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PRELIMINARY ASSESSMENT OF HANOI LAND SUBSIDENCE WITH REFERENCE TO GROUNDWATER DEVELOPMENT

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ABSTRACT: Hanoi is a lowland city in the sense that its elevation is much lower than the Red River level and the city needs to be protected by a long-standing dike system. The capital of Vietnam is currently enjoying a rapid economic, industrial and population growth. But it is also facing a lot of problems; one of those is groundwater extraction and land subsidence. Hanoi's water supply comes entirely from groundwater resource; hence, the increase in groundwater pumping to sustain the city in the future is inevitable. Land subsidence due to groundwater withdrawal has already manifested itself in a few locations in Hanoi, however its investigation is still sporadic and in its infancy stage, with very few monitoring data of good quality. For the current situation, both underestimation and exaggeration of land subsidence caused by groundwater pumping may have a serious impact on groundwater and infrastructure development of this growing city. In this paper, a preliminary assessment and analysis of Hanoi land subsidence was done based on the initial results of investigations by both Vietnamese and foreign researchers. Emphasis was on the application of a fast and practically reliable technique based on a bilinear compression model and Terzaghi's consolidation equation in a primary assessment of Hanoi land subsidence.

INTRODUCTION

The flat deltaic plains in the South East and North East Asian countries are very densely populated areas, where cultural, political, industrial and economic centers have been developed for thousands of years. Civilizations used to begin on the deltaic plains because the young alluvial soils were much more fertile than the leached upland soils, and irrigation for crops on these soils is rather simple (Cox 1968). In the later half of the 20th century, however, due to fast growing economies accompanied by strong industrialization and urbanization, the alluvial deltaic soils have been extensively exploited for groundwater and infrastructure development. Unfortunately, in contrast to their agricultural advantage, the alluvial deltaic soils present considerable geotechnical problems for infrastructure development (e.g., groundwater extraction, construction of roads, highways, subways, tunnels, domestic and industrial buildings, airports, harbors). Vietnam, as a late comer in the race for economic development in the region, should learn from lessons other countries have experienced during the last several decades. Among major problems related to weak alluvial deltaic soils, the compression of soft clays overlying the pumped aquifers is one of the most environmentally serious issues, as it causes land subsidence of the urban areas. The most obvious example is from Bangkok, where extensive pumping in the 1960-1980's from the underlying aquifer system led to significant declines of piezometric heads, maximum up to 40-50 m in the exploited aquifers, and consequently a land subsidence of Bangkok city. The maximum

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subsidence observed during 1933 to 1987 was 160 cm, and that between 1978 to 1987 was 75 cm (Nutalaya et al. 1989). As Bangkok is located in a lowland, having elevations varying from 0 to 1.5 m above MSL, land subsidence here has aggravated flooding and caused a significant cost increase in infrastructure development.

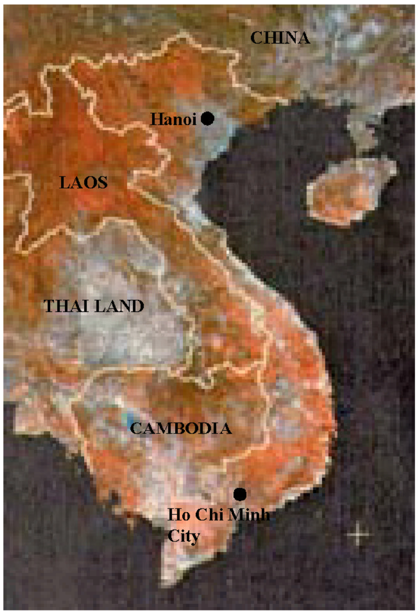


Fig. 1 Study location, Hanoi

Hanoi's water supply is fully dependant upon groundwater resources. Due to the city's fast economic growth in recent years, continuous groundwater extraction to meet the city's domestic and industrial water supply demands has certainly brought the concern that a land subsidence of Hanoi would lead to a significant increase in the cost of infrastructure construction and to the hindrance or even prohibition of groundwater extraction, similar to what is happening in Bangkok nowadays. Many experts are afraid that Ho Chi Minh City and Hanoi will follow Bangkok's pattern of rapid economic, industrial and population growth, and uncontrolled urbanization, resulting with a boom of public and private groundwater wells. As Hanoi's groundwater extraction has just started to develop strongly, the time is ripe to have a primary assessment and analysis of the city's groundwater extraction and land subsidence investigation.

This paper will covers the following: (i) a brief review on situation of Hanoi groundwater extraction and Hanoi aquifer system; and (ii) a preliminary assessment on Hanoi's land subsidence and its investigation; (iii) a land subsidence analysis, using a simple but practically reliable technique based on a bilinear compression model and Terzaghi's consolidation equation which has been successfully applied for the Bangkok aquifer system (Giao 1997; Giao et al. 1999).

