ACADEMIA | Letters

Urban growth and landslide risk in Tijuana, Mexico

Aldo Onel Oliva González, Grupo ITEICO Euroamericano / UDCI
David Mascareño Jiménez, GEOCIM
Romel Jesús Gallardo Amaya, UFPSO
Marco Antonio Berumen Rodríguez, GEOSERVICIOS

Introduction

The rapid and disorderly growth of many cities in the world has negatively transformed the physical environment, urbanizing areas of irregular topography where natural conditions are not appropriate for the construction of structures and infrastructures because the terrain is very susceptible to instability. These transformations favor the occurrence of landslides, while generating very complex scenarios for the analysis and evaluation of the risk produced by these phenomena. Unfortunately, during planning, development, and management of urban environments, only socio-economic parameters are usually taken into account and, as a consequence, in vulnerable places such as hillsiles with steep slopes and / or degraded soils, movements in landmasses often occur, that cause significant damage to exposed communities, disrupt the social and economic network, and cause loss of human life and property (Bathrellos et al. 2012). The city of Tijuana, located in the extreme northwestern part of the Mexican Republic and the main border crossing to the state of California (USA), has experienced an accelerated and chaotic urban expansion in the last four decades, with territorial growth rates of up to 3.5 hectares / day and population growth rates of more than 6% per year. The subsoil where the Tijuana metropolitan area sits has complex geological, geomorphological, and hydrological characteristics and is subject to permanent seismic activity. These factors, as well as the combined forces of urbanization and rapidly expanding industry, have not been adequately controlled and, in many cases, not considered during urban growth. As

Corresponding Author: Aldo Onel Oliva González, aldo.oliva@iteico.com / aldo.oliva@udc.edu.mx
Citation: Oliva González, A.O., Mascareño Jiménez, D., Gallardo Amaya, R.J., Berumen Rodríguez, M.A. (2021). Urban growth and landslide risk in Tijuana, Mexico. *Academia Letters*, Article 3386.
https://doi.org/10.20935/AL3386.

a consequence, more than 30% of the population (more than 600,000 people) reside and / or work in areas of hillsides with steep slopes and in poorly resistant and potentially unstable terrain (Oliva et al. 2012, Oliva et al. 2019).

Urban landslides in Tijuana

On average, more than two landslides per year occur in the Tijuana urban area, producing direct and indirect negative impacts on physical assets, vital lines, and people; and generating chaos, suffering, and helplessness in the affected communities, as well as considerable material losses in various economic sectors. Due to their frequency and magnitude, these events generate emergencies, the management of which by the authorities is increasingly difficult, and have adverse effects on the socio-economic structure of the municipality (Fig. 1).

Fig. 1 Some landslides occurred in Tijuana urban area. (a) Landslide in the Laderas de Monterrey neighborhood, 2010; (b) Landslide in the Sánchez Taboada neighborhood, 2016; (c) Landslide in the Liberal Lomas del Rubí neighborhood, 2018; (d) Landslide in the Cumbres del Rubí neighborhood, 2020.

From 2000 to December 2020, more than forty urban landslides have been registered,

Corresponding Author: Aldo Onel Oliva González, aldo.oliva@iteico.com / aldo.oliva@udc.edu.mx
Citation: Oliva González, A.O., Mascareño Jiménez, D., Gallardo Amaya, R.J., Berumen Rodríguez, M.A. (2021). Urban growth and landslide risk in Tijuana, Mexico. *Academia Letters*, Article 3386.
https://doi.org/10.20935/AL3386.

which have totally or partially destroyed more than nine hundred buildings, mainly homes, and a large number of vital lines such as road networks, electricity, drinking water, and drainage (Table 1).

Time frame	Landslides	Homes totally or partially damaged
2000 – 2009	27	221
2010 – 2020	22	720

Table 1. Summary of landslides that occurred in the urban area of Tijuana from January 2000 to December 2020 and their impacts on households.

Although the number of landslides was slightly lower in the last decade, the magnitude and intensity of the events and their impacts on urban structures and infrastructures experienced significant growth between May 2010 and October 2020. Four of the landslides that occurred in this period affected approximately 70 hectares of the urban area and destroyed more than 680 homes. Currently, these landslides are active and the unstable land masses continue to move, putting the property and lives of many people at risk (Fig. 2).

Corresponding Author: Aldo Onel Oliva González, aldo.oliva@iteico.com / aldo.oliva@udc.edu.mx
Citation: Oliva González, A.O., Mascareño Jiménez, D., Gallardo Amaya, R.J., Berumen Rodríguez, M.A. (2021). Urban growth and landslide risk in Tijuana, Mexico. *Academia Letters*, Article 3386. https://doi.org/10.20935/AL3386.

Fig. 2. Area affected by a landslide that continues to be active.

