Geotechnical characterization of Mexico City subsoil

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ABSTRACT
This contribution presents a brief state of the art on the geotechnical characterization of Mexico City subsoil. Since the pioneer works by Carrillo, Marsal and Zeevaert, substantial progress has been achieved based on data obtained during the development of the infrastructure of this huge city. Following the dramatic 1985 earthquake, important field and laboratory research works have been performed on the very special properties of Mexico City lacustrine clays in static and dynamic conditions. Experience regarding foundations and underground structures behaviour has also been accumulating. Geographic Information Systems for geotechnical borings, hydraulic conditions and other aspects such as subsidence and soil fracturing are now available. This information has been organized and processed to develop 1D, 2D and 3D models of different parts of Mexico City valley. This has been useful to provide preliminary geotechnical information for new projects and to update the geotechnical zoning map included in Mexico City building code.

RESUMEN
En este trabajo se evalúa brevemente el estado actual de la caracterización del subsuelo del valle de la ciudad de México. Desde los trabajos pioneros de Carrillo, Marsal y Zeevaert, se han logrado avances significativos gracias a la información obtenida durante el desarrollo de la infraestructura de esta enorme ciudad. Después del dramático sismo de 1985, se han realizado múltiples trabajos de investigación de laboratorio y de campo respecto a las muy especiales propiedades de las arcillas lacustres de la Ciudad de México en condiciones estáticas y dinámicas. Experiencias relativas al comportamiento de cimentaciones y estructuras subterráneas se han ido también acumulando. Sistemas de información relativos a sondeos geotécnicos, a las condiciones hidráulicas y otros aspectos tales como la subsidencia y el fracturamiento del subsuelo se encuentran actualmente disponibles. Se ha realizado un esfuerzo sistemático para organizar y procesar esta información y para desarrollar modelos uni, bi y tri dimensionales del subsuelo de diferentes zonas del valle de México. Esto ha resultado de gran utilidad para disponer de información preliminar para nuevos proyectos y para actualizar la zonificación geotécnica del Reglamento de Construcciones de la Ciudad de México.

1 INTRODUCTION

Characterization of Mexico City subsoil is a never ending task that has been going on since the foundation of the Mexican capital. Important contributions during the last centuries were those of Tellez-Pizarro (1899), Nabor Carrillo (1948), Marsal & Mazari (1959) and Zeevaert (1952, 1973). The Mexican Society for Soil Mechanics also collected important data that were the basis for elaborating detailed geotechnical maps with increasing extension following the rapid development of the city (Reséndiz *et al.* 1970; Del Castillo *et al*., 1978). A new impulse was given to research works on the subsoil after the 1985 earthquake struck the city. Significant advances were registered concerning the exceptional static and dynamic properties of the lacustrine soils of the city and their behaviour in seismic conditions (Romo & Auvinet, 1992). Recently, the availability of powerful computing tools has allowed processing the large amount of geotechnical data available to develop Geographical Information Systems describing Mexico City subsoil. Data have also been collected on a number of phenomenons affecting the subsoil such as the general subsidence induced by deep pumping and soil fracturing. These information systems have been useful for new projects and building code purposes. This paper presents an overview of the present state of knowledge on Mexico City subsoil and some conclusions and perspectives.

2 GEOLOGICAL AND HISTORICAL CONTEXT

Geologically, the so-called valley of Mexico is actually a closed basin located in the highest part and southern end of the Mexican plateau. It is located between parallels 19° 00' and 20°12' north and meridians 98°10' and 99°33' west. It is bounded on the north by the mountains of Tepozotlan, Tezontlalpan and Pachuca, east by the plains of Apan and the Sierra Nevada, south by the mountains of Chichinautzin and Ajusco and west by the Sierra de las Cruces, Monte Alto and Monte Bajo. Its surface is about 9600 km^2, of which only 30% is flat.

