00
G – G (Lower zone)	1.04 – 1.15	8.00
G – G (High zone)	1.19 – 1.28	7.00
H – H (Lower zone)	1.20 – 1.24	13.00
H – H (High zone)	1.10 – 1.15	12.00
Note: In the pseudo-static condition, a seismic ground acceleration of 0.30g (30% of the gravity acceleration) was considered.		

Source: Authors

Figure 5 shows the failure mechanisms corresponding to the minimum safety factors.

Figure 6 shows the behavior of horizontal and vertical displacements, which are estimated to occur in the terrain around the profiles with the highest probability of instability.

These movements could be unacceptable for the structures and infrastructures to be built.

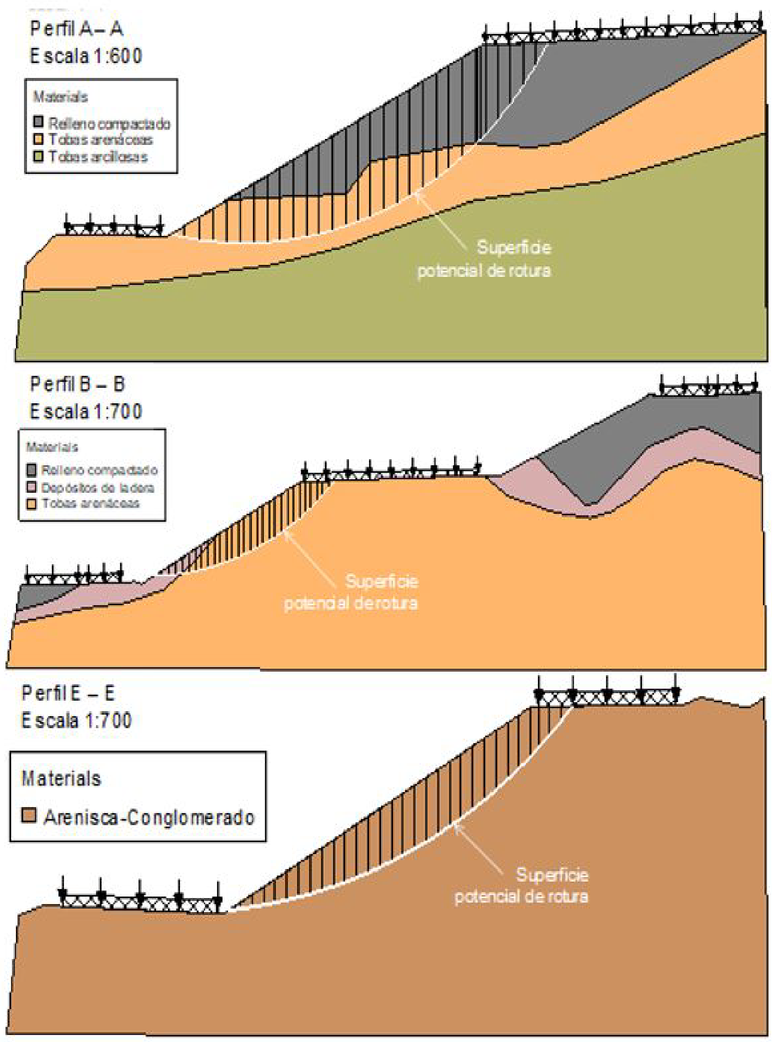

Figure 5. Potential breakage mechanisms.
Source: Authors

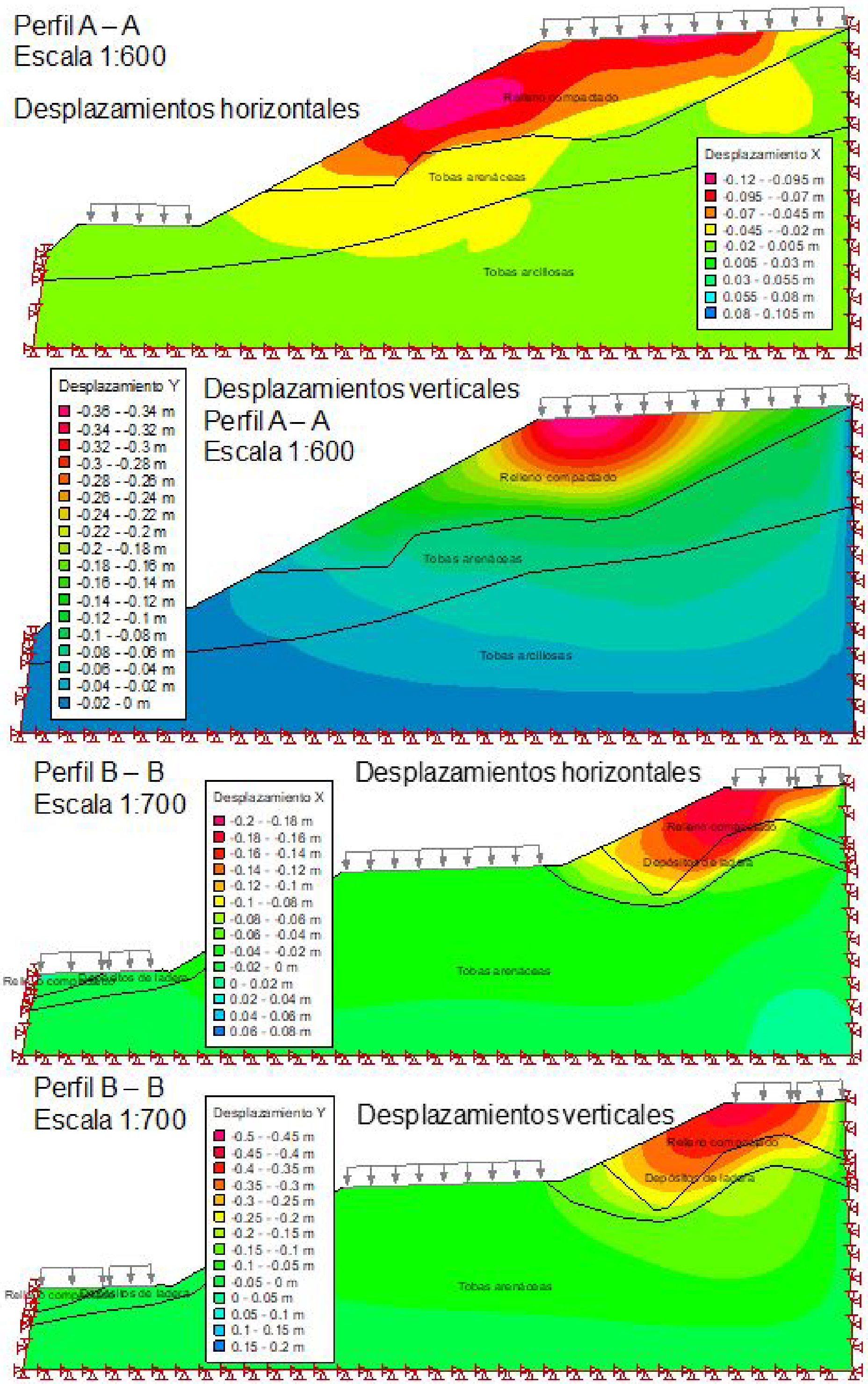

Figure 6. Estimated maximum displacements
Source: Authors

The calculated factors of safety, the depths of the rupture surfaces and the estimated displacements indicate that there is a high probability of occurrence of potentially destructive instability phenomena in the vicinity of profiles A and B.

- Susceptibility analysis

The influence of the instability conditioning and triggering factors identified in the study area was evaluated (Table 4).

Table IV. Evaluation factors considered in the susceptibility analysis

Valuation factor	Concept	Obtained as a function of:
Dependent on intrinsic characteristics of the slope	Morphology and topography	Terrain shape and slope
	Hydrogeology	Soil slope and degree of saturation
		Soil thickness
	Vegetation	Type of vegetation
		Foliage density
		Area covered
		Root type
Dependent on regional site conditions	Earthquakes	Seismic coefficient
	Erosion and scour	Surface soil characteristics
		Area of basins and sub-basins
		Drainage systems
	Human activity	Cuts or excavations
		Overburden
		Deforestation
Dependent on quantitative stability analysis	Rupture surface	Depth
	Factor of safety	Value

Source: Authors

The results of the susceptibility analysis are presented in Table 5.

