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LAND SUBSIDENCE DUE TO WITHDRAWAL OF DEEP-GROUNDWATER

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ABSTRACT: This paper presents a case history of land subsidence due to withdrawal of groundwater from deep marine sediments at the mid-northern part of Boso Peninsula, Chiba, Japan. Since 1969, subsidence has been observed in a large area. The maximum accumulative subsidence in the past 33 years has been about 0.85 m. In order to obtain overall information, 3D FEM analysis was conducted to calculate the land subsidence resulting from extraction of deep-ground water. The calculation method is based on the theory of groundwater flow through saturated and unsaturated media. This is an uncoupled approach for consolidation analysis. The compressibility of ground is considered in the calculation. In the calculation, the behavior of hydraulic conductivity and the compressibility of reservoir rock (Plio-Pleistocene sediments) under high pressure were determined by laboratory odometer tests and take into consideration. The analytical results were compared with the field-observed data. The results showed that this approach simulated the field case fairly well.

INTRODUCTION

Effective stress changes in the soft ground cause consolidation of sediments. Human activities such as reclamation, underground structure construction, construction of embankment, and withdrawal of groundwater, etc. will cause effective stress changes in the ground. In the prediction of settlement caused by consolidation, some cases, such as those of embankment and tunnel construction, can be simplified into a two-dimensional problem. In engineering practice, most of the cases are three-dimensional. In predicting the land subsidence resulting from withdrawal of groundwater, because groundwater withdrawal usually occurs over a large area, one-dimensional consolidation analysis has been generally adopted. However, it is difficult to predict the subsidence of a large general area and its surroundings (Nishigaki et al. 2002). Table 1 tabulates some of the approaches for prediction of consolidation (Nishigaki 2002). As seen in Table 1, the 1D analytical solution can only be applied to extremely simple problems; 2D axi-symmetric analysis is difficult to apply to the problems involving a large area; because there is greater freedom of each node for a large area and a deep groundwater extraction problem, 3D-coupled elasto-plastic analysis requires a large computer memory and a long calculation time. Therefore, a more simple approach in 3D was developed in order to analyze the land subsidence resulting from extraction of groundwater, and especially from that of deep-groundwater (Nishigaki et al. 2002; Shen et al. 2003). This paper discusses the application of the simple approach to analyze land subsidence in 3D based on groundwater flow theory proposed by Nishigaki et al. (2002). First, the calculation approach is briefly introduced. Then a state-of-the-art water-dissolved natural gas field in South Kanto, Japan, is presented (Horiguchi, 1998; Takeuchi et al. 2001). Finally, the method was applied to the field case. The results show that the approach proposed by Nishigaki et al. (2002) can predict the land subsidence resulting from withdrawal of deep-groundwater fairly well.

Table 1 Prediction approaches in consolidation analysis (after Nishigaki 2002)

Approaches	Merit and demerit
Strict analytical solution	Solve only the extremely simple problems
2D Axi-symetric analysis	Difficult to apply to the large area problem in practice
3D coupled elasto-plastic analysis	Many unknown parameters and need large computer memory and calculation time.

OUTLINE OF SOUTH KANTO GAS FIELD

The South Kanto gas field produces natural gas dissolved in water. Figure 1 shows the location of the gas

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Note: Discussion on this paper is open until December 2004

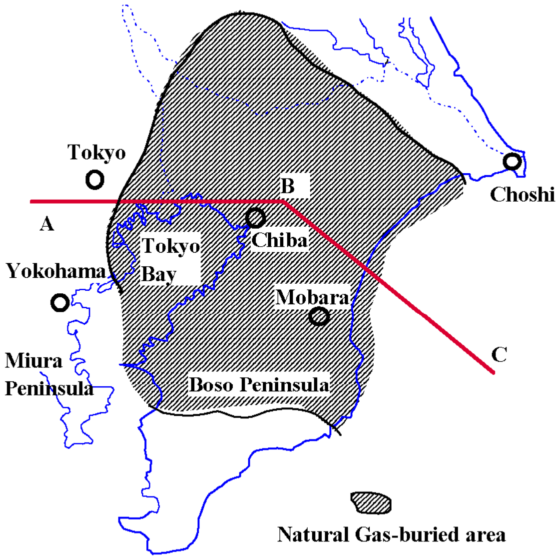


Fig. 1 Natural gas buried area in South Kanto (after Mitsunashi et al. 1980)

