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The Risk of Liquefaction Associated with Water Head Fluctuation in the Low-lying Area of Tokyo

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Abstract: In the wide area of the eastern part of Tokyo, the ground level is less than mean sea level. This area is more vulnerable to disasters than other areas. If large flood damage such as storm surge should occur in this area, the disaster would be a long-term catastrophe. On the coast of Tokyo Bay, countermeasures have been taken by tide embankments and floodgates. However, considering the damage scale when it occurs, an analysis in this area is very important. In this area, ground settlement occurred and groundwater head dropped because groundwater excessively withdrew by the industrial purpose during the period of economic growth. Currently, the groundwater head recovers and the ground settlement has been subsided. However, due to the groundwater head fluctuation, pore water pressure distribution had been different from hydrostatic pressure distribution. Therefore, in the analysis in this area, it is necessary to consider past groundwater head fluctuation. In this research, the ground settlement and the distribution of pore water pressure are simulated from groundwater level fluctuation over the past 100 years. Then, we conducted the seismic analysis by input the distribution of effective stress calculating from the simulated ground water pressure. The sites analyzed in this research are Tokyo Sea Life Park at the mouth of Arakawa River.
Keywords: Liquefaction; Dynamic analysis; Groundwater level.

1. Introduction

Recently, in the Kanto region, the Tokyo Inland Earthquake is concerned. It is said that the Tokyo Inland Earthquake will occur with a probability of 70% within the next 30 years. Therefore, countermeasures against the Tokyo Inland Earthquake are being considered by the national government, local governments, etc., assuming the magnitude 8 class earthquake that occurred at intervals of 200 to 400 years.

Currently, in the eastern part of Tokyo, the zero-meter area where the ground height is lower than the sea level is widely distributed. Tokyo zero-meter area is one in which ground settlement occurred by pumping up groundwater in the past, groundwater hoisting was largely regulated in the 1970s, then settlement of ground subsided. The storm surge caused by the Kitty typhoon in 1947 and the Ida typhoon in 1958 caused the flood of Tokyo zero-meter area to suffer great flood. In the metropolitan area, tidal facilities such as embankment, tidal banks, floodgates, landlocks, etc. are installed to prevent storm surge in the coastal area. Although countermeasures have been taken in this way, the possibility of unexpected damage cannot be denied. Suppose that a large earthquake such as Tokyo Inland Earthquake causes to fail the function of the tide equipment such as a water gate and embankment, and it will suffer the storm surge before the repair is over. If seawater enters the zero-meter area from the point of failure, the entered seawater will not be receded even after a long time, and it is considered to be a catastrophe. Fig. 1 shows the ground level in eastern Tokyo [1]. As shown in Fig. 1, the area where the ground height is lower than the sea level at the time of high tide is very wide and it can be seen that there is a danger of storm surge in the wide area. In order to prevent such a situation, we think that it is necessary to carry out a simulation for the eastern lowland of Tokyo and verify a risk of liquefaction.

In this research, an earthquake response analysis is performed on the eastern lowland of Tokyo, where there is a risk of serious damage when a large-scale earthquake occurs. The area around the zero-meter area in Tokyo is influenced by the past groundwater level variation, and the water pressure distribution is different from the hydrostatic pressure distribution. Therefore, in order to analyze Tokyo zero-meter area, it is necessary to conduct earthquake response analysis considering the groundwater level change.

Matsumoto et al.[2] have analyzed the Tokyo Sea Life Park in the vicinity of Arakawa estuary and simulated the distribution of pore water pressure by considering the groundwater pumping. In order to calculate the distribution of effective stress to input to the earthquake response analysis, the same method as Matsumoto et al. is applied in this research.

