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ASSESSMENT OF LAND SUBSIDENCE DUE TO GROUNDWATER EXTRACTION IN HO CHI MINH CITY

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Abstract

Located in the transition zone between highland and Mekong delta, HCM city has an average elevation of 0.0 to 2.0 m. In the Southeast, the city is boundered by the sea with a coastline of 30 km. Thus, HCM city often suffered from inundation especially in the rainy season and tide high period. Land subsidence possibly resulted from groundwater over-extraction had been doubted since some manifestations of ground surface sinking were observed at the well fields in the districts No. 6 and Binh Tan in 2004. The common way to investigate land subsidence is to construct a network of monitoring stations to record two main parameters, i.e., settlement and pore pressure change. There are a few land subsidence monitoring stations that have been installed in HCM city since 2005. However, these monitoring data have not been available for public information. Due to the lack of studies on land subsidence, there are different opinions about the causes of subsidence in HCM city. Some scientists considered that groundwater extraction is the main cause of land subsidence, while others are in favour of natural self auto-compaction of the young soft clay sediment due to construction loads. Therefore, it is necessary to understand thoroughly land subsidence due to groundwater extraction. This study, the theory and methodology to calculate land subsidence due to groundwater extraction for HCM city using 1D FEM consolidation method, the TZP computer package, based on hydrogeological and geotechnical data. Initial calculated results for the central area of HCM city with the drawdown data taken from monitoring period of 1999 - 2009 show that land accumulative subsidence due to groundwater extraction could be as much as 63.8 cm, 85.2 cm, and 97.6 cm for 2010, 2040, and 2100, respectively.

Keywords: Land subsidence; Drawdown; Groundwater extraction; TZP program; HCM city.

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1. Fundamental of land subsidence due to groundwater extraction

1.1. One-dimensional consolidation theory for a clay layer

Most of the subsiding areas, especially in Asia, are lying over semi-confined or confined aquifer systems, containing aquifers of coarse-grained sediments (i.e. sand and/or gravel of high permeability and low compressibility) interbedded with aquitards of fine-grained sediments (i.e. clays or silty clay of low vertical permeability and high compressibility). These aquifer systems often compact in accordance with increase of effective stress caused by head decline in the aquifers and time-dependent pore pressure reduction in the compressible aquitards, causing land subsidence.

The theory of one-dimensional consolidation of fine-grained and deformable materials by Terzaghi (1925) is the basis solution for many practical soil mechanics and settlement problems, particularly to calculate the magnitude and rate of settlement or compaction that occur in fine-grained sediments under a given change in load (stress). The compaction is caused by the slow escapement of pore water from the loaded sediments, accompanied by a gradual transfer of stress from the pore water to the granular structure of the sediments. The relationship of stress components inside the soil is described by the Tezaghi's effective stress principle as follow:

$$\sigma' = \sigma - u \quad (1)$$

Where:

σ' is the effective stress, kPa

σ is the total stress, kPa

u is pore water pressure, kPa

As decline of head in the confined aquifer system does not change the total pressure, the increase of effective stress in the confined aquifers is equal to the decrease of the pore water pressure. The aquifers respond essentially as elastic bodies. Consequently, their compaction is immediate and can be recoverable if water pressure is restored, but it is usually small. The aquitards (clay layers) have low hydraulic conductivity/permeability and high water content, the vertical escapement of the water and adjustment of pore pressure are slow and time-dependent. Terzaghi derived the 1D consolidation equation describing that essence as follows:

$$C_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \text{ and } C_v = \frac{k}{m_v \gamma_w} \quad (2)$$

Where: C_v is the coefficient of vertical consolidation (m^2/yr);

u is excess pore water pressure in the clay (kPa)

k: hydraulic conductivity of the clay layer (m/d)

m_v: volumetric compressibility of the clay layer (1/kPa)

γ_w: unit weight of the water (kN/m^3)

1.2. Land subsidence calculation due to groundwater extraction

Land subsidence caused by groundwater extraction consists of the compression of sand and clay layers in which clay layers contribute a major part in the total compression of the soil profile. The compression of clay layers due to lowering of groundwater level in adjacent aquifer can be calculated based on Tezaghi's one-dimensional consolidation theory. Firstly, changes in the piezometric head are calculated based on groundwater model and input as a boundary condition to solve equation (2.2) to find the distribution of pore pressure in the clay layers adjacent to the pumped aquifer. As decrease in the pore pressure is equal to the increase in the effective stress, the time-dependent compression of a clay layer can be calculated as follows (Giao et al., 1999):

$$Sc(t) = b\left[RR\log\left(\frac{P_{\max}}{\sigma'_{vo}}\right) + CR\log\left(\frac{\sigma'_{vo} + \Delta u(t)}{P_{\max}}\right)\right] \quad (3)$$

