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Soil Characterization and Land Subsidence Prediction for the First MRT Line in HCM City

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ABSTRACT: The Mass Rapid Transit (MRT) system is being constructed in HCM city to meet the transportation needs of a fast growing population and rapid urbanization. Being located in the Sai Gon-Dong Nai delta HCM city area has low elevations and is underlain by a sequence of clayey, silty and sandy soil layers. Land subsidence due to groundwater extraction had been suspected and observed in HCM city. With the increasing groundwater pumping, land subsidence is unavoidable and its effect on infrastructure development of the city has to be seriously considered and controlled at certain degree. The presence of the underlying thick and soft clay layer is another important factor to contribute to land subsidence of the city. In this study, geotechnical characterization of the subsoil along the first MRT line was carried out. Prediction of land subsidence along this MRT line was conducted using a FEM consolidation code. As a result, a subsoil profile of 9 soil layers was characterized, including a soft and compressible clay layer located on top of the soil profile from surface to the depth of more than 20 m. The land subsidence analysis results found that the soft clay layers are vulnerable to drawdown caused by groundwater extraction. With a drawdown of 5.5 m in the second aquifer for a period from 1999 to 2009 a total subsidence of 0.35m can be reached after 20 years at Km. 2.0, the junction zone between the underground metro segment and the elevated train segment, while a maximum subsidence of 0.45 m could be found after 20 years at Km 3.0 where the very soft and soft clay layer is thickest.

KEYWORDS: HCM City, Subsoil database, Land subsidence, MRT line, Groundwater extraction, Soft clay, Sai Gon- Dong Nai delta

1. INTRODUCTION

HCM city transportation system covers a total area of about 10.817 km^2 equivalent to 5.16% of the natural land area, in which the roads constitute the main component with a total length of 3,670 km. However, the existing road network has very low density and percentage of the packing area. In addition, the number of vehicles are increasing day by day, e.g., the total number of registered vehicles in the city in 2005 was three million for motorcycles and 220,000 for cars, which increased to 4,071,567 for motorcycles and 408,688 for cars in 2009 (HCMDOT, 2012). The low capacity of the road infrastructure combines with the continuously increasing number of vehicles has caused serious traffic congestion in HCM city. In order to resolve traffic jam problem in HCM city, the plan to develop HCM city's transport system by 2020 and the vision beyond that with a planning radius of 30 to 50km, including HCM city and seven surrounding provinces were approved by the Prime Minister on 22 Jan 2007 ((HCMDOT, 2012) as seen in Figure 1a. In the city center, constructions of four urban expressways and railway systems with 06 metro and 01 monorail lines are being started, in which the first MRT line connects Ben Thanh Market in the central area with the amusement park at Suoi Tien in District 9 over a 19.59-km long route running from SW to NE with the first underground segment of 2.26 km (from Ben Thanh to Bason stations) and the second segment of 17.33 km elevated section (from Bason to Suoi Tien stations) as seen in Figure 1b.

Some questions related to this very first MRT line of HCM city are: i) how a land subsidence in the long-term would affect it? and ii) how to assess such an effect in the condition of lacking the subsidence monitoring data?. This study aims to answer these two questions by studying the geotechnical characteristics of the subsoil profile and perform a land subsidence analysis along the first MRT line. Accordingly, a subsurface database was constructed to manage and visualize subsoil layers as well as to provide the input soil parameters for the land subsidence analysis using 1D FEM consolidation code developed by Giao (1997).

