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1D ANALYSIS OF LAND SUBSIDENCE IN SHANGHAI

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ABSTRACT: Land subsidence in Shanghai is investigated. The subsidence was mainly caused by excessive withdrawal of groundwater and since 1921, the measured subsidence was 2 to 3 m in the central area of the city. One-dimensional (1D) finite element consolidation analyses were conducted to simulate and predict the subsidence at Point-A, eastern part of Shanghai. The analysis result fairly simulated the field measured tendency and it indicates that the compression of the mucky clay layer, the silty clay layer in aquitard I and the third compression layer (aquitard II) contributes about 80% of the total subsidence. Also, it is shown numerically that for consolidation caused by groundwater level drawdown in an aquifer, the final state is a steady state water flow toward the aquifer, and the relative values of hydraulic conductivity of clayey layers above the aquifer have an important effect on calculated amount of settlement. Further, three possible scenarios were assumed for discussing the future subsidence. In the case of maintaining the groundwater level as it was in 2001, the predicted subsidence in 50 years is only about 2 mm. In the case of continuous drawdown of groundwater (1 m/year for aquifer IV and V, 0.5 m/year for aquifers II and III, and 0.2 m/year for aquifer I), in 50 years the predicted subsidence is about 1.25 m. If the groundwater level is recovered to zero elevation in all aquifers in the next 50 years, the predicted amount of heave is about 0.20 m..

Keywords: Land subsidence; groundwater; consolidation; finite element analysis.

INTRODUCTION

Shanghai is located on the deltaic deposit of the Yangtze River. The thickness of the Quaternary deposit is about 300 m (the Shanghai Geology Office, 1976; 1979). Excessive pumping of groundwater caused the compression of the Quaternary deposit and subsidence in Shanghai. In Shanghai the monitoring of land subsidence was started in 1921, and up to the present, the recorded cumulative subsidence has been 2 to 3 m in the central area of Shanghai. This subsidence has caused several problems. The most noticeable problem is the increase in the possibility of flooding. From 1981 to 1994, rainfall flooding occurred 22 times, at a rate of almost twice per year (Liu, 2001). The possibility of tidal flooding increased also. From 1956, the height of the dike along the coast line was increased 4 times with the crest elevation rising from 5.0 m to 6.8 m. Other problems caused by the land subsidence are damage to the sewerage system, roads, buildings, and subway tunnels, etc.

After 1965, due to strict control of groundwater pumping, the rate of subsidence substantially reduced and slight rebound was observed in some areas. However, there has been a tendency of increase in the rate of subsidence after 1990, and land subsidence has become a social problem in Shanghai again. There are questions such as what will happen in the future? What will be the maximum subsidence? In this paper, firstly the history of land subsidence in Shanghai and its relation with the amount of groundwater withdraw is discussed briefly. Then for a selected point, point-A at eastern part of Shanghai, with relatively detailed information about soil profile, groundwater level variation and settlement records are simulated by one-dimensional (1D) finite element analyses. Finally, the future tendency and possible amount of the subsidence is investigated by three assumed scenarios.

A BRIEF DESCRIPTION OF LAND SUBSIDENCE IN SHANGHAI

The Quaternary deposit in Shanghai consists of five aquifers separated by 5 clayey layers (aquitards). Based on the data reported by the Shanghai Geology Office (1976; 1979), an illustrative soil profile with some available physical and mechanical properties is given in

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Note: Discussion on this paper is open until December 2005

Fig. 1 (after Chai et al. 2003). The values of hydraulic conductivity given in Fig. 1 are the recommended reference values by the Shanghai Construction and Management Commission (2002) for site investigation in Shanghai. The detailed description on the properties of each aquifer and aquitard can be found from Chai et al. (2003).

