Correlation of near-surface stratigraphy and physical properties of clayey sediments from Chalco Basin, Mexico, using Ground Penetrating Radar

Dora Carreón-Freyre*, Mariano Cerca, Martín Hernández-Marín

Centro de Geociencias, Universidad Nacional Autónoma de México, Campus Juriquilla, Queréétaro, Apartado Postal 1-742, Queréétaro 76001, Mexico

Received 21 September 2001; accepted 19 May 2003

Abstract

Detailed measurements of water content, liquid and plastic limits, electric conductivity, grain-size distribution, specific gravity, and compressibility were performed on the upper 7 m of the lacustrine sequence from the Chalco Basin, Valley of Mexico. Eight stratigraphic units consisting of alternating layers of clay, silt, sand, and gravel of volcanic origin are described for this sequence. The analysis of contrasts in the physical properties permitted to identify potential reflectors of radar waves: (i) change in the electrical conductivity at 0.4 m depth; (ii) increment in the clay and water content at 0.8 m depth; (iii) bimodal behavior of the water content at 1.3 m depth; (iv) increment in the sand content and decrease in water content at 2.6 m depth; and (v) the presence of a pyroclastic unit at 3.7 m depth. Radargrams with frequencies of 900 and 300 MHz were collected on a grid of profiles covering the study area. Correlation of radargrams with the reference section permitted the spatial interpolation of variations in the physical properties and the near-surface stratigraphy. Contrary to the expected in these clayey sediments, electric contrast enhanced by variations in water content and grain size permitted the recording of the near-surface sedimentary structures. Distinctive radar signatures were identified between reflectors. Furthermore, lateral discontinuities of the reflectors and their vertical displacements permitted the identification of deformational features within the sequence.

© 2003 Elsevier B.V. All rights reserved.

Keywords: Clayey sediments; Near-surface stratigraphy; Physical properties; Radargram; Radar signature; Fractures

1. Introduction

Sedimentary sequences filling the Valley of Mexico, and other basins in Central Mexico, consist generally of various types of fluvial and lacustrine deposits with particle sizes varying from gravel, sand, and silt to clays, often interbedded with pyroclastic rocks and lava flows. These materials present a high variability in their properties such as strength, grain-size distribution, mineralogical composition, and water content. Major heterogeneities can be present also at near-surface sequences of soils or single layers. The mineralogical composition of the shallower layers, generally bearing clay-size particles, can vary lateral-
ly to different kinds of crystallized and amorphous clay minerals (Warren and Rudolph, 1997). Understanding the mechanical behavior and precise characterization of the near-surface stratigraphy of these sequences may be critical to geological engineering and geotechnical studies for the development of urban infrastructure.

It has been demonstrated that electrical and geotechnical properties of clayey sediments are closely related (Saarenketo, 1998; Fam and Santamarina, 1997; Ohtsubo et al., 1983). Since the mechanical behavior of fine-grained sediments also depends on water content, Ground Penetrating Radar (GPR) provides a useful nondestructive method for geotechnical characterization of these sequences. In the last 25 years, GPR applications for the stratigraphic prospecting of sediments and for engineering geology and civil engineering studies have been widely presented in literature (Kruse et al., 2000; Saarenketo and Scuillon, 2000; Van Overmeeren, 1998; Doolittle and Collins, 1995; Lorenzo, 1994; Goodman, 1994; Davis and Annan, 1989; Ulriksen, 1982; Morey, 1974). Nevertheless, a detailed correlation of the reflected patterns of radar wave with physical and mechanical properties of clayey sediments has not been presented yet. The aim of this paper is to correlate the spatial variation of water content, grain-size distribution, and compressibility within a sedimentary sequence of lacustrine-volcanic origin with the recorded reflectors in GPR sections.