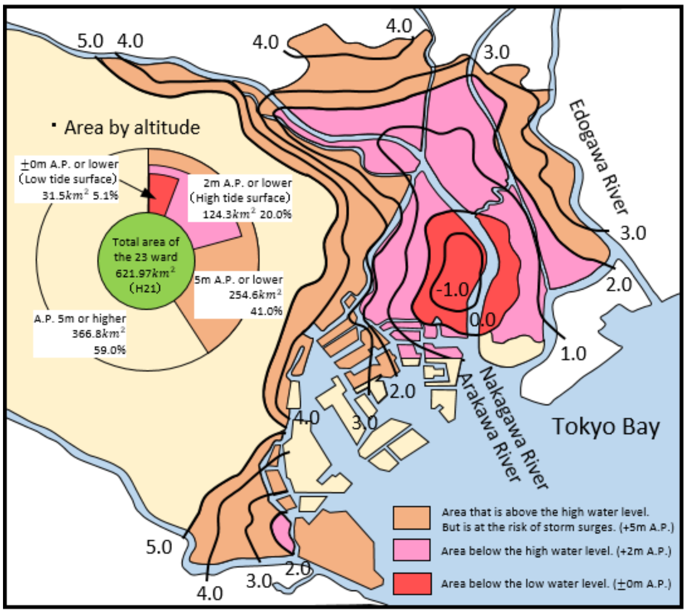


Fig. 1. The ground level in eastern Tokyo [1]

2. Analysis method

In Tokyo zero-meter area, excessive pumping of groundwater was carried out and ground settlement occurred due to the influence of the decline in groundwater level. Groundwater pumping was regulated in the 1970s. As a result, the groundwater level recovered and the ground settlement gradually subsided. However, under the influence of past groundwater level fluctuation, the pore water pressure distribution had been different from the hydrostatic pressure distribution. Therefore, in the case that we analyze the ground behavior in this area, it is necessary to consider fluctuations in the groundwater level in the past. In this study, the ground settlement and the distribution of pore water pressure are simulated based on the history of the groundwater level fluctuation in the past 100 years. Then an earthquake response analysis is performed by input the distribution of effective stress obtained from the simulated distribution of pore water pressure as an initial condition. The time history of groundwater level fluctuation and the settlement of analyzed site are those observed by Tokyo Metropolitan Government Bureau of Construction. Fig. 2 shows the Arakawa area and its surroundings. In the figure, the location of analyzed site, settlement gage and well to observe the ground water level are also shown. The groundwater level fluctuation and ground settlement history used for the analysis are shown in Fig. 3. In this seismic response analysis, we are using two types of input motion: the 2011 off the Pacific coast of Tohoku Earthquake motion observed near Yumenoshima and the Taisho Kanto earthquake motion. The mesh used in the analysis is assumed to be a vertical column of 0m width and 63m height from G.L.-7m to G.L.-70m and is consist of a nine-nodes iso-parametric element. The groundwater level has been observed at G.L.-70m. In Fig. 4, the As and Ac indicate the sandy soil layer and the clay layer of Yurakucho layer respectively, the Nac and Nas indicate the clay layer and the sandy soil layer of the Nanago layer respectively, Tog indicates the Tokyo gravel layer. A linear elastic model is used for Tog layer. The elasto-plastic constitutive model which is called EC model is used for Ac1 layer, Ac2 layer, Nac1 layer, Nac2 layer, As layer and Nas layer. EC model was proposed by Ohno et al. [4]. Ohno et al. assumed that the relation between the volumetric change of normally consolidated clays due to contractancy (negative dilatancy) and the stress ratio can be represented nonlinear functions such as exponential or logarithmic curves thus developed the constitutive model named EC model and LC model respectively. The yield function of EC model is

$$f = MD\ln\frac{p'}{p'_0} + \frac{MD}{n_E}\left(\frac{\eta^*}{M}\right)^{n_E} - \varepsilon_v^p = 0$$

in which M is critical state parameter, D is coefficient of dilatancy proposed by Shibata [5], p' is effective mean principal stress and η^* is generalized stress ratio [6]. n_E is the parameter describing the nonlinearity of the contractancy and the stress ratio curve.