Where:

Sc(t) is settlement of the clay layer at time t, y

$\Delta u(t)$ is the deficit of pore pressure at time t in the clay layer, induced by the drawdown in the adjacent aquifers, kPa

P_{max} is the maximum past pressure, kPa

CR is the compression ratio, CR=Cc/(1+e_o)

RR is the recompression ratio, CR=Cr/(1+e_o)

σ'_{vo} is the effective stress, kPa

The elastic compression of an aquifer (sand layer) due to groundwater extraction can be calculated by the following relationship:

$$S_a = \frac{1}{E}.b/\gamma_w.dh = b.m_v.\gamma_w.dh = b.S_s.dh \quad (4)$$

Where: S_a is settlement of the sand layer, m

b is the thickness of the sand layer, m

E is modulus of compression, kPa

γ_w is the unit weight of water, (kPa/m^3)

m_v is the coefficient of volume compressibility, (1/kPa)

S_S is the coefficient of specific storage (1/m),

dh is the head drop/drawdown, m.

The total subsidence (St) at a point on the ground surface is the sum of the compression of all aquifers (coarse-grained layers) and aquitards (fined-grained layers) beneath that point:

$$S_t = \sum_{i=1}^{n}(S_{c,i} + S_{a,i}) \quad (5)$$

Where: n is the number of soil layer under consideration.

i is the soil layer index (either sand or clay)

2. Land subsidence analysis

TZP program is a 1D Finite Element (FEM) consolidation coded by Giao (1997). This computer package was successfully applied for analysis of land subsidence caused by a long-term groundwater extraction over a large area underlain by a deltaic subsoil like Bangkok plain (Giao et al., 1999). A short explanation of FEM formulation of the 1D consolidation equation as follows:

Applying Green's Lemma for Terzaghi's consolidation equation (2), one can obtain the weak form for a generic element, which is linear in this case, as follows:

$$\int_{\Omega^e} c_v \frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z} u_j d\Omega^e + c_v N_i \frac{\partial N_j}{\partial z} u_j \Big|_{R^e} - \int_{\Omega^e} N_i N_j \frac{\partial u_j}{\partial t} d\Omega^e = 0 \quad (6)$$

The second term is the flux term, which can be neglected, thus Eq. (6) becomes:

$$\int_{\Omega^e} c_v \frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z} u_j d\Omega^e - \int_{\Omega^e} N_i N_j \frac{\partial u_j}{\partial t} d\Omega^e = 0 \quad (7)$$

Where: Ni and Nj are so-called the shape function. Based on this FEM formulation, the TZP program was coded in Fortran (Giao, 1997) to calculate pore pressure dissipation in the confining aquitards due to head change in adjacentpumped aquifers, which will be further introduced into a bi-linear compression model to calculate the subsidence

In this study, the land subsidence analysis was carried out using TZP in the following steps:

➢ The compressible layer (aquitard), which is overlying the pumped aquifer, was divided into a number of sub-layers with small thickness of 1 m.

➢ The drawdown in the pumped aquifer, calculated from a groundwater model, was served as boundary condition for the consolidation model.

➢ Identify and assign soil parameters (UW, Cv, CR, RR, OCR) for each sub-compressible layer. This can now be readily assisted with the help of the newly constructed subsoil database.

➢ The pore pressure dissipation in aquitard due to head change (drawdown) in adjoining aquifers is calculated.

➢ Based on the pore pressure change, the compression of each sub layer at a time can be calculated using the relationship given below:

$$dS_c\left(z,t\right)=b_i.\left[RR\left(z\right).\log\frac{P_c^{'}\left(z\right)}{\sigma_{v0}^{'}\left(z\right)}+CR\left(z\right).\log\frac{\sigma_{v0}^{'}\left(z\right)+\Delta u\left(z,t\right)}{P_c^{'}\left(z\right)}\right. \qquad (8)$$

The consolidation of a compressible layer consisting of n sub-layers is as follows:

$$S_c\left(t\right)=\sum_{z=1}^{n}dS_c\left(z,t\right) \qquad (9)$$

Where: dSc(z,t) is the consolidation settlement of the sub-layer at z depth, time t.