2. GPR prospecting of sedimentary sequences

The principles of the GPR method have been explained extensively in literature (Davis and Annan, 1989; Ulriksen, 1982; Morey, 1974). GPR transmits high-frequency electromagnetic pulses in which

Fig. 1. Location of the studied area. The Mexico Valley is located in the central part of the Trans-Mexican Volcanic Belt and comprises several lacustrine basins. The Chalco Basin is located in the southern part of the Mexico Valley. It is bounded by the Santa Catarina, Las Cruces, and Chichinautzin ranges. Location of the studied sequence and previous studies are indicated.
ranges the dielectric permittivity of materials predominates over electrical conductivity (Ulriksen, 1982). For simplicity, in this text we use the term “permittivity” to refer to relative permittivity (ratio between permittivity of the prospected media and free space). This parameter indicates the polarization of the elements forming geologic materials, caused by the application of an electrical field. At radar frequencies polarization affects mainly the bipolar molecules of water (Topp et al., 1980) in saturated material such as clayey materials. According to Fukue et al. (1999), the physical characteristics of sediments such as microstructure, grain size, water content, and mechanical characteristics in clay-bearing materials are also related to other electric properties such as resistivity. Furthermore, Saarenketo (1998) showed that variations of dielectric properties in clay and silty particles are related with their Cation Exchange Capacity (CEC). This author concluded that the lower the CEC the more orderly is the arrangement of water molecules around the soil particles.

In particular, Warren and Rudolph (1997) reported a direct relation between the clay-mineral phase (allophane, smectite) with its CEC, porosity, and water content for the basin of Mexico. Thus, radar-wave behavior is influenced by: water content, physico-chemical characteristics of pore water, solid–liquid–air proportion, structure, and voids ratio of the solid phase. The contrasts in these properties can be recorded as reflectors in radar sections or radargrams. In addition, these parameters are directly related with different geological and mechanical aspects of the sedimentary materials (Fam and Santamarina, 1997). Several authors have shown that variations in the water content and water retention capacity of soil particles are related with its geological depositional conditions.

![Fig. 2. Correlation of the near-surface stratigraphy (7 m depth) in the Chalco lacustrine plain. The stratigraphic columns are presented in their relative positions from southwest to northeast: (a) Core B (Caballero and Ortega-Guerrero, 1998); (b) BH4 Core (Zawadski, 1996); (c) CH core and Site 2 excavation presented in this work; and (d) Site 1 excavation (Zawadski, 1996). Note variations in depth of pyroclastics layer. Grain-size data presented were previously reported by Zawadski (1996).](image-url)
(see Chandler, 2000, for clay sediments; Van Overmeeren et al., 1997; Freeland et al., 1998, for sandy deposits). These studies validate GPR surveying as a useful tool for physical and geotechnical prospecting of clayey sequences.

3. Near-surface stratigraphy of the Chalco site

The Valley of Mexico is a volcanic-bounded basin located in the central part of Mexico within the Trans-Mexican Volcanic Belt (Fig. 1). Volcanic activity has been intense in this area from Pliocene to recent times. A lacustrine system characterized the Valley of Mexico until pre-Hispanic times. Later, the urbanization of the valley has forced the withdrawal of groundwater level leaving only lake remnants and large extensions of plains. The near-surface clayey deposits of the Mexico Basin are mainly composed by saturated smectitic clay and amorphous material derived from weathering of volcanic ash (Warren and Rudolph, 1997). The complex mechanical behavior of the “Clays of Mexico City”, especially brittle failure associated with high water contents on highly compressible materials, has been extensively studied and different mineralogical and grain-size distributions have been reported (Peralta-y-Fabi, 1989; Mesri et al., 1975; Marsal and Mazari, 1969; Lo, 1962).

The Chalco Basin is located at the southernmost end of the Valley of Mexico (Fig. 1). It is a horizontal plain (formerly a lake) filled with lacustrine sedimentary sequences overlying a regional granular aquifer. According to Urrutia-Fucugauchi et al. (1994), drainage was restricted about 780,000 years ago by the formation of the Chichinautzin volcanic field to the south. Important variations in salinity or water level related to changes in weather have occurred through the time in the Quaternary volcanosedimentary sequence of the Chalco Basin (Urrutia-Fucugauchi et al., 1994; Lozano et al., 1993). We have selected a study site in the north margin of the Chalco Basin near the Santa Catarina village. Access to the area is provided by a north–south paved road and it is important to mention that an electricity line runs adjacent to it (Fig. 3). Urbanization in the Chalco area began in the early 1980s and has not covered the total extent of the plain; in this part, the land is still used for agriculture. Regional extraction of groundwater is made by a line of 14 wells named Ramal Mixquic of the Santa Catarina well field.