In the analysis of consolidation due to the groundwater fluctuation, the boundary conditions of displacement is set as that the bottom surface is fixed in the both of x and y direction, and the side surface is fixed only in the x direction. The top surface is set to be the drained condition, the side surface is the undrained condition, and we input the bottom surface and Nas layer the groundwater level shown in Fig. 3. Because of changing this water head boundary along the data from 1887 to 2015, we reproduce consolidated subsidence due to groundwater level fluctuation.

In the seismic response analyses, we input the earthquake motion on the bottom surface. As the hydraulic boundary conditions, the top surface is set as drained condition, and side and bottom surface are set as undrained condition. Both side surfaces are set as periodic boundary condition.

Fig. 5 shows a determination procedure of material parameters needed for EC model [7]. We determined soil parameters from this procedure and various soil tests.

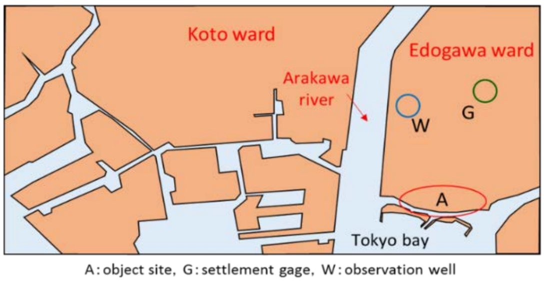


Fig. 2. Observation well and level base point map

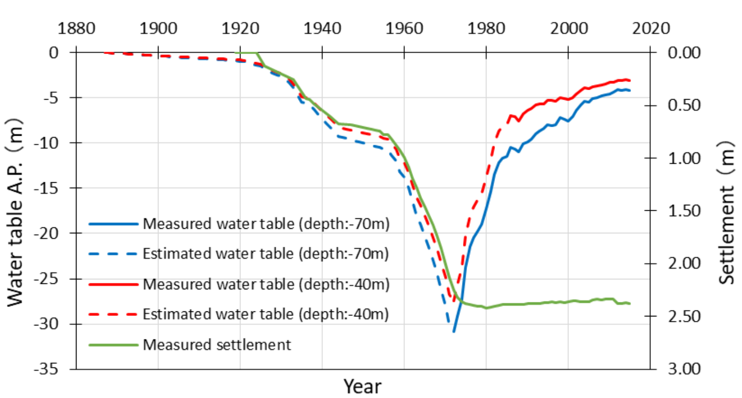


Fig. 3. Groundwater level variation and ground settlement history [3]

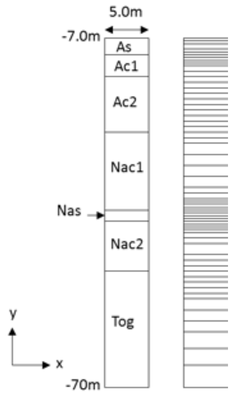


Fig. 4. Analysis mesh diagram

3. Results

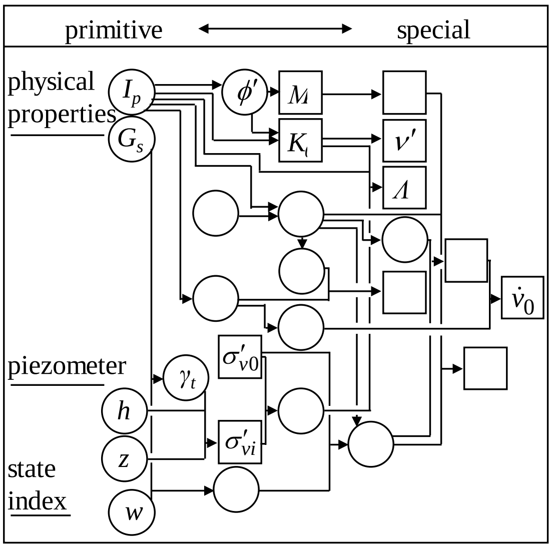
3.1 Consolidation analyses due to groundwater fluctuation

We compare the compression obtained by calculation with the measured settlement shown in Fig. 3. The measured settlement is the compression from deep underground to the ground surface. The compression obtained by calculation is the compression from underground 70m to the ground surface. Therefore, to compare the compression obtained by calculation with the measured value, it is necessary to estimate the compression from underground 70m to ground surface. In the eastern part of Tokyo, it is known that the compression shallower than 70m underground is about 55% of the ground surface settlement.