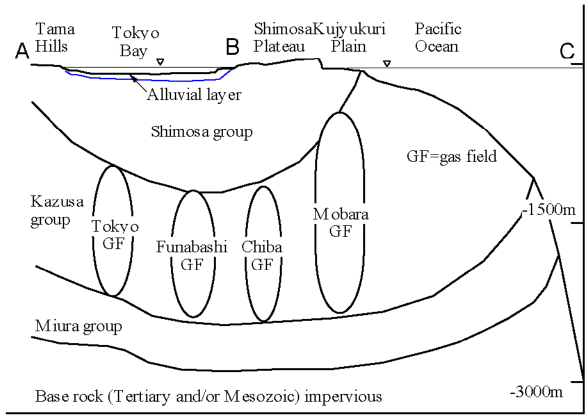


Fig. 2 Sectional view of south Kanto gas field

field. The total area of this gas field is about 4300 km^2 including the majority of the Boso Peninsula in Chiba Prefecture, Japan (Horiguchi 1998). The amount produced by this field is more than 90% of the total dissolved-in-water type natural gas produced in Japan. Gas-dissolved brine contains a high concentration of iodine, which is purified for medical and industrial uses. The amount of iodine produced from Chiba Prefecture is about 40% of the world production. A sectional view of the gas reservoir is plotted in Fig. 2. As shown in the figure, gas-dissolved brine water is included in the Kazusa Group, the Plio-Pleistocene sediments, according to geological classification. This group distributes in the middle and north part of Boso Peninsula, the north part of the Miura Peninsula, and the Tama Hills area, as shown in Fig. 1. Thus, it includes the Tokyo gas field, Funabashi gas field, Chiba gas field, and Mobara gas field (Mitsunashi 1980).

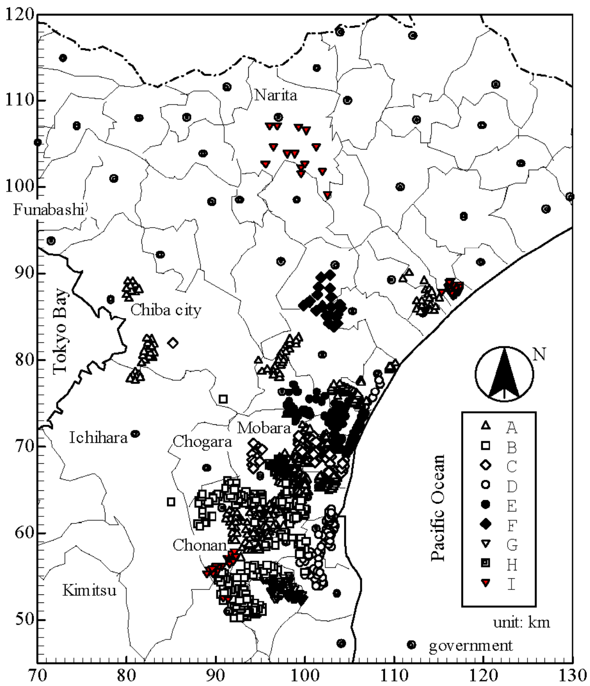


Fig. 3 Distribution of deep wells in the mid-northern part of Boso Peninsula

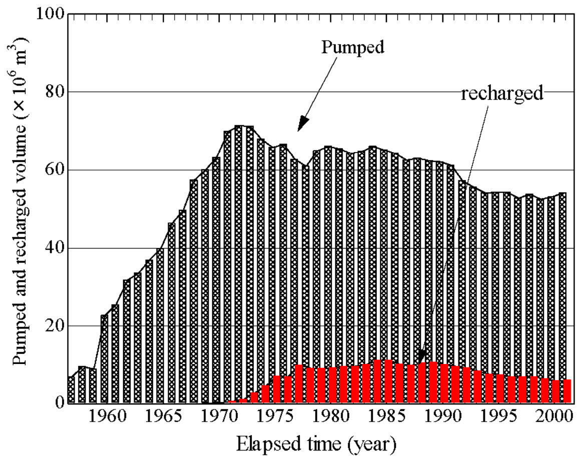


Fig. 4 Total pumped groundwater volume and recharged volume

All of these gas fields have been in production since the mid 1950s. However, since a serious subsidence issue arose in the Tokyo and Funabashi gas fields, these two gas fields ceased production in the early 1970s (Horiguchi, 1998). In the Chiba gas field only fewer wells are remained Awkward. Do you mean “only a few wells remain”?. Kujyukuri plain became the main production area. However, the volume of pumped brackish water was controlled within a moderate range, with the intention of having less impact on the underground environment and causing less subsidence. More than 1400 deep-wells have been excavated since mid-1950s in the Boso Peninsula. The distribution of the deep-wells is plotted in Fig. 3. The depth of the wells is from 500 m to 2400 m (Horiguchi, 1998). Fig. 4 shows the groundwater pumped and recharged in the Kujyukuri and Chiba areas. The amount peaked in 1971. Once large land subsidence was found, the pumped volume was decreased.