Detailed stratigraphic sections of the upper part of the sequence are available for the marginal and central parts of the Chalco lake. The upper 7 m record a time span between ca. 17,450–14,500 years to the present according to $^{14}$C dating made in a core from the central part of the basin (Caballero and Ortega-Guerrero, 1998). Zawadski (1996) described the upper 6 m of the sequence from the margin of the lake that consists of 11 layers of alternating clay, organic silt, sands and gravel of volcanic origin, with thicknesses ranging from 5 to 60 cm. Caballero and Ortega-Guerrero (1998) assigned four stratigraphic units (brown silt with lapilli, brown silt, gray diatomite, and black-brown clay from top to bottom) and seven tephra layers for the first 7 m from the central part of the lake sequence. The physical correlation of these sequences is based on the reconnaissance of the Tlapacoya 2 unit (Ortega-Guerrero and Newton, 1998) in the studied CH core (see Fig. 2).
The study area is affected by a north–northeast trending regional fracture of several tens of meters long, with uplifted borders, and a surface opening of more than 1.0 m that closes with increasing depth (Figs. 3 and 4a). The fracture is filled with clayey sediments but opens seasonally. This fracture is the most evident structural feature observed in the surface; however, it has been shown that numerous subsurface fractures and subsidence affect the lacustrine sequences (Ortega et al., 1993).

Fig. 4. (a) Panoramic view of the Chalco Plain to the southwest, the regional fracture with uplifted borders and the location of CH core are indicated; (b) excavation in Site 2 permitted to detail the stratigraphy of the upper 2 m, and small fractures within the clay sequence were observed.
4. Characteristics of the GPR used

The GPR Zond 12c, manufactured in Latvia by Radar Systems, was used for the soundings. A portable computer connected to the control unit permits the direct recording of raw data collected by the radiating–receiving antennae. With this equipment, a single operator moves the antennae along the surveyed surfaces in monostatic mode (the antenna operates both as radiating and receiver). Table 1 summarizes the measurement parameters of the survey.

The alternate application of two transmission frequencies in the same profile, using shielded 900- and unshielded 300-MHz antennae, permitted the recognition of the particular types of structural features recorded by each frequency. The analysis of a normalized frequency spectrum indicates that the effective frequencies through the studied media were ca. 500 and 100-MHz for the 900- and 300-MHz antennae, respectively.

Since the available antennae of the GPR were monostatic, the analysis of subsurface velocities provided by the common midpoint (CMP) method could not be performed. However, the detailed near-surface stratigraphy observations permitted a satisfactory evaluation of investigation depths (see Figs. 3 and 4b). By matching the position in depth of a specific reflector (a stratigraphic boundary associated with contrast in physical properties in most of the cases) with the reflectors on the radargrams, we obtained an accurate evaluation of the bulk velocity of propagation of electromagnetic waves through the media. This methodology allowed the time/depth conversion using a bulk velocity of propagation for the sequence of 4.7 cm/ns. Vertical variations in the bulk velocity of propagation could be taken into account only for the 900-MHz sections, in which we obtained a lower velocity (4.0 cm/ns) by adjusting the depths of well-known reflectors such as sand lenses.

Eight profiles were obtained in two perpendicular directions (N 20° E and N 70° W) in order to identify the spatial variations of the recorded reflectors (Fig. 3). North–south profiles a, b, c, and d were obtained parallel to the regional fracture observed in the area, whereas the east–west profiles e, f, g, and h were perpendicular to this structure. The length of each line profile was 30 m, except profile g that had a total length of 40 m.

5. Methodology of laboratory analysis

Assuming that physical and mechanical variations can produce sufficient electric contrast to be recorded in a radargram, then the depth of specific reflectors can be obtained from the detailed analysis of a reference stratigraphic section. This method has been used recently with success for correlation of radar data with different properties of soils (Oleschko et al., 2003). Representative samples of approximately 20 cm each from the Chalco core (CH) were analyzed at the Geomechanical Laboratory of the Center of Geosciences (National University of Mexico, UNAM). For the first 2 m, the data were complemented with the analysis of disturbed samples collected in the Site 2 excavation (Fig. 4b). The sequence below the water table that occurs at about 0.8 m was considered to be in saturated conditions.