In this study, we compare 55% of the ground surface settlement with the compression obtained by calculation. Fig.6 shows the comparison between the betcalculated values with the measured value from 1887 to 2015. It is found from this result that we could roughly reproduce the actual ground behavior. In the case of actual grounds, once the ground settlement occurred by the lowering of the groundwater level, the settlement didn't recover even after the groundwater level recovers. However, in the calculation result, the ground settlement recovers slightly as the groundwater level recovers.

In Fig. 7, we compare calculated pore water pressure and measured water pressure. In 1887, the pore water pressure distribution is assumed to be the hydrostatic pressure. Because of the ground water level lowering, the water pressure distribution changes for the smaller than the hydrostatic pressure. After that, the pore water pressure distribution approaches the hydrostatic pressure as the groundwater level recovers. Compared with the measured water pressure in 1985, we find that we could reproduce the actual pore water pressure roughly.

We input the effective stress state obtained by consolidation analysis as initial condition and perform dynamic analysis that input earthquake ground motion. By this dynamic analysis, we verified the influence of the fluctuation of the groundwater level on the dynamic analysis.



$$\sin\phi' = 0.81 - 0.233\log I_p$$
$$\mathrm{M} = 6\sin\phi'/(3-\sin\phi')$$
$$\Lambda = \mathrm{M}/1.75$$
$$K_0 = 0.44 + 0.0042 I_p$$
$$K_0 = 1 - \sin\phi'$$
$$\nu' = K_0/(1+K_0)$$
$$e_i = wG_s$$
$$\gamma_t = G_s\gamma_w(1+w)/(1+G_s w)$$
$$\sigma'_{vi} = \gamma_t z - p_w$$
$$OCR = \sigma'_{v0}/\sigma'_{vi}$$
$$K_i = K_0(OCR)^{0.54\exp(-I_p/122)}$$
$$e_0 = e_i - \lambda(1-\Lambda)\ln\left(\overline{OCR}\right)$$
$$\overline{OCR} = \frac{1+2K_0}{1+2K_i}OCR$$
$$\lambda = 0.434C_c$$
$$e_0 = 3.78\lambda + 0.156$$
$$m_v = 3\lambda/[(1+e_0)(1+2K_0)\sigma'_{v0}]$$
$$k = m_v c_v \gamma_w$$
$$t_c \approx t_{90} = H^2 T_v(U = 90\%)/c_v$$
$$\alpha_e/\lambda = 0.05 \pm 0.02$$
$$= 0.07 \pm 0.02$$
$$\alpha = \alpha_e/(1+e_0)$$
$$\dot{v}_0 = \alpha/t_c$$
$$D = \lambda\Lambda/[\mathrm{M}(1+e_0)]$$
$$\lambda = 0.015 + 0.007 I_p$$
$$\log c_v(\mathrm{cm}^2/\mathrm{min}) = -0.025 I_p - 0.25 \pm 1$$

Fig. 5. Proposed determination procedure of input parameters [7]

