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Practical procedure for the assessment of the stability and probability of failure of cut slopes in the urban area of Tijuana, Mexico

Procedimiento práctico para evaluar la estabilidad y probabilidad de falla de taludes de corte en el área urbana de Tijuana, México

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ABSTRACT

Keywords:

Slope stability, slope failure, safety level, probability of failure.

Slope failures in the urban area of Tijuana affect many structures and infrastructures every year, causing significant losses in various sectors of the economy. This paper presents a practical and innovative procedure for the assessment of the stability of shear slopes in a sector of the urban area, based on existing information about the study area, as well as on the judgment and experience of the authors. This procedure makes it possible to determine the safety level of slopes with different geometries, seismicity, and saturation conditions; and to estimate the probability of instability phenomena occurring, based on a correlation between the safety factors and the annual probability of failures, or by applying a probabilistic model based on historical records of failures in areas where the conditioning and triggering factors of instability are like those of the study area. The application of the approach and procedure in some real cases show that they are feasible and could be a very useful tool both for the design of slopes and for the correction of the failures that occur in these earth structures.

RESUMEN

Palabras clave:

Estabilidad de taludes,
fallas de taludes,
nivel de seguridad,
probabilidad de falla

Las fallas de taludes en el área urbana de Tijuana, afectan cada año gran cantid ad de estructuras e infraestructuras, produciendo cuantiosas pérdidas en diversos sectores de la economía. En este trabajo se presenta un procedimiento práctico e innovador para evaluar la estabilidad de taludes de corte en un sector del área urbana, basado en información existente sobre el área de estudio, así como en el juicio y experiencia de los autores. Dicho procedimiento permite determinar el nivel de seguridad de taludes con diferentes geometrías, condiciones de sismicidad y de saturación; y estimar la probabilidad de que se presenten fenómenos de inestabilidad, a partir de una correlación entre los factores de seguridad y la probabilidad anual de fallas, o mediante la aplicación de un modelo probabilístico basado en los registros históricos de fallas ocurridas en zonas donde los factores condicionantes y desencadenantes de inestabilidad sean similares a los del área de estudio. La aplicación del enfoque y procedimiento en algunos casos reales, demuestran que son viables y que podrían ser una herramienta de mucha utilidad tanto para el diseño de taludes, como para la corrección de las fallas que se producen en estas estructuras térreas.

1. Introduction

Slope failures result from a combination of geomorphological, geological, geotechnical, and hydrological conditions, as well as geodynamic processes, land use, and human activities. The frequency, magnitude, and intensity of natural phenomena such as rainfall and earthquakes can also modify these conditions. The presence of faults is subject to various degrees of uncertainty due to the potentially unstable land mass, which may consist of different materials and exhibit different types of movements, velocities, and rupture mechanisms. Additionally, there are uncertainties related to the reliability of the data used to model the problem, as well as uncertainties stemming from human factors and the mathematical models employed to analyze the problem. Anthropogenic transformations caused by accelerated growth and inadequate territorial planning in many cities

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create conditions that lead to geotechnical failures. Especially the formation of slopes by means of cuts in the terrain is an important triggering factor for instability [2].

Slope failure is the downward movement of a land mass along a surface, either flat or curved, with respect to the remaining static mass. The causes and mechanisms of slope failure are generally progressive over time. The maximum shear strength along the rupture surface is typically considered applicable to the analysis of early failures, while the residual shear strength should be considered when analyzing possible reactivation of old movements [3]. To determine whether a slope is stable, the factor of safety is generally used, whose definition and values along the potential failure surface have been widely studied and debated by different authors [4-5-6-7-8-9].

To address slope instability issues, it is crucial to accurately assess its safety level by effectively managing the geotechnical fundamentals that govern its stability. There are various methods and procedures available to determine the factor of safety, and they typically yield similar results when properly applied [10-13]. If the factor of safety falls below certain admissible limit values that ensure stability, the slope is considered potentially unstable. It is then necessary to estimate the probability of failure. Three accepted ways of estimating slope failure probabilities are reported in the technical literature: based on historical data of frequencies of observations, from the mathematical model of probability theory, or by quantifying subjective probabilities using expert judgment.

