Integration of geological properties in the study of the subsidence and fracturing phenomena in two urban areas of Mexico

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Abstract: We compare the mechanical behaviour of the near surface materials in two sedimentary sequences with contrasting grain size and water content. The methodology includes detailed laboratory measurements of physical properties such as specific gravity, grain size distribution, water content, Atterberg limits, electrical conductivity, and compressibility performed in samples from geotechnical excavations. Contrast in the physical properties can be identified in Ground Penetrating Radar (GPR) profiles to obtain the geometry of the deformational features. The basin of Mexico is characterized by a recent lacustrine sequence with high water content and clay bearing sediments intercalated with pyroclastic deposits. Deformational features in this basin reflect an interplay between the geological history (depositional conditions), load history, seismic activity, and faulting. Plastic mechanical behaviour predominates in these clayey sediments and differential deformation locally triggers brittle fracturing and/or subsidence of the surface. In this case, the fractures are planes of weakness that reduce the bulk strength of the clay and increase its hydraulic conductivity. In contrast, the near surface sequence of the Valley of Queretaro is characterized by highly heterogeneous unsaturated sand-and-silt bearing sediments with intercalated pyroclastic layers. The mechanical behaviour of these materials is characterized by dilatant fractures and associated shear bands with a normal displacement. Failure of the sequence is caused by a general compaction of the sedimentary refill and the presence of a pre-existing buried fault scarp localizes strain in a 5 km long narrow band with a N-S orientation. Differential deformation plays an important role only in the near surface sequence as a response to applied loads. Relating the mechanical behaviour of the studied sequences with physical and geological properties should be taken into account to estimate subsidence and risk of fracturing for urban development.

Résumé: On compare le comportement mécanique des matériaux près de la surface dans deux séquences sédimentaires présentant granulométrie et teneur d'eau contrastées. La méthodologie du travail comprend des déterminations en laboratoire de propriétés physiques tels que poids spécifique, granulométrie, teneur d'eau, limites d'Atterberg, conductivité électrique et compressibilité des échantillons prélevées dans des tranchées. Les contrastes des propriétés physiques identifiés dans les profiles du Radar de Pénétration Terrestre ont permis de caractériser la géométrie de la déformation des matériaux. Le basin de Mexico est caractérisé par une séquence lacustre argileuse présentant une élevée teneur d'eau intercalée avec des matériaux pyroclastiques. Les caractéristiques de la déformation dans ce basin montrent l'étroite relation existant entre l'histoire géologique du dépôt, l'histoire des charges, l'activité sismique et la fracturation. Dans ces matériaux argileux prévaut un comportement plastique, cependant leur déformation différentiel déclanche une fracturation locale de type fragile et/ou une subsidence généralisée de la surface. Dans ce cas, le réseaux de fracturation deviennent des plans de faiblesse réduisant la résistance globale des argiles et augmentant leur conductivité hydraulique. Par contre, la séquence de la Vallée de Queretaro est caractérisée par des matériaux limon sableux, non saturés et très hétérogènes intercalés avec des couches pyroclastiques. Le comportement mécanique de ces matériaux est caractérisé para fractures dilatantes associées aux bandes de cisaille avec an déplacement normal. La fracturation de la séquence est due à sa compaction mais l'escarpe d'une faille régionale préexistante conditionne son extension comme une étroite bande de 5 km de largeur et direction N-S. La déformation différentiel des matériaux joue an rôle important seulement dans la partie la plus près de la surface et est due principalement aux charges appliquées. La corrélation des comportements mécaniques des séquences étudiées avec leur propriétés physiques et géologiques doit être considérée dans les estimations des risques de subsidence et fracturation dans les plans du développement urbain.

Keywords: Deformation, sediments, clay, consolidation, discontinuities, mapping.

INTRODUCTION

Fracturing and land subsidence has become a problem in urbanized areas of central Mexico. Compaction of sediments related to groundwater withdrawal has caused subsidence in areas with rapidly increasing population (i.e. Mexico City, Queretaro, Celaya, and Salamanca). Thus, the engineering geology study of the shallow stratigraphy and structural discontinuities of soil sequences in areas affected by fractures or subsidence is necessary for the planning of urban infrastructure. Furthermore, the analysis of these phenomena requires a multidisciplinary approach for a better understating of the triggering mechanisms and propagation of fracturing. The near surface stratigraphy below many cities in central Mexico consist of fluvial or lacustrine sediments with particle sizes varying from gravel, sand, and silt to clays, with interbedded layers of pyroclastic rocks and lava flows. In particular, clay size particles are composed of different kinds of clay materials (crystallized and amorphous minerals). Carreón-Freyre *et al.* (2003) proposed a methodology for the study of such sedimentary sequences, which includes a detailed geotechnical characterization of samples obtained in excavations and non-destructive analysis of the stratigraphy with Ground Penetrating Radar (GPR). GPR offers the possibility to obtain continuous vertical profiles of the subsoil with a high resolution (for depths <10 m). Contrast in physical properties of materials can be related to reflectors recorded in GPR profiles, and the comparative analyses of profiles provide radar signatures that can be accurately correlated with vertical and lateral variations of physical properties of sediments. The results of the methodology for two case studies in the valleys of Mexico (Chalco sub-basin) and Queretaro has been presented previously (Carreón-Freyre *et al.*, 2003; Carreón-Freyre & Cerca, 2006) (Figure 1). The results show that the type of fractures present in each area is originated by a combination of the physical properties of the sequence and the geologic setting. In this work, we contrast the mechanical and subsidence characteristics of each area in terms of their physical properties, heterogeneities and geological setting. The discussion focus on the identification of the critical parameters required to compute the risk of fracturing.