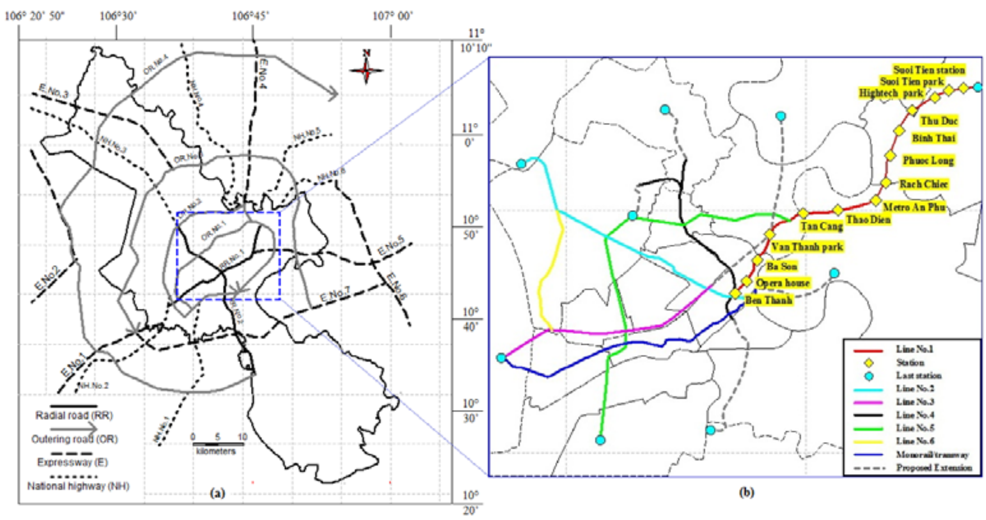

Figure 1 (a) HCM city's transportation development plan; (b) HCM city's MRT development plan (HCMDOT, 2010)

2. CONSTRUCTION OF THE SUBSOIL DATABASE FOR MRT LINES

Construction of a subsurface database using the software Rockworks16 is explained in this section. Rockworks16 is an integrated software package for geological data management, analysis, and visualization provided (Rockworks, 2010). There are 165 geotechnical boreholes were drilled along the first metro line with the depth ranges from 40 m to 80 m. The borehole and soil testing data from site investigation reports were collected. The workflow to construct and visualize the subsoil database of HCM city is explained in the followings.

Firstly, a new project file was created for metro line database that named as HCM METRO. Boreholes codes started by L1 (which stands for Line 1), followed by a dash (-), and end with the ordering number from 01 to 165 (corresponding to the first to the last station). General information of each borehole is input to the database including borehole code, total drilled depth, and coordinates using *borehole location tab.* Next, a generalized soil profile is created with units that included all possible subsoil layers encountered in all boreholes. These generic soil layer units are organized after their formation order. The soil profile, or individual soil layers, from each borehole is input into the database by entering the top and bottom depths of layers. As number of soil layers may differ from borehole to borehole one can enter the zero thickness for the missing layers by leaving the cells of these missing layers blank in the input worksheet or by entering the top and bottom depths with the same values that are equal to the depth of the last layer lying immediately above the missing layer. Final step in construction of the database was to input geotechnical parameters using the *I-data tool*, and set up the boundary coordinates and the grid spacing by scanning all boreholes coordinates using *project dimensions.*

Once all data were imported and checked, a soil cross-section in any direction can be readily generated using the *stratigraphy icon* with the *cross-section* or the *profile* tab. The *triplogs icon* was used to generate each selected borehole log and display soil parameter along borehole section.

A generic subsoil profile along the first MRT line, consisting of ten layer units was created in this study for the HCM METRO database as shown in Figure 2. This database can be developed further to include other MRT lines in future.

A short description of each soil layer is given below:

Layer 1 (Filling material) is located on top with thickness from several centimeters to several meters with an average of 2 m, consisting of construction materials such as small brick pieces, stone and concrete mix with sand, and weathered soil.

*Layer 2 (*Very soft to soft clay layer) is distributed at the areas of low elevation of less than 2 m. Its thickness varies from a few meters to more than 20 meters.

Layer 3 (Soft to medium silty clay layer) is found at boreholes in the left-hand side of river at the areas of low elevation (of less than 2m) as seen from Km 6.0 to Km 10.0 of the profile. It has an average thickness of 5 m.

Layer 4 (Loose to medium dense, fine to medium sand), the 1st aquifer, is found in the boreholes from Ben Thanh station to Tan Cang station, and from Thu Duc to Hightech Center stations . This layer has thickness from several meters to more than 10 m.

Layer 5 (Medium dense, fine to medium sand), the 2nd aquifer, is distributed at the same location as the layer 4. Its thickness varies from several meters (at Thu Duc to High-tech Center station and from Bason station to Tan Cang station) to more than 30 m (at boreholes from Bason to Ben Thanh station).

Layer 6 (Medium to stiff clay) is found in boreholes from Rach Chiec station to the last station (Suoi Tien terminal) with the thickness from 5 m to 20 m (with an average of 10 m).

Layer 7 (Medium dense, coarse sand), the 3rd aquifer, is found at the whole section with thickness from 10 m to 45 m (with an average of 25 m).

