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Land Subsidence and Associated Ground Fracturing in Urban Areas. Study Cases in Central Mexico

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Abstract. Land subsidence affects urban areas with rapid development during the last thirty years in central Mexico. The use of land represents a great challenge for urban planning, and the issue is increased when sustainable water resources management need to be added. Mexico inhabitants rely on groundwater for about 60% of water supply. Furthermore, the most of the cities are located in volcanic valleys filled with fine and coarse grained sediments interbedded with pyroclastic and volcanic materials. Three study cases are presented in this work for comparative purposes: Mexico, Querétaro and Irapuato cities. Compaction associated to groundwater depletion have caused differential subsidence, ground fracturing and reactivation of faults, depending on the local geological setting. Remote sensing monitoring methods of land subsidence have proved to be useful tools to assess this geological risk for urban planning, nevertheless more efforts need to be addressed for the implementation of in-situ monitoring and other techniques to prevent and manage damage to urban infrastructure.

Keywords. Land Subsidence, groundwater extraction, deformation, geological risk, urban development.

1. Introduction

Land subsidence affects metropolitan areas in central Mexico located over former lakes in volcanic valleys [1]. Because of structural conditions affecting the Transmexican Volcanic Belt (TMVB) [2], valleys are often bounded by faults and/or volcanic structures of ages ranging from the Miocene to the Quaternary [3] (Figure 1). The stratigraphy below these cities consists of fluvial and/or lacustrine sediments often interbedded with layers of pyroclastic materials and lava flows. Differential deformation of granular materials related to the increasing urbanization over transition zones between plain and slope areas, with high heterogeneous sequences and strong groundwater withdrawals, have caused ground ruptures in the most populated cities located in the TMVB. About 63% of Mexican population concentrates in metropolitan areas, these cities had a rapid

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development in the last twenty years and many of them rely on subsurface resources for about 60% of water supply [4].

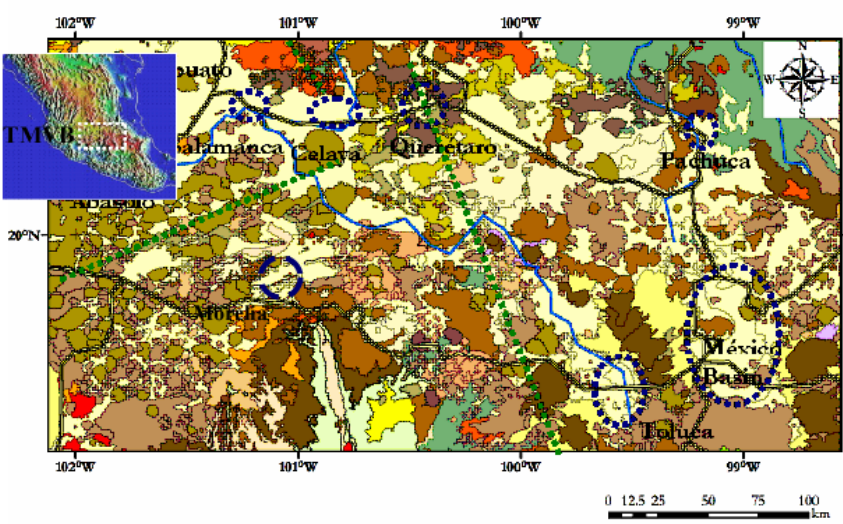

Figure 1. Location of cities affected by subsidence in central Mexico (dotted circles) located in inter-volcanic and fault bounded basins within the central Trans-Mexican Volcanic Belt. Brown colors indicate Plio-Quaternary volcanic and pyroclastic events, yellow colors indicate volcano-sedimentary and lacustrine Quaternary deposits, red colors indicate intrusive rocks. Geological map from [1].