The geology of the Valley of Mexico has been the subject of many studies, from the first surveys of Ordoñez (1893) to those made more recently by Mooser (1963, 1978) and other geologists. Physiographically, the Basin of Mexico belongs to the Neovolcanic belt, an awesome volcanic range that crosses the Mexican territory from east to west.

The metropolitan area of Mexico City is limited by large topographic elevations: the Sierra de Las Cruces to the west, the Sierra de Guadalupe to the north, the eastern Sierra Nevada and the Sierra de Chichinautzin to the south. Two major volcanic units dominate the East Valley: Popocatepetl and Iztaccihuatl. Within the valley, some isolated volcanic domes such as Peñon de los Baños, Peñon del Marqués, Cerro de la Estrella and those forming Sierra de Santa Catarina protrude from the lacustrine area.

The Valley of Mexico is mainly formed by volcanic and pyroclastic materials interspersed with alluvial deposits covered in the center of the valley by lacustrine clays. According to Mooser (1978), before the Pleistocene, the basin drained south to the Amacuzac River by two deep ravines passing through Cuautla and Cuernavaca. During the late Pliocene, fractures occurred predominantly in the WE direction in the area of Puebla and south of Toluca, and large outpourings of basalt formed the Sierra de Chichinautzin in the Quaternary. According to paleomagnetic measurements, massive eruptions occurred during the last 700.000 years. These events transformed the valley into a closed basin. The Sierra de Chichinautzin, lying between Sierra de Zempoala in the West and Popocatepetl in the East, and resting in the center on the Tepozteco massif formed a huge natural barrier that dammed the valley of Mexico.

Until the end of the XVIIIth century, the valley of Mexico remained a closed basin, with a number of shallow lakes. Mexico City (then Tenochtitlán) was founded in a small island of the Texcoco Lake. The valley became an open basin when the Nochistongo cut was completed in 1789. During the XXth century, the lakes were drained through the Tequisquiac tunnel, completed in 1900, and the Deep Drainage tunnel (Emisor Central), built in 1967. A new drainage tunnel (Emisor Oriente), 7m in diameter and 62 km long is now being built. Today, with the exception of small remaining bodies of water, the lakes have practically disappeared. A large part of the city was built on lacustrine sediments. These are highly plastic soft clays interbedded with layers of silt, sand and sandy gravels of alluvial origin. With 20 millions inhabitants, the metropolitan area of Mexico Valley is now one of the largest urban conglomerates in the world.

3 MEXICO CITY SOILS

3.1 Geotechnical zoning

The urban area of Mexico Valley is traditionally divided in three main geotechnical zones (Marsal and Mazari, 1975): Foothills (Zone I), Transition (Zone II) and Lake (Zone III). Figure 1 shows the three zones as defined in the present building code. In the foothills, very compact but heterogeneous volcanic soils and lava are found. These materials contrast with the highly compressible soft soils of the Lake Zone. Generally, in between, a Transition Zone is found where clayey layers of lacustrine origin alternate with sandy alluvial deposits.

3.2 Typical soil profiles

In Figure 2, typical soil profiles are presented (Marsal, 1975). Borehole Pc-28 corresponds to the Lake Zone. The water table is close to the surface. Three clayey layers are to be distinguished, denominated upper (*Formación Arcillosa Superior*, FAS), lower (*Formación Arcillosa Inferior*, FAI) and deep deposits (*Depósitos Profundos*, DP). The clays of FAS are separated from FAI by a hard layer (*Capa Dura*, CD), a sandy clayey stratum, some 3m thick, lying at a typical depth of 30 to 35m. Generally, FAS is covered by a desiccated crust and/or an artificial fill several meters thick.