Table V. Susceptibility assessment

Valuation factor	Profile A-A	Profile B-B
Morphology and topography	0.47	0.47
Hydrogeology	0.85	0.675
Vegetation	1.00	1.00
Seismic activity	1.00	1.00
Erosion and scour	0.25	0.45
Human activity	0.83	0.83
Quantitative stability analysis	0.875	1.00
General factor	**0.75**	**0.78**
Note: Factors with a value of 0.75 are considered to have a high influence on ground instability.		

Source: Authors

Table 6 and Figure 7 present the results of the terrain instability hazard analysis and assessment.

Table V. Threat classification

Profile	($F.S_{min.}$)	Threat $H_i = f(S,P)\|_t$	Level threat
A – A	< 1.00	0.750	ALTA
B – B	< 1.00	0.780	ALTA

Source: Authors

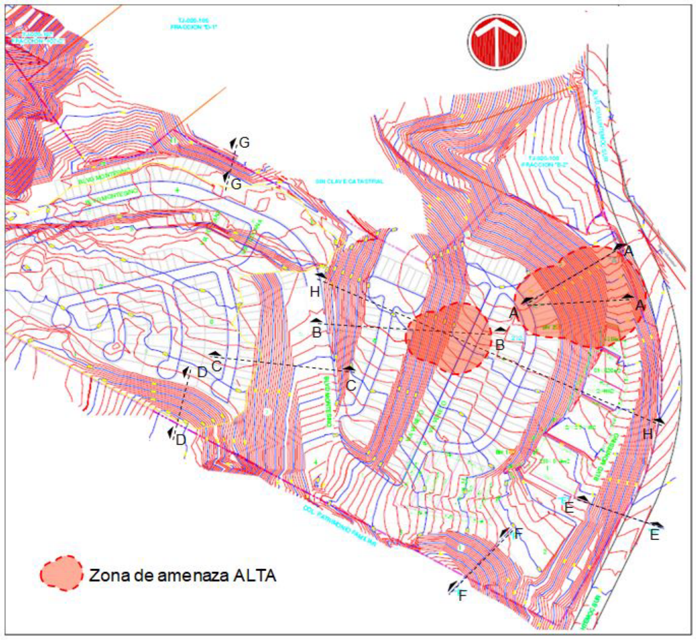

Figure 7 Terrain instability hazard zoning.

Source: Authors

Vulnerability analysis and assessment

It was performed following the following stages [5]: identification and zoning of exposed elements (Figure 8); characterization; expected damage analysis (Table 7); and vulnerability calculation.

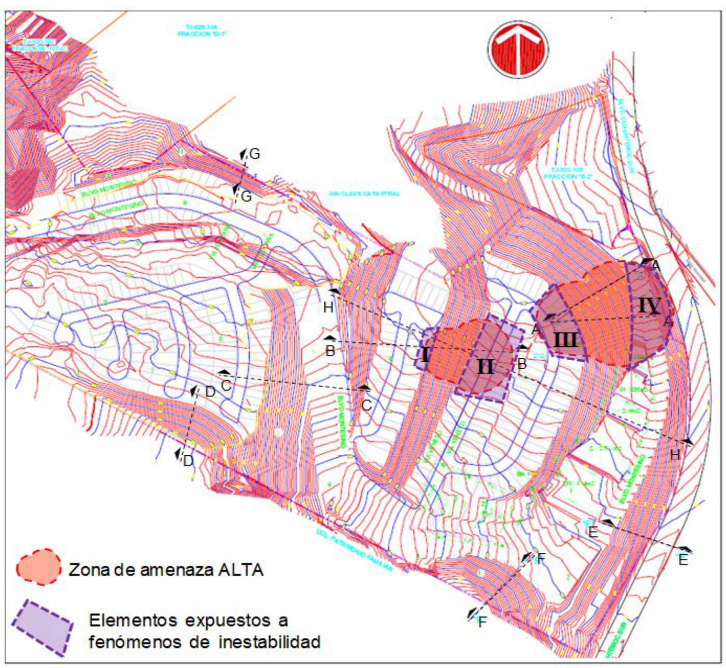

Figure 8 Elements exposed to instability phenomena
Source: Authors

- Vulnerability calculation

It was made based on the intensity (I) of the threatening movements and the fragility (F) of the exposed elements, according to equation (2) (see Table 8).

Table VII. Characterization of the exposed elements (typology and exposure scenario) in each zone, expected damage and fragility.