A great challenge is faced for urban development and natural resources management in order to manage the decrease of water availability in urban areas for the next years. An accurate evaluation of physical vulnerability in each study case regarding urban development requires a review of land and water uses. Urban planning should integrate not only geotechnical but geological risk zonations, improvement of water distribution systems and, control of groundwater extraction. Detailed geological, hydrogeological, geomechanical and morphological characterization should be accompanied by surveying of deformation by remote and in situ monitoring. Systematic studies of physical and mechanical properties of near surface sequences and accurate mapping of discontinuities in areas affected by subsidence are key tools for the design of mitigation measures to urban infrastructure damages. As examples of interdisciplinary studies, three study cases are presented in this work: Mexico, Querétaro and Irapuato cities.

2. Geological and hydrogeological context in urban areas

In Mexico, a population of 124 million inhabitants was estimated until 2017, the most of the cities with more than one million inhabitants are located in the center and are affected by land subsidence. From 1950 to 2015, the population of the country quadrupled and went from being mostly rural to predominantly urban (from 11 to 92 million inhabitants). The concentration of inhabitants in urban localities implies strong pressure on the environment due to the increase in the demand for services, such as water availability. Furthermore, two thirds of the territory are arid or semi-arid zones and, by 2015 105 of the 653 aquifers were considered over-exploited [4]. Compaction of sediments related to groundwater withdrawal has caused land subsidence in many areas: Mexico City, Toluca, Puebla, Queretaro, Celaya, Leon, Abasolo, Salamanca Morelia, San Luis Potosi, Aguascalientes, and Guadalajara, among others) [3]. The near surface stratigraphy below these cities is composed by fluvial and lacustrine sediments with particle sizes varying from gravel, sand, and silt to clays, often interbedded with layers of pyroclastic rocks and lava flows [1].

The Mexico Valley Basin is a special case, during the last centuries as the lake water level descended, the basin was divided in several sub-basins including Mexico City, Chalco, Texcoco. Xochimilco, and Zumpango [5]. Over-exploitation of a shallow aquifers has caused piezometric water level declines of about 50 m and near to 13 m of land subsidence in the central part of Mexico City [6]. These recent and high compressible fluvio-lacustrine deposits, composed mainly by clay and silt particles, with gravimetric water contents varying between 200 to 400%, have a widely documented complex mechanical behavior [7]. Subsidence has been reported since 1925 and was first related with groundwater decline in 1947 [8][9][10]. Lateral variations of subsidence and related fracturing have increased and caused numerous problems to urban infrastructure [11]. Hydrogeology studies in the basin of Mexico show that piezometric levels continuously decline in the aquifer, and subsidence continue to increase because of transient response of the overlying aquitard [12].

In Queretaro and Irapuato cities groundwater depletion may reach 3 m/year and piezometric levels are located between 150 and 200 m depth [13][14]. The two cities are located in the north boundary of the TMVB in the limit with the *Sierra Madre Occidenta*l volcanic range. Regional faulting delimits structural grabens where fine and coarse grained sediments were deposited alternatively with volcanic materials [2][13]. The high heterogeneous stratigraphy of these basins records alternative episodes of sedimentation, volcanism and faulting [13]. Major faulting and high lithological contrasts cause complex groundwater withdrawal patterns that can not be analyzed by the interpolation of piezometric levels of water wells. Land subsidence affects compressible materials, and ground fracturing are close related with the reactivation of geological faults [15][16]. The near surface sequences consist of partially saturated (ap. 30% gravimetric water content) fluvio-lacustrine coarse grained deposits and pyroclastics interbedded with fractured andesites and basalts [2][16]. Land subsidence and faulting in this region was reported with fracture slips varying from 0.8 to 2.0 m [17][18]. Moreover, unplanned urbanization extends to aquifer recharge areas exacerbating the decrease of groundwater availability [19].