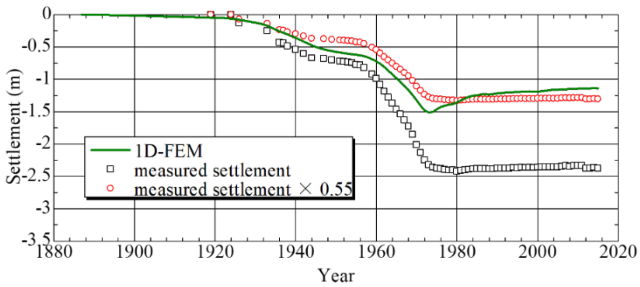


Fig. 6. Comparison of calculated compression and measured settlement

3.2 Dynamic analyses

In this dynamic analysis, we input the effective stress state at 1887, 1923, 1972 and 2011 calculated by consolidation analysis. We input the same earthquake ground motion at these different timings. In these analyses, the earthquake ground motion of the Taisho Kanto earthquake and the 2011 off the pacific coast of Tohoku earthquake is adopted as a huge earthquake occurred in the past in the Kanto. Compared the Taisho Kanto earthquake and the 2011 off the pacific coast of Tohoku earthquake, the Taisho Kanto earthquake is more accelerated, however the 2011 off the pacific coast of Tohoku earthquake continues for a prolonged period of time. Earthquake motion in the east-west direction and earthquake motion in the north-south direction are separately inputted. We denote the north-south direction and the east-west direction as NS and EW, respectively. Regarding the 2011 off the pacific coast of Tohoku earthquake, the earthquake motion in the vertical direction is also input. In the dynamic calculation, the plastic hardening models which are the subloading surface model [8], the extended subloading surface model [8], the rotational hardening model [8], the shear hardening/softening model [8] are employed. The parameters needed for these plastic hardening models which is used in the calculations are summarized in Table 1. m is parameter for the subloading surface model, c is parameter for the extended subloading surface model, b_r and M_r are parameters for the rotational hardening model, μ and M_d are parameters for the shear hardening/softening model, n_E is parameter for EC model.

Table 1. Parameters for the plastic hardening models

	m	c	b_r	M_r	μ	M_d	n_E
Clay layer	0.1	10	1.0	0.5	0.0	0.0	1.2
Sand layer	0.1	30	1.0	0.5	2.0	0.8	1.2

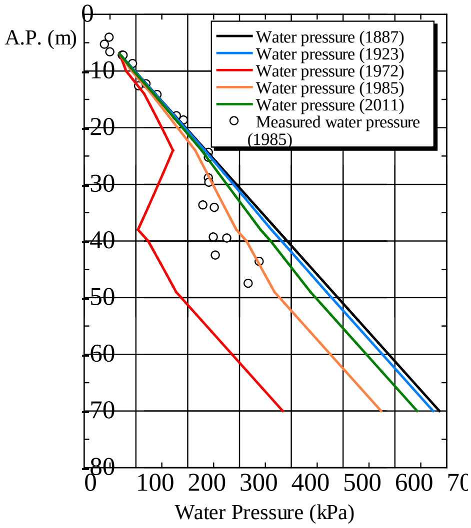


Fig. 7. Water pressure distribution

Figs. 8 to 15 show the depth direction distribution of the maximum excess pore water pressure ratio. The excess pore water pressure ratio is a value obtained by dividing the excess pore water pressure by the initial effective vertical stress. It is considered that liquefaction tends to occur as the excess pore water pressure ratio becomes larger. It is generally considered that liquefaction occurs when the excess pore water pressure ratio is more than 0.95.

Regarding each pattern, the result shows that excess pore water pressure ratio rises greatly in the upper sand layer and liquefaction tends to occur easily. In general, it is considered that liquefaction tends to occur in the loosely deposited upper sand layer, therefore the result is considered to be reasonable. Actually, liquefaction was observed in some places near the site analyzed when the 2011 off the pacific coast of Tohoku earthquake occurred.

Focusing on the difference in the effective stress state set as initial condition, the distribution of the maximum excess pore pressure ratio is similar in case of using the initial conditions of 1887, 1923 and 2011 where the pore pressure distribution is similar. In 1972 the groundwater level drops sharply and the pore pressure distribution is greatly different from other years. Comparing the distribution of the maximum excess pore pressure ratio, when using the initial condition of 1972, the distribution of the maximum excess pore water pressure ratio is significantly different from the other cases.