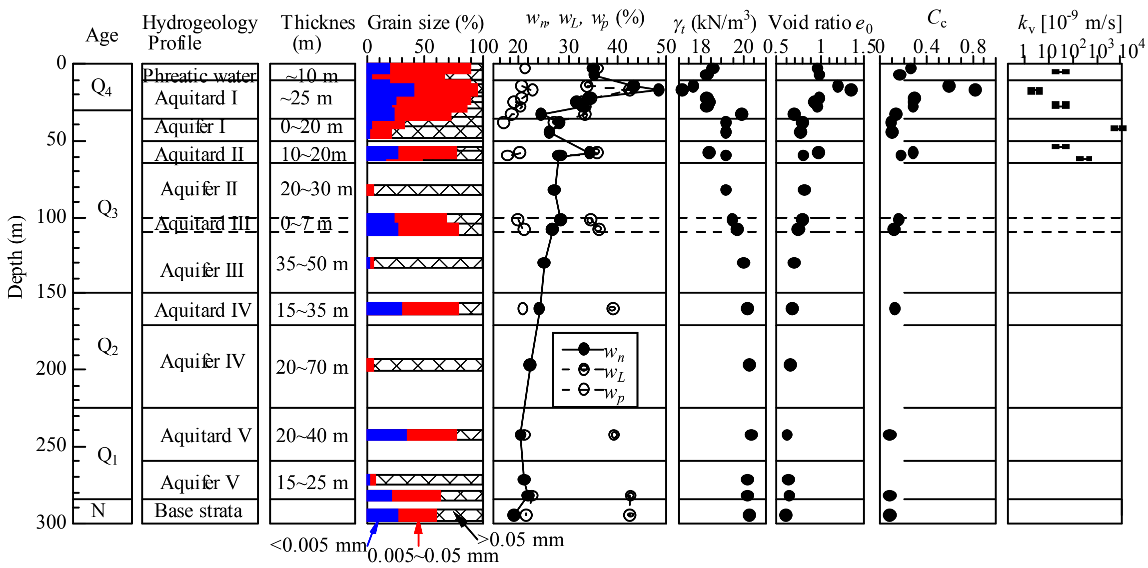

Fig. 1 An illustrative soil profile at Shanghai (after Chai et al. 2003)

Figure 2 (after Chai et al. 2003) shows the surface settlement curves for some benchmarks at the center of Shanghai. The locations of the benchmarks are shown in Fig. 3. Figure 4 (after Chai et al. 2003) gives the amount of groundwater pumped and recharged from 1961 to 2001. Before 1965, the settlement rate was high but after 1965, the settlement rate was reduced dramatically. Comparing Fig. 2 with Fig. 4, it can be seen that the dramatic reduction of the settlement rate corresponds with a significant reduction of the groundwater pumping rate.

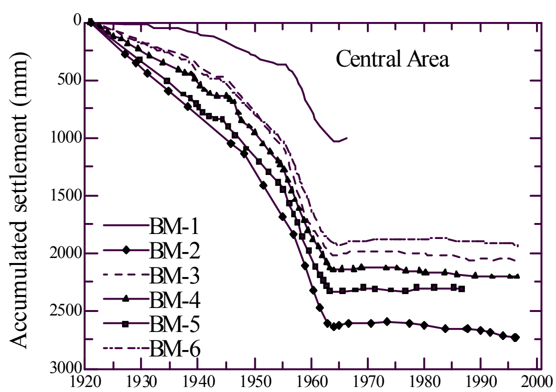

Fig. 2 Subsidence curves of some benchmarks in the center area of Shanghai (after Chai et al. 2003)

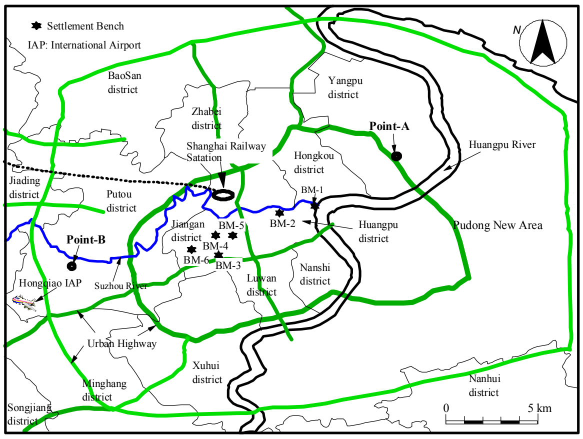

Fig. 3 Location of monitoring points

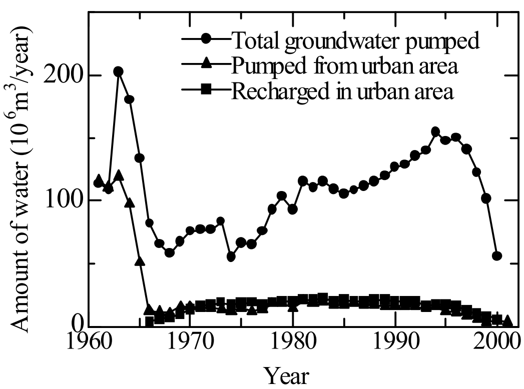

Fig. 4. Amount of groundwater pumped and recharged (after Chai et al. 2003)

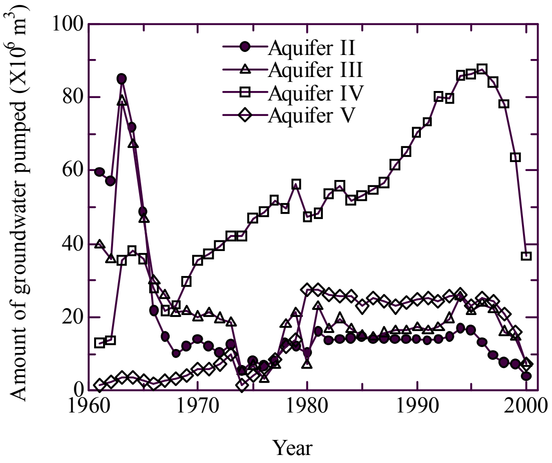

Fig. 5 The amount of groundwater pumped from each aquifer (after Chai et al. 2003)

