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Monitoring of land subsidence and fracturing in Iztapalapa, Mexico City

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Abstract The metropolitan area of Mexico City is one of the most populated in the world and the Iztapalapa Municipality, situated on the eastern border, presents the highest population density of the city. This area is located over the geological contact between the "Sierra de Santa Catarina" volcanic range and a lacustrine basin. Inherently, the geological materials of the subsoil are horizontally and vertically heterogeneous and deform differentially under applied loads (natural and anthropogenic). As a consequence, the Iztapalapa urban infrastructure is extremely affected by fracturing and land subsidence and it is possibly one of the places with the highest social-related vulnerability in Mexico. Since localization of fracturing and deformation during land subsidence are highly dependent on local geological, geomechanical, and hydraulic conditions of the subsoil, a multidisciplinary approach for a better understanding of the fracture triggering and propagation mechanisms was established. The methodology includes: (1) detailed geological survey, (2) high resolution geophysical prospecting, (3) stratigraphic correlation of lithological logs from water extraction wells, (4) geotechnical characterization of near surface sequences, and (5) hydrogeological analysis, including the monitoring of groundwater piezometric levels. All the obtained information is referenced and analysed using a Geographical Information System (GIS), which is directly related to a main Digital Information System (SID) available via the Internet to the Iztapalapa authorities for the support of decision making. As a result of good academic–government collaboration, the former Monitoring Centre of Ground Fracturing was transformed into the Centre of Geological Risk Evaluation (*Centro de Evaluación de Riesgo Geológico*, CERG) that belongs to the Coordination of Civil Protection of the Iztapalapa Municipality. The physical vulnerability of the Iztapalapa area to land subsidence, ground fracturing and other geological hazards is evaluated through the analysis of the generated information based on thematic maps, which should allow better planning of mitigation strategies, urban development, land use management, and groundwater exploitation.

Key words database management; monitoring; ground fracturing; vulnerability; geological hazards; Iztapalapa

INTRODUCTION

The metropolitan area of Mexico City is one of the most populated in the world with almost 20 million inhabitants. The "*Delegación Iztapalapa*", one of the 16 administrative entities of the city, has the greatest inhabitant density of the country, with approximately 1 850 000 people distributed in an area of 105.8 km^2, and presents one of the highest rates of urbanization. Furthermore, the expansion of the city in the 1970s triggered the exploitation of groundwater for urban supply in this area. Iztapalapa is located in the eastern part of Mexico City over the geological contact between the "Sierra de Santa Catarina" volcanic range and a former lacustrine basin (Fig. 1). Inherently, the geological materials of the subsoil are horizontally and vertically heterogeneous. The Iztapalapa urban infrastructure is greatly affected by fracturing and land subsidence and it is possibly one of the places with the highest social-related vulnerability in Mexico. The studies performed on different urban areas reveal the coexistence of several factors determining the characteristics of fracturing at different spatial scales. One of the most important triggering factors of fracturing is groundwater withdrawal and the associated increase in effective stress; however other factors such as the structure of the subsoil, overloading and pre-existing fractures, can also play an important role. This is why the understanding of nucleation and propagation of fractures in the heterogeneous geological media require monitoring and systematic analysis of the deformation of the sequence by the integration of its physical and geological characteristics.