Tijuana, Mexico, is an example of rapid and disorderly urban expansion. The urban area has historically experienced territorial growth rates of up to 3.5 hectares per day and population growth rates of over 6% per year. Currently, it is expanding towards areas of irregular topography characterized by canyons and steep slopes. Anthropogenic factors, together with geomorphological, geological, and geotechnical complexity, as well as seismic activity, make it difficult to predict the risk of slope failure occurrence [13-14]. In Tijuana's urban area, residential and industrial developments coexist on potentially unstable slopes and on land masses previously affected by landslides [15]. This paper presents a procedure for the assessment of the stability and probability of failure in a sector of the urban area of Tijuana, developed from a practical approach based on existing geologic and geotechnical information, the historical record of past failures, expert judgment, and the authors' experience.

1.1 Shear slope failure in the urban area of Tijuana

Over the past three years, shear slope failures have been reported in five urban neighborhoods, resulting in severe damage to at least 25 homes and putting nearby structures and infrastructure at risk (see Figure 1).

Figure 1. Sites affected by slope failures in the urban area of Tijuana.

1.2 Conditioning and triggering factors of slope instability

1.2.1 Conditioning factors. These factors are related to terrain characteristics that promote instability, with geological, geotechnical, geomorphological, and tectonic conditions standing out for their significant influence. In the Tijuana sub-basin, which extends to the city of San Diego, California (United States of America), deposits from the Rosarito Beach and San Diego geological formations are present.

The Rosarito Beach Formation lies on continental deposits comprising mudstones and lacustrine sandstones. The San Diego Formation was subsequently deposited on top of it, consisting of two lithostratigraphic units: a lower unit mainly composed of fine sandstones, and an upper unit formed by sandstones and conglomerates (refer to Figure 2). Minch (1967) identified two more members of the San Diego Formation. The lower member comprises fine to medium-grained sandstones with occasional conglomerate lenses, while the upper member consists of medium to coarse-grained sandstones and sandy conglomerates. Basically, the predominant stratigraphy in the urban area comprises siltstone-sandstone, basalt, sandstone-conglomerate, alluvium, conglomerate, sandstone, and igneous rock [17-18-19]. However, a significant portion of the city is constructed on superficial deposits consisting of boleos, gravels, sands, silts, and interbedded clay lenses.

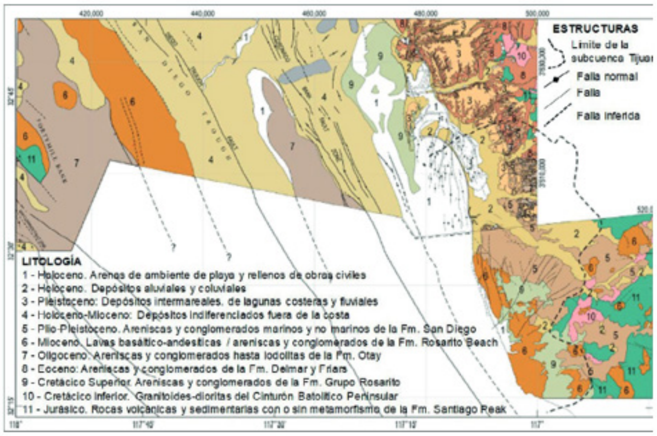


Figure 2. Geologic map of the San Diego, California, USA - Tijuana, Baja California, Mexico area. Source. [16].

Tijuana's primary geomorphological feature is the river that shares its name. The river flows through a plain that is approximately 2 km wide and 18 km long. To the northeast of the river lies an area of plateaus, while to the southwest, a mountainous massif is characterized by a high density of dissecting natural drainages. Some of these drainages flow towards the Tijuana River, while others flow towards the Pacific Ocean [20-14]. The city's expansion in the river basin and its tributary micro-watersheds has been facilitated by this geomorphology. More than half of the urban area is situated on slopes with gradients of over 35%. In these areas, water currents cause erosion that weakens the terrain.