The main physical characteristics that were measured in the sequence in order to identify physical discontinuities that can be related to electrical contrasts were:

(a) Gravimetric ($W_{\text{grav}}\%$) water content is the weight ratio between pore water and solid fraction

---

<table>
<thead>
<tr>
<th>Table 1</th>
<th>GPR measurement parameters and characteristics of the radar wave in the Chalco site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency of antennae (MHz)</td>
<td>300</td>
</tr>
<tr>
<td>Impulse power</td>
<td>400</td>
</tr>
<tr>
<td>Length of antennae (cm)</td>
<td>102</td>
</tr>
<tr>
<td>Resolution (cm)</td>
<td>100</td>
</tr>
<tr>
<td>Recording time window (ns)</td>
<td>240</td>
</tr>
<tr>
<td>Battery power supply (V)</td>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristics of the geological media</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated frequency through the media (MHz)</td>
</tr>
<tr>
<td>Permittivity</td>
</tr>
<tr>
<td>Velocity (cm/ns)</td>
</tr>
<tr>
<td>Maximum depth of penetration (m)</td>
</tr>
<tr>
<td>Recorded feature</td>
</tr>
<tr>
<td>Thickness (cm)</td>
</tr>
</tbody>
</table>
averaged from three measurements obtained by the oven-drying method (American Society for Testing and Materials, ASTM D2216-92, 1998a), whereas volumetric water content \( W_{\text{vol}} \% \) was computed by the ratio between \( W_{\text{grav}} \) and the porosity (Santamarina et al., 2001); \( W_{\text{grav}} \% \) is a parameter widely used for geotechnical characterization of soils (see Das, 1997), a value of 300% frequently obtained for the clays of Mexico means that for each gram of solid there are 3 g of water;

(b) Atterberg limits (ASTM D4318-95) were determined using the Casagrande coup for the liquid limit (LL) and the Terzaghi method for the plastic limit (PL);

c) Electric conductivity (EC) was measured using a Cole Parmer TDS Conductivity meter in a suspension of soil–water (1:2.5) (saturated paste, USDA, 1996);

(d) grain size was determined by hydrometer and sieve analysis (ASTM D422-63, 1998b) of samples representative of each 20 cm; clay and silt contents were added and presented as fine-grained sediments in Fig. 6;

e) specific gravity of particles was determined by the pycnometer method (ASTM D854-92, 1998c), and;

(f) compressibility index was computed as a variation of the void ratio in a log pressure cycle of the compressibility curve (Lambe and Whitman, 1969), determined by the one-dimensional consolidation test (ASTM 2435-96, 1998d).

6. Results

6.1. Description of the near-surface sequence of Chalco

The description of the stratigraphic units defined in the CH Core was based on a correlation with available column descriptions. The BH4 core and Site 1 excavation of Zawadski (1996) are located within the study area, whereas Core B of Caballero and Ortega-Guerrero (1998) is located in the center of the lake (Figs. 1 and 2). Notably, greater thickness of the sequence above the Tlapacoya 2 unit is observed in Core B. Within the study area, smaller variations in thickness can be related to local depositional changes and/or deformation features. Eight stratigraphic units (Fig. 5) are described for the first 7 m depth of the studied CH core: (unit A) a layer of organic soil with abundant vegetal roots of approximately 0.5 m with an upper horizon of high-salinity soils; (unit B) a layer of pale-brown silt with pyroclastic rock fragments that suggest intense volcanic activity during the deposition of this layer, with thickness ranging from 1 m in the center of the lake (Core B) to 0.1 m in the margins; (unit C) a brown clay of high plasticity; (unit D) underlying there is a brown-reddish clay layer with carbonate concretions reaching 2 m depth, vertical fractures were observed in the lower part of this unit in Site 2; (unit E) a brown clayey silt separated from the overlying clay layer by a thin lens of sand (see Fig. 3b); (unit F) a sandy layer of variable thickness (10–30 cm); (unit G) black silty clay of approximately 1 m thick; (unit H) 25 cm of pyroclastic gravel that correlates with Tlapacoya 2 unit of Ortega-Guerrero and Newton (1998) reported at ~ 5 m depth in Core B (Caballero and Ortega-
Guerrero, 1998); and (units I and J) comprises a sequence of brownish to greenish gray clays characteristic of redox lacustrine environment and a grey-brown clay layer with pyroclastic rocks observed at 6 m depth. The results obtained in the characterization of the upper 7.0 m are presented in Fig. 6.