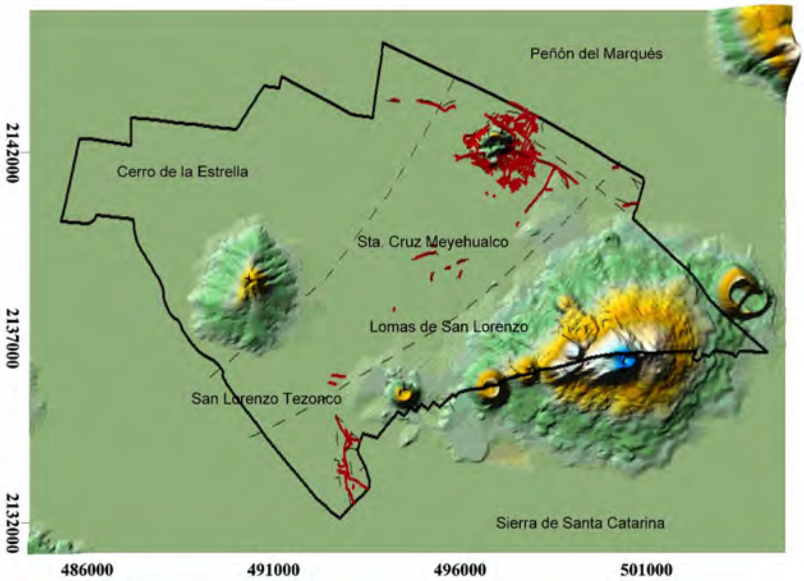

Fig. 1 Morphology of the "*Delegación Iztapalpa*". The range shown in the southeastern part is called Sierra de Santa Catarina, the shield volcano in the middle western part is called Cerro de la Estrella, the Peñón del Marques is located in the northeastern part of the study area, surrounded by a large number of fractures. These three geological structures delimit the fluvial-lacustrine plain. Fractures are marked with red lines.

A collaboration project between the *Centro de Geociencias* of the *Universidad National Autónoma de México* (UNAM) and the government of the *Delegación Iztapalapa* was initiated in 2007 for the characterization of land subsidence and ground fracturing. Since localization of fracturing and deformation during land subsidence are highly dependent on local geological, geomechanical and hydraulic conditions of the subsoil, a multidisciplinary approach for a better understanding of the triggering and propagation mechanisms was established. As a result of good academic–government collaboration the former Monitoring Centre of Ground Fracturing was transformed into the Centre of Geological Risk Evaluation (*Centro de Evaluación de Riesgo Geológico*, CERG) that belongs to the Coordination of Civil Protection of the Iztapalapa Municipality. The methodology implemented for the CERG operation includes (Fig. 2): (1) techniques of mapping, geophysical prospecting and sampling in the field, (2) a database management strategy (i.e. Digital Information System, DIS), and (3) facilities including a laboratory for physical and mechanical characterization of soils and sediments, and an interactive hall for outreach and educational purposes. The physical vulnerability of the Iztapalapa area to land subsidence, ground fracturing, and other geological hazards is evaluated through the spatial analysis of the generated information based on thematic maps that should allow better planning of mitigation strategies, urban development, land-use management and groundwater exploitation (Fig. 2).

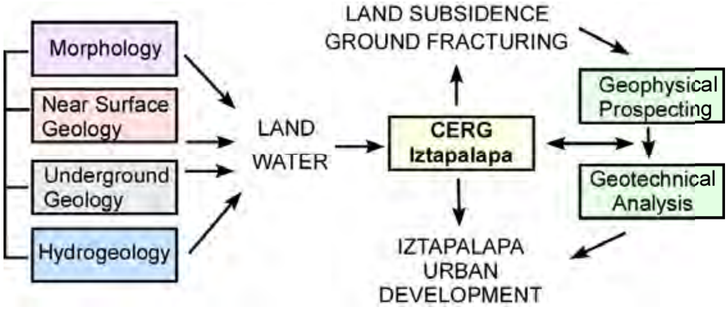

Fig. 2 Flow diagram showing the operation of the Centro de Evaluación de Riesgo Geológico (CERG).