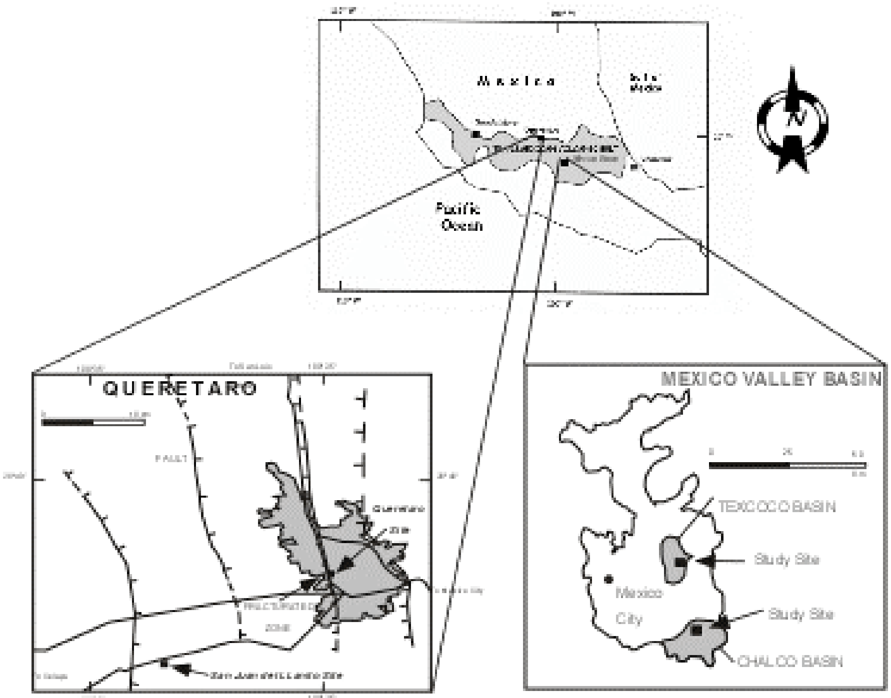

Figure 1. Location of the areas studied in the central part of the Trans Mexican Volcanic Belt. Note contrasting regional geological framework of each basin. The Queretaro area is crossed by a regional network of NNE-SSW fracturing. The Mexico Valley was an extensive basin which was further divided into many lacustrine sub-basins.

METHODOLOGY

Detailed measurements of specific gravity, water content, liquid and plastic limits (Atterberg limits), grain-size distribution, electric conductivity (EC), and compressibility (C_c , Compressibility Coefficient) were performed on the near surface stratigraphy of the selected sites. In the case of Chalco, the physical properties were determined for the upper 7 m of the lacustrine sequence in a geotechnical core and detail of the upper 2 m was achieved in an excavation near to the core. In the case of Queretaro, physical properties were measured for the upper 7 m in two excavations perpendicular to the main fracture system. Representative samples of approximately 20 cm were analyzed at the Geomechanical Laboratory of the Center of Geosciences (National University of Mexico, UNAM). The methodology of determination of physical properties is described in detail by Carreón-Freyre *et al.* (2003). Variations in depth of the physical properties: gravimetric water content and plasticity, specific gravity, grain-size, and conductivity for the studied sites are presented in Figure 2. The determinations of C_c in the Chalco cores are also presented on Figure 2a.

In the field, the results of physical properties were related to the response of electromagnetic waves by the method of Ground Penetrating Radar (GPR). A relationship between electrical and geotechnical properties of soils has been documented extensively (Santamarina *et al.* 2001, Saarenketo 1998, Fam & Santamarina 1997, Doolittle & Collins 1995). Since the mechanical behaviour of fine-grained sediments also depends on water content GPR becomes a useful tool for geomechanical characterization of near surface sequences. For instance, Fam & Santamarina (1997) documented changes in electric, physical, and chemical characteristics of clay soils for different consolidation stages and for variations in Atterberg limits. Furthermore, it has been suggested that the physical characteristics of clay-bearing soils such as micro-structure, grain-size, water content, and mechanical characteristics are related to their electrical resistivity (Fukue *et al.* 1999). In this way, contrasts in the physical properties such as water content, grain size, and compaction can produce a reflection of the radar waves. The methodology consisted in identifying contrasts in the physical property profiles enough to produce a reflection in the GPR profiles. Several continuous GPR profiles were collected parallel and perpendicular to the main fracture patterns in both studied sites. Distinctive patterns of reflection (or radar signatures) were recognized along GPR profiles and permitted the identification of subtle stratigraphic heterogeneities related to differences in water content and grain size. Radar signatures also allowed an appropriate extrapolation of the sedimentary structures, such as the presence of sand lenses or clayey layers. Near vertical perturbation of the radar signatures permitted to delineate the geometry towards depth of the fractures affecting the sequences. For the studied cases, best definition of sedimentary and structural features was obtained using a 300 MHz antenna, whereas textural variations were best recorded using a 900 MHz antenna.