The analysis of the physical properties permitted to identify five potential reflectors of radar waves (Fig. 6): (i) a decrease from 15 to 3 mS/cm in the electrical conductivity at 0.4 m depth, this contrast is slightly above ( ~ 10 cm) that can be added to the grain-size contrast in the upper boundary of the pyroclastic silt unit B; (ii) an increment in the clay content associated with an abrupt increase in gravimetric water content (from 100% to 300%) that is observed at the upper boundary of unit C (0.8 m depth); (iii) a bimodal water content in the brown-reddish clays associated with the lower boundary of the unit C at 1.3 m depth and decrease in the clay content; it is important to mention that fracturing of the clay layers increases below this level; (iv) an abrupt increment in the sand content (volcanic ash layer) and a decrease in water content from 100% to 50% at 2.6 m depth; and (v) a lens of pyroclastic gravel at 3.7 m depth.

Because of its heterogeneous composition and high water content a ductile–brittle mechanical behavior was expected in the Chalco clayey sequence. As mentioned above, units C and E present water contents higher than their liquid limit, which suggest that these materials can behave as fluids when their structure is disturbed. In particular, a strong contrast in the physical properties is observed in unit C, elevated liquid and plastic limits, high compressibility index (Cc ~ 3), and decrease of specific gravity. We emphasize that the water table occurs at about 0.8 m coincident with the increment of the water content and
electric conductivity slightly increases below unit C. Finally, unit F represents a major contrast in grain size, with greater sand content, low water content, and greater specific gravity.

6.2. Spatial correlation of physical and mechanical properties with GPR profiles

We present the first GPR records of stratigraphic and structural features for the lacustrine sequence of Chalco, Mexico. GPR surveying has permitted the identification of subtle stratigraphic heterogeneities related to differences in water content and grain size within the studied sediments, and allowed interpolation of sedimentary characteristics such as the continuity of sand or clay units. Radar sections collected along profile a, with 900- and 300-MHz antennae (Fig. 7a and b), were used to correlate radar signatures with the reflectors identified previously. The projected location of the core on profile a is portrayed in radargrams in Fig. 7. The above-defined potential reflectors were then identified in the radargrams based on the

![Diagram of GPR profiles](image)

Fig. 7. Correlation of the stratigraphic column and reflectors recorded in 900- and 300-MHz radargrams of profile a. Correlation of the near-surface stratigraphy was based on projection (showed with an arrow) of the CH core located at a distance of 0.5 m from this profile. Coherent and continuous reflectors along the radargram were associated to changes in physical properties or stratigraphic boundaries. Nomenclature of stratigraphic units is presented in Fig. 5. The stratigraphy of the first 1.5 m is better adjusted assuming a velocity of propagation of electromagnetic waves of 4.0 cm/ns (permittivity 55 indicated in italics) instead of the calculated bulk velocity of 4.7 cm/ns (permittivity 40) for the whole profile. Calculated depths of investigation for both velocities are presented in the right side of the 900-MHz profile.
changes in well-defined radar signatures and the presence of coherent radar wave reflectors. The reconnaissance of a reflector assumed to be the upper boundary of the sand layer at ca. 100 ns permitted the estimation of a value of 40 for the bulk permittivity of the sequence. However, for the 900-MHz antenna, best adjusting of the depth of reflectors was achieved with a permittivity of 55 (velocity of propagation \( v \approx 4.0 \text{ cm/ns} \)). The velocity of propagation in the media is assessed using the simplified formula \( v = \frac{c}{\varepsilon^{1/2}} \), where \( c \) is the velocity of propagation of waves in the air and \( \varepsilon \) is the real part of the permittivity. We present between parenthesis and italics the calculated depths and velocity obtained with both values of permittivity for the 900-MHz radar sections through the figures. The five reflectors were observed in the 300-MHz antenna; however, best definition of reflectors i, ii, and iii was obtained using the 900-MHz antenna.

### 6.3. 900-MHz profiles

The records of radargrams in two perpendicular profiles with the 900 MHz are portrayed in Fig. 8.

Lateral continuity of coherent reflectors at constant depths along the total distance is observed in both profiles. Small disturbances in reflectors are observed only within the profile e perpendicular to the regional fracture in particular, before 10 m and between 15 and 20 m in distance. It is important to note that a diffraction hyperbola probably related to the electricity line was recorded at the eastern part of all the profiles perpendicular to the fracture.