GEOMECHANICAL PROPERTIES OF LACUSTRINE MATERIALS BENEATH MEXICO CITY

The area covered by the municipality of Iztapalapa is located within the Basin of Mexico, which was formed by the interaction of faults and volcanic activity since the Miocene times. The regional stratigraphy of the Basin of Mexico has been studied in relative detail by many authors, among others Zeevaert (1953), Marsal & Mazari (1959), Mooser (1975), De Cserna *et al.* (1988), Orozco & Figueroa (1991). According to the geotechnical zonation proposed by Marsal & Mazari (1959) the Iztapalapa area includes two main morphological areas, the lacustrine plain area and the hills area. The higher elevations in the Iztapalapa area correspond to volcanoes formed by andesite, basalt, and pyroclastic rocks of Pliocene age that outcrop in the Sierra de Santa Catarina, Cerro de la Estrella and Peñon del Marques (see Fig. 1). The valley, surrounded by volcanic edifices, is composed of volcanic and pyroclastic rocks as well as lacustrine sediments. Within the sedimentary sequences of lacustrine basins, such as Mexico Basin where volcanic activity is quite recent and contemporaneous with the deposition of the sedimentary fill, the rapid weathering of volcanic ash generates allophane and imogolite (clay incipient minerals, similar in mechanical behaviour to colloids; Carreón Freyre *et al.*, 1998). The mineralogical composition of clays of the Valley of Mexico has been well documented since the middle of last century, mainly due to its heterogeneity and the complexity of their mechanical behaviour (i.e. brittle fracture in plastic, compressible and high water content; Carreón Freyre & Cerca, 2006). Understanding this behaviour is of the uppermost importance for the monitoring of ground deformation. Early works reported contrasting compositions for the sediments of the Basin of Mexico (Zeevaert, 1953; Marsal & Mazari, 1959; Mesri *et al.*, 1976). There is an intimate relationship between the mineralogy of the clayey materials and their mechanical properties, which depend mainly on water content and are directly related to their low permeability. The relationship between the mineralogy of clay and the consolidation has been widely discussed (Ohstubo *et al.*, 1983; Warren & Rudolph, 1997; Saarenketo, 1998; Wesley, 2001). However, there are few studies relating to the geological conditions with variations in mineralogical, mechanical and hydraulic characteristics of lacustrine sequences (Carreón Freyre *et al.*, 2005), and therefore little is known about the response of these systems and mechanisms of propagation of fracturing.

The first results of the detailed geological mapping show that the regional scale fracturing is related to the interface between the volcanic material of the Sierra de Santa Catarina and fluvio-lacustrine sediments in the valley (Fig. 3). According to available records of piezometric levels, the areas of greatest depression of groundwater cannot be directly correlated to the areas of greatest subsidence, nor are the flow patterns of further decline of groundwater spatially associated with major fracture zones. This verifies that it is necessary to establish the conditions of mechanical–hydraulic coupling between volcanic and sedimentary materials to identify the relationship between groundwater withdrawal and its contribution to the propagation of the deformation. Fracture systems in fluvio-lacustrine sequences can be studied according to their size and the association of factors from which they originate. As “regional” and “local” are relative concepts that depend on the scale and type of study, this paper assumes the following criteria: (a) Regional structures are larger than the urban area. The irregularity of fractured basement underlying the sedimentary sequences largely determines the location of the fracture that propagates from deep to shallow sedimentary sequences along pre-existing planes of weakness. (b) At an intermediate scale, the fracture systems that mainly affect the top of the fluvio-lacustrine sedimentary sequence, often interbedded with pyroclastic materials and volcanics, are considered. For this work, only the first 300 m are considered at this scale because it corresponds to the current average depth of groundwater exploitation wells. (c) The local scale of analysis refers to subsidence and fracturing in restricted areas and may vary from a few to tens of metres (the geomechanical properties of the materials can be directly characterized). This is the scale at which most studies of soil mechanics are carried out the. The factors of scale and composition of clay sequences should allow an appropriate design of monitoring systems and lead to an accurate evaluation of the hazards related to ground fracturing in urban areas.