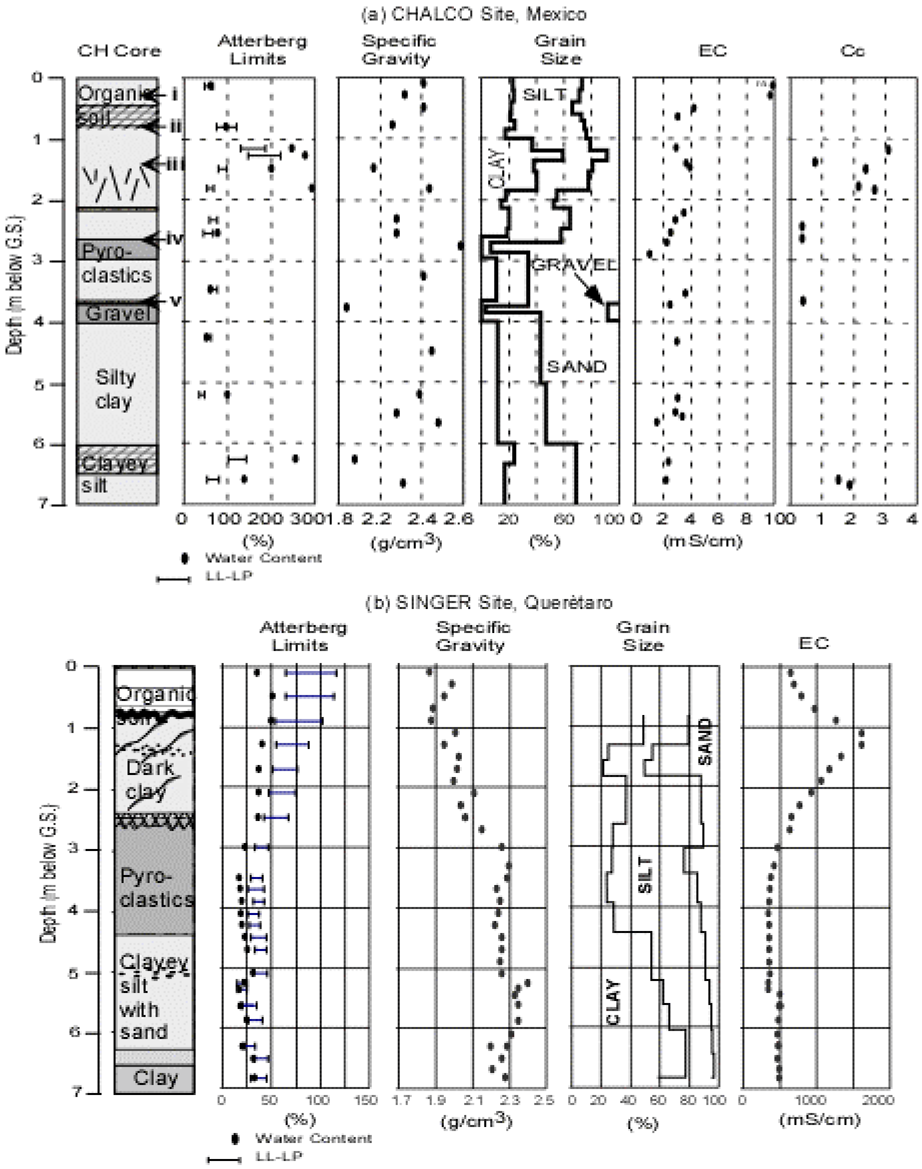

Figure 2. Vertical profiles of the physical properties in the valleys of Mexico and Queretaro: (a) Physical and mechanical determinations in the core samples of the Chalco basin (CH site shown in Figure 3); (b) Physical determinations in samples from an excavation in the Singer site (located on the trace on the main fracture system that crosses the city, shown in Figure 5) (modified after Carreón-Freyre *et al.* 2003 and Carreón-Freyre & Cerca 2006).