Tijuana is situated in a tectonically active zone referred to as the "Southern California Shear Zone" [21]. This zone is delineated by the Transverse Sierras to the north in the western United States, the "Agua Blanca" fault system to the south, the "San Andres" fault zone to the east, and the "San Clemente" fault system to the west. In the northern region of the Baja California peninsula, a complex arrangement of seismically active faults, oriented to the northwest, has developed, creating a condition of high seismic risk (see Figure 2). This tectonic framework serves as a significant factor in generating vibrations and inertial forces that trigger ground instability phenomena. Several residential and industrial zones in the urban area are exposed to high vulnerability due to these conditions [22-23].

1.2.2. Triggering factors. Triggering factors can modify initial conditions and significantly affect the stability of terrain, leading to slope failures. In the urban area of Tijuana, weathering, erosion, and human activity are the most important factors that produce destabilizing actions, such as changes in terrain geometry, increased loads, modification of surface and groundwater flows, changes in vegetation cover, and deforestation [15]. The urban landscape is characterized by predominant geoforms, large gullies, and deep furrows on slopes and hillsides, which reflect the effects of weathering and erosion on the exposed ground surface. The anthropic factor that most contributes to terrain instabilities and slope failures in the urban area of Tijuana is the cutting of slopes without prior geotechnical studies or designs.

2. Methodology

The methodology used to formulate a procedure for assessing slope stability in urban areas prone to ground instability phenomena is described. The methodology encompasses the following phases or stages:

- Identification of areas susceptible to instability.
- Elaboration of abacuses to determine slope safety factors.
- Analysis and assessment of methods to estimate the probability of slope failure.

2.1 Identification of areas susceptible to instability

Based on geological-geotechnical studies and historical records of geotechnical instability phenomena, areas susceptible to slope failures were identified (see Figure 3).

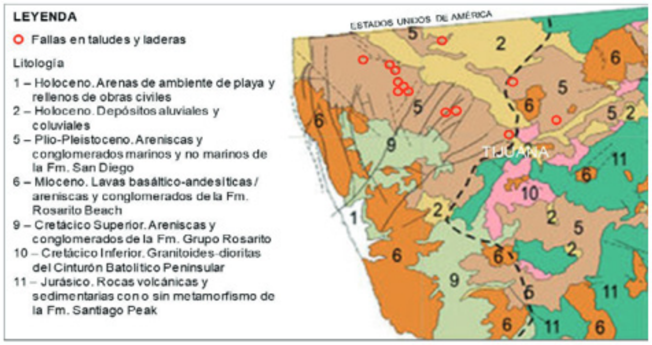


Figure 3. Slope and hillside failures recorded in the urban area of Tijuana (between 2010 and 2020).

Most of the failures have occurred in lithologic unit 5, characterized by marine and non-marine sandstones and conglomerates of the San Diego Formation [16]. In their natural state, these formations consist of silty and clayey sands with gravels and boleos.

2.2 Development of abacuses for determining slope safety factors

Abacuses were developed based on the minimum safety factors of cut slopes in areas prone to instability (lithological unit 5, see Figure 3). These factors were calculated using limit equilibrium methods, taking into account the following considerations:

- Ranges of values of physical-mechanical parameters of the terrain, obtained by laboratory tests and analysis, were used (Table 1).

Table 1. Geotechnical parameters considered in the stability analysis.

Soil type / Geological Fm	Volumetric Weight (KN/m^3)	Angle of friction (degrees)	Cohesion (Kpa)
Sandy and clayey sands with gravels and volleys /San Diego Fm	18 - 21	28 - 32	10 - 15

- The study analyzed the stability of shear slopes with varying heights (H) and inclinations (α) ranging from 26° to 64°. The seismic accelerations (a) established by the NTC of Baja California [24] and different levels of ground saturation (S) were taken into consideration.
- Minimum safety factors were calculated for potential fault surfaces located above and below the foot of the slope (see Figure 4).