GROUNDWATER EXTRACTION FROM THE HANOI AQUIFER SYSTEM

Hanoi, the capital of Vietnam (Fig. 1), is a lowland city. Because its elevation is lower than the water level of the Red River, the city has to be protected by a long-standing dyke system. Hanoi boasts of having an abundant aquifer system. Groundwater extraction in Hanoi started in 1909 at a rate of 40,000 m^3/d. When the Vietnam War ended, in 1975, the daily extraction rate was about 150,000 m^3/d. In 1990 it was about 300,000 m^3/d. Seven years later in 1997, the daily extraction rate increased to 400,000 m^3/d. It is projected to be double (more than 800,000 m^3/d) in the year 2000, and it will be more than 1 mil. m^3/d by 2020. It was estimated that there are 135 production wells from 8 main public well fields and more than 10 other small fields. However, with the recent economic and urban development, a significant number of private wells have been developed. Based on a survey conducted in 1999, there are about 530 wells from factories and hotels, pumping at a rate of about 100,000 m^3/d, which is equal to about one fourth of the total production of the public wells (K2 1999). But a much larger number of household wells were not counted at all. The total pumpage of these household wells is certainly very significant as there is a common trend in Hanoi nowadays to drill a 30 to 60 m deep water well with each newly built house. The groundwater extraction and demand based on the public wells of Hanoi, projected up to 2020, are presented in Fig. 2a. Data of population growth (Ham 1994) are plotted with the daily groundwater extraction and shown in Fig. 2b, which shows an ever-increasing trend, especially after 1985. Due to groundwater extraction from the Hanoi aquifer system, the piezometric from the exploited aquifer has been lowered in many locations. A large area was estimated to be affected by groundwater level declines due to pumping, and namely, about 80 km^2 having more-than-8 m drawdown and about 20 km^2 is very strongly affected having more-than-14 m drawdown (K2 1999). The Hanoi aquifer system essentially consists of four units from the ground surface to a depth of 80 to 100 m, i.e., the Holocene aquifer, the aquitard, the Pleistocene aquifer, the Neogene sandstone bedrock (Fig. 3). The Holocene aquifer (qh) is the uppermost unit and of unconfined type, whose thickness varies from 3 to 33 m, with an average value about 15 m. The qh aquifer is developed mostly in the areas near the Red River. It consists essentially of alluvial and lacustrine soils, i.e., sand, clayey sand, gravel and cobbles. The water level is from 3.0 to 4.6 m below the ground surface. The aquifer is recharged by irrigation, surface water, and rainwater and discharges to lakes, rivers and the lower Pleistocene aquifer. There is observed a very close relationship between monthly rainfall and the water level in this aquifer (K2 1999). The water is fresh, from soft to hard, of calcium bicarbonate type.

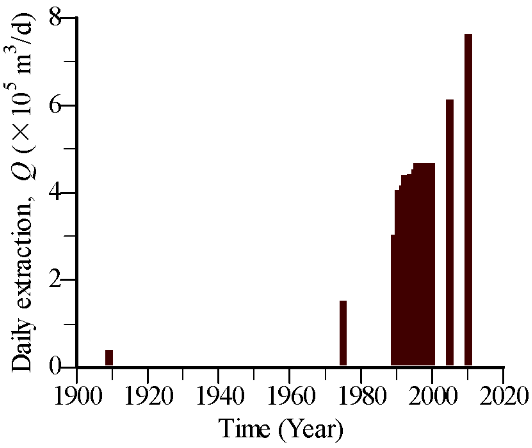


Fig. 2a Demands of groundwater extraction projected up to 2020 in Hanoi

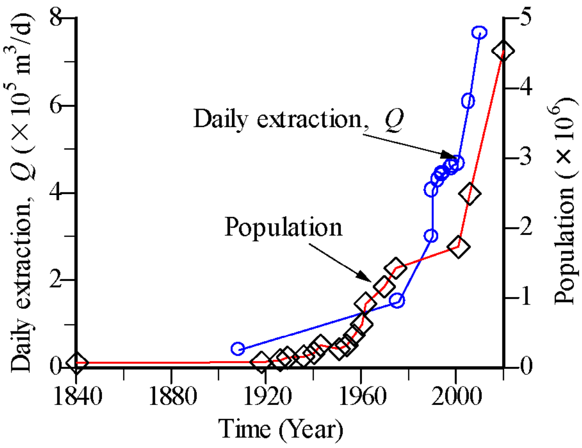


Fig. 2b Groundwater extraction versus population growth in Hanoi

The aquitard underlying the Holocene aquifer consists of clay, clayey silt, and peat in some places. This clayey soil layer is not continuously extending, it tends to be laminated and disappearing near the Red River. Due to the existence of the clay layer, it is missing a direct hydraulic connection, called hydraulic window, between the Holocene and Pleistocene aquifers. The hydraulic conductivity of this confining layer is from 0.0036 m/d to 0.065 m/d.

The Pleistocene aquifer (qp) is more extended than the Upper Holocene aquifer and is present in most of the Hanoi area, except in some northern areas where the bedrock outcrops. It consists of alluvial sand, gravel, pebble and cobble, being in general, coarser toward the lower part. The aquifer is the main productive aquifer with thickness varying from several meters to ten meters. The water is fresh, of calcium bicarbonate type. The initial groundwater level is from 2 to 5 m, but in many places it was much lower due to hundreds of extraction wells, thus causing an induced recharge from the Red River during the rainy season. Because of the existence of an intercalation of clay, although it is not continuous, the Pleistocene aquifer can be separated into two sub-layers: the Upper Pleistocene aquifer with an average thickness of about 15 m, and the Lower Pleistocene aquifer with an average thickness of about 25 m. The hydraulic conductivity of the later is about 150 m/d. The transmissivity varies from 600 m^2/d to about 3000 m^2/d. The Lower Pleistocene aquifer is abundant and is the most important productive aquifer.