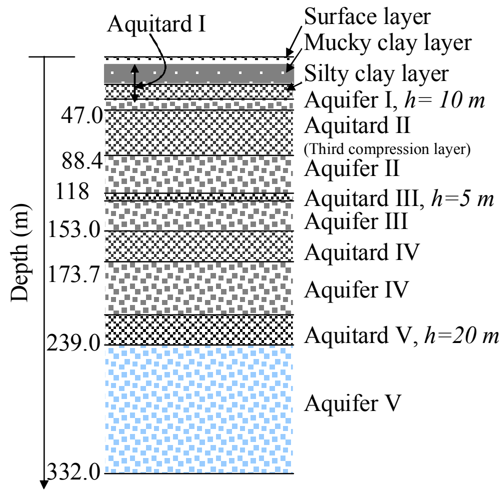

Fig. 6 Cross-section at Point-A

Figure 5 (after Chai et al. 2003) shows the amount of groundwater pumped from each aquifer in Shanghai area. Before 1965, the groundwater was mainly pumped from aquifers II and III. After that time the groundwater pumping locations were shifted to aquifers IV and V reasoning that the compressibility of the lower soil layers is lower than the upper layers. This variation of the amount of groundwater pumped from each aquifer resulted in the change of groundwater level in each aquifer (details will be discussed in the next section).

SIMULATION AND PREDICTION

Analysis Model and Parameters

The settlement induced by the excessive pumping of groundwater is a three-dimensional (3D) problem. However, to conduct a 3D analysis, one of the important factors is to define a proper hydraulic boundary condition. Normally this is a difficult task. As described previously, for some points, the water level and the compression of each stratum were measured. A 1D analysis can be conducted by specifying the water level in each aquifer and simulating the consolidation process. Then the interaction between aquifers and the distribution of pore water pressure in each aquitard can be analyzed numerically with a verified numerical procedure and parameters (including the stress state in the ground). The possible future subsidence under some assumed scenarios can be evaluated. Point-A at the eastern part of Shanghai was selected for the simulation and its geological strata are shown in Fig. 6. The values of the thickness of aquifer I, aquitard III and V are not available and they were assumed referring to the report of the Shanghai Geology Office (1976). The 1D finite element mesh and boundary conditions are shown in Fig. 7. The locations for defining the pore water pressure (based on the field measurements) are also indicated in the figure. The foundation soil was represented by 8-node quadrilateral elements with 9 integration points. Finite element program used was CRISP-AIT (Chai, 1992), which was modified version of original CRISP program (Britto and Gun, 1987). Also, substepping technique proposed by Sloan (1987) was used to obtain a better integration of the elasto-plastic stress/strain relationship.

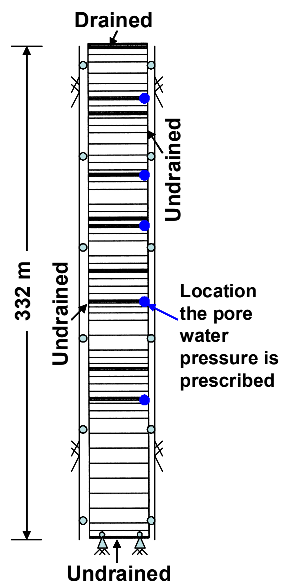

Fig. 7 Mesh and boundary conditions

To set up the initial conditions and soil parameters, the following assumptions and methods were adopted.

(*a*) Initial conditions. The phreatic level is 1.0 m below the ground surface. The ground elevation at Point-A is about 3.0 m, and therefore, the elevation of phreatic surface is about 2.0 m. It was assumed that at 1921, the water pressure in each aquifer was the same as the static water pressure, and only the surface layer was in an over-consolidated state with an over-consolidation ratio (OCR) of 2 to 4, and all other layers were in a normally consolidated state before groundwater drawdown.

