Development of three-dimensional ground model based on ground information densified by geophysical exploration and its application to numerical analysis

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ABSTRACT

A three-dimensional ground model from the foundation to the surface of the ground was constructed using the borehole investigations and microtremor exploration for the Oaki district, of Toba city, Mie prefecture, Japan, where thick clayey soil is deposited on the uneven bedrock depth. Long term deformation behavior due to the reclamation or housing land development was evaluated by three-dimensional coupled analysis by finite element method. The analysis result is that consolidation is preceded at a point where the clayey soil layer thickness is small and gradually settles late at a point where the layer thickness is large. When the long time passes, the settlement amount becomes to be proportional to clay layer thickness. In addition, lateral displacement due to unevenness of the bedrock was also recognized, and it was found that multidimensional deformation which cannot be evaluated by one-dimensional analysis can be expressed by performing three-dimensional coupled analysis.

Keywords: three-dimensional ground model; three-dimensional finite element method; long-term deformation

1 INTRODUCTION

It is indispensable to develop a three-dimensional subsoil model with high precision to obtain a realistic solution to the ground where the bedrock and sedimentary structure are not uniform particularly for the evaluation of differential deformation and seismic response of grounds. In this study, a three-dimensional subsoil ground model was developed for Oaki District of Toba City, Japan based on the existing borehole data and a series of microtremor observation (Tanaka, 2018). The estimated subsoil model through microtremor observation was used for the linear interpolation between the existing boreholes. Then the developed subsoil model was applied to the coupled finite element analysis to assess the long-term differential settlement caused by the reclamation. Description of three-dimensional deformation associated with lateral displacement of the uneven soft clay deposits is shown by comparing with the results through one-dimensional analysis and the necessity and superiority of high-quality three-dimensional subsoil model is discussed.

2 INVESTIGATION SITE

Fig. 1 shows the map of the Oaki district and the location of existing borehole and microtremor observation by Tanaka (2018). The Oaki district has two-layer structure consisting of clayey soil and bedrock. The depth of bedrock is not uniform and the thickness of the clayey soil layer varies significantly. As a result, differential settlement has continued over the district since the reclamation in 1971 (Mimura et al., 2010). In this research, a three-dimensional subsoil model was developed using the data in Fig. 1. and applied to numerical analysis.

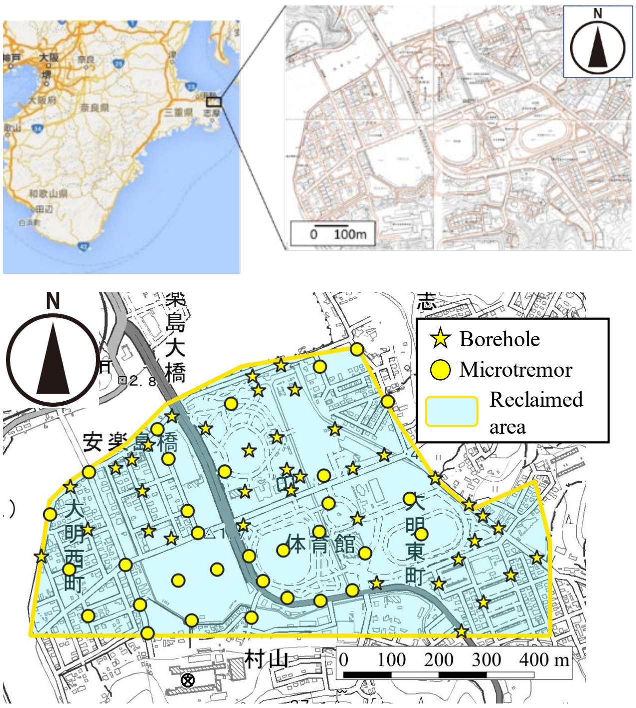


Fig. 1. Map of Oaki district and distribution of ground information

3 THREE-DIMENSIONAL SUBSOIL MODEL

A three-dimensional ground model applicable to numerical analysis was constructed by adopting numerical analysis software PLAXIS. In addition to the existing borehole data, by inserting the microtremor data interpolated by Tanaka (2018) as estimated subsoil information, a three-dimensional subsoil model was created as shown in Fig. 2.