GEOLOGIC SETTING OF THE VALLEYS OF MEXICO AND QUERETARO

The Valley of Mexico

The Valley of Mexico is located in the central part of the Miocene to Quaternary Trans-Mexican Volcanic Belt (TMVB) and its near-surface stratigraphic sequence consists mainly on lacustrine sediments often interbedded with pyroclastic rocks and other volcanic materials. During the last century, as a consequence of the descending water level, the main valley was divided in several clay bearing fluvio-lacustrine sub-basins, that include the Mexico City, Chalco, Texcoco, Xochimilco and Zumpango basins (Figure 1). Here, we only refer to the physical properties of near-surface sediments beneath Mexico City and Chalco. Several attempts have been made to classify the geomechanical behaviour of the lacustrine sediments and other materials within the Basin of Mexico. A widely used geotechnical classification of the Mexico City area in (a) lacustrine plain, (b) transition zone and, (c) hills zone, was proposed by Marsal & Mazari (1959). However, this classification does not consider detailed stratigraphy nor vertical or lateral variations of physical properties of sediments. The area affected by subsidence in Mexico City is built on fine-grained lacustrine sediments overlying a regional granular alluvial-pyroclastic aquifer. Over-exploitation of the aquifer has caused piezometric water level decline of about 50 m and near to 10 m of land subsidence in the central part of Mexico City and in the Chalco basin. The subsidence related with the water decline has been documented since the 1940´s (Carrillo 1947). The lacustrine sediments in Mexico City are also fractured and several hypotheses have been proposed to explain their origin. Local fractures have been reported on the former lacustrine plains within the basin of Mexico City by Carrillo (1947); Marsal & Mazari (1959) and Zeeavert (1953, 1991). Since then, the intensity of fracturing has increased and causes numerous problems to urban infrastructure. Hydrogeology studies in the basin of Mexico (Ortega *et al.* 1993, Rudolph & Frind 1991, Rivera & Ledoux 1991, Murillo 1990) show that piezometric levels continuously decline in the aquifer, and that subsidence and fracturing continue to increase because of transient response of the overlying aquitard. Estimations of infrastructure damage are in the order of several thousands of millions of dollars.

The complex mechanical behaviour (brittle failure associated with high water contents in high compressibility materials) of the Mexico City sediments has been widely studied and explained for different mineralogical compositions (Diaz-Rodriguez & Santamarina 2001, Diaz-Rodriguez *et al.* 1998, Peralta-y-Fabi 1989, Mesri *et al.* 1975, Lo 1962, Marsal & Mazari 1959). For instance, Peralta-y-Fabi (1989) suggested that differences in the reported clay components of the clayey sediments are due to the variations in the mineralogical content with respect to depth. The same author related the mechanical behaviour of the clayey sequence with complex micro-structural discontinuities. Besides, stratigraphic and depositional conditions, such as variations in salinity or water level, related to changes in weather and/or drainage, of the Quaternary vulcano–sedimentary sequences have been reported for the Mexico City and Chalco basins (Urrutia *et al.* 1994, Lozano *et al.* 1993). The rapid decline of water level in the last century is expected to have changed some of the properties of the clay bearing sediments. Indeed, based on an analysis of the composition of clay bearing sediments in the adjacent Texcoco sub-basin, Gutierrez-Castorena *et al.* (2005) suggested that grain size, apparent density, moisture retention capacity, cation exchange capacity and the solubility of Si, Al, and Fe, are physical and chemical properties that change due to the loss of water in lacustrine sediments.

In the Chalco sequence, where similar complex mechanical behaviour is expected, we started characterization studies in order to identify the geological factors affecting mechanical properties and generating fracturing. Subsidence of the Chalco site is caused by the consolidation of the near surface silty-clayey sediments. We selected a site near a fracture ca. 400 m long with an overall orientation N10 that opens and closes seasonally (Figure 3). The upper 16 m of the sequence were described in a geotechnical core adjacent to the fracture and consist of five distinctive layers with montmorillonite and allophone as the predominant mineralogy (Hernández-Marín *et al.* 2005).

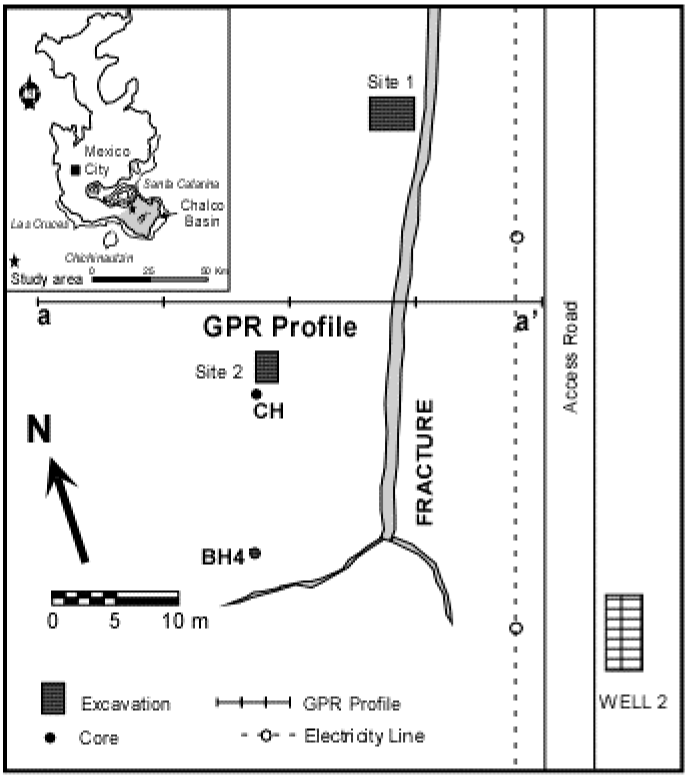

Figure 3. Location of Chalco site near Mexico City. The schematic plan view shows the orientation of a major plane of fracturing, the location of the analysed core (CH), two excavation sites (marked as site1 and site 2) for comparing lateral variations on physical properties, and the location of a representative GPR profile (a-a' profile shown on Figure 4) (modified after Carreón-Freyre *et al.* 2003).