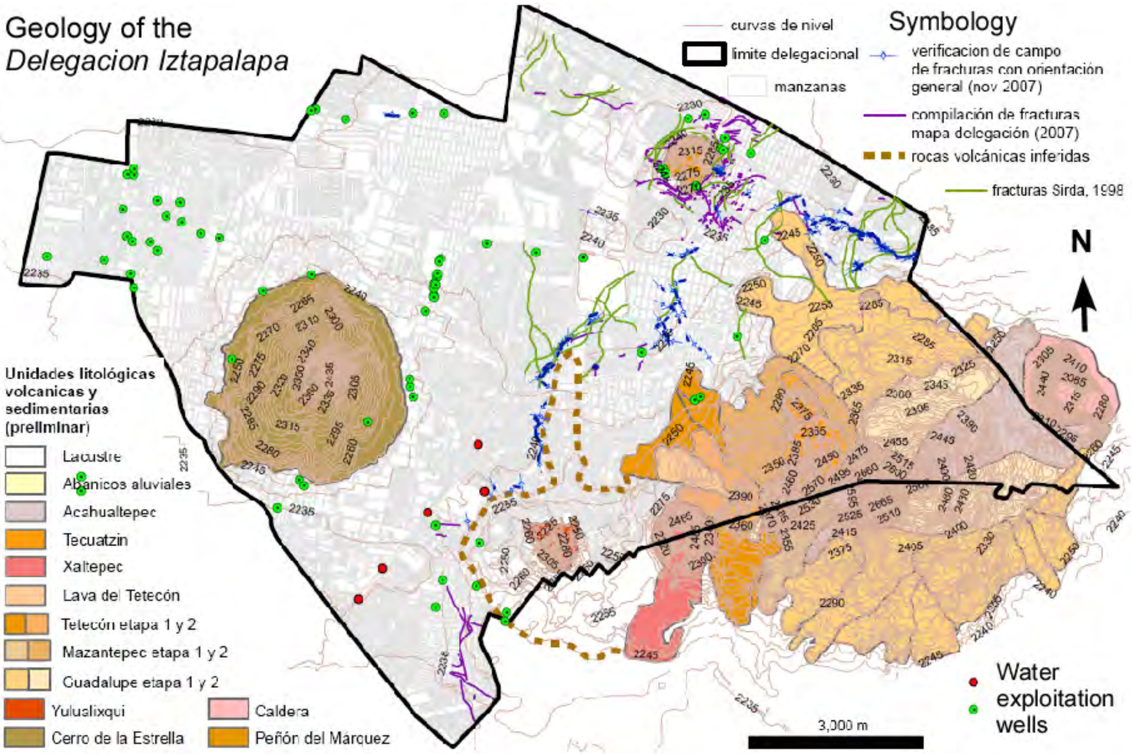

Fig 3 Geology map of the *Delegación Iztapalapa*, the lithology of the volcanic formations is shown. Fractures are marked with blue and pink lines. Water extraction wells surround the volcanic highlands.

To perform the mapping of the fractures in the Iztapalapa area, we consider their spatial and temporal continuity (i.e. they are mappable fractures with horizontal lengths and present evidence of their long-term activity). The results show that the phenomenon of regional fracturing is related to the buried border of the Sierra de Santa Catarina (now urbanized).

OPERATIONAL METHODOLOGY OF THE CERG

The methodology of systematic analysis established in the *Centro de Evaluación de Riesgo Geológico* (CERG) includes:

- Detailed geological survey (in the field and interpretation of satellite imagery).
- High resolution *geophysical prospecting* using the Ground Penetrating Radar (GPR) method, to characterize the structure of the first 10 m depth and variations in water content (Fig. 4); and the Surface Seismic Waves (SSW) method to characterize the structure of the subsoil at 50–70 m depth and variations in density and compaction of subsoil materials.
- *Stratigraphic correlation* of lithological logs from 20 m depth (geotechnical) and 150 m depth (water extraction wells). An example of the correlation is shown in Fig. 5.
- *Geotechnical characterization* (compressibility and shear strength) of near surface sequences.
- *Hydrogeological analysis*, including the monitoring of groundwater piezometric levels.