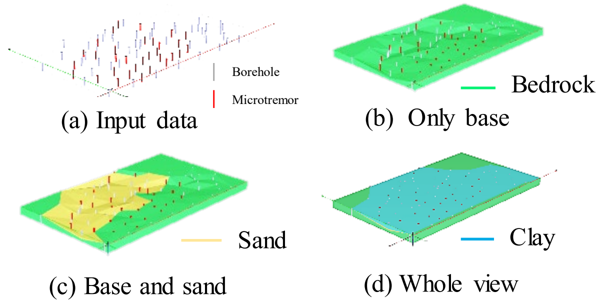


Fig. 2. Three-dimensional ground model for Oaki district

4 NUMERICAL APPLICATION

Long-term deformation in terms of consolidation induced settlement associated with lateral displacement due to reclamation was evaluated. For the clayey soil, the elasto-viscoplastic constituted model (1977) was adopted. The parameters of clayey soil were determined based on the existing report (2014) and summarized in Table 1. As far as the loading sequence is concerned, the actual total loading stress $\Delta\sigma$ of reclamation was calculated with the thickness of reclaimed fill, 2.5m and the wet unit weight γ_t = 17.64 kN/m^3. The reclamation loading, $\Delta\sigma$ = 44.1 kN/m^2 was assumed to be applied to the ground proportionally in a year.

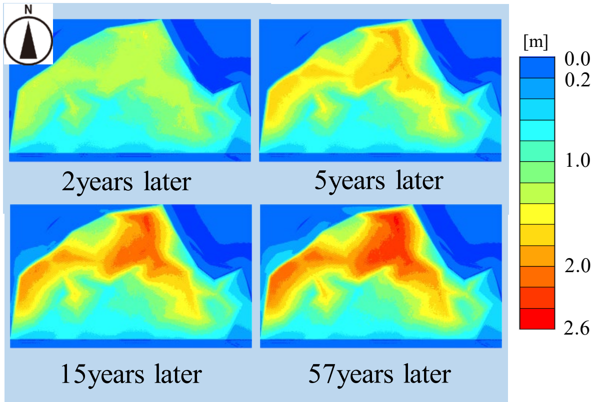
Table 1. Parameters for clayey soils

Viscoplastic model (Sekiguchi and Ota)					
γ_{sat}	kN/m^3	16	M		1.200
e_0		1.882	$K_{0,x}$=$K_{0,y}$		0.5333
$\dot{v}_0$	1/day	1.27E-05	c	kN/m^2	15
C_c		0.793	φ	°	15
C_s		0.144	OCR		1
C_α		3.97E-02	k_x=k_y=k_z	m/day	9.27E-04

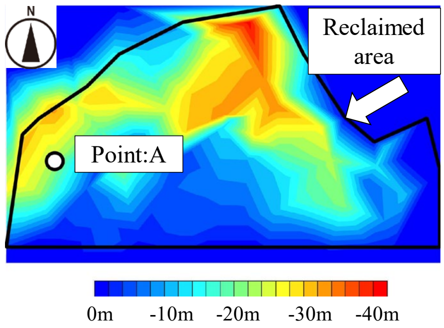
5 RESULTS AND DISCUSSIONS

5.1 Long-term settlement

The calculated contours of total settlement are shown in Figh.3 (a) with the elapsed time and the distribution of the depth of the bedrock is shown in Fig. 3 (b). The contours of total settlement are shown for 2, 5, 15 and 75 years after the completion of reclamation. Because the thickness of the soft clayey layers is thin, the consolidation converged early at the place where the depth of the bedrock is shallow. In other words, settlement occurred in the area where the clayey layer is thin. With the elapsed with time, however, the settlement of the thick clayey area where the depth of the bedrock is deep is found to be larger. Then the contours of settlement coincide with the distribution of the depth of the bedrock (thickness of soft clayey layers).



