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Factors that condition physical vulnerability to ground fracturing in Mexico City

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Abstract. In spite of subsidence being a well-studied geological phenomenon in Mexico City, its effects and risks for urban infrastructure and inhabitants have been neglected. Damage in the short, medium and long term implies maintenance and important mitigation costs. There are not systematic studies that address methodologies for the estimation of physical vulnerability of the geological media to fracture. In this work, factors conditioning the deformation and susceptibility to fracturing are analyzed using a deterministic approach. The identified physical variables were mapped, measured and integrated into a database that allowed for an adequate correlation of the parameters that condition fractures spatial distribution. A methodology for estimating a vulnerability index to fracturing (VIF) useful for decision making is proposed in this work.

1 Introduction

According to historical reports, earth fissures and ground fractures affected the Mexico City subsoil before 1900 and have been studied since the mid-twentieth century. The persistent subsidence and the associated differential (Gayol, 1925) deformation have caused damage to housing and urban infrastructure, mainly to roads, water pipes and drainage. The first subsidence measurements and ground fractures developed after the beginning of groundwater extraction in the central part of the lacustrine plain were reported in 1925. Since then, a total subsidence of 13 m has been reported at the center of Mexico City. Land subsidence was first numerically associated with groundwater extraction in the 1950s. The local authorities began to restrict groundwater pumping in the most affected areas nevertheless, and by the 1970s groundwater extraction was translated to the eastern side of the city (around the remnants of Lake Texcoco). With a fast-growing population and an increased need of water, ground fractures also developed in this zone, and by the 1990s fractures propagated and covered a larger area (Fig. 1).

Land subsidence has been widely studied in Mexico City during the last 5 decades (Zeevaert, 1953); nevertheless its effects in the mid and long term and risks for urban infrastructure and inhabitants have not yet been assessed properly. Damages in the long term implies maintenance and important mitigation costs (Carreon-Freyre et al., 2019). There are not systematic studies that address a methodology for the estimation of physical vulnerability to the fracture of the geological media. In this work, factors conditioning the deformation and susceptibility to fracturing are analyzed using a deterministic approach. A total subsidence of 13 m has been reported at the center of the lacustrine plain in Mexico City (Cabral-Cano et al., 2008; López-Quiroz et al., 2009).

Brittle fracturing of the near-surface clayey sediments of the lake has been attributed to subsidence related to high groundwater exploitation rates (Carrillo, 1947; Carreón-Freyre et al., 2006; Ovando-Shelley et al., 2012). Surficial deformation features can be related to shallow groundwater flows, and, consequently, fractures open and close seasonally (Carreón Freyre, 2010; Carreon-Freyre et al., 2016; Aguilar-Pérez et al., 2006). Moreover, a generalized consolidation state of thick clayey sequences related to deep groundwater depletion has been established; deep ground fracturing is a non-dilatant fracture in silts and clay sequences and may propagate through weak planes associated with lithological

(a) (b)

Figure 1. **(a)** Camarón Street fracture, Tláhuac, Mexico City. **(b)** Fracture in Albarradas, Iztapalapa, Mexico City.

contacts or major structural features from depth to the surface. A complex pattern of ground fractures dissects the lacustrine plain of Mexico City, which threatened the urban infrastructure. Recently the map of fractures was integrated into the Mexican *National atlas of risks* (Carreón Freyre et al., 2017) (Fig. 2).

2 Physical variables conditioning physical vulnerability of the media to fracture development

The general concept of physical vulnerability that considers a "degree of damage" can be defined differently in each discipline; for this work we consider the physical vulnerability as the "characteristic of the geological media that describes its susceptibility (or resistance) to the impact of the hazard of fracturing" in agreement with the definitions stated by the glossary presented in Schmidt-Thomé et al. (2007) and Kappes et al. (2012). The evaluation of physical vulnerability requires the implementation of an interdisciplinary methodology including: (a) the review of groundwater management, especially in urban areas; (b) detailed geological, hydrogeological and morphological characterization; and (c) the monitoring of groundwater piezometric evolution, land subsidence and ground differential displacements. The interdisciplinary analysis allows for a better understating of the triggering mechanisms of differential settlements, the generation and the propagation of ground fracturing (Ochoa-González et al., 2018).