3. Mapping and modeling of fractures

The correlation of geological, mechanical and hydraulic parameters suggests a dynamic interplay between the mechanisms of fracturing and the stress history of the local sequences. In the lacustrine Mexico basin, deformation features can be related to shallow groundwater flows and, consequently, fractures open and close seasonally [3] [5][11][20] (Figure 2). Simultaneously, a generalized consolidation state of thick clayey sequences related to deep groundwater depletion has been established, ground fracturing is related to non-dilatant fractures in silts and clay sequences. In Queretaro and Irapuato arid regions, groundwater decline modifies the state of stress, which is modified by the preexisting discontinuities that localize strain (Figures 3 and 4).

The mechanical response corresponds mainly to brittle dilatant fractures and faulting determined by local variations in the grain size (silt, sand) and differential strength of geological materials.

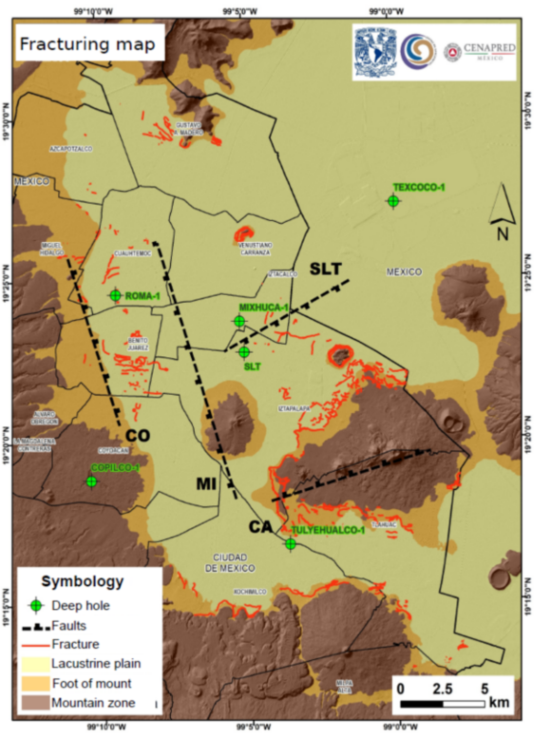

Figure 2. Ground fracture mapping in Mexico City [11]. Red lines indicate fractures and dotted black lines indicate regional faults.

The three study cases presented in this work, show the increase of the effective stresses inducing greater differential deformation, but it does not solely explain the propagation of deformation. Fracturing is caused by the interaction of different factors: (1) geological preexisting discontinuities caused by variations in the depositional environment [5], (2) stress history determining the geometry of early fracturing, (3) variations in compressibility and permeability of geological materials, that control short-term and local-scale deformation [16] and, (4) exhaustive exploitation of aquifers causing a decline of the pore water pressure leading to subsidence and creating vertical and horizontal tension stresses [8] [12] [21] [22]. Coexistence of one or several of the mentioned factors determines the mechanism of fracturing at diverse scales. In many reported Mexican case studies, fracturing has been considered only at a single scale so simplifying the related phenomena; however, the multi-scale characteristics of fractures need to be considered for risk assessment in urban areas [3].

Linear numerical analyses of groundwater depletion and increase of effective stress in Mexico were developed by several authors during the last six decades [8] [20] [23]. A drawdown of 35 m in the hydraulic head over the last 40 years, causing a land subsidence of 6–8 m in the northeast of Mexico City has been reported [20].

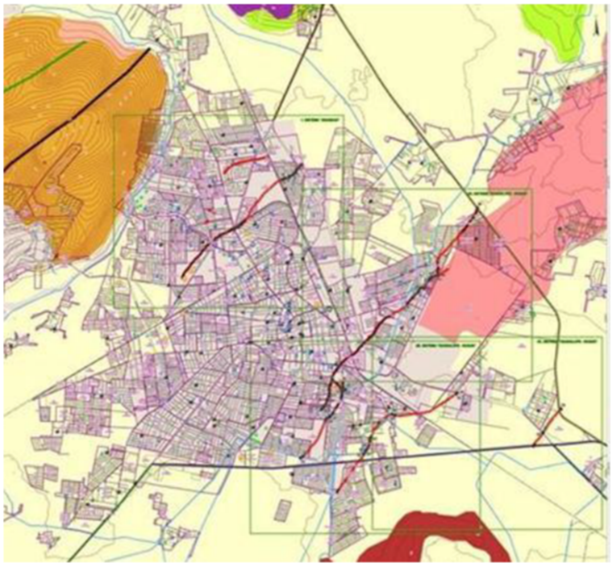

Figure 3. Ground fracture mapping in Irapuato City. Red lines indicate fractures and regional faults [13].

