Land Subsidence, Associated Hazards and the Role of Natural Resources Development
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Land subsidence processes and associated ground fracturing in central Mexico

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Abstract Land subsidence has become a general problem in the metropolitan areas of central Mexico. Differential compaction of sediments, related to the increasing urbanization over compressible materials and groundwater withdrawals, have caused the associated phenomena of subsidence and fracturing. These high-population cities developed rapidly in the last twenty years and rely on subsurface resources for more than 70% of water supply, which represents a great challenge for natural resources management that needs to be faced with respect to use of land and groundwater. Different mechanisms of land subsidence and fracturing can be identified in each case depending on their local geological setting: in some urban areas, such as Querétaro, Celaya, San Luis Potosí, Morelia and Aguascalientes cities, the structural control of regional faults generates deformation and fracturing at the base of the covering of shallow sequences that propagate to the surface; in the recent lacustrine areas of the Valley of Mexico differential deformation of clayey and silty compressible materials that have been stressed over their bearing capacity, generates fracturing in the near-surface sequences; in volcanic valleys (i.e. Toluca) the stratigraphic contacts of granular materials interbedded with lava flows are weak planes that localize tensile stresses; toward the western part of the country, such as in Guadalajara City, the presence of huge quantities of fine grained pyroclastic materials are related to a collapsible behaviour and hydraulic fracturing because of groundwater withdrawal. An accurate evaluation of the physical vulnerability of each study case requires the implementation of an interdisciplinary methodology including geological characterization, detailed monitoring of land subsidence, groundwater flow and ground displacements.

Key words differential deformation; groundwater management; vulnerability; faulting; fracturing; Mexico

INTRODUCTION

Most of the Mexican cities affected by land subsidence are located over former lakes in valleys bounded by faults and/or volcanic structures, of ages ranging from Miocene to Quaternary, that belong to a geological province named the Transmexican Volcanic Belt (TMVB). The near-surface stratigraphy below these cities is highly heterogeneous and consists of fluvial and/or lacustrine sediments with particle sizes varying from gravel, sand and silt to clays, with inter-bedded layers of pyroclastic rocks and lava flows. Additionally, in mature and extended lacustrine environments, such as in Mexico Basin, clay size particles are composed of different kinds of clayey materials (crystallized and amorphous minerals) that have a complex mechanical behaviour. Compaction of sediments related to groundwater withdrawal has caused land subsidence in areas with rapidly increasing population (i.e. Mexico City, Toluca, Puebla, Querétaro, Celaya, León, Abasolo, Salamanca Morelia, San Luis Potosí, Aguascalientes and Guadalajara, among others). Thus, study of the shallow stratigraphy and structural discontinuities of soil sequences in areas affected by subsidence and fracturing is necessary for the planning of urban infrastructure. Furthermore, the analysis of these phenomena requires an interdisciplinary approach to obtain a better understanding of the triggering mechanisms of differential settlement and the generation and propagation of ground fracturing.

At study sites in central Mexico it has been reported that the nucleation and propagation of fractures in granular materials is caused by the interaction of diverse factors: (1) geological, pre-existing discontinuities and the depositional environment greatly influence the nucleation and geometry of fractures; (2) stress history influences the geometry of early fracturing, the first-formed fractures modify the local stress tensor and influence their evolution (e.g. Tuckwell *et al.*, 2003); (3) heterogeneities in the compressibility and permeability of geological materials control short-term and local-scale variations of deformation; (4) drastic climatic changes determine the structure of fluvio-lacustrine sediments and create weak planes that may be developed by internal changes of stress such as water extraction, loads, or other anthropogenic activities; and (5) exhaustive exploitation of aquifers that causes a decline of the pore water pressure, and may lead to compaction and land subsidence and create vertical and horizontal tension stress (Carrillo, 1947; Zeevaert, 1953; Marsal & Masari, 1959; Holzer & Davis, 1976; Holzer, 1984). A lateral effect of water extraction is the hydraulic fracturing caused by local tension stresses in the solid particles (Alberro & Hernández, 1990; Juárez-Badillo, 1991). 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.

LOCAL GEOLOGICAL SETTINGS

Fluvio-lacustrine basins located within the TMVB may present contrasting stratigraphy and also geomechanical behaviour. Lacustrine conditions prevailed until recently in the southeast of the TMVB, whereas Tertiary-Quaternary basins delimited by major faults predominate in a semi-desert area named the "Bajio Region" (i.e. Querétaro, San Luis Potosí, Morelia, Aguascalientes cities) (Fig. 1).