According to previous studies ground fracturing is generated by the interaction of different factors (Carreon-Freyre et al., 2019): (1) geological preexisting discontinuities caused by variations in the depositional environment (Carreón-Freyre et al., 2006); (2) stress history due to climate changes determining the geometry of early fracturing; (3) variations in the compressibility and permeability of geological materials that control short-term and local-scale deformation (Carreon-Freyre et al., 2016); and (4) the exhaustive exploitation of aquifers causing a decline of the pore water pressure leading to subsidence and creating vertical and horizontal tensile stresses (Carrillo, 1947; Rivera and Ledoux, 1991; Holzer, 1984; Juárez-Badillo and Figueroa Vega, 1984). The propagation of fractures is conditioned by the interaction of physical variables that can be mapped, measured and integrated into a database. Coexistence of one or several of the mentioned factors determines the mechanism of fracturing at diverse scales.

3 Estimation of the vulnerability index to fracturing

We have followed a deterministic approach and the indicator-based methodology proposed by Kappes et al. (2012) for the study of multiple variables that can be mapped, measured and integrated into a database for spatial correlation analysis. For the development of the vulnerability index to fracturing (VIF) a weighted numerical analysis was performed to determine the potential areas of Mexico City that are prone to subside, develop ground fractures and/or present severe differential deformation (Fig. 3). Susceptibility of the variables was estimated and normalized for each variable that includes the addition of the weighted values: terrain slope from the geomorphologic map (W_{gm}), piezometric descent (W_{pd}), gradient of subsidence (W_{gs}), fracture type (W_{f}) and lithological variations or contacts (W_{lit}), as shown in the following equation:

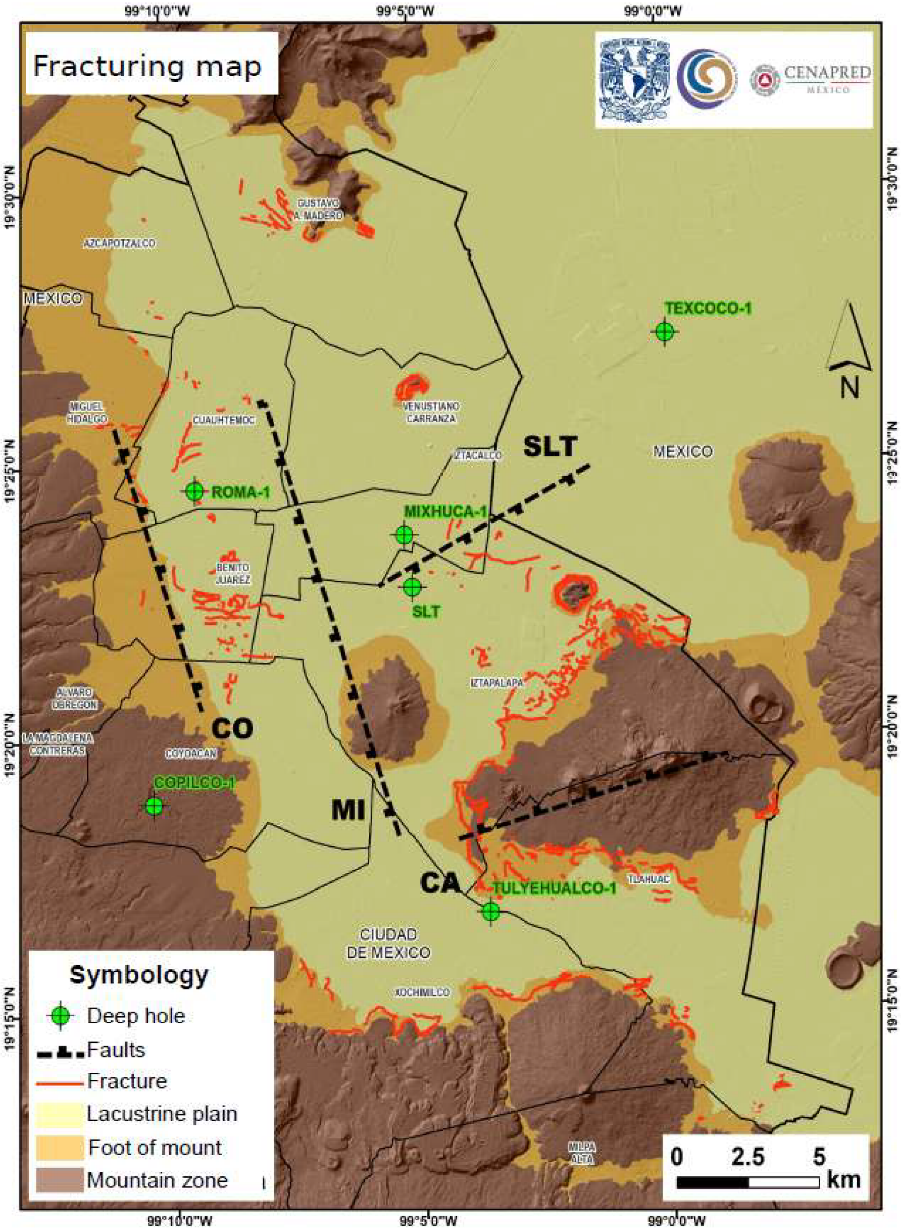

Figure 2. Ground fractures distribution in Mexico City (red lines) and main regional geological reported faults (black dotted lines) (Carreón Freyre et al., 2017).

$$\mathrm{VIF} = \left[\sum_{i=0}^{n} W_{\mathrm{gm}} + W_{\mathrm{pd}} + W_{\mathrm{gs}} + W_{\mathrm{f}} + W_{\mathrm{lit}} \right] / n \,, \quad (1)$$

where n is the number of variables.

The assignation of the weighted values considered a different percentage of the total amount recorded in the study area. For example, to estimate the "gradient of subsidence" (g_{s}), two tables were defined for absolute (Table 1) and weighted values (Table 2).

The spatial correlation of the physical variables allowed for identifying zones of fracture generation and estimating

Table 1. Rated values for the gradient of subsidence (g_{s}) in Mexico City.

Gradient of subsidence	Assigned value
Low (< 4 cm)	0 %
Medium (4–12 cm)	65 %
High (> 12 cm)	35 %
Total assigned value	100 %

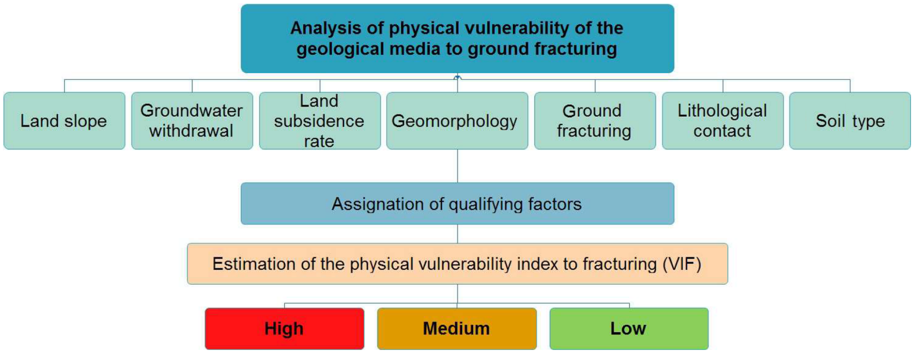

Figure 3. Flowchart for the determination of the physical vulnerability index to fracturing.