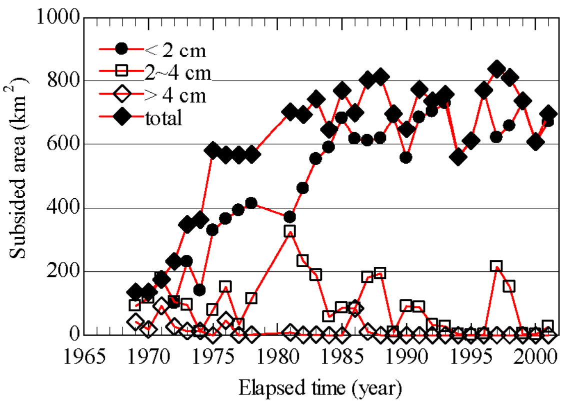


Fig. 5 Subsided area in Boso Peninsula versus time (Environmental Division, 2002)

FIELD INVESTIGATION OF LAND SUBSIDENCE

Field investigation of land subsidence resulting from withdrawal of deep-groundwater began at the end of the 1960s (Environmental Division 1970-2002). Figure 5 presents the variation in subsided area in Chiba prefecture since 1969. As shown in this figure, the subsided area before 1970 was about 160 km^2. From 1970 to 1974, the total subsided area gradually increased to 600 km^2. After 1980, the subsided area varied between 600 and 800 km^2. As can be seen in this figure, before 1984 the area with subsidence of more than 2 cm represented about one-third of the total subsided area. After 1984, subsidence over the majority of the subsided area was less than 2 cm per year. Figure 6 plots the measured subsidence in Boso Peninsula in 2001 (Environmental Division 2002). The subsided regions were concentrated on the Kujyukuri Plain, in the eastern portion of the peninsula. The maximum subsidence was 3.2 cm at Mobara city, where wells with the heaviest production were allocated (**see Fig. 3**). In the western coastal part of the peninsula, no subsidence was found in 2001. Figure 7 gives the value of accumulated subsidence at the measured points since 1969.

ANALYTICAL METHOD

The basic equation for 3D groundwater flow in saturated and unsaturated media is expressed as the following equation (Nishigaki et al. 2002; Nishigaki 2002):

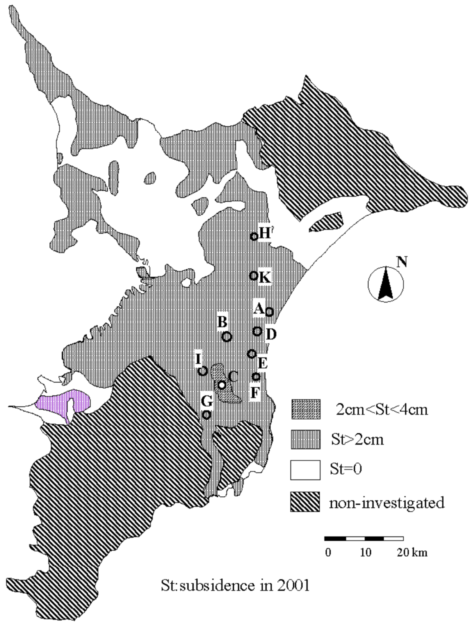


Fig. 6. Subsided area in 2001 in Chiba Prefecture (Environmental Division, 2002)

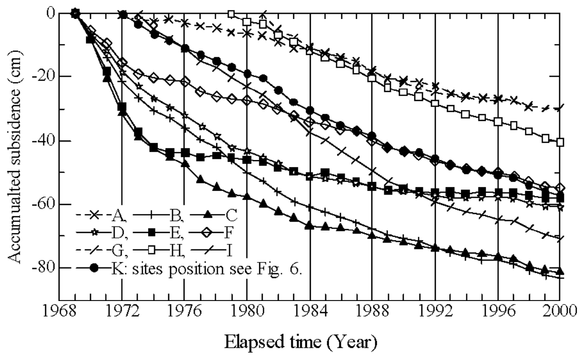


Fig. 7 Accumulated subsidence of some measured places at Kujyukuri Plain versus time since 1969 (Environmental Division, 1970-2002)