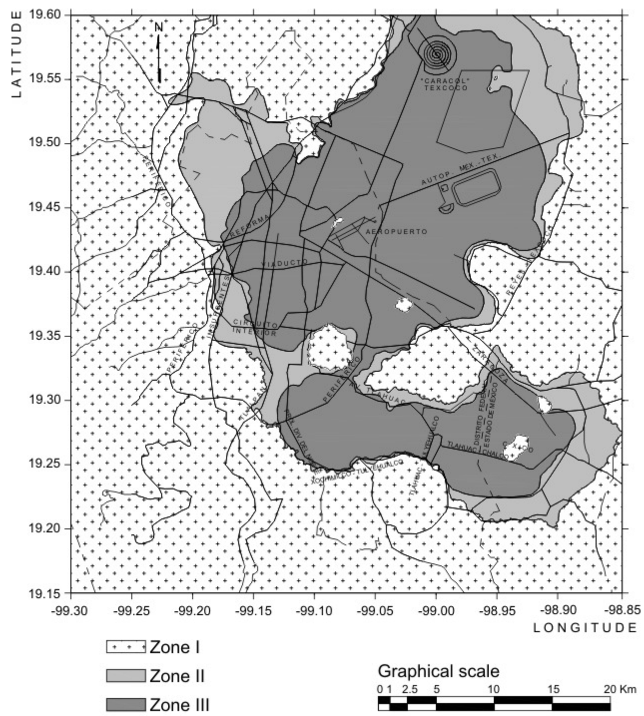

Figure 1. Geotechnical zones in Mexico City (Mexico City building code, 2004)

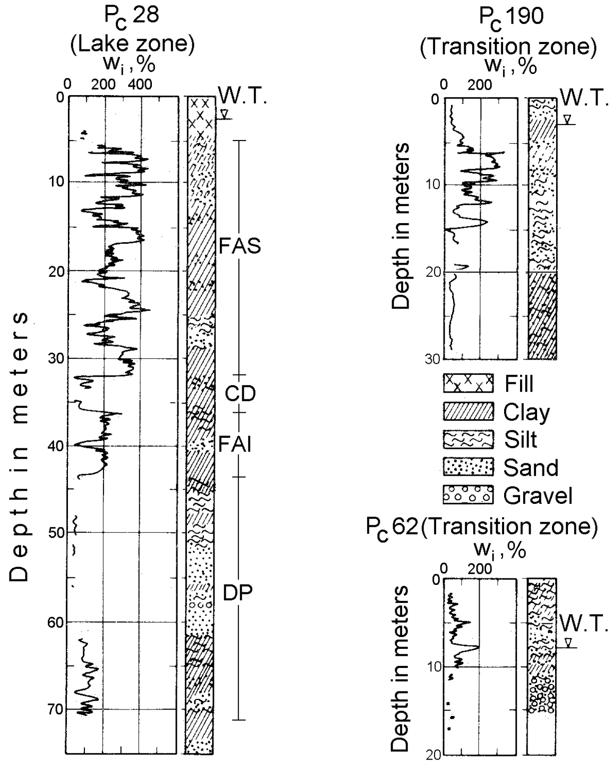

Figure 2. Soil profiles in Mexico City (Marsal, 1975)

3.3 Properties of Mexico City clays

3.3.1 Index properties

Average values of index properties for borehole Pc 28 are presented in Table I. In some areas of the lacustrine zone, the water content of this exceptional material can indeed be higher than the value indicated in Table 1 since it often exceeds 500% while its plasticity index (PI) may exceed 300%.

Table I. Typical average values of index properties in Lake Zone (Borehole Pc-28, Marsal, 1975)

PROPERTY	FAS	CD	FAI
Water content, %	270	58	191
Liquid limit w_L, %	300	59	288
Plastic limit, w_P, %	86	45	68
Density of solids, S_s	2.30	2.58	2.31
Initial void ratio, e_0	6.17	1.36	4.53
Unconfined compressive strength, q_u, kN/m^2	85	24	160

3.3.2 Structural and physico-chemical aspects

The unique properties of Mexico City clays have induced a number of studies performed to assess their mineral composition and structure (Zeevaert, 1949; Marsal and Mazari, 1959; Leonards and Girault, 1961; Lo, 1962; Mesri, Rokhsar and Bohor, 1975; Gómez-Looh, 1987; Peralta y Fabi, 1989; Díaz-Rodríguez *et al.* 1998). Most of these studies are inconclusive. This heterogeneous volcanic lacustrine clay appears to be a complex mixture of clayey and non-clayey minerals with microorganisms, dissolved salts and organic components. The presence of microfossils such as ostracodes and diatoms could explain some of the properties of the material including its high water content.