The areas affected by subsidence in the Mexico basin are built over silty-clay lacustrine sediments with a high gravimetric water content (100–300%) overlying a regional granular alluvial-pyroclastic aquifer. Over-exploitation of the aquifer has caused piezometric water level decline of about 50 m, and almost 13 m of land subsidence in the central part of Mexico City. Ground fracturing in Mexico City has been reported since 1925 by Gayol, and was analysed by

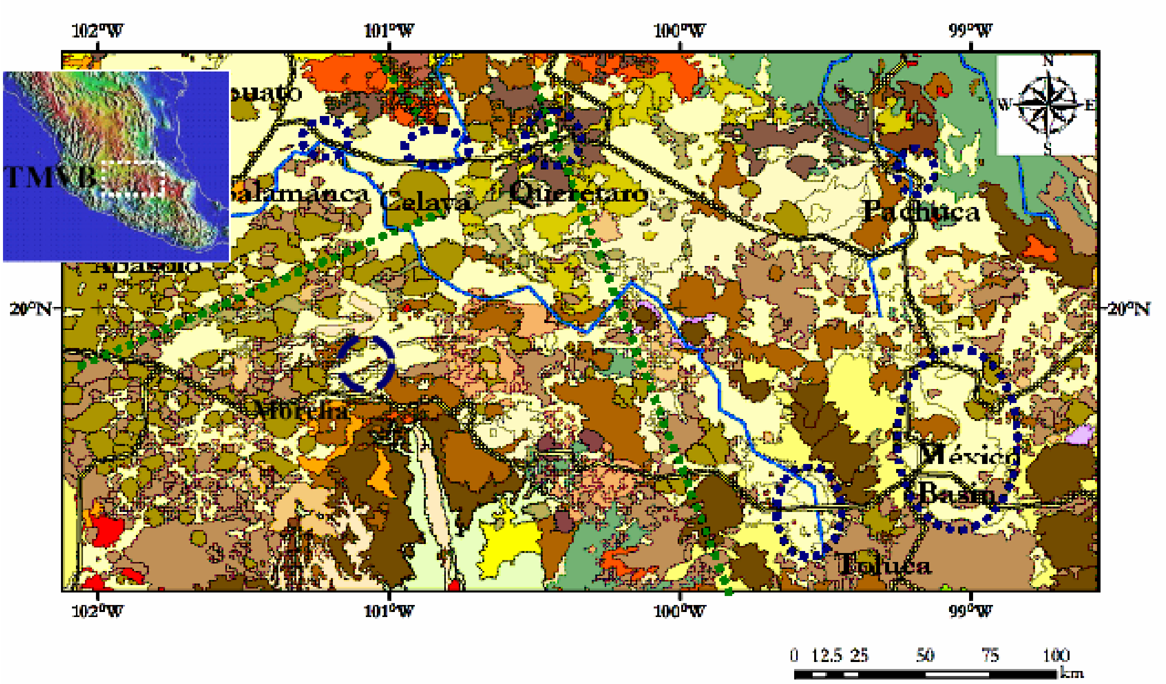

Fig. 1 Location of some cities of central Mexico with subsidence problems (dotted circles) that are located in inter-volcanic and fault bounded basins within the central Trans-Mexican Volcanic Belt Brown colours indicate Plio-Quaternary volcanic and pyroclastic events, yellow colours indicate volcano-sedimentary and lacustrine Quaternary deposits, red colours indicate intrusive rocks (geology map from Ferrari *et al.*, 2007).

Carrillo (1947), Marsal & Mazari (1959) and Zeevaert (1953, 1991) during the first half of the 20th century from the mechanical point of view, considering linear Terzaghi consolidation of the uppermost clayey aquitard. It should be noticed that regional subsidence in the Basin of Mexico was observed before intensive extraction of groundwater by pumping in the last century. Hydrogeological studies in the Basin of Mexico (Murillo, 1990; Rivera & Ledoux, 1991; Rudolph & Frind, 1991) show that subsidence and fracturing continue to increase because of transient responses of the overlying aquitard. The intensity of fracturing increases with the time and causes numerous problems to urban infrastructure.