Layer 8 (Very dense, fine sand), the Upper 4th aquifer, is distributed at the same location as the layer 7. Its thickness is around 5 m.

Layer 9 (Very dense, sand with gravel), the Lower 4th aquifer, is found at the depth from 53 m to 70 m with an average thickness of 4 m. Geotechnical properties of soil layers from 2 to 9 are shown in Table 1.

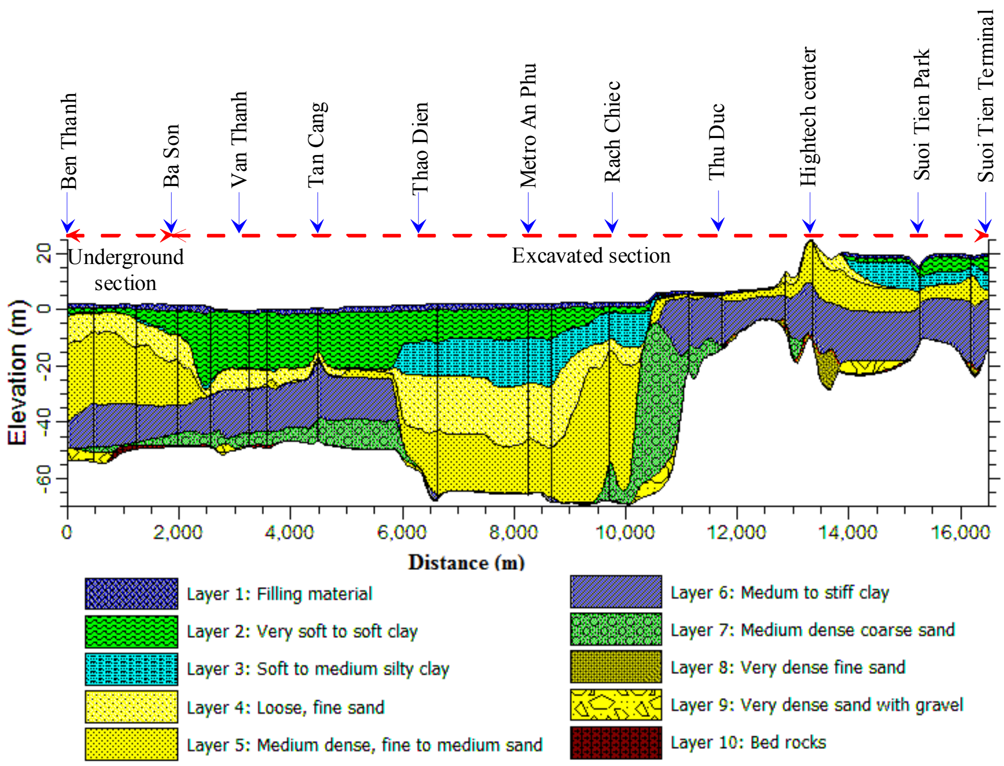

Figure 2 General subsoil profile along the first MRT line in HCM City

Table 1 Geotechnical properties of soil layers underlying the MRT no.1

Layer No.	Layer name	Clay fraction (%)	W (%)	UW (kN/m^2)	Gs	LL (%)	PL (%)	e_o	CR	RR	OCR
2	Very soft to soft clay	42.12	75.56	15.18	2.68	77.34	35.17	1.98	0.29	0.021	1.1
3	Medium to soft silty clay	36.11	34.10	18.3	2.74	45.89	24.01	1.45	0.175	0.043	1.78
4	Loose to medium dense, fine to medium sand (1st aquifer)	9.57	18.77	20.28	2.67						
5	Medium dense, fine to medium sand (2nd aquifer)	20.94	19.94	20.30	2.96						
6	Medium to stiff clay	31.58	18.72	19.35	2.73	45.18	17.05	0.65	0.11	0.019	2.5
7	Medium dense, coarse sand (3rd aquifer)	10.16	19.07	19.51	2.72						
8	Very dense, fine sand (Upper 4th aquifer)	6.07	18.17	20.20	2.74						
9	Very dense, sand with gravel (Lower 4th aquifer)	3.91	19.14	20.30	2.95						

3. GEOTECHNICAL CHARACTERISTICS OF THE VERY SOFT TO SOFT CLAY LAYER (SOIL LAYER 2)

The thickness of very soft to soft clay layer (Soil Layer 2) varies from several meters to more than 20 m. Figure 3 showed the geotechnical profile of the soft clay layer at Km 2.0, at the junction zone between the underground and elevated train sections of MRT line no. 1. The clay layer has the thickness of 20 m.