Conditioning and triggering factors

The factors that condition landslides in Tijuana are related to the characteristics and physical aspects of the terrain that favor its instability, highlighting, due to their significant influence, the geological, geotechnical, tectonic, and geomorphological conditions. The stratigraphic column that predominates in the region is formed by seven main types of terrain: siltstone-sandstone, basalt, sandstone-conglomerate, alluvium, conglomerate, sandstone, and igneous rock (Minch 1967, Gastil et al. 1975, Delgado-Argote et al. 2012, Delgado-Argote et al. 2017). However, most of the metropolitan area is built on superficial deposits constituted by boulder, gravels, sands, silts, and intercalated clays, whose stratified structure was formed by the deposition of fluvial and marine sediments. Most of these materials have poor compaction, are not very resistant, and very susceptible to erosion and weathering. From the geomorphological point of view, the main feature of the urban area is the Tijuana River, which runs through a plain of 2 km in average width and approximately 18 km in length. Towards the northeast of the river there is an area of plateaus and, to the southwest, a mountainous massif that is characterized by a high density of dissection of natural drainages that drain both towards

Corresponding Author: Aldo Onel Oliva González, aldo.oliva@iteico.com / aldo.oliva@udc.edu.mx
Citation: Oliva González, A.O., Mascareño Jiménez, D., Gallardo Amaya, R.J., Berumen Rodríguez, M.A. (2021). Urban growth and landslide risk in Tijuana, Mexico. *Academia Letters*, Article 3386.
`https://doi.org/10.20935/AL3386`.

the Tijuana River and the Pacific Ocean (Delgado-Argote et al. 1993, Oliva et al. 2012). This relief has fostered the growth of the city in the river basin and in its tributary micro-basins, for which more than half of the urban area is located on hillsides with slopes greater than 35% and in canyons where the terrain is weakened by the runoff water erosion. Regarding seismic activity, the area is considered high risk because it is located in a tectonically active region where two tectonic plates converge (North American and Pacific) that maintain a significant relative movement of 5 cm / year and, as a consequence, large stresses concentrations occur in the earth's crust.

On the other hand, the triggers of landslides in Tijuana are related to natural or anthropic processes that modify the initial conditions of the physical environment, which can significantly affect the stability of the terrain and trigger movements in the masses of soil and rock. In the metropolitan area, weathering, erosion, and human activity are the most important factors, because they produce destabilizing actions such as changes in the geometry of the land; increased loads; modification of surface and underground water flows; changes in vegetation cover; and deforestation (Oliva et al. 2019). Erosion and weathering produce removal and dragging of surface soils, weakening of their structures, and the modification of their resistance and permeability, affecting the stability of the terrain (Wiegand 1979, Aragón 1994). Human activity associated with rapid and disorderly urban growth, as well as the construction of structures and infrastructures that accompany it, produce transformations in the physical environment that significantly modify the already unfavorable existing geological, geotechnical, and geomorphological conditions, alter the natural balance of terrain, and increase the landslides risk to levels difficult to predict.

Hazard, vulnerability and risk of landslides in the Tijuana urban area.

Unfortunately, the studies focused on the analysis and evaluation of the hazard, vulnerability, and risk of landslides in Tijuana have been few and with many limitations of time and resources. The work has been carried out after the events occurred, as part of corrective management by the authorities, and has been limited to the zoning of the affected areas and their surroundings in safeguard, protection, and buffer polygons, based on the damage inventory. and, in the best of cases, the estimation of risk based on the judgment of experts.

Studies carried out in two neighborhoods of the urban area (Oliva et al. 2018, Oliva 2018), indicate that the landslides hazard is high, both in terms of probability of occurrence and of the terrain's susceptibility to instability. This was validated by the results of the stability analysis, in which safety factors lower than those accepted by the regulations were obtained

Corresponding Author: Aldo Onel Oliva González, aldo.oliva@iteico.com / aldo.oliva@udc.edu.mx
Citation: Oliva González, A.O., Mascareño Jiménez, D., Gallardo Amaya, R.J., Berumen Rodríguez, M.A. (2021). Urban growth and landslide risk in Tijuana, Mexico. *Academia Letters*, Article 3386. https://doi.org/10.20935/AL3386.

under seismic conditions and with different levels of saturation; and by the valuation factors obtained in the qualitative stability analysis.

In the same studies, it was determined that the relationship between the structural fragility of the exposed elements and the intensity of the hazarding landslides generates high vulnerability in buildings located both on potentially unstable land masses and in areas with the possibility of being affected by retrogression effects.

Discussion

The need for adequate management of the landslides risk in Tijuana is evident, which allows to prevent and mitigate the impact of these phenomena in the urban area. In addition to corrective management to reduce the existing risk, prospective management is required to avoid the worsening of the land's susceptibility to landslides and the increase in the probability of occurrence of destructive events; as well as the creation of new vulnerabilities. To achieve this, it is essential to analyze and evaluate risk and its components (hazard and vulnerability) from a multidisciplinary, inter-institutional, and multisectoral perspective, with the coordinated participation of civil society, exposed communities, local authorities, and governing institutions in matters of risks. and emergencies, under the guidance and supervision of experts.