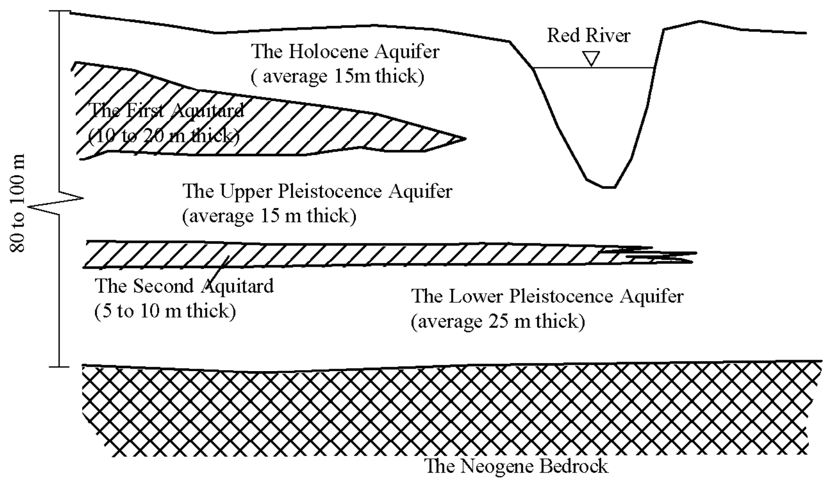


Fig. 3 Sketch of the Hanoi aquifer system

The Neogene is largely extended, consisting of consolidated cobbles, gravels and sands, interbedded with siltstone and claystone. The groundwater level is from 2 to 4 m. The water is of calcium-bicarbonate or sodium bicarbonate type. It is essentially an impermeable rock layer, however, in some locations it may be fissured and become water-bearing.

The hydraulic connection between the upper and lower aquifers as well as between these aquifer layers and Red River exists. Pumping from an aquifer may cause a drawdown from another aquifer. It was observed that during the rainy season, water is recharged to the aquifers from the Red River, and vice versa during the dry season. This evident hydraulic connection represents a very big advantage of the Hanoi aquifer system in terms of groundwater exploitation, however, at the same time it also make the aquifers more exposed and vulnerable to pollution and contamination.

HANOI LAND SUBSIDENCE INVESTIGATION

A monitoring network was installed and run by the Hydrogeological Division No.2 (commonly known as K2) during the 1988 to 1995 period (Plancenter and HWBC 2000). In 1988, 30 surface settlement indicators were installed by K2 in 1988. The number increased to 43 in 1992. There were two types of surface settlement indicators. The first type was made of concrete plate buried at 0.5 m depth with a ceramic piece on top as the levelling point. The second type was installed at the base of a pre-existing groundwater well. Since 1988, the levelling has been carried out once a year between October and November, using the standard levelling method, for a total closed route of 396 km. The reference benchmark, which is a national benchmark, is located in a mountainous area at Do Lo, Chuong My. The K2 monitoring network is shown in Fig. 4. The K2 network also included three pore pressure monitoring stations, installed at Mai Dich, Phap Van and Luong Yen (Koponen and Dan 1995). In each pore pressure station, electrical vibrating wire piezometers were installed at 4 depths and pore pressures were recorded on a monthly basis. Some results at the Phapvan station are plotted in Fig. 5, which indicates that the decline of pore pressure had just started at the bottom of the clay layer. The land subsidence monitoring by the K2 network has been stopped since 1995 due to the lack of funding.

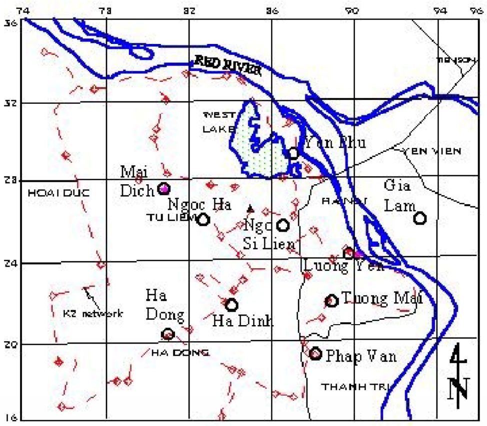


Fig. 4 Some major well fields (water plants) in Hanoi and land subsidence levelling network by K2

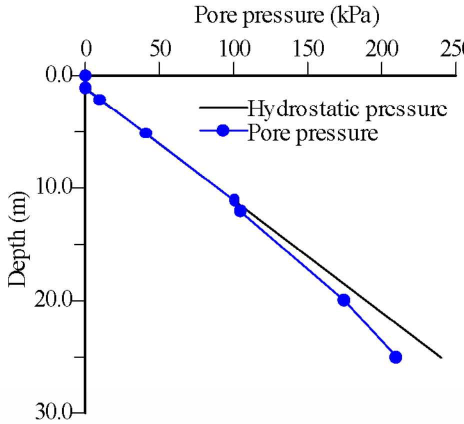


Fig. 5 Pore pressure profile recorded at Phap Van from 18/8/94 to 30/9/95 (based on Koponen and Dan 1995)