The clay fraction is from 33% to 60 % with an average of 45 %. The water content (W) is from 65 % to 80 % with an average of 72 %; liquid limit (LL) is around 63%; and plastic limit (PL) is around 38%. Initial void ratio, e_o, is from 1.89 to 2.10.

Unit weight, UW, ranges between 14.8 and 15.4 kN/m^3. Compression index, Cc, is various from 0.72 to 1.2 with an average of 0.92. Compression ratio, CR, is from 0.24 to 0.39 with an average of 0.30. The undrained shear strength from field van shear test (Su) ranges between 10 and 40 kPa, following a linear relationship with depth, i.e., Su = 1.28D + 0.12, where D is depth in meter as seen in Figure 3.

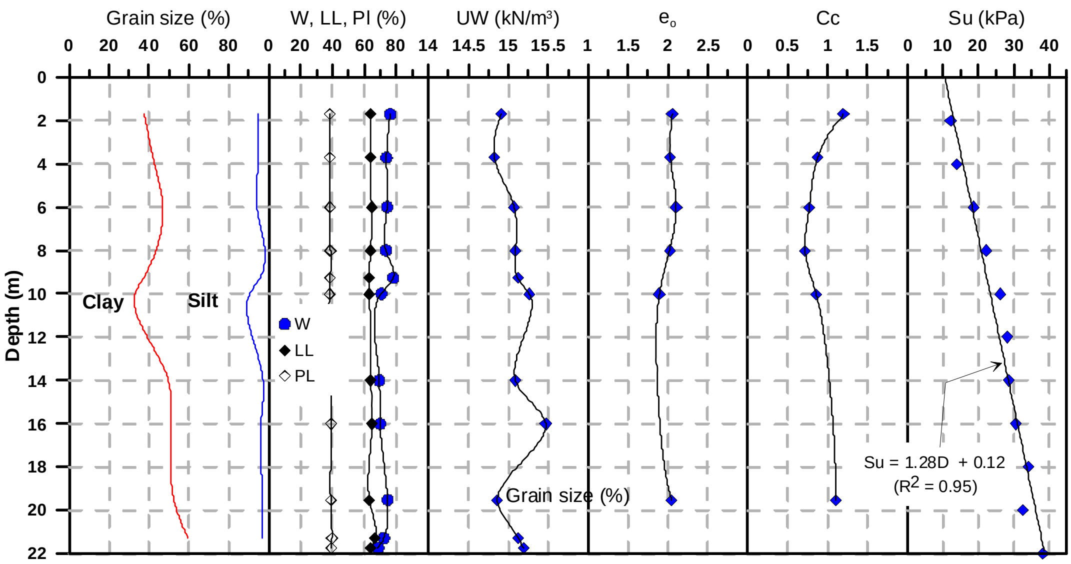

Figure 3 Geotechnical parameter of the soft clay layer at Km 2.0

The plasticity chart of soft clay is plotted in Figure 4a. The plasticity index ranges from 24 to 27, indicating a medium plasticity. Figure 4a shows that the soft clay is of MH-OH type. Figure 4b shows that the activity value of soft clay varies from 0.38 to 0.9 indicating the predominant clay minerals are illite and kaolinite. The sensitivity values calculated from vane shear tests varies from 4.5 to 6 as seen in Figure 4c.