Concerning the planning, development, and management of the urban environment of Tijuana, decision-makers, engineers, architects, planners, and managers must take into account the characteristics of the physical environment, the susceptibility of the land to instability, and, very especially, the triggers of landslides related to the anthropic processes typical of urban growth. Considering the existing geological, geotechnical, geomorphological and hydrogeological conditions, as well as the human activities that can affect the stability of the terrain in the urban area, is essential to guarantee the sustainable management of the land and for the protection of people, their assets and properties.

Based on the current problem, the urgent need for physical intervention actions with stabilization and protection works on hillsides and slopes are anticipated, as well as the relocation of families living in areas declared of very high risk and in homes in a state of imminent failure. In the medium and long term, as part of prospective management, non-structural measures are required such as geological and geotechnical studies, perception surveys, monitoring, and early warning systems, elaboration of analysis models, training, and institutional strengthening, among others. Only in this way, it will be possible to properly identify, analyze and evaluate the possible hazard and different vulnerabilities of the communities in the face of the eventual occurrence of landslides, in the complex scenarios of the urban area.

Corresponding Author: Aldo Onel Oliva González, aldo.oliva@iteico.com / aldo.oliva@udc.edu.mx
Citation: Oliva González, A.O., Mascareño Jiménez, D., Gallardo Amaya, R.J., Berumen Rodríguez, M.A. (2021). Urban growth and landslide risk in Tijuana, Mexico. *Academia Letters*, Article 3386. https://doi.org/10.20935/AL3386.

References

Aragón M.J. (1994). "Evaluación de riesgo geológico debido a movimientos de laderas en la ciudad de Tijuana, B.C., México". Tesis de Maestría, CICESE. Ensenada, México, p. 124.

Bathrellos, G.D., Gaki-Papanastassiou, K., Skilodimou, H.D. et al. (2012). "Potential suitability for urban planning and industry development using natural hazard maps and geological–geomorphological parameters". Environ Earth Sci 66, 537–548. https://doi.org/10.1007/s12665-011-1263-x

Delgado-Argote et al. (1993). "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". Departamento de Geología. CICESE, México: División Ciencias de la Tierra.

Delgado-Argote et al. (2012). "Factores geológicos y antrópicos de riesgo en Tijuana, Baja California: el caso del fraccionamiento Jardines de Agua Caliente". GEOS, 32 (2), 342 – 366.

Delgado-Argote et al. (2017). "Interpretación geológica y geoeléctrica de un deslizamiento rotacional relacionado con paleodrenaje en el fraccionamiento Valle del Sur, en Tijuana, Baja California". GEOS, 37 (2).

Gastil G.R. et al. (1975). "Reconnaissance Geology of the state of Baja California". The Geological Society of America, Inc., Memoir 140. Boulder Colorado p. 170.

Minch J.A (1967). "Stratigraphy and structure of the Tijuana-Rosarito Beach area, northwestern Baja California, Mexico". Geological Society of America Bulletin, 78 (9), 1155 – 1178.

Oliva, A. O., Rosquillas, A., Moldrano, R., González, C., and Álvarez, M. I. (2012). "Urban development and human activity as factors in terrain instability in Tijuana". Eng. Fail. Anal., 19, 51– 62. https://doi.org/10.1016/j.engfailanal.2011.09.005

Oliva, A. O. y Gallardo, R. J. (2018). "Evaluación del riesgo por deslizamiento de una ladera en la ciudad de Tijuana, México". Revista Tecnura, 22(55), 34 – 50. https://doi.org/10.14483/22487638.12063

Oliva, A. O. (2018). *Evaluación del riesgo por deslizamientos de laderas en zonas urbanas.*

Corresponding Author: Aldo Onel Oliva González, aldo.oliva@iteico.com / aldo.oliva@udc.edu.mx
Citation: Oliva González, A.O., Mascareño Jiménez, D., Gallardo Amaya, R.J., Berumen Rodríguez, M.A. (2021). Urban growth and landslide risk in Tijuana, Mexico. *Academia Letters*, Article 3386. https://doi.org/10.20935/AL3386.

Estudio de casos en la ciudad de Tijuana, México. Letonia: Editorial Académica Española.

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

Wiegand, J. W. (1979). "Evidence of San Diego-Tijuana faults." Assoc. Eng. Geologists Bull V7, 107 – 121.

Corresponding Author: Aldo Onel Oliva González, aldo.oliva@iteico.com / aldo.oliva@udc.edu.mx
Citation: Oliva González, A.O., Mascareño Jiménez, D., Gallardo Amaya, R.J., Berumen Rodríguez, M.A. (2021). Urban growth and landslide risk in Tijuana, Mexico. *Academia Letters*, Article 3386. https://doi.org/10.20935/AL3386.