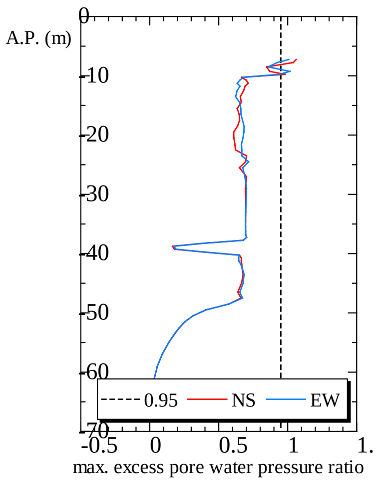


Fig. 8. Max. excess pore water pressure ratio distribution in 1887 (Taisho Kanto earthquake)

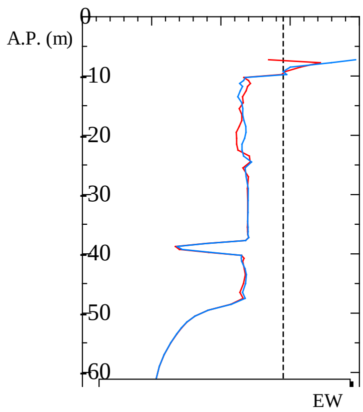


Fig. 9. Max. excess pore water pressure ratio distribution in 1923 (Taisho Kanto earthquake)

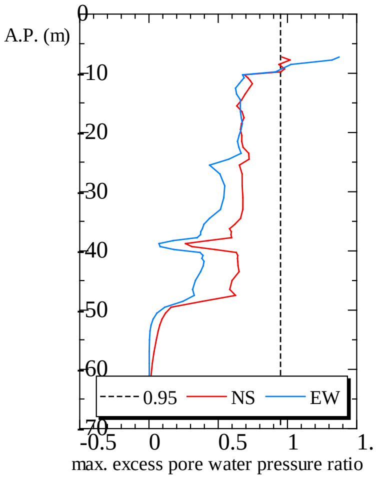


Fig. 10. Max. excess pore water pressure ratio distribution in 1972 (Taisho Kanto earthquake)

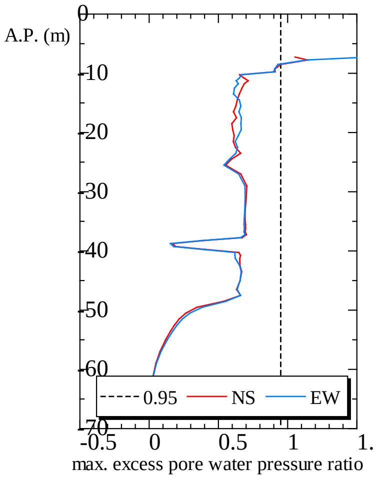


Fig. 11. Max. excess pore water pressure ratio distribution in 2011 (Taisho Kanto earthquake)

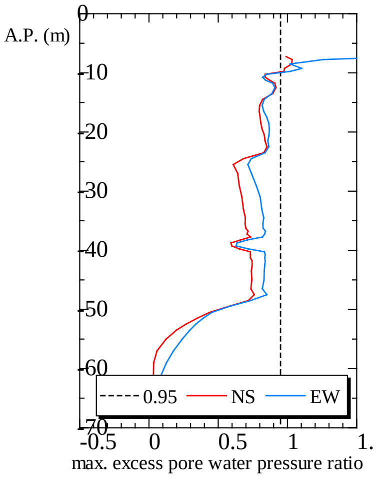


Fig. 12. Max. excess pore water pressure ratio distribution in 1887 (2011 off the pacific coast of Tohoku earthquake)