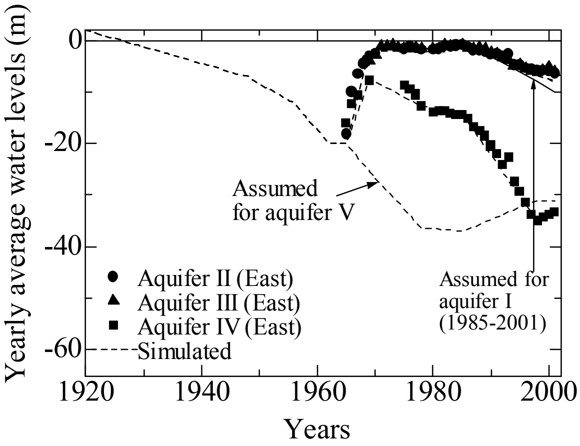

Fig. 8 Yearly average groundwater level variations at Point-A

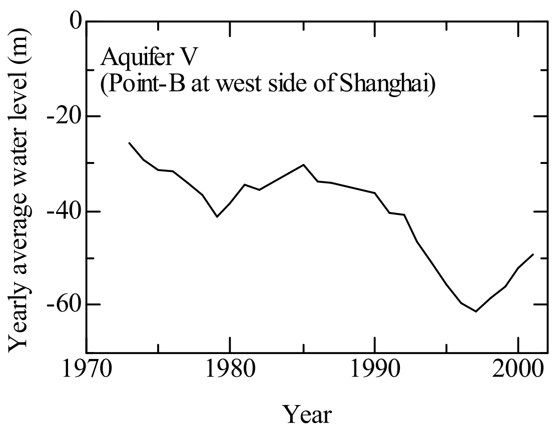

Fig. 9 Yearly average groundwater level variations of aquifer V at Point-B

(*b*) Water level variation in aquifers. At Point-A, the available measured data on water level variation in the aquifers were from 1965 (solid dots in Fig. 8). However, the earliest recorded groundwater level is from 1962 (The Shanghai Geology Office 1976), and from 1962 to 1965 there were not much change on groundwater level. For defining the water level variation at Point-A from 1921 to 1964, it was assumed that this period can be subdivided into four sub-periods, namely sub-period-1 of 1921 to 1948, sub-period-2 of 1949 to 1956, sub-period-3 of 1957 to 1962, and sub-period-4 of 1963 to 1964. Considering the characteristics of settlement curves, it was assumed that the groundwater level drawdown rate in sub-period-2 was two times of that in sub-period-1, and in sub-period-3 it was two times of that in sub-period-2 (four times of the sub-period-1). In sub-period-4, there was no groundwater level change. After 1965, the measured data were used for aquifer II, III, and IV. For aquifer V at Point-A, the values were assumed by referring the measured data at Point-B (see Fig. 3 for location) as shown in Fig. 9 as well as the characteristics of measured compression of aquifer V. There are no data available for aquifer I. Before 1985, it was not specified and after 1985, it was assumed in such a way to have a better simulation on the compression of the upper soil layers. The variation of groundwater in a year was not modeled and only the yearly average values were used in simulation (dash lines in Fig. 8).

(*c*) Hydraulic conductivity (k_v) of each layer. There are no data available about k_v of each layer at Point-A. Aquifer I is a fine sand layer and a k_v value of about 9×10^{-6} m/s has been suggested by The Shanghai Construction and Management Commission (2002). For aquifers II to V (coarse sand layers), a value of 10^{-4} m/s was assumed. Within 50 m depth, the suggested average k_v values are 3×10^{-9} m/s for the mucky clay and 3.5×10^{-8} m/s for the silty clay as indicated in Fig. 1 (data from the Shanghai Construction and Management Commission, 2002). Test data for deeper aquitards are not available. The k_v values of the lower aquitards were calculated from the k_v values of aquitard I for the corresponding silty clay and mucky clay by using Taylor's equation (1948).

$$k = k_0 \cdot 10^{-(e_0 - e)/C_k} \quad (1)$$

where k_0 is initial hydraulic conductivity, e_o is initial void ratio, k is current hydraulic conductivity, e is current void ratio, and C_k is a constant (C_k =0.5e_0, Tavenas *et al*, 1986). In Eq. (1), using the void ratio of aquitard I as e_0 and the corresponding hydraulic conductivity as k_0, and the void ratio of the lower aquitard layers as e, then the corresponding k value were estimated. For the stiff clay layers (aquitards II to V), the value of silty clay layer of aquifer I was used as k_0 in Eq. (1). During the process of consolidation, the k_v value of each soil layer varies with e according to Eq. (1).