3.3.3 Mechanical properties

Materials from the clayey deposits of Mexico City subsoil are characterized by their extraordinary compressibility (Marsal and Mazari, 1959). The coefficient of compressibility, defined as the quotient between the decrement of void ratio and the respective increment of applied pressure may reach values as high as 6 cm^2/kg (0.06 m^2/kN).

The clay shear strength is higher than what could be expected taking into account the exceptionally high water content, showing that this material is highly structured. However, undrained strength can be lower than the unconfined compressive strength value indicated in Table 1. Average values of 40kN/m^2 for the FAS are not uncommon, with extreme values as low as 20 kN/m^2.

Experimental investigations show that the dynamic response of clays strongly depends on the strain level induced. At low deformations, the response is relatively linear, the clay has low capacity to dissipate energy and degradation with the number of stress cycle applications is negligible. For large deformations, the response is strongly non-linear, damping increases notably and stiffness degradation may be important. The threshold shear strain between linear and non-linear behavior of clays depends on clay characteristics. It has been shown that of all factors that affect the degree of non-linearity of clay behavior, the most important appears to be the plasticity index, PI. The upper bound seems to be given by the highly plastic clays of Mexico City (PI > 200 %). The behavior of these clays remains practically elastic with low damping up to an angular strain level of the order of 0.5%. This contributes to explain the large site effects registered in the lake zone of Mexico City during earthquakes (Romo and Auvinet, 1992). For large amplitude cyclic strains, the clay structure degrades continuously causing pore water pressure variations and reductions in stiffness and strength.

In the lake bed area soft clay deposits (FAS) shear wave velocities range from 40 to 90 m/s. Superficial fills and the hard crust above the clay may however present a much higher velocity.

3.3.4 Constitutive laws

Mexico City clay is commonly described as an elasto-plastic material. The initial yielding surface of typical Mexico City clay samples was defined performing a number of triaxial tests following distinct different stress paths (Díaz-Rodríguez *et al.* 1992). Wheeler (2003) adjusted the model presented in Fig. 3 to these results.

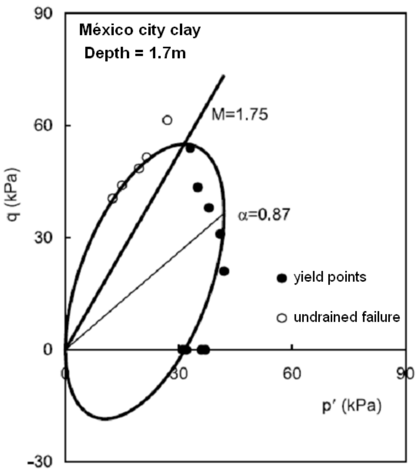

Figure 3 Initial yielding surface for typical Mexico City clay (Wheeler, 2003)

For modeling of deep foundations, tunnels, and other geotechnical structures in Mexico City clay, the *Soft-Soil* model (*Plaxis software*) has been used with satisfactory results (Rodríguez, 2011). To take into account the anisotropic behavior apparent in Fig. 3, models such as the *S-Clay1* should be preferred. Visco-elastic behavior of Mexico City clay has also been assessed and the results are being incorporated into new constitutive models (Ossa, 2004).

4 SPATIAL VARIATION OF SOIL PROPERTIES

4.1 Database and Geographic Information System

Many of the numerous geotechnical borings performed in the urban area of Mexico valley along the years have been used to create a geotechnical data base.