The sequence is characterized by a maximum clay content of 28%, minimum specific gravity of 1610 kg m^{-3}, high values of porosity ~ 86 %, and gravimetric water content of ca. 350%. The vertical variations in depth of the physical properties measured in a core and excavation permitted to define contrasts that could produce a reflection in the electromagnetic waves (these are potential reflectors marked with i, ii, iii and iv in Figure 2a). The reflectors were then projected into a grid of GPR profiles that cover the area of the core and the fracture (Carreón-Freyre *et al.* 2003). The interpretation of GPR signatures shows differential deformation between clayey and sandy layers and vertical fractures that accommodate strain as shown in the interpretation of the GPR profile on Figure 4. Shear stresses are induced in the soil mass by differential compaction. This, in turn is influenced by the high contrast in compressibility and water content between the clay and sand layers. Fractures propagate preferentially along previous weak planes, not only fractures formed by desiccation processes in the palaeosurfaces of the lake but also thin layers of ash and sand lenses. The presence of two contrasting mechanical behaviours (plastic deformation and brittle fracturing) in the same clay layer can not be easily explained in the frame of a typical stress-strain relationship analysis. We rather prefer a cinematic analysis in which the morphology of synforms and antiforms recorded in the GPR profiles are the combined product of differential deformation and allow location of shear planes or fractures.

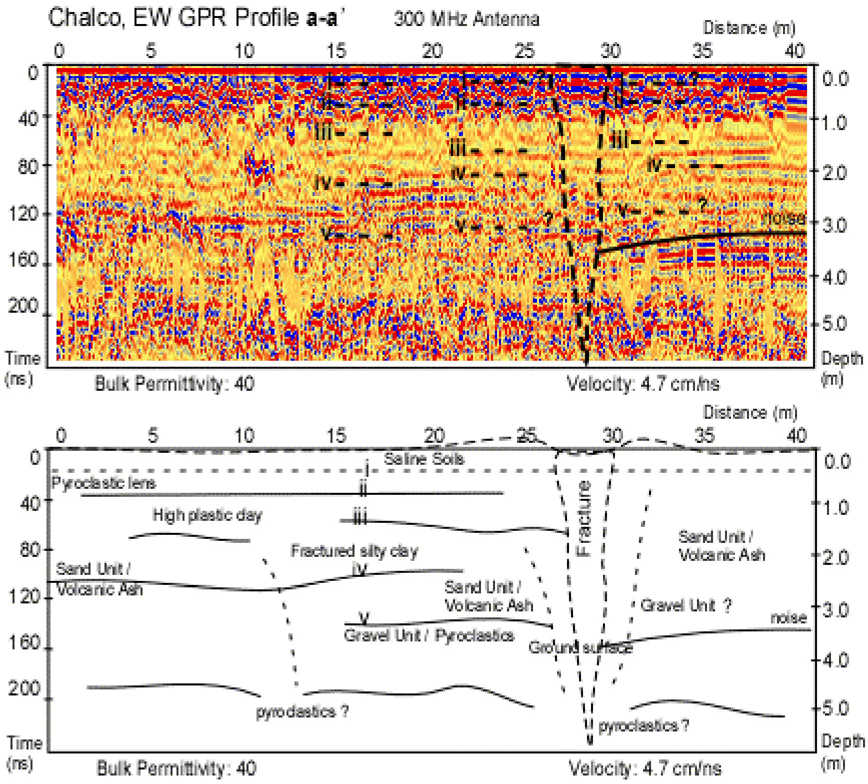

Figure 4. GPR profile representative from Chalco detection achievements with the 300 MHz antenna. The recorded reflectors marked i, ii, iii, iv, and v correspond with important variations in depth of physical properties shown on Figure 2a. Discontinuities are marked with dotted lines on the profile; note the wedge form of the regional fracture plane. The interpretation of the profile shows the differential deformation of the clayey sediments and the associated fracture planes (after Carreón-Freyre *et al.* 2003).

The Valley of Queretaro

The Valley of Queretaro is located ~200 km to the northwest of Mexico City. In the last few decades, the rapid development of the urban infrastructure in the Valley of Queretaro has caused an increase of ground water demand. Being in a semi-arid climate the growth of the city depends mainly on groundwater supply leading to a dramatic decline of the piezometric levels from a few metres to below 120 m depth. The uppermost natural layer is composed of black-clay that fractures easily when dried amplifying the geotechnical challenge. Below the dark-clay, the near surface sequence consists of fluvio-lacustrine coarse grained deposits, basalts and partially saturated pyroclastic rocks (approximately 30 % of water content). This sequence fills a fault-bounded ~N-S oriented basin that began to form in the Miocene (Figure 1) (Alaniz-Álvarez *et al.* 2002, Carreón-Freyre *et al.* 2005). Queretaro City occupies mainly the eastern part of the plain surface of the valley. Detailed stratigraphy of the near surface sequence in the urban area was described by Trejo-Moedano & Martinez-Baini (1991) based on core descriptions, and by Carreón-Freyre & Cerca (2006) in two geotechnical excavations. Below the upper 1.0 m of refill used for construction, there is a dark clay layer, with high plasticity and medium to firm consistency, grading to medium plastic silt that presents desiccation cracks. Between 3.0 and 4.0 m depths there is a sand layer of highly variable width depending on the proximity to fluvial systems. Below 4.0 and above 7.0 m depth there is a silty stratum with medium plasticity. In contrast with the Chalco sequence, the Valley of Queretaro sequence is characterized by a maximum clay content of 78 %, minimum density of 2000 kg m^{-3} and gravimetric water content of ca. 30 % (Figure 2b).