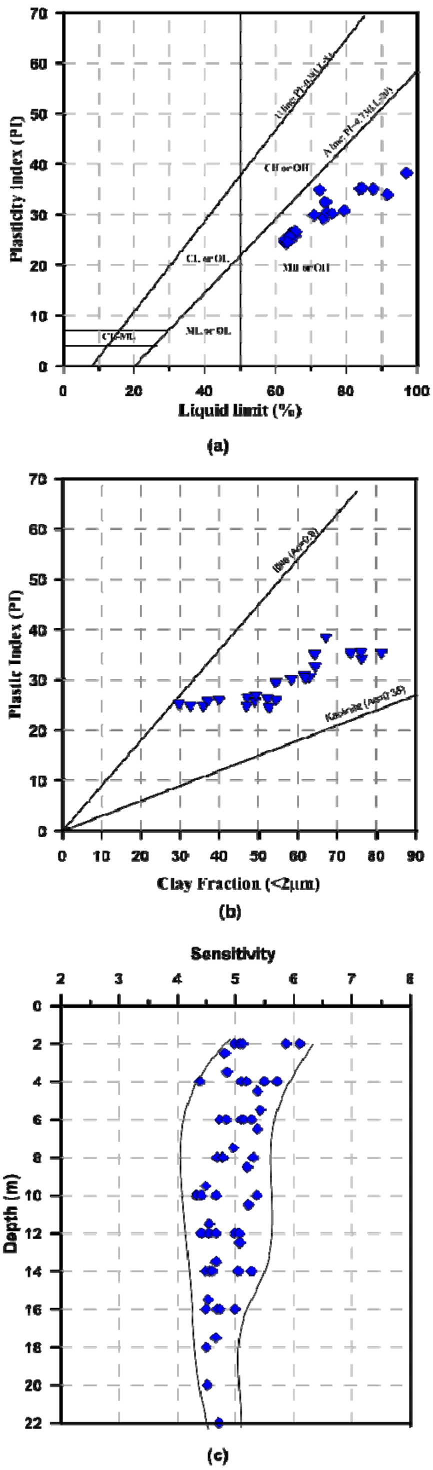

Figure 4. Plasticity (a), Activity (b) vs depth and Sensitivity (c)

4. LAND SUBSIDENCE ANALYSIS

In this study land subsidence analysis was done using a 1D Finite Element consolidation analysis code developed by Giao (1997), which was successfully applied for land subsidence analysis for many places, e.g., Bangkok (Giao et al., 1999) or Hanoi (Giao and Ovaskainen, 2000) etc. a short explanation of FEM formulation of the 1D consolidation equation is given as follows:
Starting with Terzaghi's consolidation equation below:

$$C_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \tag{1}$$

Where: u is the pore pressure (kPa); c_v is the consolidation coefficient (m^2/y); z is the depth (m); and t is consolidation time. For finite element formulation of Eq.1, by applying Green's Lemma one can obtain the weak form for a generic element, which is linear in this case, as follows:

$$\int_{\Omega^e} c_v \frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z} u_j d\Omega^e + c_v N_i \frac{\partial N_j}{\partial z} u_j \bigg|_{R^e} - \int_{\Omega^e} N_i N_j \frac{\partial u_j}{\partial t} d\Omega^e = 0 \tag{2}$$

The second term is the flux term, which can be neglected, thus Eq. (2) becomes:

$$\int_{\Omega^e} c_v \frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z} u_j d\Omega^e - \int_{\Omega^e} N_i N_j \frac{\partial u_j}{\partial t} d\Omega^e = 0 \tag{3}$$

Where: Ni, Nj are so-called the shape function. Based on this FEM formulation, TZP program was developed. It calculates pore pressure dissipation in the confining aquitards due to head change in adjoining aquifers which will be introduced into a bilinear compression model to calculate the subsidence as shown in the equation below:

$$dS_c(z,t) = b_i.[RR(z).\log\frac{P'_c(z)}{\sigma'_{v0}(z)} + CR(z).\log\frac{\sigma'_{v0}(z)+\Delta u(z,t)}{P'_c(z)} \tag{4a}$$

$$S_c(t) = \sum_{z=1}^{n} dS_c(z,t) \tag{4b}$$

Where: dSc(z,t) is the individual consolidation settlement of a layer at depth z, time t; Sc(t) is the total consolidation settlement of all layers at time t; b_i is the thickness; P'c(z) is the preconsolidation pressure; σ'vo(z) is the effective stress of the considered layer; Δu(z,t) is the dissipation of pore pressure of the considered layer at time t; CR(z) is the compression ratio ; RR(z) is the recompression ratio.