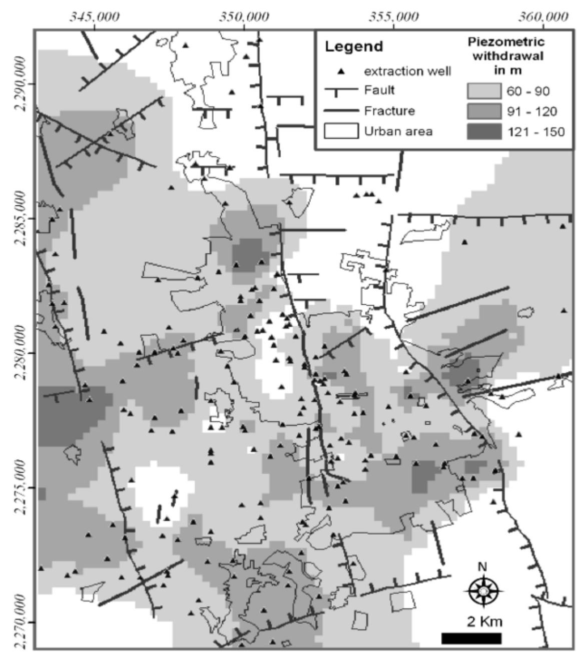

Figure 4. Ground fracture mapping in Queretaro City. Black lines indicate fractures and regional faults, gray colors indicate ranges of groundwater depletion [14] [16].

Recently, numerical analysis integrating groundwater flow and geomechanical equations for land subsidence due to groundwater extraction has been developed for the Queretaro City study case [14] (Figure 5).

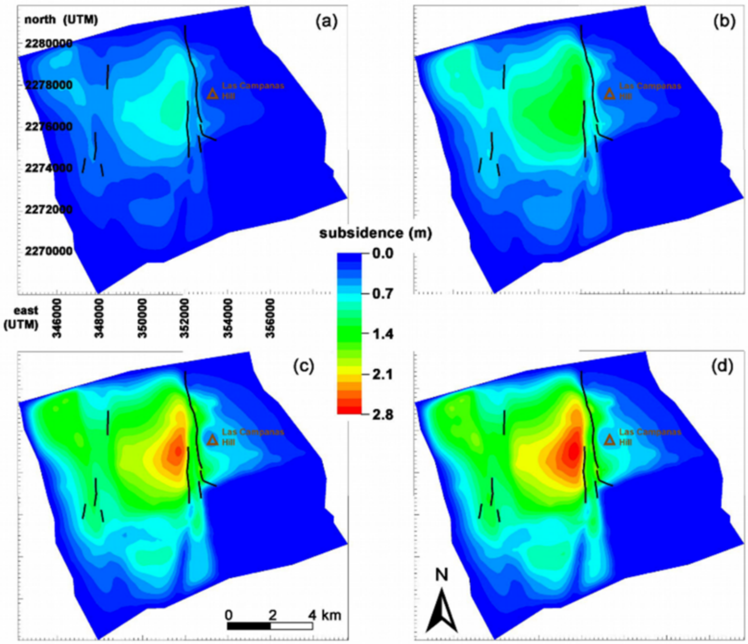

Figure 5. 3D Geomechanical model of subsidence in Queretaro City. Black lines indicate fractures and regional faults. Red colors indicate highest subsidence ranges [14].