The Hanoi Institute of Construction (HIC) installed six land subsidence monitoring stations by now, numbered from 1 to 6, at Ngoc Ha, Phap Van, Thanh Cong, Luong Yen, Ha Dinh and Mai Dich, respectively. Except Thanh Cong station, locations of these stations are shown in Fig. 4. Each HIC station consists of a deep reference benchmark about 80 to 100 m, a set of 4 compression indicators and another set of 4 piezometers. The inner pipe of the reference benchmark is used like a standpipe piezometer to monitor piezometric head in the pumped aquifer. The instrumentation of the land subsidence monitoring stations is of AIT type (AIT 1981) with some small modifications. The layout of a HIC monitoring station is shown in Fig. 6. In general, the pore pressure and compression measurements are taken on a monthly basis. The surface settlement at the reference benchmark is measured by two dial gauges of 1 cm and/or 5 cm capacity. The compression measurements indicate relative elevation change between the compression indicators and the reference benchmark. The available data of surface settlement in 1998, recorded at 6 stations, are shown in Fig. 7. The yearly rate of subsidence in 1998 was not the same at these stations. It was about 30 mm at Thanh Cong, 20 mm at Phap Van, 10 mm at Ha Dinh and Luong Yen, 3 mm at Mai Dich, and about 1 mm at Ngoc Ha. The differential rate of subsidence at the locations can be explained by local soil conditions, groundwater extraction duration and rate, errors in data monitoring, and consolidation time as well. It would be interesting and useful, although quite difficult, to clarify and simulate this differential rate of subsidence in the future.

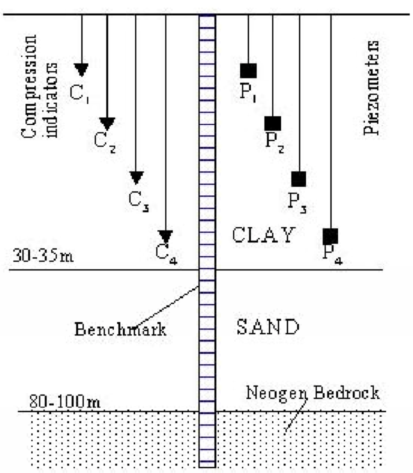


Fig. 6 Layout of a HIC land subsidence station

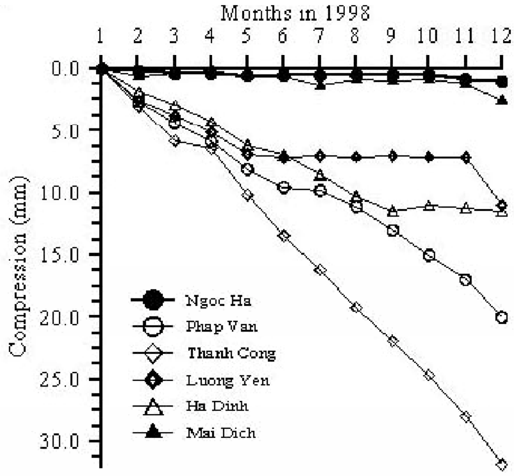


Fig. 7 Compression monitoring data in 1998 at six HIC stations (based on Dung et al. 2000)

ANALYSIS OF LAND SUBSIDENCE

General

Traditional analysis of land subsidence used to consist of two parts; groundwater modeling and consolidation settlement analysis. The former is used to analyze groundwater flow in the pumped aquifers, while the later is used to calculate the compression of the adjacent aquitards. The mechanism of land subsidence due to pumping can be briefly described as follows: drawdowns from the pumped aquifer induce a pore pressure dissipation from the overlying and underlying clay layers, increasing in this way their effective stress and consequently causing their compression. The drawdowns in the pumped aquifers, calculated from a groundwater model, can serve as boundary conditions for the consolidation model. The drawdowns are actually time-dependent, but for a small area like that of a well field, a pseudo-steady state flow in the pumped aquifer would reach quickly comparing to process of pore pressure dissipation from the adjacent aquitards. Therefore, in many situations, the drawdowns can be assumed as the fixed head boundary conditions. For a multi-aquifer system of Bangkok or a bi-aquifer system of Hanoi, a quasi-3D groundwater model (Giao 1997; Giao et al. 1999) or a 3-D groundwater model would be more appropriately used. However, for the purpose of a preliminary assessment and analysis of land subsidence at a location of a Hanoi well field, the use of a 2-D groundwater model in combination with a 1-D consolidation model would be enough. The FEM formulation of the models are briefly presented below.