Sc(t) is the total consolidation settlement of the whole compresible layer at time t;

b is the thickness of the considered sub-layer, m

P’c(z) is the preconsolidation pressure of the considered sub-layer;

σ’vo(z) is the effective stress of the considered sub-layer;

Δu(z,t) is the dissipation of pore pressure of the considered sub-layer at time t;

CR(z) is the compression ratio of the considered sub-layer;

RR(z) is the recompression ratio of the considered sub-layer.

3. Results and discussions

3.1. Land subsidence analysis for a location at Binh Tan district

A location in Binh Tan district, denoted as BTA - 72. At this location, evidences of casing protrusion were observed. The geotechnical parameter profile (trip log) of this location was shown in Fig. 1, which shows a 26-meter-thick, very soft to soft clay layer overlying the medium dense sand layer or the 2nd aquifer (Middle-Upper Pleistocene).

The land subsidence estimation was made for this clay layer due to groundwater pumping in the 2nd aquifer for 10 years from 1999 to 2009. A drawdown of 7.5 m drawdown was read from the drawdown contour map, soil parameters taken from trip log (UW) and consolidation parameter table (CR, CR and OCR), and Cv value assumed as 5.0 m^2/yr) were input to FEM consolidation code and analysis TZPprogram.

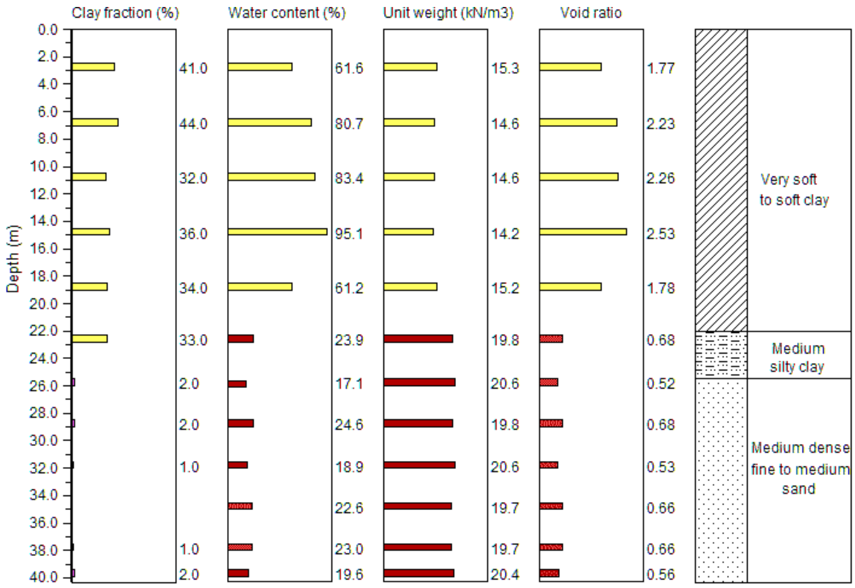


Figure 1: Borehole log and geotechnical parameters of borehole BTA - 72

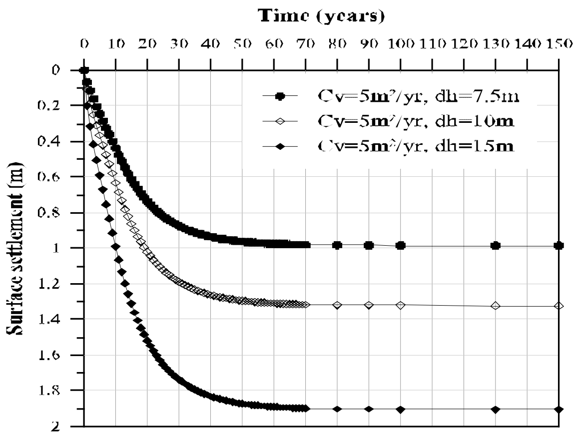
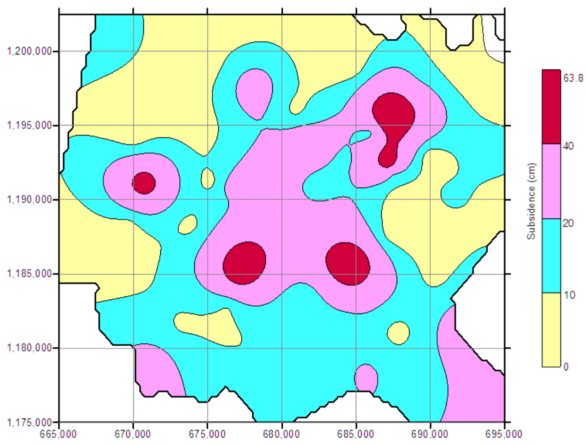