$$\frac{\partial}{\partial x}\left(K_r\left(K_{xx}{}^{s}\frac{\partial\psi}{\partial x}+K_{xy}{}^{s}\frac{\partial\psi}{\partial y}+K_{xz}{}^{s}\left(\frac{\partial\psi}{\partial z}+1\right)\right)\right)$$
$$+\frac{\partial}{\partial y}\left(K_r\left(K_{yx}{}^{s}\frac{\partial\psi}{\partial x}+K_{yy}{}^{s}\frac{\partial\psi}{\partial y}+K_{yz}{}^{s}\left(\frac{\partial\psi}{\partial z}+1\right)\right)\right)$$
$$+\frac{\partial}{\partial z}\left(K_r\left(K_{zx}{}^{s}\frac{\partial\psi}{\partial x}+K_{zy}{}^{s}\frac{\partial\psi}{\partial y}+K_{zz}{}^{s}\left(\frac{\partial\psi}{\partial z}+1\right)\right)\right)-q=(\beta S_s+C)\frac{\partial\psi}{\partial t} \quad (1)$$

where k=hydraulic conductivity, ψ=hydraulic head, q=external flux, S_s=coefficient of specific storage, C=specific water content, and β=0 for unsaturated area or 1 for saturated area.

Because the coefficient of specific storage S_s denotes the porosity change resulting from variation of the hydraulic head as expressed in the following expression.Awkward. This is not a complete sentence.

$$S_s = \frac{\partial n}{\partial h} \tag{2}$$

where n=porosity and h=hydraulic head.

Variation of porosity can also be denoted with the effective stress change, as:

$$\frac{\partial n}{\partial h} = \frac{\partial n}{\partial \sigma'}\frac{\partial \sigma'}{\partial h} \tag{3}$$

where σ'=effective stress.

The coefficient of volume compressibility for one-dimensional compression, m_v, is defined as following expression:

$$m_v = \frac{\partial \varepsilon_v}{\partial \sigma'} \tag{4}$$

where ε_v=volumetric strain.

By considering the small strain behavior, that is, $\partial \varepsilon_v = -\partial n$, we can obtain

$$-\frac{\partial n}{\partial \sigma'} = m_v \tag{5}$$

Because $e = \dfrac{n}{1-n}$, we obtain

$$m_v = \frac{1}{1+e}\frac{\partial e}{\partial \sigma'} \tag{6}$$

where e=void ratio.

If we assume that the slope of the e-logσ' curve is C', then

$$C' = -\frac{\partial e}{\partial(\log_{10}\sigma')} = -\frac{\partial e}{\partial \sigma'}\frac{\partial \sigma'}{\partial(\ln \sigma')}\frac{\partial(\ln \sigma')}{\partial(\log_{10}\sigma')} = -2.303\sigma'\frac{\partial e}{\partial \sigma'} \tag{7}$$

Hence, from Eqs. 5 and 6 together with Eq. 7,

$$\frac{\partial n}{\partial \sigma'} = -\frac{1}{1+e_0}\frac{C'}{\sigma'}\frac{1}{2.303} \tag{8}$$

$\partial \sigma' = -\gamma_w \partial \psi$, $h=\psi$, then,

$$\frac{\partial \sigma'}{\partial h} = -\gamma_w \tag{9}$$

Combining equations (8) and (9), we get

$$S_s = \frac{\partial n}{\partial h} = \frac{\partial n}{\partial \sigma'}\frac{\partial \sigma'}{\partial h} = \frac{\gamma_w}{1+e_0}\frac{C'}{\sigma'}\frac{1}{2.303} \tag{10}$$

Compression of soil layer can be expressed as: Insert line break.

$$S_t = m_v \Delta\sigma_z H = \frac{S_s}{\gamma_w}\Delta\sigma_z H \tag{11}$$

Thus, we can calculate the compression of the soil layer with variation in the effective stress from specific storage S_s. This approach has already been incorporated into the computer code of UNSAF3D (Nishigaki et al. 2002).

The consolidation compression value obtained by using the proposed approach was compared with the results from Terzaghi's 1D consolidation theory. It was confirmed that the proposed approach has sufficient accuracy for solving engineering problems (Nishigaki 2002; Shen et al. 2003).