The fast and unplanned development of the cities located in the Bajio region, in the last three decades, has caused an increase of groundwater demand that lead to a dramatic decline of the piezometric levels from a few metres to below 120 m depth. The near surface sequence that fills these fault-bounded basins consists of partially saturated (approximately 30% gravimetric water content) fluvio-lacustrine coarse grained deposits and pyroclastics interbedded with fractured andesites and basalts (Alaniz-Álvarez *et al.*, 2002; Carreón-Freyre *et al.*, 2005b; Pacheco *et al.*, 2006). Land subsidence and the related faulting in this region was reported previously (Trujillo-Candelaria, 1989; Trejo-Moedano & Baini, 1991; Álvarez-Manilla, 2000; Carreón-Freyre & Cerca, 2006). Fractures and normal faults with slips varying from 0.80 to 2.00 m affect the plain surfaces of the cities. As in the case of Mexico City, surface rupturing has been widely associated with subsidence and the exhaustive extraction of groundwater. The very heterogeneous stratigraphy of these basins records alternative episodes of sedimentation, volcanism and faulting (Carreón-Freyre *et al.*, 2005b; Noyola *et al.*, 2009). Major faulting and high lithological contrasts cause complex water withdrawal patterns and groundwater flows can not be analysed only by the interpolation of piezometric levels of water wells.

The correlation of geological, mechanical and hydraulic parameters suggests a dynamic interplay between the mechanisms of fracturing and the stress history of the local sequence. In the Bajio region groundwater decline modifies the state of stress, which is in turn modified by the pre-existing discontinuities that localize strain. 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. By contrast, in the lacustrine Mexico Basin, some deformation features can be related to shallow groundwater flows (perched aquifers) and as a consequence fractures open and close seasonally. At the same time, a generalized differential consolidation state of thick clayey sequences, related to deep groundwater depletion and lowering of the piezometric surface, has been established. In this case, ground fracturing is related to non-dilatant fractures in high plasticity clays. In both cases, an increase of the effective stresses induces greater differential deformation, but it does not solely explain the propagation of deformation.

GEOMECHANICAL STUDIES OF LACUSTRINE SEQUENCES

The complex mechanical behaviour of fluvio-lacustrine sediments in volcanic areas, brittle failure associated with high water contents in highly compressible fine grained materials, has been widely studied and explained by the identification of different mineralogical compositions (Marsal & Mazari, 1959; Lo, 1962; Mesri *et al.*, 1976; Peralta-y-Fabi, 1989; Díaz-Rodríguez *et al.*, 1998; Díaz-Rodríguez & SantaMarína, 2001; Carreón-Freyre *et al.*, 2002; Carreón-Freyre, 2005). The relationship between the mineralogy of the clay and the consolidation has been widely discussed (Warren & Rudolph, 1997; Saarenketo, 1998; Wesley, 2001). Understanding the relation between the mineralogy and mechanical behaviour of clayey deposits is of the uppermost importance for the study of ground deformation. It is known that the mineralogy of the clays determines their water content. Ohstubo *et al.* (1983) correlated the limits of consistency (plasticity) with the variation in water holding capacity of soil particles according to the chemical characteristics of the clay and pore water, and described three different basic types of pore water in clayey materials: (1) intermolecular water, as a part of the structure of allophane; (2) the water adsorbed tightly to mainly smectite clay particles and; (3) the free water that moves easily between aggregates, intergranular contact and/or microfractures in the clay matrix and that is related to the primary building materials. In sedimentary basins where volcanic activity is contemporaneous with the deposition of the sedimentary fill, the rapid weathering of pyroclastic materials (mainly ashes) generates pumice rich soils, allophane and imogolite, incipient clay minerals similar to low-order gels (Carreón-Freyre *et al.*, 1998). If environmental conditions are favourable to their dehydration, these materials are transformed into gibbsite and halloysite (Righi & Meunier, in Velde, 1995). The allophane is amorphous to the X-ray diffraction method, but with an electron microscope (Wada, 1987) appears as spherical particles of about 4 nm in diameter, which are hollow, irregular and mainly composed of silica and aluminium. The imogolite has a tubular shape and is frequently associated with allophane giving the soil an open porous structure (Wesley, 2001) hence the high compressibility of these materials.

Early research reported contrasting compositions for the clayey sediments of the Basin of Mexico (Zeevaert, 1953; Marsal & Mazari, 1959; Mesri *et al.*, 1976). Peralta-y-Fabi (1989) concluded that the divergence in reported results is due to changes in mineralogy with depth. Since then more studies have been carried out on the mineralogy of these materials, their changes with depth and their related mechanical behaviour (Díaz-Rodríguez *et al.*, 1998; Mazari-Hiriart *et al.*, 2000; Díaz-Rodríguez & SantaMarína, 2001; Gutiérrez Castorena *et al.*, 2005). De Pablo-Galan *et al.* (2001) made a systematic measurement of changes in mineralogy and its influence on the viscosity for two samples at depths of 26 and 60 m, identifying a non-uniform differential behaviour between the samples. A review of the results of the mineralogical composition of the clay fraction reported by different authors has been presented by Carreón-Freyre *et al.* (2006); however, there are few studies relating the geological conditions with variations in the mineralogical, mechanical and hydraulic behaviour of lacustrine sequences (Carreón-Freyre, 2005; Hernandez-Marin *et al.*, 2005), and therefore little is known about the response of these systems and the mechanisms of propagation of fracturing.