All the obtained information is referenced and analysed using a Geographical Information System (GIS) which is directly related to a main System of Digital Database (SDD) that is available, via the Internet, to the Iztapalapa authorities for the support of decision making.

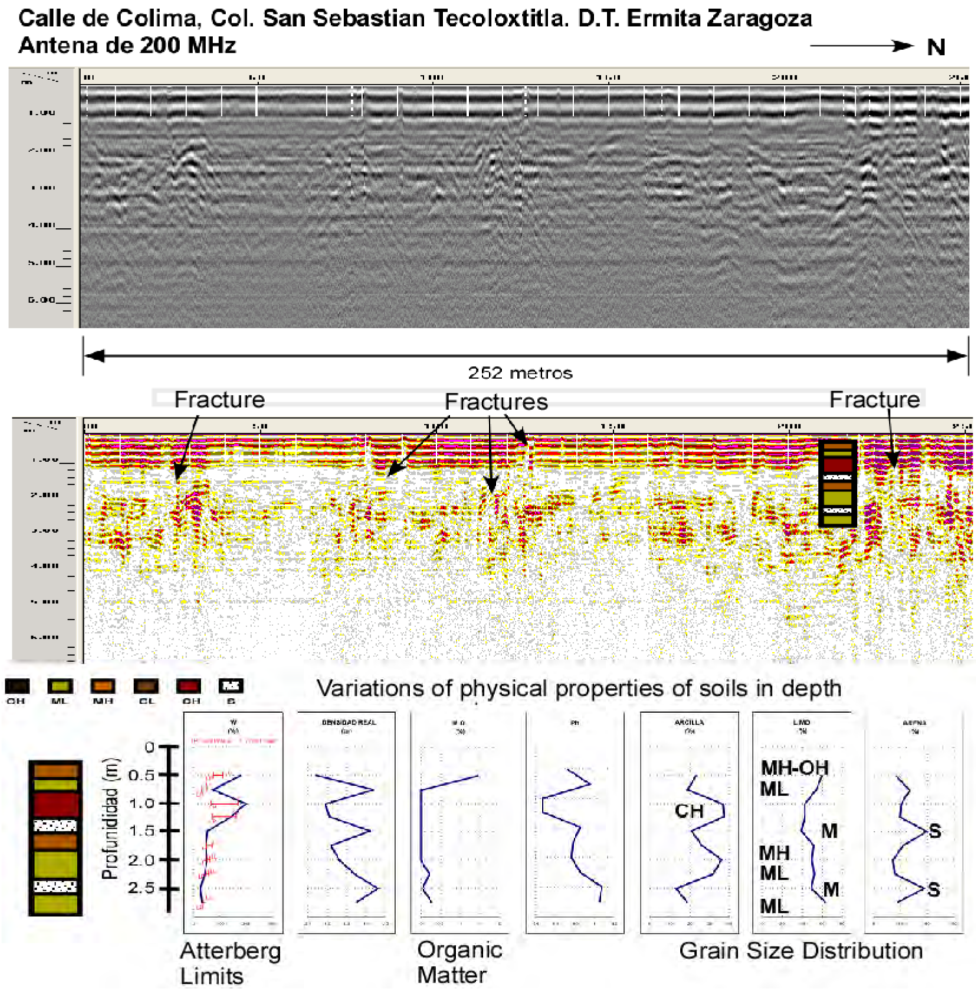

Fig. 4 Correlation of Ground Penetrating Radar (GPR) recorded features with the variations of physical properties of the near surface granular materials (soils, pyroclastics and sediments). Depth of investigation 5 m.