FEM 2-D Groundwater Model

The governing equation of 2-D groundwater flow in a confined aquifer

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) \pm Q = S\frac{\partial h}{\partial t} \tag{1}$$

where, h is the head in the confined pumped aquifer; T_x, T_y are the aquifer transmissivities along x and y-directions; S is the aquifer storage; Q is pumping rate (the sign is minus for discharge and plus for recharge, respectively)

The FE formulation of Eq. (1), by Galerkin's method, for a generic domain, is as follows:

$$\int_{\Omega^e}\left(T_x\frac{\partial N_k}{\partial x}\frac{\partial N_l}{\partial x}+T_y\frac{\partial N_k}{\partial y}\frac{\partial N_l}{\partial y}\right)h_k d\Omega^e+\int_{\Omega_e} SN_kN_l\left(\frac{\partial h_k}{\partial t}\right)h_k d\Omega^e-\int_{\Omega_e} QN_l d\Omega^e$$
$$-\int_{R^e} N_l\left(T_x\frac{\partial N_k}{\partial x}+T_y\frac{\partial N_k}{\partial y}\right)h_k dR^e=0 \qquad (2)$$

FEM 1-D Consolidation Model

Terzaghi's consolidation equation is commonly found under the following form:

$$c_v\frac{\partial^2 u}{\partial z^2}=\frac{\partial u}{\partial t} \qquad (3)$$

where, u is the pore pressure function; c_v is the consolidation coefficient. Applying Green's Lemma one can obtain the weak form for a generic element, which is linear in this case, as follows:

$$\int_{\Omega^e} c_v\frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z}u_j d\Omega^e + c_v N_i\frac{\partial N_j}{\partial z}u_j\,|_{R^e}-\int_{\Omega^e} N_iN_j\frac{\partial u_j}{\partial t}d\Omega^e=0 \qquad (4)$$

The second term is the flux term, which can be neglected, thus Eq. (4) becomes:

$$\int_{\Omega^e} c_v\frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z}u_j d\Omega^e-\int_{\Omega^e} N_iN_j\frac{\partial u_j}{\partial t}d\Omega^e=0 \qquad (5)$$

Calculation of Time-dependent Compression

Calculation of primary consolidation of a clay layer due to pore pressure change which has been induced by the drawdown in the underlying aquifer can be done as follows: the compressible layer, which is overlying the aquifer, is divided into a number of sub-layers of small thickness, e.g., 1 or 2 m. The pore pressure change inside the compressible layer due to pumping can be calculated by a FEM 1-D consolidation model, using TZP program developed by Giao (1997). Based on the pore pressure change, the compression of each sub-layer can be calculated using the relationship given below:

$$dS_c(z,t)=b_i.[RR(z).\log\frac{P_c'(z)}{\sigma'_{v0}(z)}+CR(z).\log\frac{\sigma'_{v0}(z)+\Delta u(z,t)}{P_c'(z)} \qquad (6)$$

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

$$S_c(t)=\sum_{z=1}^{n} dS_c(z,t) \qquad (7)$$

where, $dS_c(z,t)$ is the consolidation settlement of the sub-layer at z depth, time t; $S_c(t)$ is the total consolidation settlement of the whole clay layer at time t; b_i is the thickness of the considered sub-layer; $P'_c(z)$ is the preconsolidation pressure of the considered sub-layer;

$\sigma'_{vo}(z)$ is the effective stress of the considered sub-layer; $\Delta u(z,t)$ 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.

Fig. 8 Land subsidence at the Phap Van water plant: (i) Left: Differential settlement at the sedimentation basin; (ii) Right: Cracks of the steps to the office buildings

Phap Van Well Field

Phap Van wellfield consists of nine individual wells. The area of the well field is approximately 0.2 km^2. The first five wells were drilled in 1987 and the most recently well was drilled in 1999. The total extraction rate of the well field is about 25,000 m^3/d. At this well field, damage to well structures, the water treatment plant and other buildings due to land subsidence can clearly be observed as shown in Fig. 8. From 1997 to 2000, a drawdown of 3m occurred (Plancenter and HWBC 2000). In general, the piezometric head of the pumped aquifer could go down to 10 to 20 m inside and around the well field from the initial piezometeric level as observed and based on a simple 2-D groundwater flow analysis for a confined aquifer. The rate of subsidence is also significant, about 2 cm/y as observed in 1998 (see Fig. 7). To show the effect of groundwater pumping on the compression of the overlying clay layer, three consolidation analyses were performed, considering three drawdowns of 10, 15 and 20 m in the pumped aquifer. These served as the boundary conditions of the consolidation problem, which correspond to three hydraulic loadings of 100, 150 and 200 kPa, respectively.

Table 1 Soil profile and assumed geotechnical parameters for consolidation analysis

Soil type	Soil description	Depth (m)	w (%)	γ (kN/m^3)	c_v (m^2/y)	OCR	CR	RR
Top soil	Fill, weathered clay, olive gray, oxides of iron and sand lenses	0-2	30.0	1.95	5	7	0.3	0.06
Silty clay	Soft, high water content, brown and gray colour. Contains some organic matters.	2-15	55.0	1.60	5	1.1	0.5	0.10
Clayey silt	Soft, dark brown colour.	15-30	30.0	1.90	5	1.5	0.25	0.05
Sand (the pumped aquifer)	Medium to fine sand, gray colour.							