GROUND FRACTURING RELATED TO GROUNDWATER EXPLOITATION IN MEXICO

The rapid development of the urban infrastructure in the increasingly urbanized areas has also caused an increase of water demand and the mechanical and hydraulic equilibrium of the subsoil is disturbed by groundwater overexploitation (Holzer, 1984; Rojas *et al.*, 2002; Carreón-Freyre *et al.*, 2005a). Spatial variations in the piezometric decay can be caused by structural or compositional heterogeneities and greatly affect the initial nucleation of a fracture, and are reflected in the overall mechanical behaviour resulting in differential settlement (Zeevaert, 1953; Kreitler, 1977; Ellstein, 1978). In areas with high subsidence rates and major stratigraphic variations, fractures can originate and propagate from depth to the surface.

Analysis of groundwater flow, water management and land subsidence have been documented systematically in Mexico since the 1940s (Carrillo, 1947). Durazo & Farvolden (1989) documented the Mexico Basin as a discharge zone evidenced by large springs along the edge of the valley before the heavy pumping initiated in 1930s. By 1990, these and other authors reported water consumption of about 60 m^3/s and a recharge of about 43 m^3/s, from around 1000 wells at 70–200 m depth, and land subsidence in Mexico City (of up to 8 m) and nearby areas (Murillo *et al.*, 1990; Morales *et al.*, 1991; González-Morán *et al.*, 1999). Several other cities have exploitation deficits of groundwater that have been related to land subsidence and an increase in ground fracturing. For instance, Huizar-Álvarez *et al.* (2003) describes how the Pachuca-Zumpango sub-basin supplies local needs and Mexico City; Carreón-Freyre *et al.*, (2005b) in Querétaro reported a deficit on the aquifer supply of 30%; Noyola-Medrano (2009) reported the groundwater mining of the San Luis Potosí Valley aquifer were extraction is double the recharge and the deficit is increasing; and Ávila-Olivera & Garduño-Monroy (2008) also reported groundwater withdrawal in Morelia City.

Linear numerical analyses of groundwater depletion and increase of effective stress were developed by several authors during the last five decades (Carrillo, 1947; Herrera & Figueroa, 1969; Juárez-Badillo & Figueroa-Vega, 1984; Figueroa-Vega, 1989, 1990; Alberro & Hernández, 1990; Juárez-Badillo, 1991; Pacheco *et al*., 2006). Álvarez-Manilla (2000) and Aguilar *et al.* (2006) recently used numerical analysis integrating groundwater flow and geomechanical equations for land subsidence due to groundwater extraction. They reported 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.

In Mexico City and other cities, in addition to the problem of urban development and the associated fracturing due to groundwater withdrawal, it needs to be highlighted that the unplanned urbanization extends to the zones where the main recharge of the aquifers takes place (Carrera & Gaskin, 2008), so exacerbating the shortage of groundwater.

DEVELOPING INVESTIGATIONS TO MONITOR LAND SUBSIDENCE IN MEXICO

Near-surface geophysics

Several high resolution geophysical methods are being used in Mexico to characterize shallow fracturing structures in urban areas, such as ground penetrating radar (Rangel *et al*., 2002; Carreón-Freyre *et al*., 2003; Carreón-Freyre & Cerca, 2006; Ávila-Olivera & Garduño-Monroy, 2008), microgravity methods (Pacheco *et al*., 2006), and seismic methods to evaluate deeper structures, seismic microzonation (Lermo-Samaniego *et al*., 1999) and the seismic response of consolidated sediments (Aviles & Pérez-Rocha, 2010).

Remote sensing monitoring

Studies using interferometric synthetic aperture radar (InSAR) and global positioning system (GPS) are focused on Mexico City (Cabral-Cano *et al*., 2008) and indicate 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 (Cabral-Cano *et al*., 2008), a method to help interferogram unwrapping (López-Quiroz *et al*., 2009); and persistent scatter interferometry (PSI) to improve the imaging of differences in subsidence rates (Osmanoglu *et al*., 2010). There are few reported works about the application of these methods in other cities of the country.