In this study analysis, groundwater drawdowns observed in the second aquifer from 1999 to 2009 were used as boundary condition. Geotechnical parameters of soft clay layers overlying the pumped aquifer were taken from Table 1. Results of land subsidence predicted along this MRT line are shown in Figure 5. For the underground section from Km. 0.0 to 2.0 the total subsidence could reach 0.35 m after 20 years corresponding to an average rate of 1.75 cm/y; for the initial part of the elevated segment from Km. 2.0 to 8.00 the maximum subsidence could reach 0.65 m after 40 years with an average rate of 1.63 cm/y; and for the remained part of elevated section from Km. 8.00 to the end of the MRT line no. 1 the maximum subsidence could reach 0.1 m after 10 years with an average rate of 1.0 cm/y. It is clear that the magnitude and rate of the subsidence along the MRT line no. 1 depends very much on the drawdown in the pumped aquifer (the second aquifer) and, in particular, thickness of the soft clay layer. A special attention should be paid to the junction zone between the underground and elevated train section at around Km. 2.0, where there is a big change in the soft clay layer thickness, and consequently a significant differential settlement may occur. Similarly, effect of a long-term settlement along the elevated segment from Km. 2.00 to 8.00 has to be taken into account. More details of land subsidence calculation results including deficit pore pressure, changes in hydrostatic pressure and soil layer compression versus depth, for the location of Km. 2.0, are shown in Figure 6 as an example of output provided by TZP program.

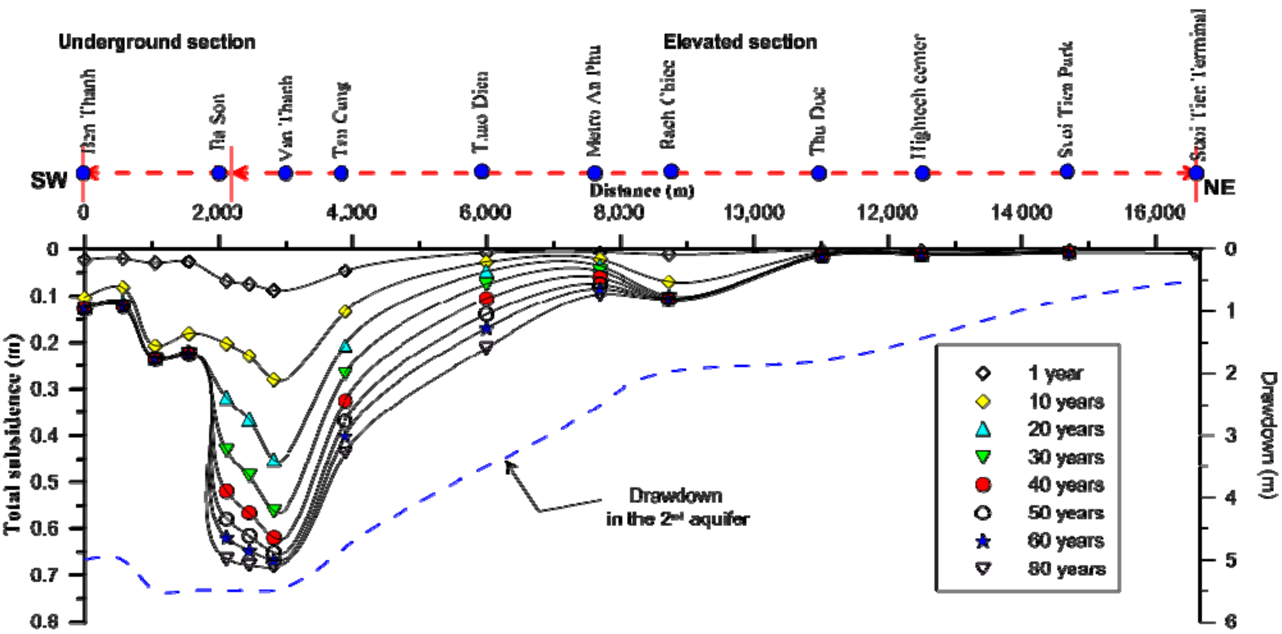

Figure 5 Land subsidence predicted along the MRT line no.1, HCM City, using 1D FEM consolidation analysis