Fractures and small normal faults (less than 3 m of vertical displacement) were reported in the urban area of Queretaro since relatively recent times (Trejo-Moedano & Martinez-Baini 1991). Nowadays, the main system of fractures and normal faults affecting the city is a 5 km long and narrow band (less than 10 m wide) with a ~N-S orientation, named Falla Central (FC). The FC affects the urban infrastructure along one of the main avenues of the city of Queretaro, the 5 de Febrero Avenue (Figure 5). Almost all the system has a vertical displacement of less than 3 m with the hanging wall to the west. The regional geology and geometrical characteristics of the deformation suggest that the FC reflects the presence of a buried and inactive fault scarp (Rojas *et al.* 2002, Carreón-Freyre & Cerca 2006). The apparition of the first fractures on the plain surface of the valley and their development to small scale normal faults has occurred in the last decades suggesting also a cause-effect relationship with groundwater withdrawal. Previous models exploring a direct relation between groundwater decline and ground fractures in Queretaro, simplify the problem assuming a rheologically homogeneous refill above the fault scarp and intense extraction in the hanging wall (i.e. Rojas *et al.* 2002, and references therein). However, the analysis of the stratigraphy of 70 extraction wells in the Valley of Queretaro suggest that important lateral changes in composition and grain size are present in the near surface sequence (Carreón-Freyre *et al.* 2005). Furthermore, the analysis of the piezometric levels performed by the same authors indicates that zones of greater depletion occur in the footwall of the fault, and a direct cause-effect of water depletion patterns with the nucleation and propagation of fractures cannot be easily established. Thus, the extensive extraction of groundwater can be the triggering factor to the formation of fractures, but the localization of strain in a regional and narrow band is determined by pre-existing discontinuities. We envisage a scenario in which the first fractures nucleated as a response to self-weight consolidation of the sedimentary sequence during and after deposition on the fault scarp. The activity of the fault during deposition of the sedimentary refill cannot be overruled during this stage. In this scenario, the rapid decline of groundwater in the last decades triggered an intense period of consolidation and pre-existing fractures propagated towards the surface. Normal faulting is caused by differential compaction in both sides of the buried scarp.

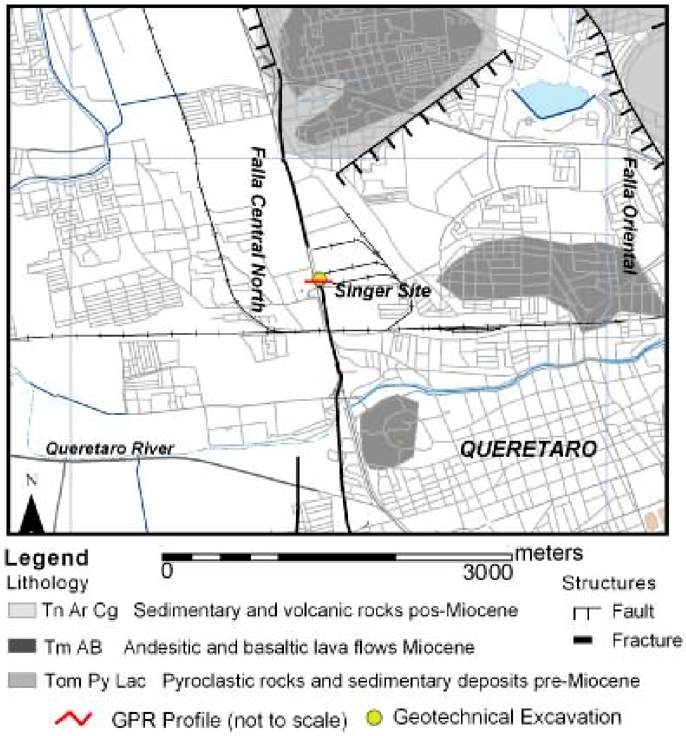

Figure 5. Location of the Singer site in Queretaro City. The map shows the northern part of the Queretaro City; note that the "Falla Central" main fracture pattern crosses by the city along one of one of the most important avenues called "5 de Febero". The red line indicates a GPR profile perpendicular to the main fracture path, shown on Figure 6 as GPR Profile A.