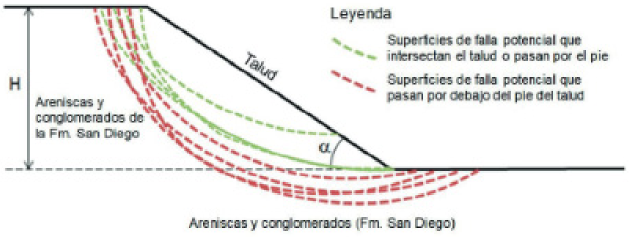


Figure 4. Schematic representation of potential failure surfaces.

2.3 Analysis and assessment of the probability of failure of slopes

To estimate the probability of failure of shear slopes in the areas susceptible to instability described in Section 2.1, the following methods were analyzed and assessed:

- Probabilistic model using historical records of occurring failures (temporal probability of occurrence)
- Correlation based on real engineering projects and obtained by quantifying expert judgment (probability of failure vs. factor of safety).

2.3.1 Temporal probability of occurrence. It can be estimated from the historical records of failures occurring in the study area. This probability was obtained using the Poisson model [25], which is mathematically expressed by equation (1):

$$P(N_L) = 1 - e^{-\frac{T}{RI}},\ RI = \frac{t}{N} \qquad (1)$$

Where T is the return period, RI is the historical mean recurrence interval, t is the time interval of the failure database, and N is the number of recorded failures.

2.3.2 Probability of failure vs factor of safety. The correlation between the annual probability of failure and the safety factor developed by Silva (2008) [26] is proposed for use. This correlation is considered adequate as it complies with the fundamental considerations of probability theory and makes good practical sense (see Figure 5).

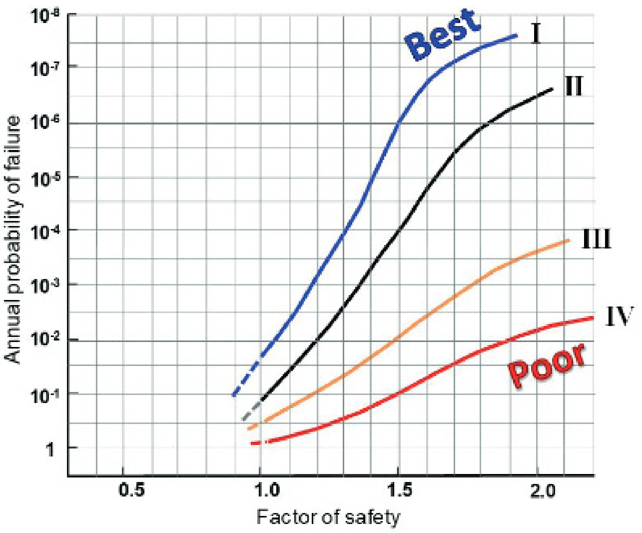


Figure 5. Annual probability of failure vs. safety factor. Source. [26].

The curves in Figure 5 represent four categories of projects based on the level of engineering, ranging from the best (category I) to the worst (category IV) [26].

- Category I: facilities designed, constructed, and operated with state-of-the-art engineering and complying with current standards and technical specifications.
- Category II: facilities designed, constructed, and operated using standard engineering practices.
- Category III: facilities that did not have design and are poorly constructed or operated.
- Category IV: facilities with little or no engineering.

3. Results

3.1 Determination of the safety level

To assess the safety level of slopes composed of silty and clayey sands with gravels and boleos of the San Diego Formation (refer to Table 1), the proposed safety factors in Tables 2 and 3 were utilized. These factors were calculated for seismic accelerations stipulated in the technical standard, as well as for various levels of soil saturation.

Table 2. Safety factors for different seismic accelerations (a).