A Geographic Information System has been developed by the Geocomputing Laboratory of Institute of Engineering, UNAM for fast and easy review of the geotechnical information (Auvinet *et al.* 1995). This Geographic Information System for Geotechnical Borings (GIS-GB or SIG-SG in spanish) for the area has been built using ArcMap ver. 9.2 (commercial software). Incorporating information from the borings in the system requires pre-processing: the information is critically reviewed and converted from analog to digital format of either raster (cell information) or vector (digitized information) type. Nowadays, the system includes a database with information on more than 7,000 geotechnical borings (type, date, location, depth, water table level, etc.) plus a number of logging results obtained during perforation of deep water wells and a database of images of geotechnical profiles, which can be readily consulted (Figure 4).

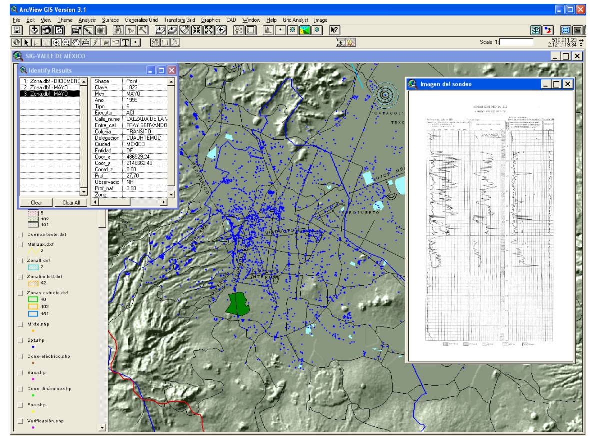

Figure 4. Geographic Information System for Geotechnical Borings

4.2 Statistical processing

Marsal & Mazari (1959) presented a large number of traditional statistical analyses of the properties of Mexico City subsoil. New techniques have been introduced in the last decades for the same purpose. Geostatistics, defined as the application of random functions theory (Matheron, 1965; Vanmarcke, 1983; Auvinet, 2002) to the description of the spatial distribution of properties of geological materials, provides valuable tools such as the *kriging* method, for estimating the thickness of a specific stratum, or the value of a certain soil property at a given point where no information is available. The correlation structure of the medium can be taken into account. Additionally, uncertainty associated to these estimations can be quantified through parameters such as the estimation variance. Fundamentals of Geostatistics applied to Geotechnics have been previously presented in detail in some publications and contributions to different conferences (Auvinet, 2002; Juárez and Auvinet, 2002). During the last decades, geostatistical techniques have been systematically used to define models of the subsoil of Mexico City and to assess the spatial variations of different soil properties. As expected, strongly anisotropic correlograms are obtained in these lacustrine soils. Special attention has been given to the spatial variations of the thickness of the different layers and of the water content, w(%). Water content is useful for identifying the typical layers of Mexico City subsoil. High values of water content indicate the presence of soft soil with low shear strength and low values are characteristic of formations with higher shear strength. Models based on CPT point resistance and SPT blow count are also available. To assess variability of mechanical properties for which only a limited number of data is available, the *co-kriging* technique has been used.

4.3 Stratigraphic models

Traditional as well as geostatistics-based estimations and interpolations have been performed to improve the accuracy of the geotechnical zoning map published for regulatory purposes of construction (Figure 1, GDF, 2004). Furthermore, geostatistics has been useful to develop 1D, 2D or 3D stratigraphic models that provide a visual appreciation of the spatial variations of soil properties in different areas of the city. These models can be easily updated by adding any new boring results to the data and running the software that has been developped.

In a large number of previous papers and theses, the geotechnical characterization of the subsoil for different parts of Mexico City and surrounding zones has been presented (Auvinet *et al.*, 2002, 2003, 2005; Morales, 2004; Jiménez, 2007; Juárez *et al.*, 2002 to 2011; Valencia, 2007; Méndez *et al.*, 2006, 2008; Pérez, 2009; Rodríguez, 2010; Hinojosa, 2011).