The soil parameters used in consolidation analysis for Phap Van location are presented in

Table 1. The most compressible layer of soft clay is found at a depth ranging from 2 to 15 m. The in-situ c_v usually can have much higher value, and consequently, the consolidation processes in reality may undertake much more quickly, at a much higher rate. Some analyses were carried out to investigate land subsidence behavior due to groundwater pumping at the Phap Van location. These analyses are presented as follows:

First, an investigation on the influence of values of coefficient of consolidation, c_v, and that of the drawdowns in the pumped aquifer due to groundwater pumping, on the magnitude of total land subsidence was made. In Fig. 9a, for a drawdown of 10 m (100 kPa), the surface settlement, caused by compression of the whole soil column from the ground surface to the 30 m, was calculated for c_v equal to 1, 5, 10 and 15 m^2/yr. The coefficient of consolidation c_v of 1 m^2/y, a commonly found value based on the conventional consolidation tests in the laboratory for many types of soft clays, is in general very conservative. The field values of c_v are usually much higher, by five to ten times or even more, due to horizontal stratification and existence of silty or sandy lenses within the clay layers etc. The analysis results in Fig. 9a clearly confirm this, i.e., the settlement curve for c_v =1 m^2/yr indicated a consolidation, whose 90% would take 200 years or so to be completed. However, with a c_v of 5 m^2/yr, the 90% consolidation time reduced drastically to just about 30 years. With a higher c_v of 10 or 15 m^2/yr, the 90% consolidation time is about 15 to 20 years. The value of c_v affected consolidation time, but it would not affect the magnitude of the final consolidation settlement.

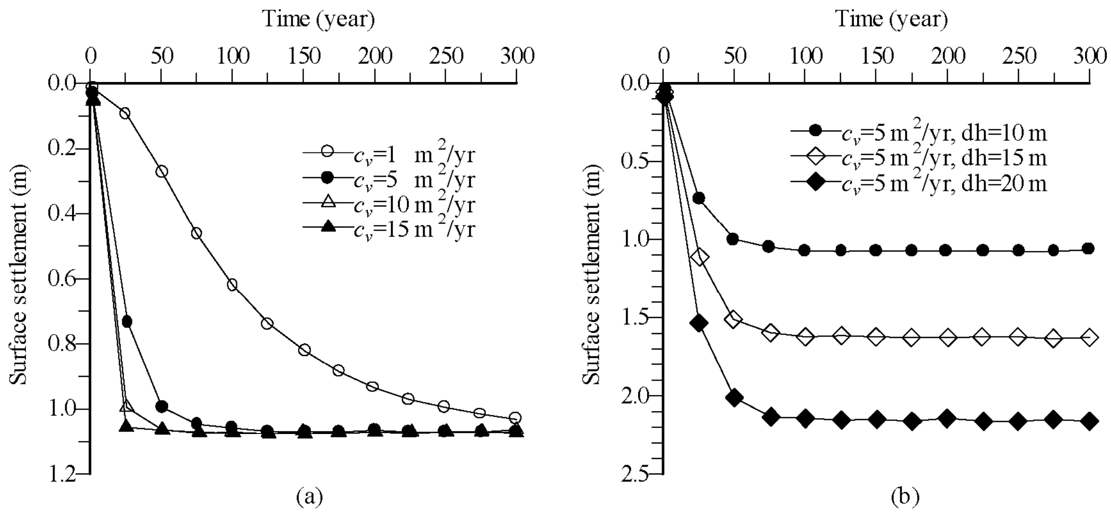
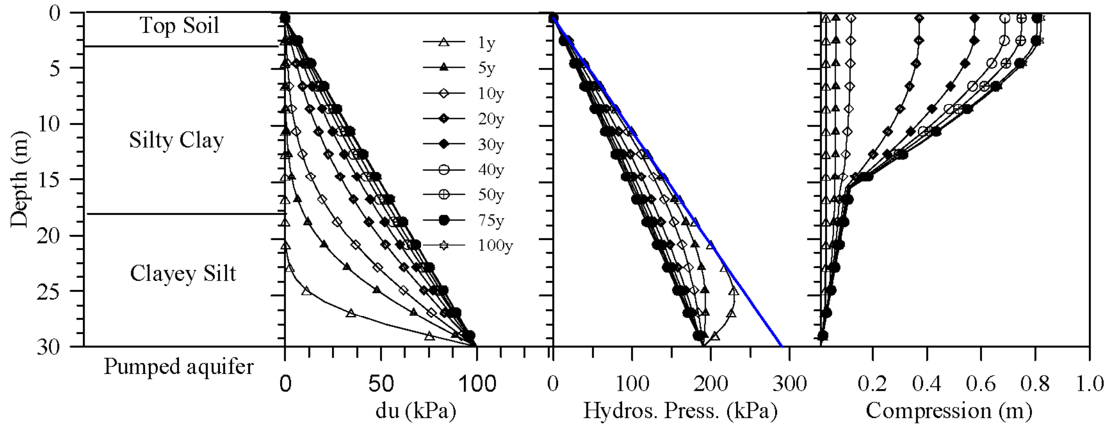
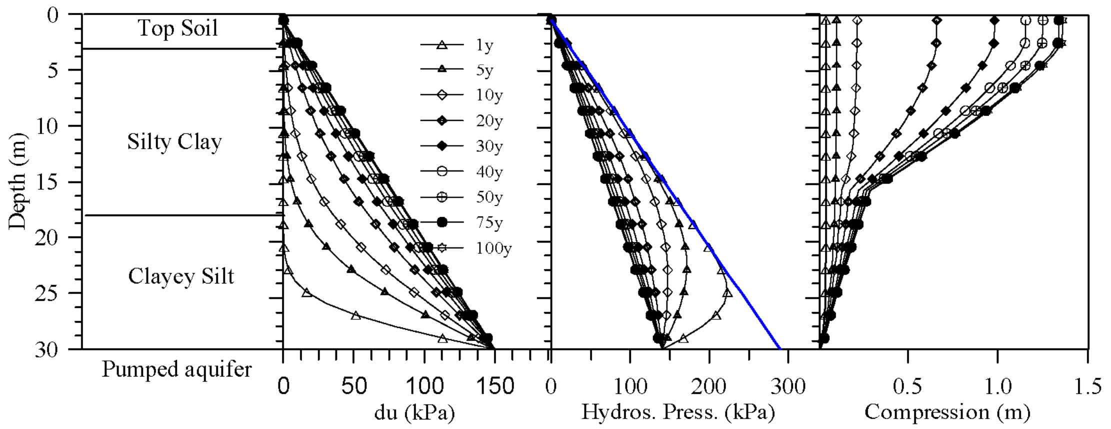