Slope		Minimum Factor of Safety (F. Smin)				
H (m)	α (°)	a=0	a= 0.24g	a=0.3g	a=0.36g	a=0.38g
3.60	31	*3.77*	*2.52*	*2.33*	*2.19*	*2.14*
4.90	35	*2.42*	*2.06*	*1.93*	*1.83*	*1.80*
6.40	38	1.96	1.73	*1.64*	1.56	1.53
8.10	42	1.63	1.46	1.38	1.32	1.30
10.00	45	1.43	1.26	1.20	1.14	1.13
12.10	48	1.20	1.10	1.05	1.01	1.00
14.40	50	1.06	0.99	0.94	0.91	
16.90	52	0.96				

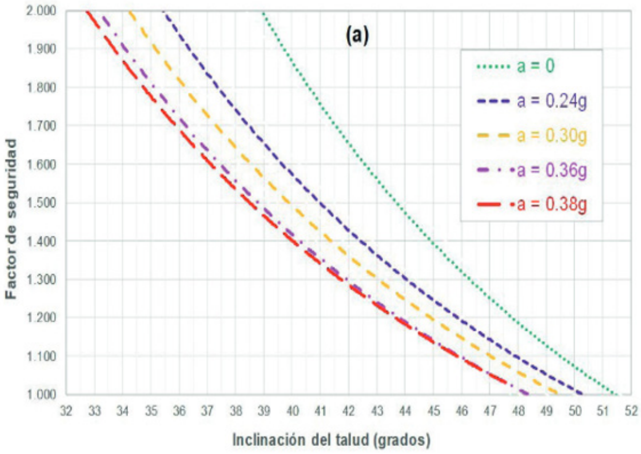
- g is the acceleration of gravity
- Factors in italics correspond to failure surfaces below the base of the slope, the rest correspond to surfaces intersecting the slope or passing through the footing.
- For the same slopes (α) and heights (H) higher than those indicated the F. Smin are reduced by approximately 3% for each meter.

Table 3. Factors of safety for different percentages of soil saturation.

Slope		Minimum Factor of Safety (F. Smin)				
H (m)	α (°)	S=0	S= 25	S=50	S=0.75	S=100
3.60	31	*3.77*	*2.86*	*2.60*	*2.44*	*2.35*
4.90	35	*2.42*	*2.26*	*2.01*	*1.81*	*1.74*
6.40	38	1.96	*1.84*	*1.61*	*1.42*	*1.36*
8.10	42	1.63	*1.53*	1.35	*1.17*	*1.08*
10.00	45	1.43	*1.39*	1.11	0.94	0.86
12.10	48	1.20	1.16	0.96	0.80	
14.40	50	1.06	1.06	0.85		
16.90	52	0.96	0.94			

- Factors in italics correspond to failure surfaces below the base of the slope, the rest correspond to surfaces intersecting the slope or passing through the footing.
- For the same slopes (α) and heights (H) higher than those indicated the F. Smin are reduced by approximately 3% for each meter.

Figures 6(a) and 6(b) show the abacuses of minimum factors of safety performance for different accelerations and soil saturation levels, respectively.



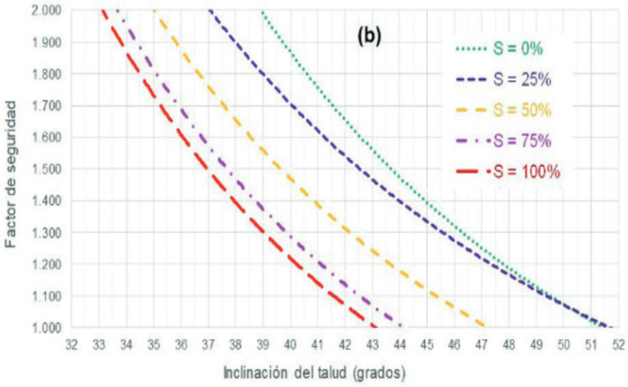


Figure 6. Minimum factors of safety vs slope inclination. (a) For different seismic accelerations; (b) for different ground saturations.

Table 4 shows the recommended inclinations to achieve acceptable safety levels for slopes with heights not exceeding 20m.

Table 4. Recommended slopes for cut slopes with H ≤ 20m in the analyzed terrain.

Recommended slope to achieve FSmin = 1.3, according to seismic acceleration			
a=0.24g	a=0.30g	a=0.36g	a=0.38g
44°	43°	42°	42°
Recommended slope to achieve FSmin = 1.3, depending on soil saturation.			
S=25%	S=50%	S=75%	S=100%
46°	42°	40°	39°

3.2 Estimation of the probability of failure

If the safety level of the slope is unacceptable because the factor of safety is lower than the limit allowed by the regulations, it is recommended to estimate the probability of failure.