(*d*) Constitutive models used. The aquitards were represented by the modified Cam Clay model (Roscoe and Burland, 1968) and the aquifers by elastic model. For aquitards, it was assumed that the slope of unloading-reloading line in e-lnp' plot (p' is effective mean stress), κ, is 1/10 of the slope of virgin loading line, λ ($0.434C_c$, C_c is compression index). The strength parameter M was 1.2. Poisson's ratio, ν, was assumed to be 0.3. To estimate the Young's modula of aquifers, the following relationship (Nakai, 1989) was used.

$$e = e_c - C(\frac{\sigma_v'}{p_a})^{0.3} \tag{2}$$

where e_c and C are constants, p_a is atmospheric pressure, and σ_v' is effective vertical compression stress under 1D condition. From this equation, the constrained modulus D can be expressed as follows:

$$D = \frac{(1+e)p_a}{0.3C}(\frac{\sigma_v'}{p_a})^{0.7} \tag{3}$$

In Japan, there is a method to estimate Young's modulus (E) from standard penetration test (SPT) N value. The equation proposed by Japan Railway is as the follows (Japanese Geotechnical Society, 1992).

$$E = 25 p_a N \tag{4}$$

For a sand layer at about 20 m depth, an N value of about 10 can be roughly estimated, which corresponds to a E value of about 25 MPa (Eq. (4)). For soil deposit in Shanghai, at 20 m depth, the effective vertical stress will be about 150 kPa. Then, using a void ratio of 0.75 and a Poisson's ratio of 0.25, the value of C in Eq. (3) can be estimated as 0.0258. The adopted initial parameters are summarized in Table 1. For sand layers, it is further assumed that (a) the unloading-reloading modulus is 3 times of the virgin loading one and (b) the virgin loading modulus varies with the effective compression stress as quantified by Eq. (3).

Table 1 Model parameters used in 1D consolidation analysis

Layers	Depth (m)	E (kPa)	ν	κ	λ	M	e_0	γ (kN/m^3)	k_v (10^{-8}m/s)
Surface layer	0-2.0		0.3	0.008	0.08	1.2	1.0	18.5	5
Aquitard I	2.0-20.0		0.3	0.028	0.28	1.2	1.2	17.7	0.3
	20.0-37.0			0.013	0.13	1.2	0.9	18.8	3.5
Aquifer I	37.0-47.0	51,300	0.25	-	-	-	0.78	19.2	1200
Aquitard II	47.0-88.4		0.3	0.009	0.09	1.2	0.85	18.8	2.71
Aquifer II	88.4-118.0	101,300	0.25	-	-	-	0.82	19.2	10000
Aquitard III	118.0-123.0		0.3	0.006	0.06	1.2	0.78	19.6	1.91
Aquifer III	123.0-153.0	116,500	0.25	-	-	-	0.71	20.0	10000
Aquitard IV	153.0-173.7		0.3	0.006	0.06	1.2	0.68	20.2	1.14
Aquifer IV	173.7-239.0	159,500	0.25	-	-	-	0.66	20.3	10000
Aquitard V	239.0-259.0		0.3	0.004	0.04	1.2	0.62	20.4	0.84
Aquifer V	259.0-332.0	201,300	0.25	-	-	-	0.64	20.2	10000

Note: E, Young's modulus; ν, Poisson's ratio; λ, slope of consolidation line in e:lnp' plot; κ, slope of unloading-reloading line in e:lnp' plot; M, slope of critical state line in q:p' plot (q is deviator stress); e_0, initial void ratio; γ, unit weight; and k_v, hydraulic conductivity in vertical direction.

Simulated Results

Figure 10 compares the simulated settlement variation in some selected depths at Point-A. The simulated surface settlement curve has a similar shape as the measured settlement curves as shown in Fig. 2. The amount of total settlement is also in the range of the measured data. The most compression occurred in top 88.4 m thick layer, i.e. above aquifer II. The comparison of the measured and simulated compression of each soil stratum is given in Fig. 11 for the data from 1965 to 2001. Generally, the simulation fairly matches the tendency of the measured data. However, for aquifers II and III and aquitard II, the simulated amount of heave is larger than measured value and for aquifer V is smaller than the measured value. It is possible that aquifer V acted more elastically and the upper soil layers acted less elastically (more plastic deformation) than what had been considered in the numerical models. Another point is that for the soil layers above 47 m depth, there is some delay on simulated compressions in comparison with the measurements. A possible explanation is that the adopted

k_v values are less than the field values. Since the recorded data on groundwater level is from 1962, it is assumed in the analysis that at 1962 the groundwater elevation reached its lowest level in 1960s. There also is a possible scenario that the groundwater level was at its lowest level before 1962.