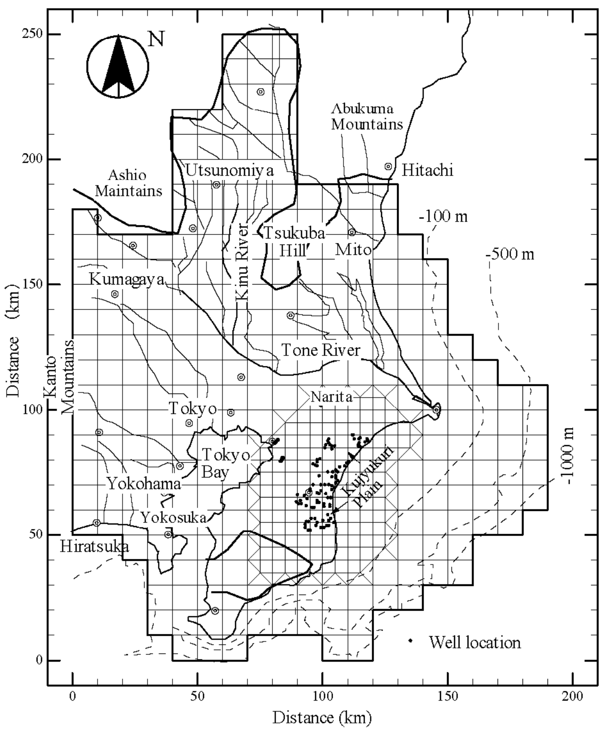


Fig. 8. Analyzed range in the plain and well locations Boundary conditions

CALCULATION OF LAND SUBSIDENCE AT BOSO PENINSULA

Calculation range

The analyzed range selected was the whole Kanto Plain, as plotted in Fig. 8. The land boundary was set at Kanto Mountain and the sea boundary was set 100 km away and 3000 m deep. The distribution of impervious base rock varies from ground surface in a mountainous area to a depth of 3500 m under Tokyo Bay, as plotted in Fig. 9. FEM mesh in the plan is set over 10 km of a large area (see Fig. 8). However, around the production area, the mesh-enclosed area was 5 km size. In a vertical direction, 12 soil layers was divided into 24 mesh layers, i.e., one soil layer was divided into two elements, as shown in Fig. 10.