3.2.1 Temporal probability of occurrence. The estimation was made using failure data recorded in the lithologic unit described as the marine and non-marine sandstones and conglomerates of the San Diego Formation (see Figure 3). Within this lithologic unit, 13 events have occurred in the last 21 years, resulting in a historical mean recurrence interval (RI) of 1,615 years, and an annual probability of failure of approximately 0.619. Figure 7 illustrates the temporal probability of occurrence of slope failures for longer return periods, calculated using equation (1).

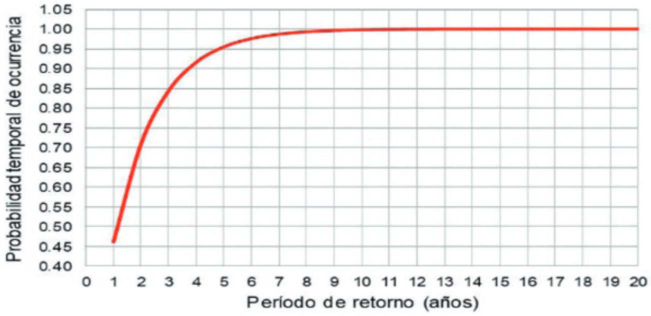


Figure 7. Temporal probability of occurrence vs. return period.

As can be seen, the probability of occurrence of cut slope failures in the study area is very high (between 0.46 and 1.00) for return periods shorter than the lifetime of any engineering project.

3.2.2 Probability of failure vs factor of safety. To use the correlation between the annual probability of failure and the factor of safety explained in section 2.3.2, the following procedure is proposed:

- Categorize the projects and facilities where the slopes under analysis are located. Prioritize geotechnical aspects during the study, design, and construction phases for the slopes, structures, and infrastructures in their immediate vicinity.
- Determine the factor of safety of the slopes, using Tables 2 and 3, or Figures 6(a) and 6(b).
- Estimate the annual probability of slope failure from the factors of safety and project categories using Figure 5.

3.3 Application of the procedure

To test the feasibility and practicability of the procedure, three slopes in the urban area where failures occurred between December 2019 and July 2020 were analyzed (Figure 8).

Figure 8. Location of slopes analyzed on the geologic map of Tijuana.

Based on the results of studies conducted subsequent to the failures, data were acquired regarding the existing structures and infrastructure at the affected sites, as well as the geometric, geotechnical, hydrological, and seismic conditions of the slopes at the time of the failures. Utilizing this information, the proposed procedure was implemented, leading to the determination of the category of the projects and facilities situated at the sites of the failed slopes. Additionally, the safety factors and annual probabilities of failure at the time of the collapse were identified (refer to Table 5).

Table 5. Results of the application of the proposed procedure on the analyzed slopes

Slope	Category of projects	Inclin.	FS mín	Annual prob. of failure
1	III. The existing structures and infrastructures at the site were not designed and the construction processes were not adequately controlled or supervised	54°	0.90	0.75
2		56°	0.80	1.00
3		63°	0.65	1.00

The results validate the proposed procedure because they indicate that the slopes had very low safety levels and a very high probability of failure.

4. Discussion

The design and construction of cut slopes in terrain with irregular topography and complex geological and geotechnical conditions have been difficult tasks for engineers throughout history. However, when these scenarios are found in urban areas where various natural and anthropogenic factors are combined and the occurrence of failures can affect not only many structures and infrastructure, but also the lives of many people; it is imperative to include risk analysis and assessment at all stages of the project, with special emphasis on decision making. Geotechnical engineers face the great challenge of correctly determining safety levels, estimating failure probabilities, and making risk-based decisions to avoid or mitigate the negative impact of slope failures on physical assets, lifelines, and people in urban areas around the world.

The aim of this work is to provide engineers with a practical and reliable tool for designing and correcting failures in earth structures, specifically cut slopes in the urban area of Tijuana. The presented procedure assesses slope stability by determining safety levels and estimating the probability of failure occurrence. It was elaborated using existing geological and geotechnical data and information on the study area, historical records of past failures, expert judgment, and the experience of the authors.