The shaded area in the upper part of the radargram corresponds to the direct wave (from 0 to 10 ns); the high attenuation of energy is controlled by the high electrical conductivity caused by a superficial high-salinity layer of soils. The position of reflector i along the profiles is defined by the decrease of electrical conductivity that occurs within the underlying organic soil layer. The response of radar waves can be added to the reflector located at the highly irregular upper boundary of unit B. Reflector ii is located at the increase in water content coincident with the contact between unit B and C. Notably, a distinctive and homogeneous radar signature is observed between reflectors ii and iii corresponding to the relatively homogeneous

![900-MHz profiles](image-url)
Fig. 9. North–south radargrams collected with the 300-MHz antenna along profiles b, c, and d. The CH core is projected from distances of 5, 9, and 17 m to profiles b, c, and d, respectively. Calculated depth of investigation using a velocity of 4.7 cm/ns is presented in each profile. The main reflectors are indicated, question marks indicate not well-recorded positions.
clayey soil mass with high gravimetric water content (≈ 300%) and without structural features.

6.4. 300-MHz profiles

Three profiles with the 300 MHz, parallel to the regional fracture, are compared in Fig. 9 in order to show the record of the identified reflectors and their in-depth variation and structure on both sides of the fracture. The depth of the recorded reflectors was fitted with the depth of defined contrasts in the projected position of the CH core. Best definition of structure patterns was obtained with this antenna; thus, disturbances in the radar signature can be related with deformatonal features. Clearly defined radar signatures observed between reflectors i–ii and ii–iii correspond roughly to pyroclastic silt unit B and to the high-plasticity clay unit C, respectively. The irregular patterns of reflection show sinuous forms that suggest differential deformation of the soils in this part of the sequence. A decrease in thickness of the clayey sequence above unit F towards the east is evident by the gradually shallower position of reflectors iv and v.

Two examples of profiles perpendicular to the regional fracture are shown in Fig. 10a and b. In this direction, lateral continuity of reflectors is highly disturbed and heterogeneous radar signatures recorded suggest that deformation effects are more intense in this direction. A satisfactory position of the reflectors was obtained by correlating the depth of reflectors identified in the north–south profiles. Differences in depth of reflectors become evident below reflector ii, and distortion of layers is best observed in the radar signature obtained between reflectors iv and v that correspond to the units F and G. These radar sections are not corrected topographically because small uplift (≈ 20 cm) of the horizontal surface is only observed in a 40-cm-wide band on both sides of the regional fracture (see Fig. 4a). The flower-like geometry of the regional fracture and the inferred effect of uplifting on reflectors are presented in the interpretative section (Fig. 10c).

7. Discussion

The Chalco near-surface lacustrine sequence consists of alternating layers of plastic clay, volcanic ashes, pyroclastic sand and gravel. The abundance of pumiceous concretions within clayey units indicates that volcanic activity was coeval with deposition of the sequence. The upper unit of the sequence is characterized by a high-salinity clayey layer formed in an arid climate that prevailed from the beginning of the Holocene (Urrutia-Fucugauchi et al., 1994).

The use of GPR has been particularly useful for the characterization of the Chalco sequence because: (a) the presence of volcanic layers within the clayey sequence increases the reflection coefficient by enhancing physical and chemical contrasts (i.e. the high water content of unit C); (b) the presence of deformation structures with a particular radar signature; and (c) the detailed stratigraphic studies available that have served as a basis for the correlation of the physical properties and stratigraphic units.

The GPR method was expected to have a low detection capacity in these high water retention capacity and low electrical resistivity clayey materials. However, water content variations and grain-size contrasts improved the capacity of detection considerably. For example, assuming a bulk 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, 1992; Davis and Annan, 1989). In more conductive clay, permittivity can increase considerably because of the salt content of pore water. An increment of ≈ 30% in the permittivity of the upper part of the sequence (from 40 cm to...
to 55) is sufficient to double the reflection coefficient (to 0.02) and a high dielectric contrast between the clay and sand layers is recorded.

Ground Penetrating Radar has proven to be an effective instrument for prospecting near-surface stratigraphic variations in saturated lacustrine sediments due to the close relation between the behavior of electromagnetic waves in the medium and physical-mechanical characteristics of soils (water content, salinity, grain size, compressibility, and plasticity).