The near surface geometry of the fractures and faults were delineated with GPR profiles collected perpendicular to the trace and in sites distributed along the FC. The main results of the GPR survey were reported by Carreón-Freyre & Cerca (2006). In this case, the physical and mechanical properties of the near surface sequence were determined in two geotechnical excavations crossing the FC in its north and south part respectively. As in the case of Chalco, the lateral variations of the radar signatures permitted to identify the variations in the physical properties of the sequence. However, in this case the changes in radar signature corresponded mainly to changes in the grain size of sediments as observed in the two excavations (Figure 6). The small scale variations in direction of the trace and vertical displacement of the FC can be related to the observed lateral variation in mechanical properties of sediments. The faults and fractures generally are open or filled with gouge material. Fault planes are well developed and have vertical striations consistent with their vertical displacement.

GPR ACHIEVEMENTS FOR ASSESSING DIFFERENTIAL DEFORMATION

Ground Penetrating Radar method is an effective instrument for prospecting shallow stratigraphic variations in fluvio-lacustrine deposits due to the close relation between the behaviour of electromagnetic waves in the medium and many physical mechanical characteristics of soils (water content, salinity, grain size, compaction, and plasticity).

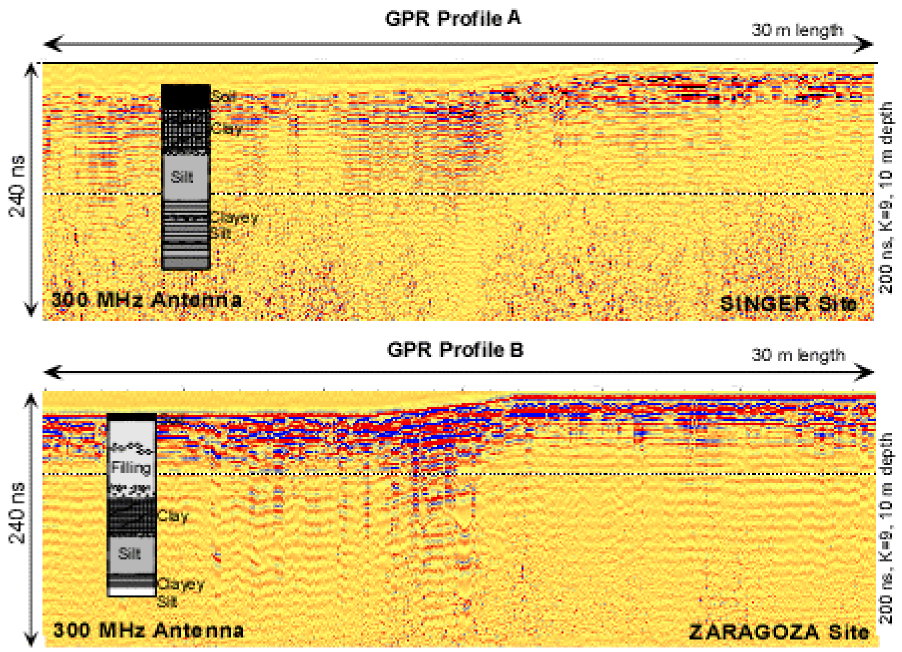

Figure 6. Representative GPR profiles near the two excavations sites crossing the FC in its north and south part (called Singer and Zaragoza site respectively) (after Carreon-Freyre & Cerca, 2006). The correlation of radar signatures can be accurately associated with physical variations in depth associated with local depositional conditions as it shown in the corresponding black and grey stratigraphic logs. The location of GPR profile A is indicated in Figure 5.

Alternating layers of clay, volcanic ash, pyroclastic sand, and gravel that characterize the stratigraphy of the lacustrine sequences are very useful for the detection of stratigraphic features because of the high contrast of their electrical properties. The clayey deposits of Chalco have low resistivity due to increasing evaporation stages in arid conditions that prevailed from the beginning of the Holocene (Urrutia *et al.* 1994). The abundance of pumiceous concretions in the upper layer is a product of the intense volcanic activity in the area. They increase the permeability and, therefore, the coefficient of consolidation (see the 1 m depth unit of the stratigraphic log shown on Figure 2a). In this way, radar signatures can provide an accurate picture of the variations in the mechanical behaviour of sediments. The lateral and vertical changes in the radar signature (i.e. Figure 4) in the same layer are very useful for computing differential deformation of the silty clayey sediments.

In general, the GPR method has a low detection capacity in saturated clayey materials due mainly to their high water retention capacity and low electrical resistivity. However, when a high dielectric contrast is present between the clay and sand layers, the capacity of detection improves considerably with increasing salinity of pore water and grain size contrasts. For example, assuming a permittivity of 30 and 40 for saturated sand and clay layers respectively, the coefficient of reflection in this contact is approximately 0.01, which lies at the limit of detection capacity of a standard radar (Annan & Cosway 1992, Davis & Annan 1989). In more conductive clay, permittivity can increase considerably because of the high salt content in pore water. An increment of 30 % in the permittivity (from 40 to 60) is enough to double the reflection coefficient (to 0.02). This can explain the satisfactory detection results in the saturated clayey surveying of the Chalco basin.