Zone	Characterization of the exposed elements
I	Elements: housing Typology: Reinforced masonry buildings. Exposure scenarios: elements located on a potentially unstable slope or slope or affected by retrogression effects. Expected damage: collapse or damage due to loss of support in the retrogression zone; differential settlement, tilting and cracking associated with slow movements; and collapse of structures associated with rapid movements. Fragility: 0.55
II	Element: housing and roads Typology: reinforced masonry buildings and interior roads. Exposure scenarios: elements located in the path of the landslide or in the deposit zone of the sliding material. Expected damage: localized damage due to impact, total collapse, obstruction, and burial, among others. Fragility: 0.55
III	Elements: housing and roads Typology: reinforced masonry buildings and interior roadways Exposure scenarios: elements located on a potentially unstable slope or slope or affected by retrogression effects. Expected damage: collapse or damage due to loss of support in the retrogression zone; differential settlement, tilting, and cracking associated with slow movements; collapse of structures associated with rapid movements Fragility: 0.55
IV	Elements: housing and roads Typology: reinforced masonry buildings and interior roadways Exposure scenarios: elements located in the path of the landslide or in the deposit zone of the sliding material Expected damage: localized damage due to impact, total collapse, obstruction, and burial, among others. Fragility: 0.55

Source: Authors

The intensity was obtained considering that the potentially unstable terrain can move at a speed of up to 3.22 m/day, estimated from the results of monitoring landslides that have occurred in nearby areas, with conditions similar to the study area.

Table VIII. Vulnerability of elements exposed to the threat of ground unstable threat

Zone	Frag. (F)	Int. (I)	Vulnerability
I	0.55	1.00	0.96
II	0.55	1.00	1.00
III	0.55	1.00	1.00
IV	0.55	0.85	0.96

Source: Authors

The results indicate high vulnerability to ground instability phenomena.

Risk analysis and assessment

- Risk analysis

This was carried out considering the hazard, vulnerability, and the value of the exposed elements (Tables 9 and 10).

- Risk analysis

Expected losses were calculated based on the approximate cost of damage, estimated from the cost of the required stabilization works (Table 11).

Table IX. Risk due to soil instability

Zone	Threat	Vulnerability	Risk
I	0.780	0.963	0.751
II	0.780	1.000	0.780
III	0.750	1.000	0.750
IV	0.750	0.963	0.722

Source: Authors

Table X. Risk expressed in economic losses (in mexican pesos)

Zone	Risk	Approximate value of the exposed elements	Risk (losses on securities)
I	0.751	\$8,800,000.00	\$6,608,727.27
II	0.780	\$22,000,000.00	\$17,160,000.00
III	0.750	\$17,600,000.00	\$13,200,000.00
IV	0.722	\$13,200,000.00	\$9,531,818.18

Source: Authors

Table XI. Categorization of the risk of land instability and actions for its reduction.

Approximate cost of damage	Category	Description
4.11%	UNDER	Usually acceptable to decision makers. Required: - Some project modifications (architectural, urban planning and infrastructure). ● - Normal slope and hillside protection and maintenance.

Source: Authors

Discussion

In the field of urbanization projects, the risk of ground instability refers to the probability of damage or loss to urban structures and infrastructure that are planned to be developed, due to the occurrence of phenomena such as subsidence, settlement and mass movements of soil and rock. In areas of rugged relief and complex geological-geotechnical conditions, the analysis and evaluation of these risks at the study stage is an essential tool for making decisions on the feasibility and viability of projects.

In the metropolitan area of Tijuana, land with good conditions for urban development is very scarce, and new projects must adapt to scenarios that require major transformations in the physical environment, which alter the equilibrium of the terrain and considerably increase the risk of instability.

The risk analysis and evaluation in the case study presented not only validated the procedure described, but also identified the sectors most likely to be affected by instability phenomena, estimated the damages that could occur and their costs, categorized the risk, evaluated its acceptability and proposed measures for its control and mitigation.

Conclusions

Ground instability may be the cause of failure of urbanization projects in areas of rugged topography and complex geological-geotechnical conditions, if the analysis and evaluation of this risk is not considered in the feasibility studies.

The analysis and evaluation of the risk due to terrain instability, carried out in the project to be developed in Tijuana, made it possible to quantify the threat of potentially destructive phenomena and the vulnerability of the elements exposed to be affected, identify the areas with a high probability of suffering damage, and estimate the approximate cost of the damage. With these results, the risk was categorized and actions for its reduction were proposed.

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