(a) Time history of ground settlement



(b)Depth of bedrock

Fig. 3. (a) Time history of distribution of ground settlement and (b) distribution of depth of the bedrock

Let us discuss about the effect of subsoil modeling on the numerical analysis. Fig. 4 shows the comparison of the calculated settlement after 15 years from the completion of reclamation for the three-dimensional subsoil models adopted in the present study and the one developed without using the microtremor observation. It can be seen that there is a large difference in the settlement distribution in borehole data blank area. In the domain surrounded by a hatched circle, lack of data is found to cause both overestimation and underestimation of settlement because the implicit interpolation is conducted among borehole data with inadequate distance. Particularly in the case of the uneven deposits such as Oaki District, sufficiently near borehole information is required. The valley structure was detected in the direction from the northwest to southwest due to the two microtremor observation between the borehole points. This valley causes a larger settlement with 2.0m for the present subsoil model whereas we got 1.4m of settlement for the one without microtremor observation. On the contrary, at the point of the southern

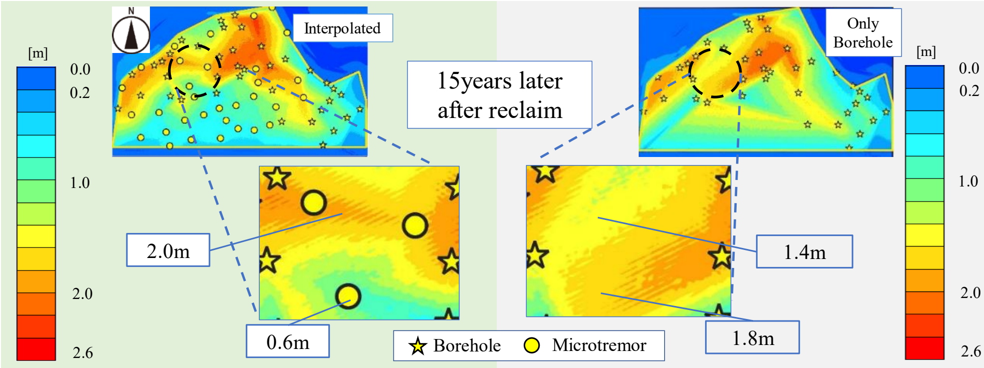


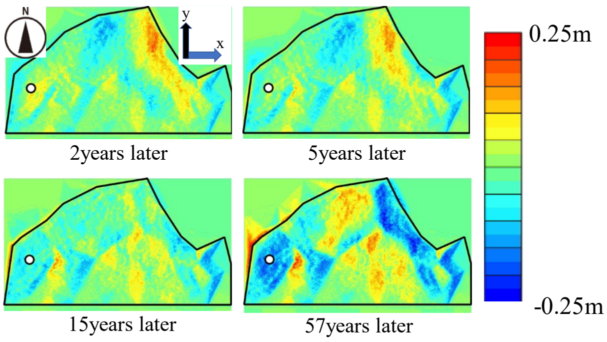
Fig. 4. Comparison of settlement distribution between interpolated model and no interpolation model

microtremor observation the calculated settlement for the subsoil model in the present study was 0.6m but the overestimated settlement of 1.8m was derived for the model without microtremor observation because the interpolated depth of the bedrock was evaluated deeper than the actual. Therefore, it can be said that the estimation of the ground structure by geophysical exploration makes a clear difference in the analysis result.