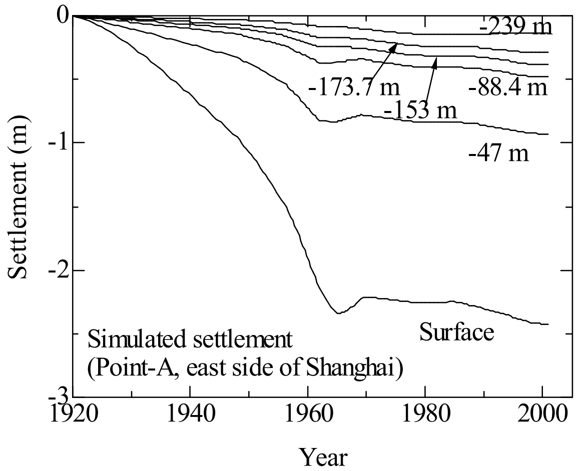

Fig. 10 Simulated settlement curves at Point-A

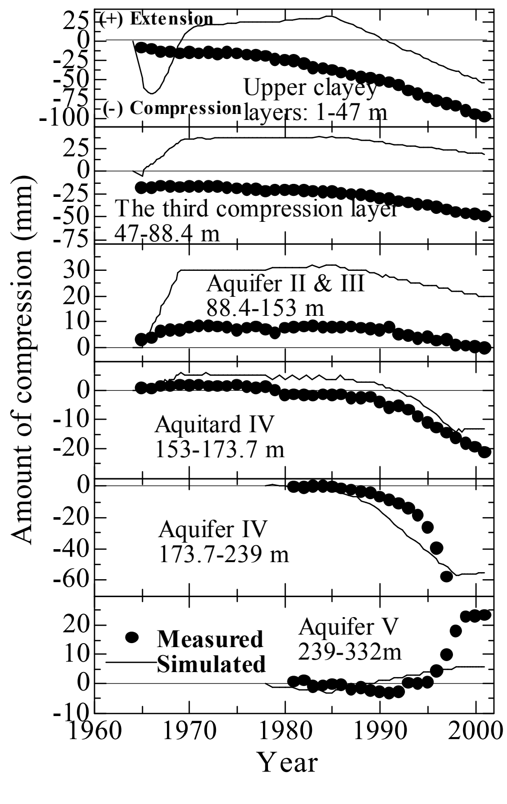

Fig. 11 Comparison of the compression of each layer at Point-A

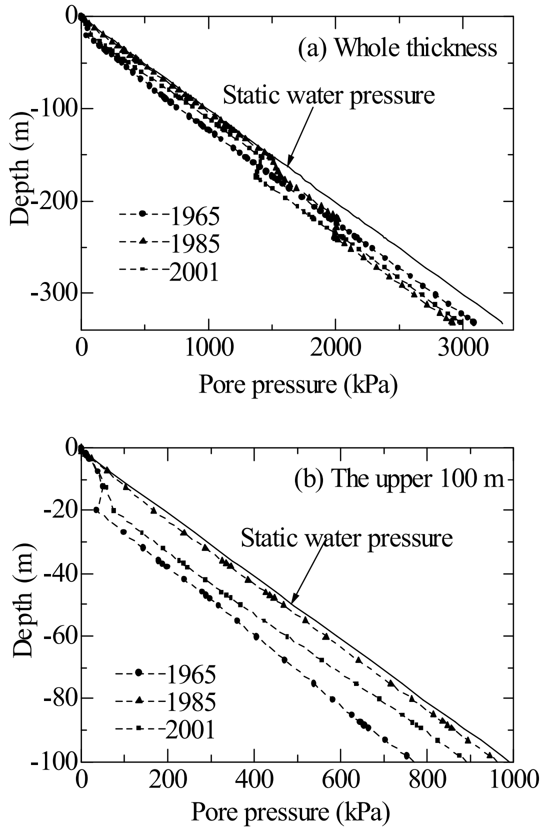

Fig. 12 Pore water pressure distributions (Point-A)

The simulated pore water pressure distributions at some given times are shown in Figs. 12(a) and (b). At 1965, except the surface and the mucky clay layers (about 0-20 m depth), the water pressure drawdown was almost the same for all layers. At 1985, the pore water pressure in the upper soil layers was recovered close to the static hydraulic water pressure line, but in the lower layers, further drawdown occurred. At 2001, comparing with the situation of 1985, there was water pressure drawdown again in the ground except for aquifer V. However, as shown in Fig. 12(b), in the upper clayey layers, the water pressure is still higher than that of 1965. Therefore, during this period the compression of the upper soil layers was the re-compression. But for aquifer IV, it was virgin compression.

Discussion on the Effect of the Relative k_v Value of Aquitards

Chai et al. (2003) discussed the mechanism of land subsidence caused by groundwater drawdown in aquifer. It has been explained that the final state is a steady water flow from the ground surface to the aquifer. If the deposit above the aquifer is layered, to satisfy the flow continuity condition, for a given amount of groundwater level drawdown in the aquifer, the relative values of hydraulic conductivity of soil layers above the aquifer play an important role on the amount of settlement. To illustrate this factor, the following two discussion cases were assumed.

(a) D-case-1. The k_v values of the third compression layer (aquitard II) and the silty clay layer in aquitard I were reduced 10 times to the values close to that of the mucky clay layer. The order of these layers is shown in Fig. 6 (from ground surface, the mucky clay layer, the silty clay layer and the third compression layer).