Fig. 9 Effects of c_v and hydraulic loading in land subsidence analysis; (a) settlement curves due to a drawdown of 10 m (100 kPa) with a c_v of 1, 5 ,10 and 15 m^2/yr; (b) settlement curved due to drawdowns of 10, 15 and 20 m, with a c_v of 5 m^2/yr.

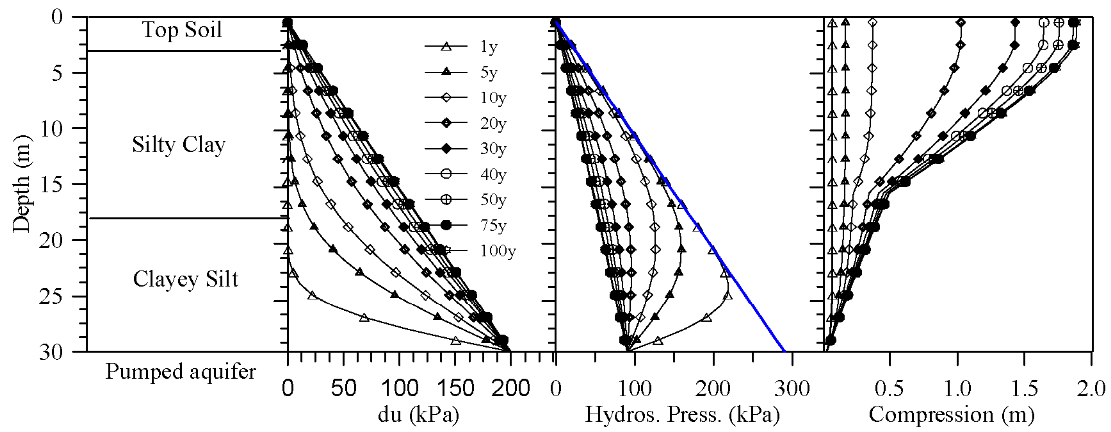
In a further analysis, the value of c_v equal to 5 m^2/yr was employed for different drawdowns in the pumped aquifer, i.e., 10, 15 and 20 m, respectively. The results are shown in Fig. 9b. Final settlements were found about 1.0, 1.5 and 2.0 m corresponding to drawdowns of 10, 15 and 20 m, respectively. The 1-D consolidation model may overestimate the final consolidation settlement because it cannot take into account lateral displacement. A correction factor of 0.8 was applied for the Phap Van location; consequently, the final consolidation settlements were determined as 0.8, 1.2 and 1.6 m for the drawdowns mentioned above.



(a) For a drawdown of 10 m (100 kPa) in the pumped aquifer



(b) For a drawdown of 15 m (150 kPa) in the pumped aquifer



(c) For a drawdown of 20 m (200 kPa) in the pumped aquifer

Fig. 10 Land subsidence analyses for Phap Van location, using c_v=5.0 m^2/yr

More details of the second analysis are shown in Fig. 10, in which the dissipation of pore pressure, the change of pore pressure profile and the cumulative compression with time and depth were calculated for the whole soil profile of 30 m which is overlying the pumped aquifer. It is interesting to realize that the cumulative compression of the subsiding soil profile became significantly increased after 10 years since the drawdown occurred in the pumped aquifer. One of explanations for this can be found in Eq. (6), and specifically, when the dissipation of pore pressure reaches a point which would make the effective stress of the analyzed soil layer higher than its preconsolidation pressure, the compression will drastically increase, usually by 5 times more. This fact is well known among soil engineers, but in many land subsidence analyses preformed by hydrogeologists, it is neglected or not well taken into account.

CONCLUSIONS AND RECOMMENDATIONS

1) The points which need to be carefully considered when making any comment on Hanoi's land subsidence are as follows: (i) Manifestation of land subsidence due to groundwater extraction is not yet abundant in and around the city, except at some locations including water plants and well fields; (ii) A number of differential settlements of buildings in Hanoi were caused by inappropriate foundation design and local conditions of weak soils. They do not need to be interpreted as being caused by groundwater extraction; (iii) The alluvial aquifers underneath the city have a good hydraulic connection with the Red River, having its groundwater level being raised in some period of the year. This constitutes a very important advantage for groundwater extraction in Hanoi compared with that in Bangkok; (iv) There is not enough monitoring data of settlement and pore pressure at the moment to support evidence of a developed land subsidence; (v) The consolidation and compression characteristics of the soil layers in Hanoi haven't been investigated enough to make any conclusive statement regarding the weakness of the soil layers overlying the pumped aquifers.