5. Conclusions

The city of Tijuana, Mexico experiences slope instability due to complex geomorphological, geological, and geotechnical conditions, as well as rapid and unplanned urban growth. The application of the procedure in three slopes where failures occurred recently, demonstrated its viability, feasibility, and reliability, since it was found that, at the time of the failures, the slopes presented very low levels of safety and, consequently, a very high probability of occurrence of failures. The study area has experienced a significant number of failures in the past 20 years. It is important to note that the presented results and recommendations are only applicable to shear slopes in the lithologic unit consisting of marine and non-marine sandstones and conglomerates of the San Diego Formation. Similar approaches and procedures, applicable to other lithologic units in the urban area of Tijuana, will be presented in subsequent works.

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7. References

[1] N. R. Morgenstern, “Toward landslide risk assessment in practice”, In Proc., International Workshop on landslide risk assessment, 15 – 23. Honolulu, Hawaii, USA, 1997.

[2] O. A. Cuanalo, A. O. Oliva, R. J. Gallardo, “Inestabilidad de laderas. Influencia de la actividad humana”, Revista Elementos, vol. 84, pp. 39 – 46. BUAP, México, 2011.

[3] R. Chowdhury, and P. Flentje, “Practical reliability approach to urban slope stability”, In Proc., 11th International Conference on Applications of Statistics and Probability in Civil Engineering, ETH Zurich, Switzerland, 2011.

[4] S. Wright, F. Kulhawy, and J. Duncan, “Accuracy of Equilibrium Slope Stability Analysis”, Journal of the Soil Mechanics and Foundations Division, vol. 99 (10), pp.783 – 791, 1973. Doi: https://doi.org/10.1061/JSFEAQ.0001933

[5] J. Lowe, “Stability Analysis of Embankments”, Journal of Soil Mechanics and Foundations Division. Vol. 93 (4). pp1 – 33, 1976. Doi: https://doi.org/10.1061/JSFEAQ.0000984

[6] J. M. Duncan, “State of the Art: Limit Equilibrium and Finite-Element Analysis of Slopes”, Journal of Geotechnical Engineering, Vol. 122 (7), pp. 577 – 596, 1996. Doi: https://doi.org/10.1061/(ASCE)0733-9410(1996)122:7(577)

[7] J. Suárez, “Deslizamientos y estabilidad de taludes en zonas tropicales”, Editorial UIS, Colombia, 1998.

[8] E. Juárez, y A. Rico, “Mecánica de suelos”, Vol. 1 y 2, Editorial Limusa, México, 2003.

[9] O. A. Cuanalo, “Metodología para la selección de procesos constructivos empleados en estabilizar deslizamientos de laderas”, Tesis Doctoral, Universidad Central Marta Abreu de Las Villas, Santa Clara, Cuba, 2004.

[10] A. O. Oliva, “Análisis de la estabilidad y seguridad de taludes”, Tesis Doctoral. Universidad de Oviedo, España, 1999.

[11] T. W. Lambe, and F. Silva, “Evaluating the stability of an earth structure”, In Proc., 12th Pan-American Conf. on Soil Mechanics and Foundation Engineering, 2785–2790. Cambridge, Mass, Verlag Gluckauf GmbH, Essen, 2003.

[12] J. M. Duncan, and S. G. Wright, “Soil strength and slope stability”, Hoboken, Wiley, N.J., U.S.A., 2005.