In 2009, the west zone and downtown area were described (Auvinet *et al.*, 2009). A companion paper presented in this conference (Juárez *et al.*, 2011) deals with the geotechnical characterization of the subsoil of the east and south zones of Mexico City valley while another paper describes the north of the basin (Juárez *et al.*, 2011) corresponding to the former Xaltocan and Zumpango lakes. Figure 5 presents a model of the subsoil in the downtown area showing the prehispanic fill found below the Metropolitan Cathedral area.

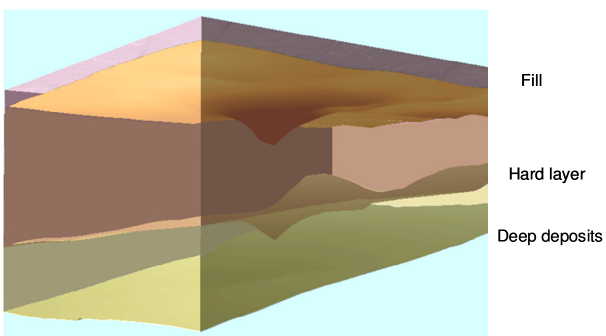

Figure 5. Model of subsoil in the downtown area showing the prehispanic fill found below the Metropolitan Cathedral

Specific models have also been developed to assist in the evaluation of geotechnical conditions in the early stage of infrastructure projects within the city such as subway lines. Figure 6 shows a water content profile along the new Line 12, with an approximate length of 25 km. Similar models have been developed for tunnels, including the new *Túnel Emisor oriente* (Juárez *et al.*, 2010), new airport projects and high rise buildings.

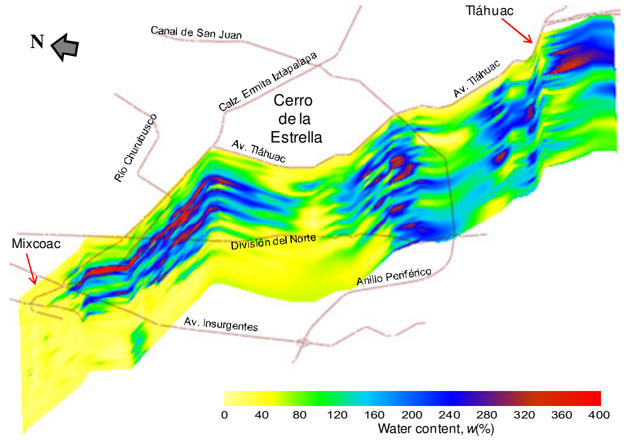

Figure 6. Water content profile along new subway line 12

5 GENERAL SUBSIDENCE AND SOIL FRACTURING

Land subsidence induced by deep well pumping has been affecting Mexico City since the end of the nineteenth century. Nabor Carrillo (1948) was the first to establish a clear correlation between subsidence and piezometric drawdown. Groundwater pumping from the thick aquifer system underneath the city is now about 52 m^3/s, representing 72% of potable water provided to the city dwellers. Recently, a reassessment of this problem has been undertaken in order to define better mitigation measures. An updated evaluation of the accumulated subsidence from 1862 to our days and a review of its consequences were presented (Auvinet, 2009, 2010). Mexico City has suffered a general subsidence that in some locations has reached 13m. Recent data show that the rate of subsidence tends to decrease in certain areas, especially in the west part of the city where pore pressures are almost completely abated. However, in newly developed urban zones such as the south of former Texcoco lake and the center of former Chalco lake, the consolidation process is still in its first stage and the rate of subsidence attains up to 40cm per year (Auvinet *et al.*, 2009, 2010). A clear correlation exists between the magnitude of accumulated subsidence and the thickness of the superficial clay layers (FAS and FAI). However, there are mounting evidences that the contribution of deep, not so compressible, deposits to subsidence is becoming increasingly significant.