2) The reasons for a likely land subsidence in Hanoi, and hence the need to investigate it, are as follows: (i) Hanoi is among very few cities in the world whose water supply is entirely dependent upon groundwater extraction. Experiences from many other countries, and especially experiences of Bangkok, Thailand have shown that such groundwater pumping would sooner or later lead to the sinking of the city if it is not well managed; (ii) Groundwater is usually extracted from an aquifer located at a depth of 30 to 70 m, which is not that deep; (iii) In large areas around the pumping well fields, groundwater plants etc. piezometric levels in the exploited aquifers have clearly been lowered. If the initial groundwater level was about 1 or 2 m below ground surface, one can estimate that it has been reduced by 15 to 20 m in many locations. An area of about 80 km^2 has more-than-8 m drawdown, in which about 20 km^2 is very strongly affected having more-than-14 m drawdown (K2 1999; Plancenter and HWBC 2000); (iv) Private groundwater wells are on the rise in Hanoi. A recent preliminary inventory showed that these private wells count for about one fourth or more of the total groundwater extraction in Hanoi. A recent inventory done by K2 (Plancenter and HWBC 2000) gave an additional number of 530 wells from factories and hotels, however, this number still did not count the smaller capacity household wells. It is a fact that almost every newly built house in Hanoi, nowadays, includes a private well ranging from 30 to 60 m deep; (v) With the passing time, when groundwater pumping overcomes a certain production limit, say 1 or 1.5 mil. m^3/d, or the groundwater level in the pumped aquifer is more than a certain critical drawdown from the land subsidence point of view, the compression of the overlying confining layer will drastically occur; (vi) The confining layer (consisting of clay, silty clay, mud etc.) overlying the pumped aquifer, as mentioned above, is spread all over the area of Hanoi and is reported to be weak in terms of compression and consolidation properties; (vii) Manifestation of land subsidence, like well protrusion and damage to buildings, are reported to be found in a number locations in Hanoi, especially near locations with groundwater

pumping activity such as Phap Van, Ha Dinh, Mai Dich, The Children's Hospital, Chien Thang Garment Factory etc.

A number of projects related to Hanoi groundwater and land subsidence were carried out during the last 8 years. The most notable things are the land subsidence monitoring network by the Hanoi Northern Hydrogeological Division (K2) and six land subsidence monitoring stations by Hanoi Construction Institute (HIC). However, the investigation of Hanoi's land subsidence is still at a very early stage with few significant monitoring and analysis results. To assure sustainable development of groundwater and infrastructure of the city, more land subsidence investigations should be done. It is also necessary to mention that the geotechnical properties of the soil profiles which are needed for a land subsidence analysis, such as consolidation coefficient, compression and recompression ratios, preconsolidation pressure, overconsolidation ratio are still very little investigated and deciphered.

3) A primary land subsidence analysis on Hanoi's land subsidence was done for the Phap Van location, employing Terzaghi's one-dimensional consolidation model in combination with a bilinear compression model by means of TZP program, developed by Giao (1997). In these analyses, soil parameters were essentially chosen based on the authors' experiences. Three drawdowns of 10, 15 and 20 m in the pumped aquifer at 30 m depth were employed as boundary conditions for consolidation analyses. The influence of coefficient of consolidation was investigated. A coefficient of consolidation of 5 to 10 m^2/y was considered appropriate for Hanoi clays. Soil preconsolidation pressure and overconsolidation ratio were taken into account in the analyses. The analysis results showed clearly that the clay layer overlying the pumped aquifer might undergo significant subsidence. 10, 15 and 20 m drawdowns which correspond to 100, 150 and 200 kPa hydraulic loadings applied at the bottom of the clay layer could have produced a final consolidation settlement up to 0.8, 1.2 and 1.6 m. A correction factor of 0.8 was applied. The 90% consolidation time would depend directly on the value of consolidation, c_v. The analyses found that it would not take too long, just one or two decades, for Hanoi clays to have significant subsidence. Thus, Hanoi groundwater resources at the moment and in the near future should be carefully developed.

4) The investigation on land subsidence for Hanoi in the future is suggested as follows: (i) Step 1, one can collect all available data of geotechnical properties of the soil concerning a consolidation analysis, a map of drawdown in the exploited aquifer is available, some sets of compression measurements at different depth levels in the soil layer overlying the pumped aquifer are available and reliable, the first land subsidence analyses will be carried for calibration; (ii) Step 2, for groundwater development (planning), a database of geotechnical properties for Hanoi subsoil should be built, the consolidation model can be coupled to the groundwater model, and different scenarios of land subsidence can be done besides those of the groundwater modelling. The outcomes will be expected as a series of Hanoi land subsidence maps in function of time and groundwater development.

5) Only the integrated management of groundwater supply could help control and mitigate land subsidence. The conjunctive use of surface water and groundwater for water supply, groundwater legislation, the use of induced recharge and artificial recharge etc. are some of useful tools for management of Hanoi's groundwater development which need to be considered. It is also recommended that a serious survey on groundwater extraction by private wells in Hanoi's be done soon. The groundwater legislation should be well enforced.

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