ASSESSMENT OF MULTISCALE GROUND FRACTURING IN FLUVIAL-LACUSTRINE SEQUENCES

The study of the deformation of silty and clay bearing materials below urban areas reveals the coexistence of several factors determining the characteristics of fracturing at different spatial scales. Groundwater withdrawal and the associated decrease in pore pressure and increase in effective stress is certainly of the most importance, but there are other factors such as static and dynamic over-loading and pre-existing discontinuities to be considered. The most accurate approach to understand the nucleation and propagation of fractures within heterogeneous geological media is by monitoring and analysis of the deformation conditions of the sequence, and integrating their physical and geological characteristics (stratigraphy, structural, mechanical and hydraulic variations of properties). Using this approach, fracture systems in fluvio-lacustrine sequences should be studied according to their size and considering the association of factors from which they are originated. Because concepts of “regional” and “local” are relative and depend on the scale and type of study, this review assumes the following criteria:

(1) **Regional structures** are larger than the urban area concerned. The irregularity of the fractured basement underlying the sedimentary sequences largely determines the location of the fracture that propagates from deep to shallow sedimentary sequences returning to pre-existing

planes of weakness, as is the case in Morelia, and Querétaro (Rojas-González *et al.*, 2002; Carreón-Freyre *et al.*, 2005a). At this scale, regional fault systems and stratigraphic variations should be considered for determining groundwater flow because these structures can promote preferential channel flow or form barriers and so important piezometric gradients (Kreitler, 1976; Carreón-Freyre *et al.*, 2005b).

(2) At an intermediate scale are the fracture systems that mainly affect the top of the fluvio-lacustrine sedimentary sequence, often interbedded with pyroclastic and volcanic materials. The first 300 m are considered because this depth corresponds to the current average depth of groundwater exploitation wells. At this scale, one of the main mechanisms of fracturing is differential deformation (e.g. differential settlement), because the materials have a heterogeneous distribution of hydraulic and mechanical properties (Zeevaert, 1953; Ellstein, 1978; Orozco & Figueroa, 1991; Carreón-Freyre *et al.*, 2003). Considering that fracture formation is only due to the lowering of groundwater piezometric levels implies a simplification of the phenomenon; it has been reported that the largest drawdowns are not related directly to the larger land subsidence phenomena in fractured areas (critical vertical displacements) (Carreón-Freyre *et al.*, 2005a). For proper assessment of the conditions of propagation of fractures at this scale, study of the vertical variations of hydraulic properties of the aquifer system and the lateral variations of the compressibility of the materials is recommended (Figueroa-Vega, 1989; Carreón-Freyre *et al*, 2005a, Carrera-Hernandez & Gaskin, 2008)).

(3) The local scale refers to subsidence and fracturing in restricted areas and may vary from a few to tens of metres (the geomechnical properties of the materials can be directly characterized). This is the scale at which most geotechnical studies are performed. Examples of local fracturing are: (a) annular stress fractures that are generated in the transitional zones of the foothills of hills (Lugo-Hubp *et al.*, 1991) and that are related to gravitational landslides (Cerca *et al.*, 2010), (b) cracks in the surface mainly generated by evaporation-drying of clays in lacustrine plains (generated by changes in climatic conditions), (c) pore pressure diminution in the lower sedimentary layers, and (d) tensional fracturing generated by the stress of localized over-pumping (Alberro & Hernández, 1990; Juárez-Badillo, 1991).

The above considerations regarding the factors of scale and composition of clay sequences should allow appropriate design of monitoring systems and lead to accurate assessment of the hazards related to ground fracturing in the urban areas of central Mexico.

DISCUSSION

Analysis of the factors that cause land subsidence in fluvio-lacustrine basins and the generation of fractures demonstrate reliable characterization of geological materials and the changes in their properties in time and space. This requires the combination of field and laboratory techniques and systematic integration of information. The analysis of the reported literature of land subsidence and fracturing case studies in Mexico show that, even if these phenomena are determined by local geological conditions, the cities affected in central Mexico are located within the TMVB and have many triggering factors in common. Other specific cases, such as sinkhole hazards that occur in the Yucatan Peninsula or in the limestone Laguna zone of Durango, are not considered.

There are a few case studies in Mexico that involve surface and subsurface deformation monitoring. There is an urgent need in Mexico to integrate networks of benchmarks to calibrate GPS and InSAR analysis in the main affected cities. Groundwater flows follow deep and complex patterns that also require real-time monitoring. A further line of research work is coupled mechanical-hydraulic modelling to simulate the nonlinear interactions between groundwater withdrawal and its contribution to the propagation of the deformation within inelastic media. We need to establish specific training programmes addressed at different levels of students (technical, undergraduate and postgraduate) to create interdisciplinary workgroups to manage the complex databases resulting from land subsidence and fracturing studies at different scales.

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