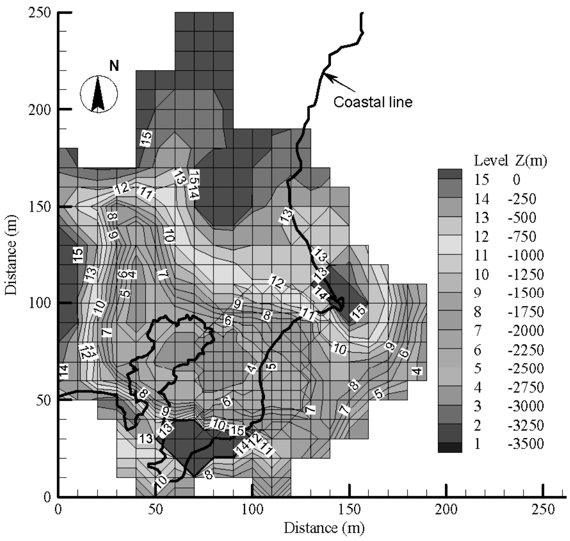


Fig. 9 Distribution of impervious base rock

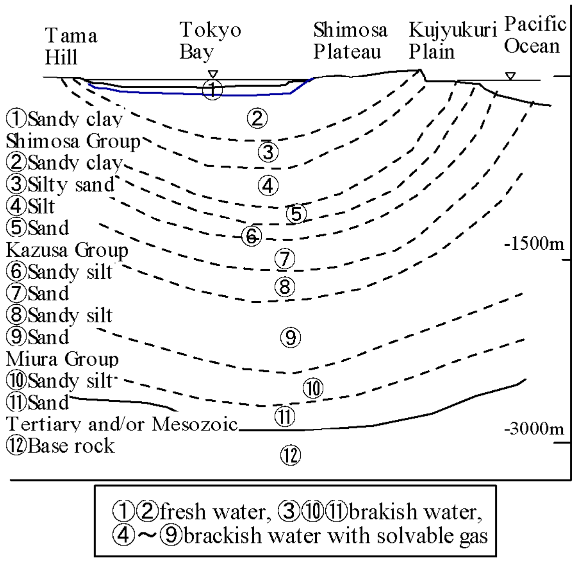


Fig. 10. Sectional view of groundwater basin, South Kanto area

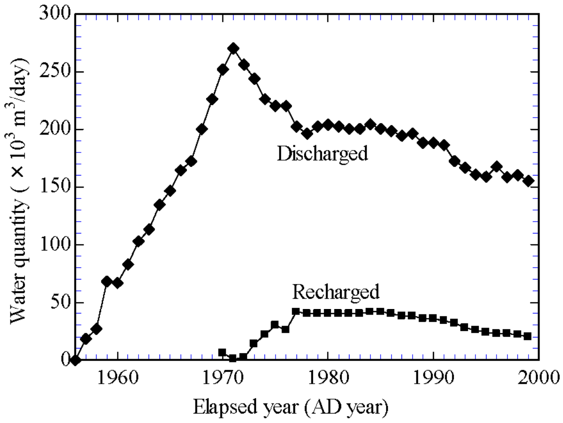


Fig. 11. Discharged and recharged water quantity

The boundary conditions set were as follows: at the ground surface, the boundary was hydraulic pressure; at sea, it was the sea surface. The water quantity extracted per day is shown in Fig. 11. The place of groundwater extraction according to the plan is shown in Fig. 12, and the depth of the groundwater extracted was from 500 to 2000 m at each node and in a vertical direction (Tohno and Shen 2002; 2003). In order to compare the calculated and the measured results, three sites, designated A, B, and C as plotted in Fig. 12, were selected.