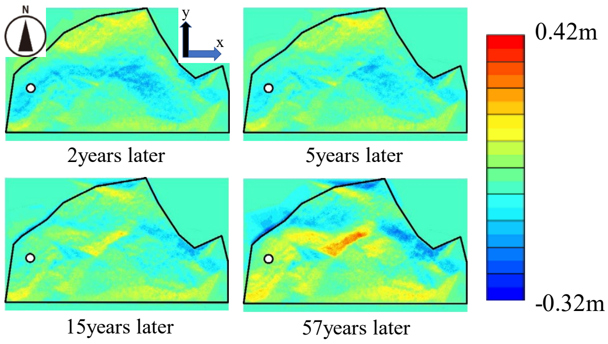
5.2 Lateral displacement

Lateral displacement of the ground is allowed to occur together with settlement under a three-dimensional condition. Fig. 5 shows the contours of the lateral displacement of the ground surface in x and y direction at 2, 5, 15 and 57 years after the completion of the reclamation. With reference to the distribution of the bedrock depth shown in Fig. 3 (b), at the early stage of consolidation (after 2 years), since consolidation of a thin clay deposits (shallow bedrock depth) is preceded, lateral displacement at the surface occurs towards to the place where large settlement occurs. However, with the lapse of time, it is natural the settlement due to the consolidation at the place having thick clay layers (deep bedrock depth) becomes large, then the direction of the horizontal displacement of the surface is reversed. Similar behavior is observed both for x and y direction. In addition, it can also be seen that the amount of the horizontal displacement of the ground surface grows large at the area where the inclination of the bedrock is steep. The area with large surface displacement is found to generally correspond to the area with steep inclination of the bedrock shown in Fig 3 (b).

A lateral displacement profile with depth at point A (Fig. 3 (b) and 5) is shown in Figs. 6 (a) and (b). For both x and y directions, lateral movement of subsoils due to shear deformation induced by filling load took place with the constraint effect of the filling material at the surface. Then the typical parabolic distribution of lateral displacement with depth can also be derived in the present study. A due attention should be paid to the fact that complex behavior that lateral displacement occurs associated with settlement and such complex behavior of soft soil foundations can only be assessed through a three-dimensional approach.

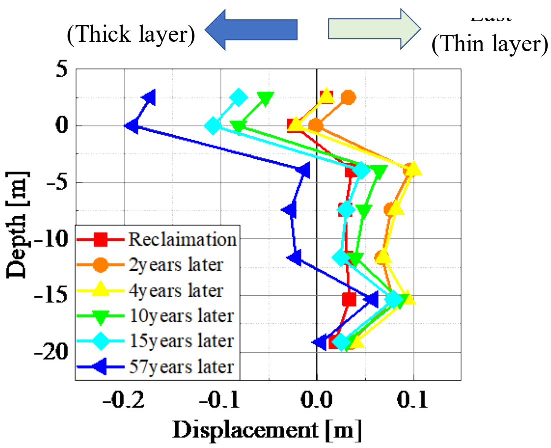


(a) x direction



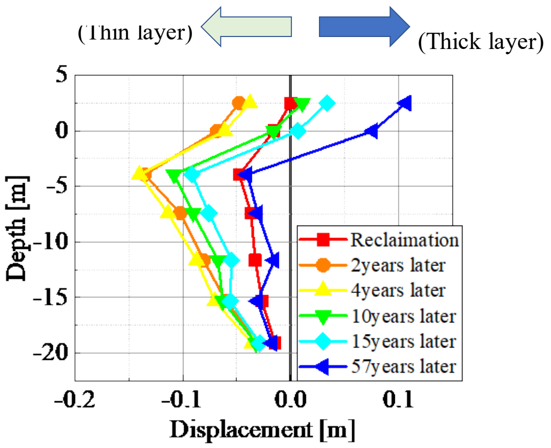
(b) y direction

Fig. 5. The contours of the lateral displacement of the ground surface in (a) x and (b) y direction