(b) D-case-2. The k_v value of the mucky clay layer was increased 10 times to a value close to that of underlain silty clay layer.

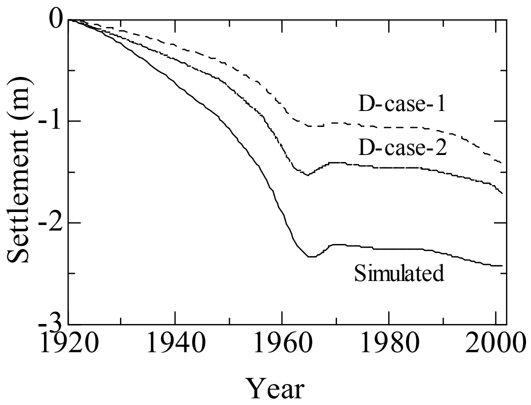

Fig. 13 Comparing the surface settlement curves of discussion cases

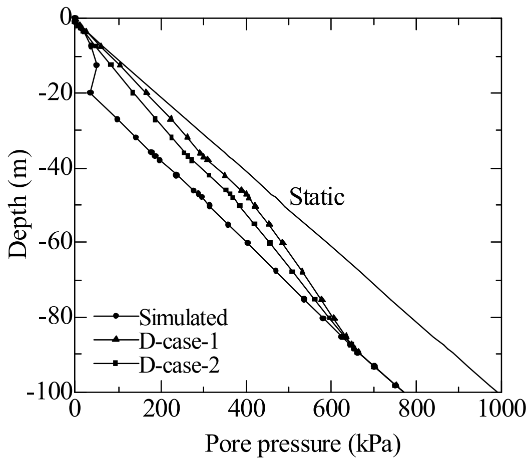

Fig. 14 Pore water pressure distribution of discussion cases

The simulated surface settlement curves are compared in Fig. 13. The both assumed cases resulted in a less settlement than the original simulated. To explain this phenomenon, the pore water pressure distributions within 100 m depth at 1965 are compared in Fig. 14. It is worth to remind that the water pressure drawdown was defined below the third compression layer, and at the ground surface, the excess pore pressure was defined as zero. With this condition, there will be water flow from the ground surface toward the aquifer II. For the original simulated condition, the k_v value of the mucky clay layer is lower than the underlain silty clay layer and the third compression layer. To satisfy the continuity condition of water flow, the hydraulic gradient in the mucky clay layer is much higher than that in underlain layers, which resulted in more pore water pressure drawdown in soil strata below the mucky clay layer. For both D-case-1 and D-case-2, the relative difference of k_v values of the mucky clay layer, the silty clay layer in aquitard I and the third compression layer (aquitard II) is reduced and the hydraulic gradient in these clay layers is almost the same (close to linear variation of pore pressure within these layers) and less effective stress increment in the silty clay layer and the third compression layer, which yielded less settlement. However, the initial k_v values of D-case-1 are 10 times less than that of D-case-2. The consolidation (settlement) process of D-case-1 is slower than D-case-2. Furthermore, k_v value was varied during consolidation also. In the third compression layer, a thin layer adjacent to aquifer II consolidated first and formed a lower k_v value "shell". The effect of this "shell" further reduced the effective stress increment within the layers above it. The higher settlement rate after 1990 for D-case-1 and D-case-2 than the original simulated one (Fig. 13) is caused by the defined pore water pressure drawdown in aquifer I, which caused more compression increment of the upper soil layers for D-case-1 and D-case-2 than the original simulated case.

Prediction of Future Subsidence

Three possible scenarios regarding groundwater level variation in future were assumed as the follows.

(*a*) P-case-1. Keep the groundwater level at the condition recorded in 2001.

(*b*) P-case-2. Groundwater level will be continuously lowered. Considering the groundwater level variation in recent years, it was arbitrarily assumed that within next 50 years, for aquifer IV and V, the groundwater drawdown is 1 m/year (total 50 m), for aquifer II and III, 0.5 m/year (totally 25 m), and for aquifer I, 0.2 m/year (total 10 m).

(*c*) P-case-3. The groundwater level recovers to zero elevation for all aquifers, which is still 2 m below the assumed phreatic water level.