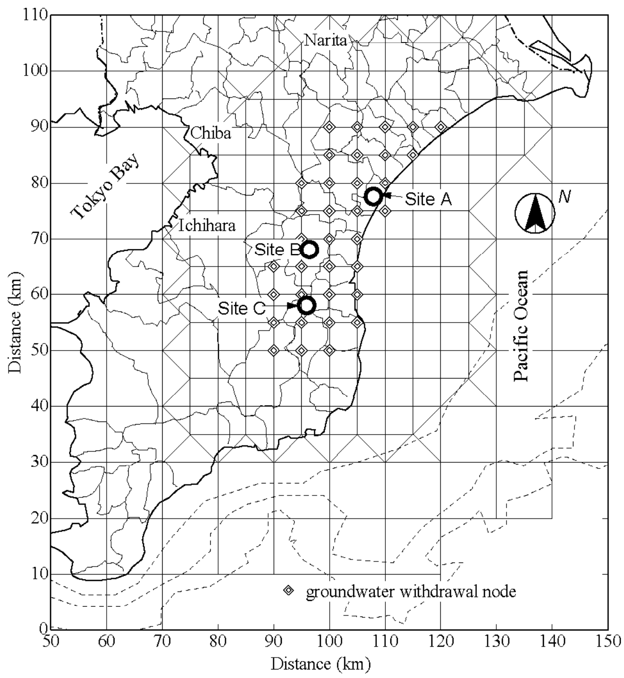


Fig. 12 Site of ground water withdrawal and FEM mesh

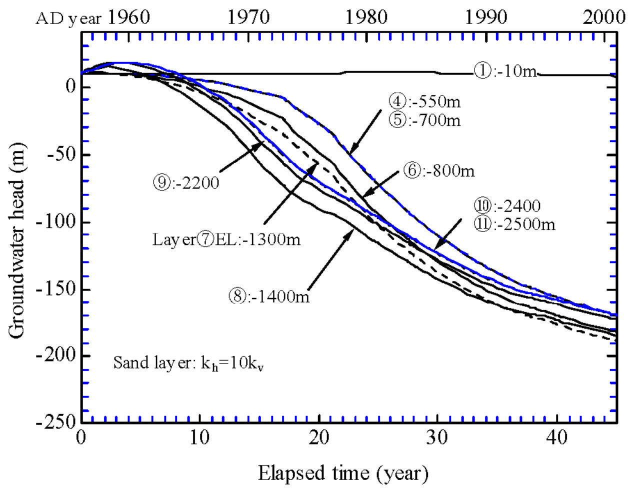


Fig. 13 Groundwater head versus time at site C

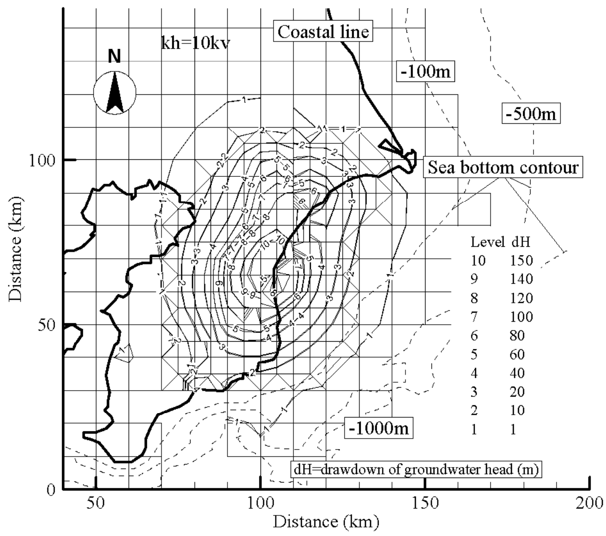


Fig. 14 Contour of groundwater drawdown for layer 7 in 2001

Soil parameters

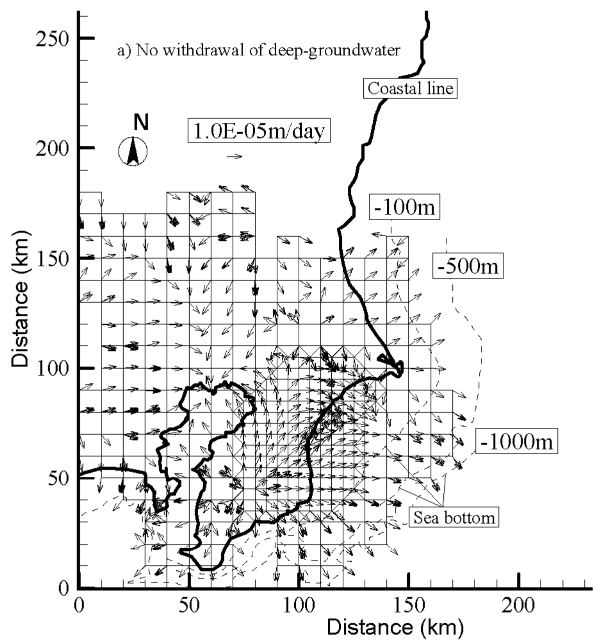
A sectional view of the groundwater basin with a geotechnical profile is shown in Fig. 10. As shown in the figure, except for the surface layer 1, which was an alluvial deposit, the underlying layers were deposited under a marine environment and are comprised of muck and sand rock overlaying one another. Layers 2 to 5 are called the Shimosa Group; layers 6 to 9 are called the Kazusa Group; and layers 10 and 11 are called the Miura Group (Tohno 1990).

In layers 1 and 2, the groundwater is fresh water (Mitsunashi, 1980) but in layers 3, 10, and 11, the groundwater is brackish water with a lower salt content. In layers 4 to 9, the groundwater is brackish water with a high salt content and soluble natural gas (Mitsunashi et al. 1980). Table 2 tabulates the soil and weak rock layers, the layer bottom elevation, and the parameters used in analysis.

Results

Figure 13 shows variation in the groundwater head with time (1956 to 2001) at site C in each aquifer layer. As seen in the figure, the analytical results show that for the layers (layers 1 to 3) without groundwater withdrawal, the variation in the water head was very small (less than 10 m, which is less than the variation caused by seasonal change in the phreatic line in the top layer over this one) over the 46-year period. In the layers beneath, from layers 4 to 10, the groundwater was pumped, and consequently the water head decreased rapidly in the initial 15 years of the 46-year period. This is because the pumped groundwater increased 10% per year in this period (see Fig. 11). Subsequently, the pumped groundwater decreased each year, and the groundwater head became smaller than it was in the initial 15 years.

Figure 14 depicts the drawdown of groundwater in layer 7. As shown in the figure, after the groundwater had been pumped for 46 year, the range of drawdown of groundwater head was about 70 km in the east-west direction and 100 km in the north-south direction. The maximum drawdown in that 46-year period was about 190 m. The water head drawn in other aquifer layers showed behavior similar to that in layer 7 (Tohno and Shen 2003).