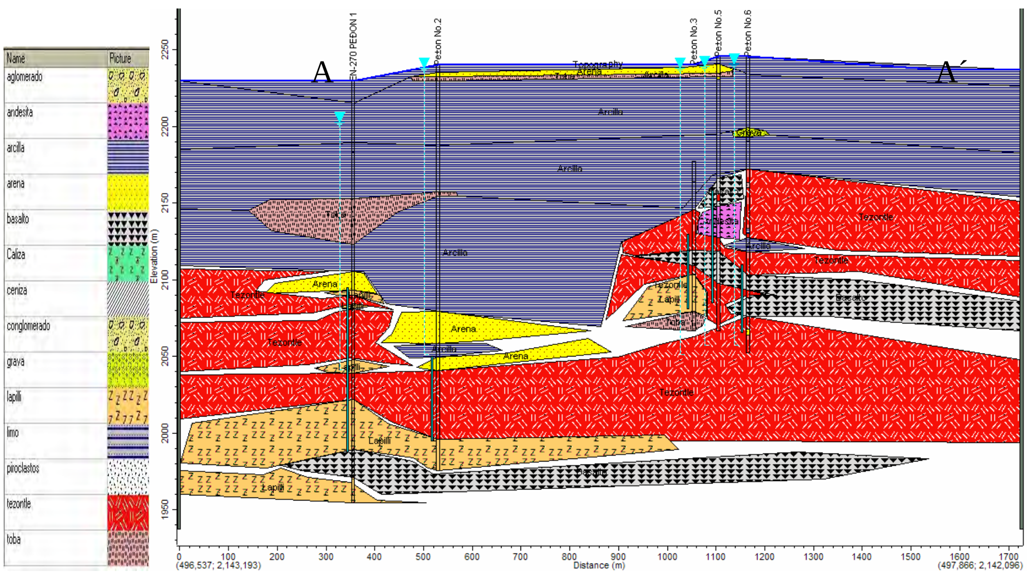

Fig 5 Example of correlation of logs from water extraction wells to build geological cross-sections, 200 m depth (using the HydrogeoAnalyst software, Schlumberger, Inc.).

CONCLUSIONS

The systematic study of ground fracturing carried out in the *Delegación Iztapalapa* is based on the consideration of the nature of geological materials. The Centre of Geological Risk Evaluation (*Centro de Evaluación de Riesgo Geológico*, CERG) has been designed with a consultative capacity, which implies that the knowledge generated about the phenomena of fracturing and subsidence should be applied in the design of mitigation measures and prevent future damage.

Fracturing in the Iztapalapa area is complex and cannot be described by a single mechanism. During our work different combinations of geological conditions and triggers factors were observed. In general, Iztapalapa fractures form due to the combined mechanisms of gradual subsidence and differential compaction of clay strata, rocks and other granular media such as sediments and pyroclastics (tuffs and ash). Pre-existing fractures and discontinuities play a fundamental role in the development of subsidence and fracturing in areas apparently not affected. The continuing reports of fractures from the 1960s in the north (Peñón del Marques) and south (San Lorenzo Tezonco) areas of Iztapalapa confirm this hypothesis. At this stage of the study, we have identified the following mechanisms of fracture:

1. Landslide associated with blocks over a detachment surface on the flanks of the volcano in the Peñon del Marques area.
2. Differential deformation (clay, tuff, organic soil) in the Santa Martha Acatitla Sur UEZ. Erratic fractures with variable dimensions (a few centimetres to several metres) are normally generated by the overload conditions of the subsoil in the lacustrine plain lake of Santa Martha Acatitla and Santa María Aztahuacán.
3. Loss of structure or collapse of unconsolidated material (pyroclastic materials, ashes or tuffs) in areas where water leaks generate infiltrations of surface water.

The physical vulnerability of the Iztapalapa area to land subsidence, ground fracturing and other geological hazards is evaluated through the spatial analysis of the generated information based on thematic maps; this should allow better design of mitigation strategies and urban development. The database includes the mapping of the physical and geotechnical properties of materials and the damaged civilian infrastructure in order to lead to improvements in the construction and development policies in geological hazard areas, as well as mitigation measures in areas susceptible to fracture occurrence. That is why the primary function of the CERG is to create a culture of co-existence with the fracturing, which unfortunately is a persistent and irreversible problem in Iztapalapa.

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