The analysis of radar profiles permitted the spatial correlation of near-surface stratigraphic characteristics as well as the identification of discontinuities of the recorded reflectors associated to subsoil deformation. The identification of coherent reflectors along the profiles related to the electric contrast was also useful for the record of deformational features observed in the clayey layers. In this way, the single vertical fractures or fractured zones could be identified in several radargrams.

The different estimated values of the velocity of propagation of electromagnetic waves in the prospected media and the achieved detection depths are summarized in Table 1. Notably, the highest resolution in stratigraphy was obtained for the first 1.5 m allowing a better calibration of the reflectors obtained with the 900-MHz shielded antenna. Using the 900-MHz antenna, the recorded reflectors correspond to vertical variations in physical properties coincident with stratigraphic boundaries. Thus, reflectors ii and iii are clearly associated with the change in water content at the upper and lower boundaries of unit C. One exception is reflector i that is better linked to a vertical change in electric conductivity because the corresponding upper boundary of unit B is highly irregular. As expected, best adjusting of the depth to reflectors was obtained using a lower velocity of propagation because shallow layers have higher values of electrical conductivity, water content, and plasticity.

A discontinuous radar signature observed between reflectors ii and iii in profiles with the 300-MHz antenna suggests deformation of unit C. Differential deformation of this high-plasticity compressible clays layers can occur by self-weight consolidation, or because they can behave as a fluid under certain externally forced conditions (e.g. produced by seismic activity or depressurization of subsoil). Lateral heterogeneities of the clayey sequences can also have an important influence on its mechanical behavior, particularly in the differential consolidation.

This deformation can also be related to the origin and propagation of the regional fracture observed in the study area. This fracture opens and closes seasonally likely due to shrinking and swelling of the clayey sequence. During dry weather conditions, the fracture opens as a consequence of the water content loss and is partially filled by detritus material. During the rainy season, the clayey sequence expands closing the fracture and, as new material has been added, the deformation is accommodated upwards.

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 used radar, the transmitted frequency, electrical contrasts, and the attenuation of the signal. The radargrams presented in this paper show that some aspects of the velocity of propagation variations within a stratified geological sequence can be qualitatively assessed. Interpolation of near-surface physical properties of soil using GPR is at an initial stage in the case of clayey Chalco. Nevertheless, encouraging results were obtained by the correlation of recorded reflectors in profiles with changes in specific physical properties and relevant applications can be envisaged both in geological and geotechnical studies.

8. Conclusions

A comparative analysis of GPR profiles supported on detailed punctual analysis of mechanical and physical properties permitted the extrapolation of lateral and vertical variations of the near-surface stratigraphy of a lacustrine sequence in the Chalco Basin. Contrary to the expected in these saturated sequences, electric contrast enhanced by abrupt changes in water content and grain size permitted satisfactory recording of the sedimentary structures. Distinctive radar signatures were obtained for each layer present between coherent reflectors. The best definition in stratigraphy and structure was obtained with the 300-MHz antenna, whereas grain size and
physical variations were best recorded using the 900-MHz antenna. An irregular radar signature with sinuous form recorded the presence and geometry of a highly plastic layer. Furthermore, lateral discontinuities of the reflectors and their vertical displacements permitted the identification of fractures zones and differential deformation within the sequence.

Acknowledgements

The authors thank Klavdia Oleschko for valuable advice. We are grateful to Gabor Korvin and Barbara Martiny for discussions and helpful comments on an early version of the manuscript. Two anonymous reviewers provided constructive criticisms that enormously helped to improve this work. We thank Ricardo Carrizosa for his help on the analysis of the Chalco cores at the Geomechanics Laboratory of the Center of Geosciences, National University of Mexico (UNAM). Financial support for this research provided by the Program of Support to Technologic Researches and Innovations UNAM, PAPIIT 1N111398 is gratefully acknowledged.

References

Caballero, M., Ortega-Guerrero, B., 1998. Lake levels since about 40,000 years ago at Lake Chalco, near Mexico City. Quaternary Research 50, 69–79.
Marsal, R.J., Mazari, M., 1969. The subsoil of Mexico City. School of Engineering, National University of Mexico (UNAM), Mexico City. 377 pp.