Subsidence of Mexico City is a source of serious damages and safety hazards. It affects the drainage of the urban area and augments flooding risks. It is also an obstacle to proper operation and conservation of transport systems and other public services of the city (López Acosta *et al.* 2009). It is one of the main causes of foundation engineering problems.

Some secondary effects such as progressive changes in index and mechanical properties of the consolidating soft clays and consequently in their seismic response have been evaluated by some researchers (Jaime, 2010; Ovando, 2007).

Another harmful effect of the regional subsidence has been the development of large cracks in the soil in transition zones between lacustrine soft clays and firm soils such as volcanic tuffs or basaltic rocks (Figure 7).

Figure 7. Soil fracture in transition zone (LGI, 2008).

These cracks have created a serious safety hazard for the population of the city and constitute an obstacle to the development of certain urban areas. A systematic monitoring of fractures in Mexico City subsoil has been undertaken. A Geographical Information System containing data obtained from surveys performed with GPS has been developed. More than 300 sites have already been evaluated. It should be stressed that not all cracks are related to regional subsidence since many other mechanisms may play an important role in their generation (Auvinet, 2008).

6 GEOTECHNICAL ENGINEERING IN MEXICO CITY SOFT SOILS

Geotechnical engineering in the soft soils of Mexico City faces difficult challenges. Consideration must be given to the high compressibility of the clays, their low shear strength and the ongoing subsidence process. Deep excavations require special techniques (Auvinet and Romo, 1998). The special systems that have been developed for foundation of buildings in the lacustrine zone affected by regional subsidence were reviewed by Auvinet *et al*. (2009). The solutions include floating foundations, friction and control piles and rigid inclusions.

Negative skin friction must be taken into account in the design of deep foundations. Numerical models have been developed to perform this type of analysis (Rodríguez, 2010). These models have been useful, together with field observations, to validate and calibrate analytical models that were proposed in the past (Reséndiz and Auvinet, 1973).

For the long term design of lining of tunnels in soft clays, piezometric drawdown and the associated subsidence must also be taken into account. As shown in Figure 8, the interaction between consolidating soil and tunnel may lead to differential vertical displacements in the soil surface and to large deformations of the tunnel. Since flexible primary lining built with prefabricated segments tends to follow the deformation of the soil, a rigid secondary lining is required. This secondary lining must be designed to withstand the changing stress conditions in the soil around the tunnel since it can be shown that the total horizontal pressure in the soil tends to decrease as the consolidation proceeds.

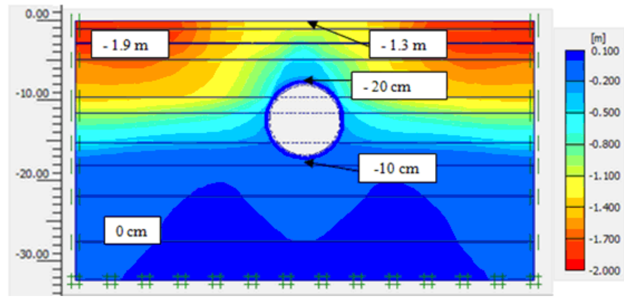

Figure 8. Expected long term vertical displacements around a tunnel in Mexico City consolidating clay (Auvinet and Rodríguez, 2010)

7 CONCLUSIONS AND PERSPECTIVES

The present state of geotechnical characterization of Mexico City valley subsoil has been briefly presented. Important new information was collected along the years. Geographic Information Systems and 1D, 2D and 3D models of the subsoil are now available for different parts of the urban area. Contours of layers thickness, as well as index and mechanical properties have also been obtained. The models and maps that have been established have been useful to provide information for new projects in the city and to update the geotechnical zoning presented in Mexico City Building code.

The task of gathering and processing information on the characteristics of Mexico City subsoil and on the spatial distribution of geotechnical properties will certainly proceed in the future since this challenging and never ending process is essential for the development of the infrastructure of the city.

ACKNOWLEDGEMENTS

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