4. Deformation monitoring systems

4.1. Near-surface geophysics

In situ monitoring using non destructive methods are very useful to estimate deformation rates and identify fractures o discontinuities in early stages. Several high resolution geophysical methods are being used in Mexico to characterize shallow fracturing structures in urban areas, such as Ground Penetrating Radar [18] [24], microgravity methods [25], and seismic methods to evaluate deeper structures, seismic microzonationand the seismic response of consolidated sediments [26].

4.2. Remote sensing monitoring

Studies using interferometric synthetic aperture radar (InSAR) and global positioning system (GPS) has been focused on Mexico City [27] indicating that rates of current land subsidence in Mexico City exceed 350 mm/year. Recently, specialists have looked for new analysis methods to improve the spatial resolution needed for surface monitoring related to faulting and fracturing in lacustrine plains: horizontal gradients of subsidence [28], a method to help interferogram unwrapping and, Persistent Scatter Interferometry (PSI) to improve the imaging of differences in subsidence rates [29]. [30] reported InSAR monitoring of land subsidence in many cities of central Mexico. The Advanced Land Observation Satellite 2 Phased Array L-band Synthetic Aperture Radar 2 (ALOS-2 PALSAR-2) mission design represents a consolidated approach for conducting research and development activities over wide areas.

An example is presented in Figure 6 where red areas show widespread land subsidence over major cities of Central Mexico for the period 2015-2018 (T. Strozzi, *personal communication*).

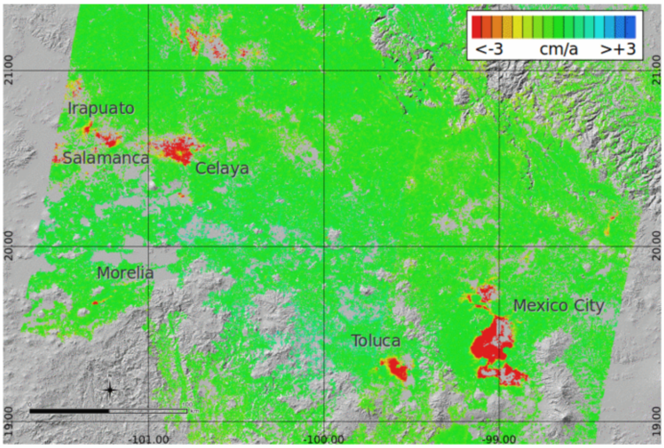

Figure 6. Land Subsidence in Central Mexico from ALOS-2 PALSAR-2 ScanSAR interferometry between 20.02.2015 and 16.02.2018 (image from T. Strozzi).

5. Conclusions

The presented study cases allowed to analyze factors causing land subsidence in fluvio-lacustrine basins and generation of fractures, based on reliable characterization of geological materials and changes in their properties in time and space. There are few case studies in Mexico that involve surface and subsurface deformation monitoring, so it is necessary to integrate networks of benchmarks to calibrate GPS and InSAR analysis and to monitor deformation in depth. Groundwater flows follow deep and complex patterns that also require real-time monitoring. A further line of research work is coupled mechanical-hydraulic modeling to simulate the nonlinear interactions between groundwater withdrawal and its contribution to the propagation of the deformation within inelastic media.

Estimations of infrastructure damage are in the order of several thousands of millions of dollars. Furthermore, the metropolitan area of Mexico City is the one in which more water is wasted, mainly due to leaks in the hydraulic network that, according to the Conagua, reach 38% [4]. Leaking can be due to a lack of maintenance and to ground fracturing. In order to face with the increase of population in urban areas and the decrease in water availability for the next years, it is urgent a paradigm shift within the Mexican water and land use management agencies. It is of the most importance to diminish the extraction of groundwater (mitigation measures should be accompanied with the increase the volumes of treated water and pluvial water collection) increase the efficiency in the water distribution systems in the cities and, to take action to reduce its demand by the increase in the separation and reuse of wastewater.

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