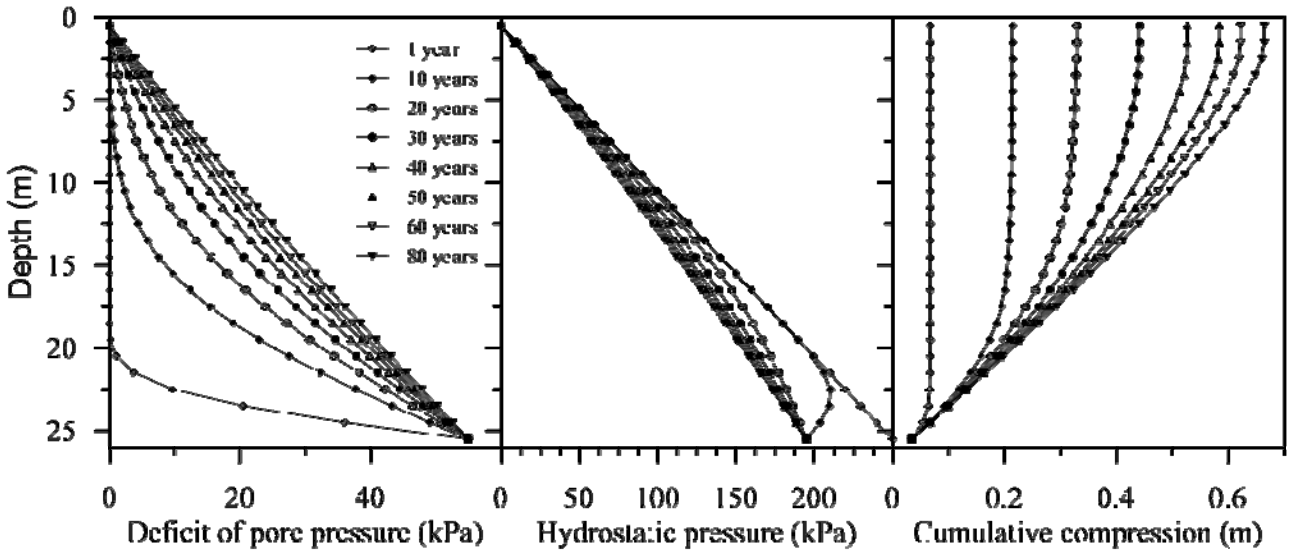

Figure 6 Results of 1D FEM consolidation analysis at Km 2.0, considering a drawdown Dh = 5.5 m and consolidation coefficient of the soft clay layer Cv = 2.5 m^2/y

5. DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

1) In this study construction of a subsoil database was initiated and successfully constructed for the first MRT line based on collection of data from 165 boreholes. First a general soil profile with 9 subsoil layers was created including the filling material (layer 1), Very soft to soft clay (layer 2), Soft to medium silty clay (Layer 3), Loose to medium dense, fine to medium sand (Layer 4), Medium dense, fine to medium sand (Layer 5), Medium to stiff clay (Layer 6), Medium dense, coarse sand (Layer 7),Very dense, fine sand (Layer 8), and Very dense, sand with gravel (Layer 9).
2) The most compressible soil layer was identified as the very soft to soft clay layer, located from Km 0.0 to Km 10.0 and Km 14 to end of the section, and found mostly from Km 2.0 to Km 9.5. Geotechnical characterization of this soft clay layer showed that the clay fraction is from 33% to 60 % , the water content and liquid limit around 72 % and 63%. The water content is higher than the liquid limit, and the liquidity index will be more than 1. In addition, the soft clay layer has a high void ratio values from 1.89 to 2.10, indicating of young and compressible soft clay. The unit weight is between 14.8 and 15.4 kN/m^3 and compression index ranges from 0.72 to 1.2 with an average of 0.92. The undrained shear strength from field van shear test (Su) ranges between 10 and 40 kPa.
3) A land subsidence analysis was done to predict subsidence along the MRT line no. 1 using the 1999-2010 in the second aquifer, from 1999 to 2010 of about 5.5m and a Cv of 2.5 m^2/yr of the top soft clay layers. A total subsidence of 0.35 m could reach after 20 years (1.75 cm/yr) at the junction zone of MRT underground and excavated segment, while a maximum subsidence of 0.45 m could be found after 20 years at Km 3.0 where the very soft and soft clay layer is thickest.
4) The results of this study showed that subsidence due groundwater pumping from the aquifers underlying HCM city can cause to settlement of the under-construction MRT lines. Further land subsidence analyses are recommended to be done, using the subsurface database and the approach of land subsidence calculation developed in this study. In addition, the network of land subsidence monitoring stations has to be constructed and operated on a regular basis. New techniques of land subsidence monitoring using satellite images have to be studied, and applied. An integrated use of traditional and modern settlement monitoring in combination with land subsidence prediction using FEM consolidation analysis will help better understand the land subsidence dynamics and assist more effectively the urban planning and infrastructure development of HCM city in general and the MRT line system in particular.

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