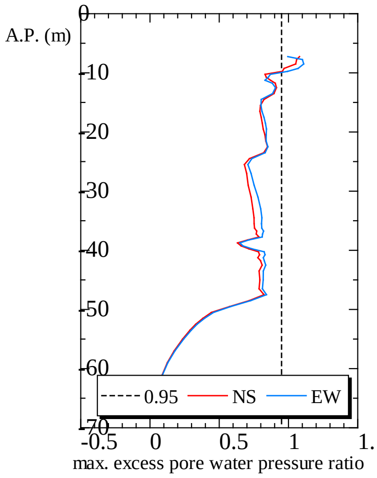


Fig. 13. Max. excess pore water pressure ratio distribution in 1923 (2011 off the pacific coast of Tohoku earthquake)

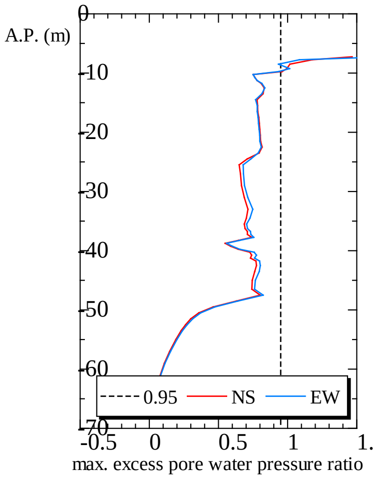


Fig. 14. Max. excess pore water pressure ratio distribution in 1972 (2011 off the pacific coast of Tohoku earthquake)

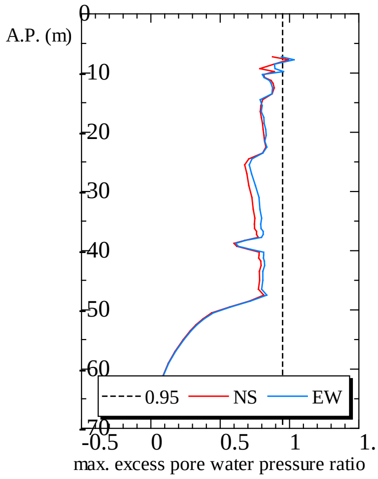


Fig. 15. Max. excess pore water pressure ratio distribution in 2011 (2011 off the pacific coast of Tohoku earthquake)

Focusing on the difference in the earthquake motion, the 2011 off the pacific coast of Tohoku earthquake tends to increase the maximum excess pore water pressure ratio of the upper clay layer than the Taisho Kanto earthquake. When using the initial conditions of 1887, 1923, 2011, the tendency that the distribution of the maximum excess pore pressure ratio is similar as seen in both earthquakes as well.

In addition, at the boundary layers with different constitutive model and the boundary layers with different analysis parameters, it can be seen that there are places where greatly different results are obtained from other places. This difference seems to be due to the unstable calculation at these boundaries. Therefore, it is necessary to improve the stability of calculation by unifying the constitutive model and considering the influence of the mesh interval.

As the groundwater level decreases, the pore water pressure decreases and the effective stress increases. Similarly, as the groundwater level recovers, pore water pressure increases and effective stress decreases. Therefore, we expect that the consolidation yield stress changes due to the groundwater level fluctuation and this fluctuation affects the results. However, the analysis result largely depends on the pore water pressure at that time and the past change history in effective stress has little influence.

4. Conclusions

In this paper, we conducted consolidation analysis with groundwater level fluctuation and dynamic response analyses considering the influence of groundwater level fluctuation

In the consolidation analysis, we confirmed that the actual consolidated settlement amount can be reproduced by taking account actual groundwater level fluctuation into the analysis condition as the hydraulic boundary condition. It seems that this method can be used to estimate the settlement even in other areas in Tokyo where ground settlement occurred due to the groundwater pumping.

In the dynamic analysis, we investigated the influence of groundwater level fluctuation on liquefaction analysis by inputting and comparing the same earthquake motion to the ground of different initial conditions. In consequence, the liquefaction analysis tends to depend on the pore water pressure at that time. In addition, the change of past pore water pressure has little influence on liquefaction analysis.

Acknowledgement

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