In the Queretaro sites, electrical conditions were favourable for the GPR prospecting. The deposits have a coarse-grained texture and were partially saturated; a bulk velocity of propagation of 0.055 m/ns was estimated for both sites. An increase in the velocity of about 17% in relation to the Chalco site improved detection depths in more than 40% for the 300 MHz antenna, and about 25 % for the 900 MHz antenna. We obtained satisfactory results for both frequencies, in the evaluation of GPR detection capacity for lateral textural changes and vertical variations in compaction and coherence (i.e. gypsum concretions and compacted clays in contact with loose sand).

Analysis of the lateral discontinuities of the radar signature suggested deformation in the subsoil that could be identified either in radargrams of the Chalco and Queretaro City sites. A favourable propagation velocity and enough electrical contrast within the stratigraphic sequence allowed a good definition of the fracture geometry in the Valley of Queretaro. Detailed GPR field studies relating detection capacity to variations of velocity of propagation in geological materials are scarce albeit theoretical studies have been developed about propagation of electromagnetic waves. A quantitative analysis should involve complex calculations considering among other parameters; the efficiency of the radar system used, the transmitted frequency, electrical contrasts and the attenuation of the signal. The radargrams presented in this paper show some aspects of these variations between the velocity of propagation in a geological sequence and the GPR detection capacities in sedimentary sequences.

DISCUSSION: MECHANISMS OF FRACTURING RELATED TO THE SUBSIDENCE PHENOMENA

Based on the historical data and field evidence presented, generation of fractures is found to be associated with variations in mechanical properties (mainly grain size) and ground water flow conditions. Fractures have been identified in many cities of Mexico at different scales affecting several stratigraphic units and, as a consequence, different hypothesis had been proposed in order to explain the interplay of different factors that condition their generation and propagation (Carrillo 1947, Marsal & Mazari 1959, Melgoza 1978, Holtzer & Pampeyan 1981, Holtzer 1984, Lugo-Hubp *et al.* 1991). Land subsidence is certainly a regional and progressive phenomenon related with groundwater, oil, ore, or gas extraction, but differential settlements and fracturing are closely related phenomena that should be understood in order to establish the conditions of formation and propagation for each study case.

The theories that explain the generation of fractures focus either on the regional geological setting or on groundwater flow dynamics, but few works try to relate both aspects in a multi-scale approach. Numerous geological factors can propitiate the nucleation and propagation of fractures, including: (i) lateral and vertical changes in the near-surface stratigraphy (depositional variations and interbedding of Quaternary lava flow and pyroclastics with the lacustrine sediments) and diagenetic changes in their chemical and mechanical properties as documented by Chandler (2000); (ii) structural features such as pre-existing regional faulting, and/or stepped bedrock topography (Rojas *et al.* 2002, Auvinet & Arias 1990, Larson 1984); and (iii) seismic activity (neo-tectonic), in areas where geological faults are active (Klreiter 1976, Melgoza 1978). On the other hand, the mechanisms of fracturing associated to groundwater flow can be grouped according to the scale of the study: (iv) micro-centrimetric fractures that can be either caused by alternate wetting and drying processes (because of climate changes) mainly present in clayey sediments or by over-pumping of groundwater in localized areas (Juarez 1962, Holzer & Davis 1976, Alberro & Hernandez 1990); (v) centrimetric-decimetric hydraulic fracturing caused by seepage flow or filtration forces also caused by over pumping in silty sequences (Lofgren 1972, Juarez & Figueroa 1989, Alberro & Hernandez 1990); and (vi) metric-decametric fractures caused by differential withdrawal of groundwater because of lateral stratigraphic variations (Holzer & Davis 1976, Jachens & Holzer 1982, Holzer 1984, Figueroa 1989).

Our results suggest a dynamic interplay between the mechanisms of fracturing and the stress history of the local sequence (Table 1). For instance in the Queretaro case, groundwater decline causes a state of stress, which is in turn modified by pre-existing discontinuities that localize strain. The mechanical response, brittle dilatant fractures and faults in low plasticity silts, of the near-surface sequence is determined by local variations in grain size and the low water content. In Chalco, the deformation features can not be associated directly to groundwater flow but only to water content in the near-surface sequence and, as a consequence, the fracture opens and closes seasonally. In this case, the mechanical response of the sequence is differential consolidation and fracturing 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.

Table 1. Comparison of the parameters that can be critical for the evaluation of fracturing in a sedimentary basin.

Engineering-Geological Features	Chalco Basin	Queretaro Basin
Main grain size	High plasticity silty clays (CH)	Low plasticity silts (ML)
Gravimetric Water content	100 – 200 %	30 %
Interstratified layers	Ash	Tuffs
Mechanism of fracturing	Differential consolidation assoc. with pre-existing micro fractures	Differential deformation assoc. with regional fracturing
Mechanism of propagation of fractures	Plastic deformation in different lateral and vertical directions	Brittle failure from down to surface
Approximate land subsidence	9 m	2 m
Vertical fault displacement	unknown	0.8 m

Acknowledgments: Funding provided by PAPIIT (in 1n111398), CONCYTEQ (2003 project ref. 29), and CONACYT (FOMIX QRO 2004) for different stages of this research is gratefully acknowledged. Martín Hernandez-Marín and Ricardo Carrizosa helped in field and laboratory analysis.

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