(a) x direciton

Fig. 6 (a). Lateral displacement profile with depth at point A in x direction



(b) y direciton

Fig. 6 (b). Lateral displacement profile with depth at point A in (a) x direction and (b) y direction

5.3 progress in stress

The stability of the soft soil foundation can be assessed based on stress paths of the representative clay elements. The effective stress paths for the representative clay elements at Point A are shown in Fig. 7. Here, 6 elements of different depths are chosen for discussion. For all elements, the effective stress paths started on K_0 line are found to move by keeping K_0 condition far from the C.S.L. during the whole period of loading and consolidation. From these results, the reclamation project in Oaki District can be concluded to be conducted under the stable condition.

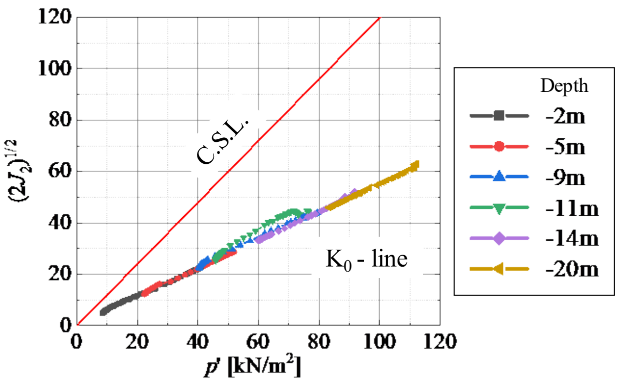


Fig. 7. Effective stress path in some depth at point A

It is also interesting to evaluate the stress-strain relations of clay materials due to reclamation. For the representative clay elements at 11m and 14m in depth, the calculated e-log$p$' curves are shown in Fig. 8. Here, the setup normally consolidated line is described in red with the inclination of C_c. For both clay elements, slight overshoot behavior can be seen due to strain rate effect caused by the finite rate of loading followed by the delayed deformation under the constant p'. It is hence found for the clay foundation of Oaki District that the steady consolidation has progressed with a typical viscoplastic behavior such as stress overshoot and secondary compression.

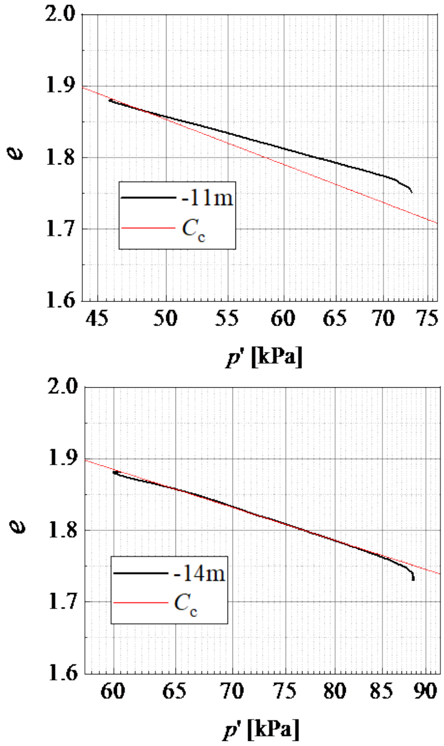


Fig. 8. e – log$p$' curves at 11m and 14m in depth.

6 Conclusions

A three-dimensional subsoil model was developed for Oaki District of Toba City Japan based on the existing borehole data and a series of microtremor observation. It is found that the interpolation between the borehole points with the estimated subsoil information through microtremor observation enhances the quality of the subsoil model for uneven soft deposits on the undulated base rock. A finite element assessment was conducted to evaluate a differential long-term deformation of this reclaimed uneven soft deposits. The calculated performance showed that remarkable lateral deformation occurred associated with the advance in consolidation that cannot be described with one-dimensional procedure. It is hence concluded that a three-dimensional subsoil model with high precision can contribute to the realistic evaluation of natural deposited ground having a complicated structure.

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