[13] A.O. Oliva-González, D. Mascareño Jiménez, R.J. Gallardo-Amaya, M.A. Berumen-Rodríguez, “Urban growth and landslide risk in Tijuana, Mexico”, Academia Letters, Article 3386, (2021). Doi: https://doi.org/10.20935/AL3386

[14] A. O. Oliva-González, J. Zambrano-García, M. A., Berumen-Rodríguez and R. J. Gallardo-Amaya, “Análisis y evaluación del riesgo por inestabilidad del terreno en proyectos de urbanización. Un estudio de caso en Tijuana, México”, Respuestas, 25(3), 234–249, 2020. Doi: https://doi.org/10.22463/0122820X.2455

[15] A. O. Oliva, M. A. Berumen, R. J. Gallardo, and H. Y. Jaramillo, “Terrain instability in the Tijuana metropolitan area: Analysis of a failure in the access road to an industrial park”, Engineering Failure Analysis, 104, pp. 354–370, 2019. Doi: https://doi.org/10.1016/j.engfailanal.2019.05.040

[16] L. A. Delgado-Argote, M. A. Pérez-Flores, F. Herrera-Barrientos, O. Sarychikhina, M. Contreras-López, L. Ochoa-Tinajero, and T. A. Avilés-Esquivel, “Interpretación geológica y geoeléctrica de un deslizamiento rotacional relacionado con paleodrenaje en el fraccionamiento Valle del Sur, en Tijuana, Baja California”, Rev. GEOS, vol. 37 (2), 1 – 17. México, 2017.

[17] J. A. Minch, “Stratigraphy and structure of the Tijuana-Rosarito Beach area, northwestern Baja California, Mexico”, Geological Society of America Bulletin, vol. 78 (9), 1155–1178, 1967. Doi: https://doi.org/10.1130/0016-7606(1967)78[1155:SASOTT

]2.0.CO;2

[18] R. G. Gastil, R. P. Phillips, and E. C. Allison, "Reconnaissance geology of the state of Baja California", Geological Society of America Memoir, 140, 1975.Doi: https://doi.org/10.1130/MEM140

[19] L. A. Delgado-Argote, J. C. Hurtado, P. Avilés, y G. Gómez, "Factores geológicos y antrópicos de riesgo en Tijuana, Baja California: el caso del fraccionamiento jardines de agua caliente", Revista GEOS, vol. 32 (2), pp. 342 – 366, 2012.

[20] L. A. Delgado-Argote, A. Hinojosa, M. Aragón, G. Chávez, R. Mendoza, V. Frías, "Estudio de riesgo geológico en Tijuana con base en análisis geomorfológicos estructurales y la respuesta del terreno en las áreas el Pasteje, el Pato y Cañada Verde", Reporte Técnico 29p. Departamento de Geología, División de Ciencias de la Tierra, CICESE, México, 1993.

[21] M. R. Legg, V. O. Wong, F. Suárez, "Geologic Structure and Tectonic of the Inner Continental Borderland of northern Baja California", In: Dauphin P. J., Simoneit B. R. T., Editors, The Gulf and Peninsular Province of the Californias, American Association of Petroleum Geologists, Memoir 47. Chapter 9, 145–77, 1991. Doi: https://doi.org/10.1306/M47542C9

[22] D. M. Criado-Rodríguez, W. A. Pacheco-Vergel, y N. Afanador-García, "Vulnerabilidad sísmica de centros poblados: estudio de caso", Rev. Ingenio, vol. 17, n.º 1, pp. 43–48, ene. 2020. Doi: https://doi.org/10.22463/2011642X.2441

[23] A. O. Oliva-González y R. Fort-Villavicencio, "Metodología para la predicción de las vibraciones del terreno inducidas por voladuras y sus efectos en las estructuras. Aplicación en un caso real", Rev. Ingenio, vol. 16, n.º 1, pp. 1–9, ene. 2019.Doi: https://doi.org/10.22463/2011642X.2381

[24] NTC (Normas Técnicas Complementarias), "Seguridad estructural en materia de diseño sísmico", SIDURT, Estado de Baja California, México, 2017

[25] R. A. Crovelli, "Probability models for estimation of number and costs of landslides", United States Geological Survey Open File Report, pp. 00 – 249, 2000. Doi: https://doi.org/10.3133/ofr00249

[26] F. Silva, T. William and W. Allen, "Probability and Risk of Slope Failure", Journal of Geotechnical and Geoenvironmental Engineering, vol. 134 (12), 2008. Doi: https://doi.org/10.1061/(ASCE)1090-0241(2008)134:12(1691)