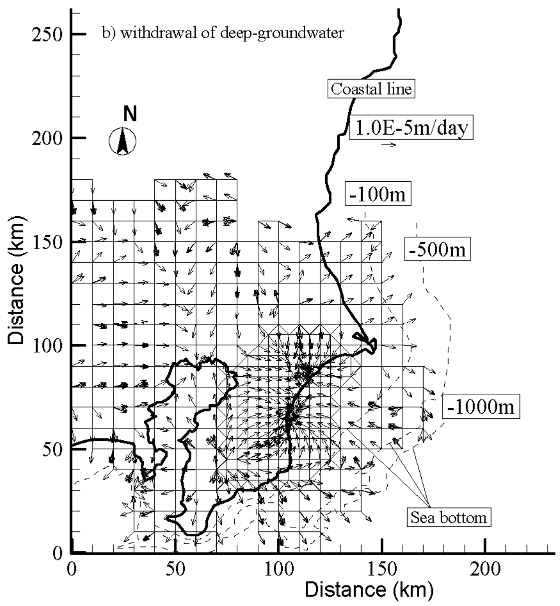


Fig. 15 Groundwater flow vector in layer 7 after 45 years (in 2001)

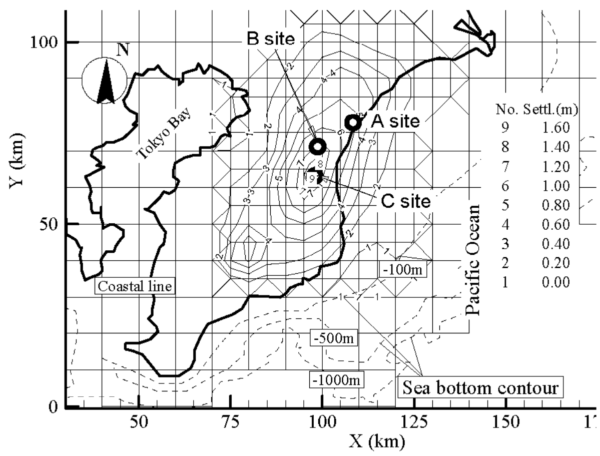


Fig. 16 Predicted surface subsidence contour at 2001

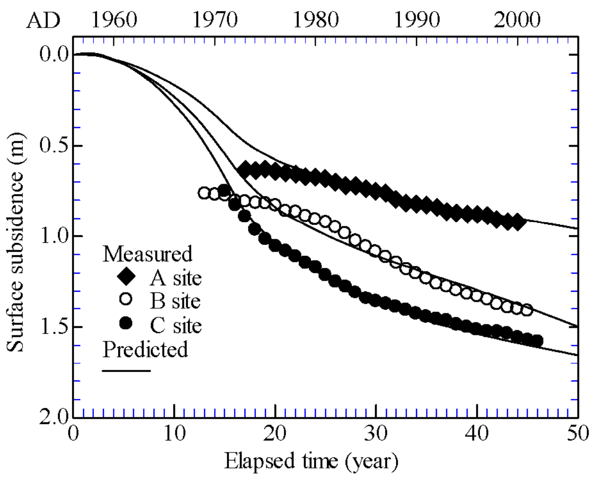


Fig. 17 Measured and predicted surface subsidence

Figure 15 plots the groundwater flow vector in layer 7. For comparison, Fig. 15a gives the case without groundwater pumping and Fig. 15b that of the case with groundwater pumping for the 46-year period since 1956. As shown in the figure, for the case without-groundwater extraction, groundwater flows from land to sea (Fig. 15a). However, for the case with groundwater withdrawal, groundwater flows from land and sea to the Kujyukuri Plain, where deep wells are located (Fig. 15b).

Figure 16 indicates the accumulated surface subsidence contour from 1956 to 2001. The maximum subsidence occurs at site C, where the wells are the most dense. The influenced range of surface subsidence is 10 to 15 km outside the well group. Figure 17 depicts the measured and the predicted accumulative surface subsidence with time at the three sites shown in Fig. 16. It should be pointed out that in Fig. 17, the measured value was added to the estimated value, and the total represents the settlement from 1956 to 1969. As seen in the figure, the proposed subsidence can simulate the field data after 1970 fairly well.

CONCLUSIONS

The following conclusions can be drawn based on the results of this study.

1. Pumping groundwater from deep sediments causes a large area of subsidence. However, the area of subsidence decreases if the pumped volume does not continuously increase.

2. Because it is difficult to determine the boundary of the area affected, in this study, the whole Kanto groundwater basin was selected for the analytical regime. The simulated results show that an obvious draw-down of the groundwater head occurred in Boso Peninsula. The maximum drawdownFormat. This is hyphenated in the preceding sentence. Use consistently. of the groundwater head was about 190 m. After 47 years, the groundwater has flowed into the pumping area.

3. In the calculation of land subsidence, the uncoupled approach proposed by Nishigaki et al. (2002) is applicable to the field case. The results showed that the proposed method can simulate the field data fairly well.

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