Figure 2: Surface settlement calculated with different drawdowns at borehole BTA - 72

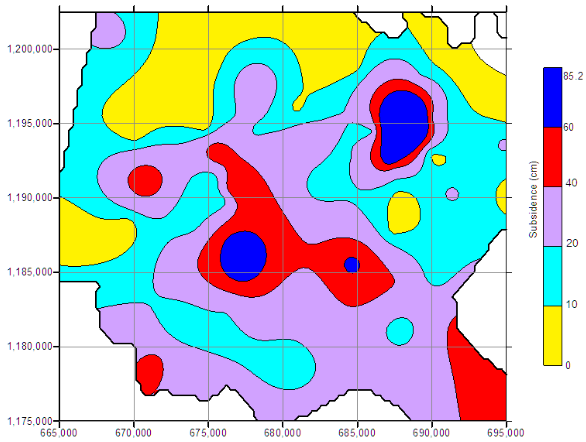
The calculation showed that the surface settlement could reach 0.44 m after 10 years equivalent to 4.4 cm/y, and 0.98 m after 40 years equivalent 2.45 cm/y. Assuming the drawdown can increase more in future in this aquifer, say, to 10.0 m and 15.0 m, the additional analyses gave a 1.32 m and 1.9 m surface settlement (subsidence), respectively, as seen in Figure 2. The change of subsidence with time indicated a relative rapid subsidence would occur with a high rate in the first 20 years, and then has gradually leveled off, reaching the ultimate consolidation settlement after 40 years. A significant increase in cumulative settlement can be observed after 10 years since the drawdown occurred. The increasing trend continues visibly until 20 years, and then it slows down.

3.2. Prediction of land subsidence for HCM city

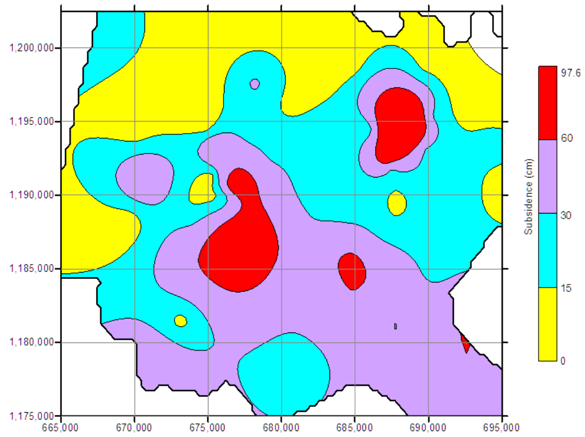
The results of land subsidence predicted for 1999 - 2020, 1999 - 2040, and 1999 - 2100 are plotted in Fig. 3a, b, & c, respectively showing maximum subsidence magnitude of 63.8 cm, 85.2 cm, and 97.6 cm, respectively. The map of 100 - year prediction of subsidence for the next 100 years was conducted for 62 locations in the center part of HCM city. Based on the analysis results, the total subsidence map from 2010 to 2100 was constructed as seen in Figure 3c. The map showed that the subsidence increases from the North to the South and can classify into four degrees: 5 - 15 cm, 15 - 30 cm, 30 - 60 cm, and 60 - 95 cm, among which the fourth degree coveres a small area, while other three degrees cover almost the same area.



(a)



(b)



(c)

Figure 3: Land subsidence estimation in the central area of HCM city (a) For the period from 1999 to 2020; (b) For the period from 1999 to 2040 (c) For the period from 1999 to 2100

4. Conclusions and recommendations

The 1D FEM consolidation program (TZP) is a useful tool to estimate land subsidence in HCMC when the conventional land subsidence monitoring network has not been fully operated and the pore pressure and subsidence monitoring data are not yet available. With increasing groundwater extraction, more subsidence may occur in Ho Chi Minh City, especially in the southern area of the city where thick soft clay layers occur. The analysis results show that infrastructure development plans need to be taken into account the impact of subsidence due to groundwater extraction.

In this study, the TZP program only applies to the upper soil layers with high compressibility, but not for the lower aquitard layers with lower compressibility and insufficient geotechnical analysis data. Besides, the TZP program is able to compute settlement resulting from on-surface infrastructure loads, but this option is not made in this study due to lack of relevant data. Systematic and comprehensive studies of the subsidence causes in the city and as well as the quantifying the proportion of each subsidence cause is necessary to be able to come up with an action plan and respond to this problem in a comprehensive and effective way.

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