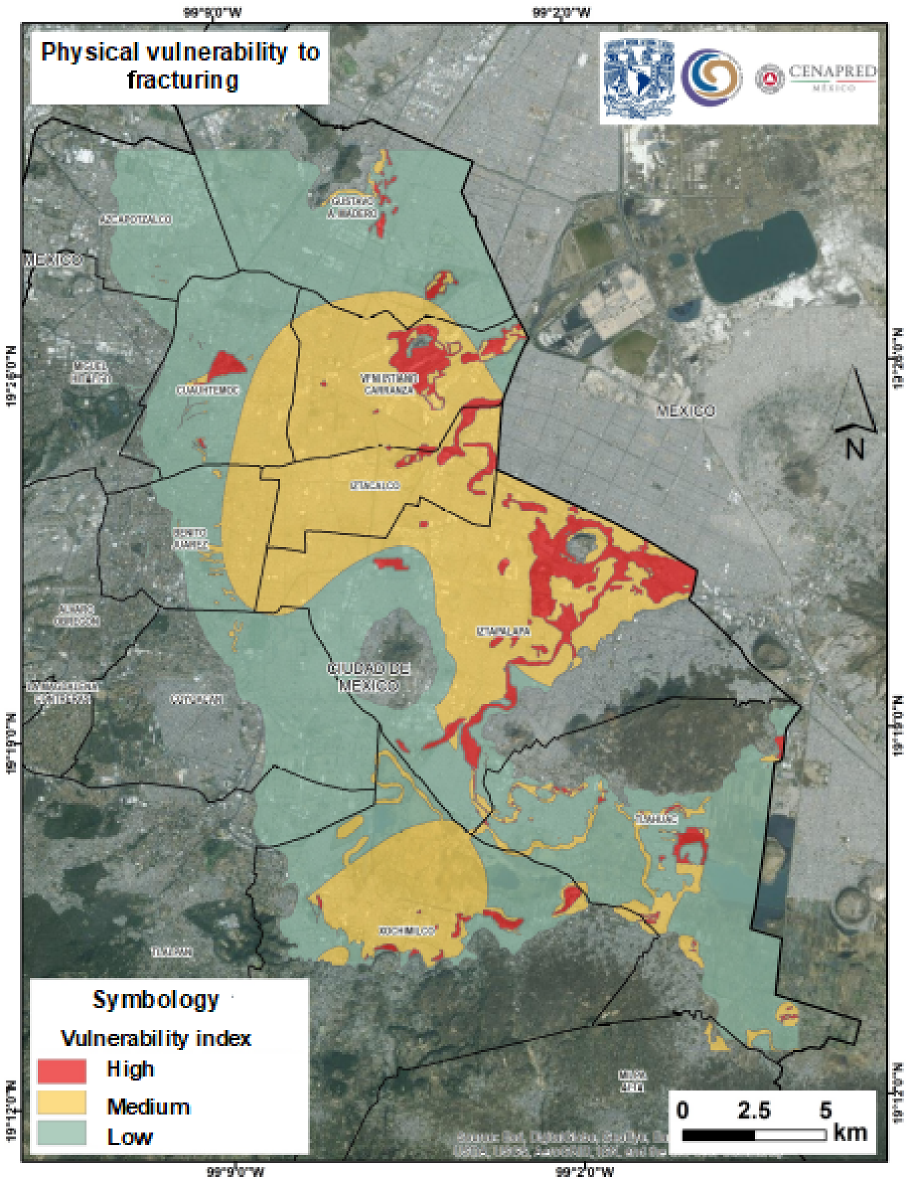

Figure 4. Mexico City distribution map of the physical vulnerability index to fracturing (Carreón Freyre et al., 2017).

Table 2. Weighted values for the gradient of subsidence (g_s).

Gradient of subsidence	Weighted value W_{gs}
Low (< 4 cm)	0 %
Medium (4–12 cm)	9.75 %
High (> 12 cm)	5.25 %
Weight of the variable	15 %

Table 3. Rates of physical vulnerability to fracturing in the Mexico City area.

Vulnerability level	Surface (km^2)	Percentage
High	23.9	3.9
Medium	143.8	23.6
Low	215.1	35.3
No subsidence	226.8	37.2
Total	609.6	100

propagation conditions (Fig. 4). The proposed vulnerability index to fracturing is easy to use for decision making and helps in the zoning of risk areas.

4 Results: map of distribution of VIF in Mexico City

The results of the analysis were integrated in a geographic information system and presented as a map defining three zones in Mexico City with values ranging from high to low physical vulnerability:

- High vulnerability represents a surface of 23.9 km^2 (3.9 % of the area of Mexico City) located mainly at the eastern part of the city, with minor areas downtown and to the southern part.
- Medium vulnerability covers a surface of 144 km^2 downtown and in the eastern and southern parts of Mexico City.
- Low vulnerability, with a surface of 215.1 km^2, corresponds mainly to the rocky highlands of the western part of the city (Table 3).

5 Conclusions

Overexploitation of the aquifer has caused a continuous piezometric water level decline reaching about 50 m and up to 13 m of land subsidence in the central part of Mexico City. Consequently, the intensity of fracturing has increased and caused numerous problems to urban infrastructure. Estimations of infrastructure damage are in the order of several billion US dollars. This represents a great challenge for land and groundwater management in Mexico. We propose a deterministic methodology for the estimation of a vulnerability index to fracturing which is easy to use for zoning. The presented results are qualitative and cannot be analyzed statistically; nevertheless the VIF has shown to be very useful for decision making. The map can be a useful tool when assessing the related geological risk in Mexico City. The accuracy of the results should be improved with a larger database. Additionally, the VIF can be useful for the design of adequate monitoring systems aimed at the optimization of mitigation measures in the damaged sites.

Data availability. The database of the fracture map of Mexico City can be consulted at the CENAPRED public web site, in the section "Aplicaciones: Sistema de Información de Riesgos. Ciudad de México" http://www.atlasnacionalderiesgos.gob.mx/portal/fenomenos/ (CENAPRED, 2020).

Author contributions. DCF and RGC designed the proposed methodology. MC supervised the analysis of geological information, and CAD created the map database. DCF prepared the paper with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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