Figure 15 shows the predicted surface settlement curves. For P-case-1, the settlement increment is about 2 mm, which indicates that the delayed settlement is small at year 2001. The amount of groundwater pumped in 2000 was about 100×10^6 m^3 and in 2001 it was about

50×10^6 m^3. At point-A, within these two years the groundwater level was not changed much with slight reduction in aquifer II and III and slight recovering in aquifer IV (Fig. 8). Another factor is that from 1965 to 1975, the yearly amount of groundwater pumped was about 60×10^6 m^3 and resulted in a groundwater level recovering. Therefore, the yearly balanced amount of groundwater in Shanghai area is from 60×10^6 m^3 to 100×10^6 m^3. However, groundwater level is influenced by the surrounding area also, which should be considered in making groundwater pumping plan. For P-case-2, the settlement increment is about 1.25 m. It can be seen that there is an increased settlement rate and especially after about 25 years. As discussed previously, at year 2001, the pore water pressure within the highly compressible layers (above 100 m depth) was still higher than that at 1965. The continuous pore water pressure decrease gradually brings the compressible layers from an over consolidated state to a normally consolidated state and result in an increased rate of settlement. In case of P-case-3, the predicted amount of heave is about 0.2 m. Before obtaining more data regarding the reloading behavior of the soil strata, no comment can be made on the reliability of this value.

The predicted pore water pressure distributions at year 2050 for the three assumed scenarios are shown in Fig. 16. For P-case-1 and P-case-2, there will be groundwater flow from aquifer III to aquifer IV. It is worth to mention that even P-case-2 is not an extreme worst condition. The extreme worst condition is that at the top of each aquifer the pore water pressure becomes zero. Therefore, if the groundwater levels continuously drawdown, a large subsidence can occur.

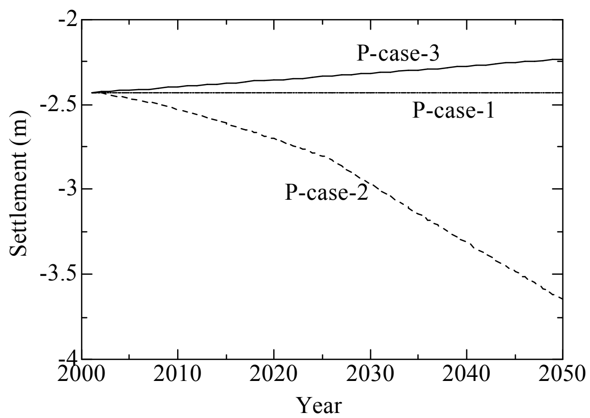

Fig. 15 Predicted ground surface settlement in future

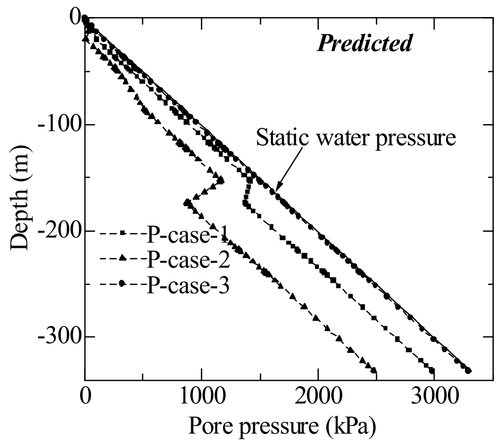

Fig. 16 Pore water pressure distributions for three assumed cases

SUMMARY AND CONCLUSIONS

The land subsidence in Shanghai was investigated based on the field measured data as well as the numerical analysis results. The main points are as follows.

(*a*) Excessive pumping groundwater is the main reason causing the land subsidence in Shanghai. From 1921, the measured accumulated amount of subsidence is 2 to 3 m in the center area of Shanghai. The field data show that there is a strong correlation between the rate of net groundwater pumping and the rate of land subsidence.

(*b*) Point-A at eastern part of Shanghai was analyzed by 1D finite element consolidation analysis. In the analysis, the groundwater drawdown in each aquifer was defined using the field measured data. Then, the compression of each layer was calculated and compared with the measured data. The analysis results indicate that the compression of the mucky clay layer, the silty clay layer in aquitard I and the third compression layer (aquitard II) contributes about 80% of the total subsidence.

(c) For a given amount of pore water pressure decrease in an aquifer, the effect of the relative values of hydraulic conductivity of the soil layers above the aquifer on the amount of subsidence is investigated numerically. If a lower (or lowest) hydraulic conductivity layer is located just above the aquifer, the settlement will be smaller than the case that the lower (or lowest) hydraulic conductivity layer is at ground surface.

(*d*) Three possible scenarios were assumed to investigate the future subsidence. In the case of maintaining the groundwater level as it was in 2001 (P-case-1), the subsidence after 50 years is only 2 mm, which indicates that the delayed subsidence was small in 2001. In the case of continually drawdown of groundwater (1 m/year for aquifer IV and V, 0.5 m/year for aquifer II and III, and 0.2 m/year for aquifer I), the subsidence in 50 years is about 1.25 m (P-case-2). If the groundwater level is recovered to zero elevation in all aquifers within the next 50 years, the predicted amount of heave is 0.2 m (P-case-3). These numbers can serve as reference for making groundwater-pumping plan.

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