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SOIL / WATER COUPLED ANALYSIS FOR CONSTRUCTION MANAGEMENT OF HIGHWAY EMBANKMENTS ON SOFT CLAY

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ABSTRACT: In the limited budget of highway construction, it is necessary to carry out the construction management which systematically utilizes management resources. This paper presents the applicability of soil / water coupled FE analysis for use in construction management of highway embankment on soft clay. At the first stage of analysis, the computer simulations of existing highway embankments on soft marine clay are conducted to verify their predictability. The constitutive model used in the analysis is an elasto-viscoplastic model proposed by Sekiguchi and Ohta (1977). At the second stage, the simulations of construction sequences, as case studies, with slow to fast banking rates are trialed to find better alternatives. It is a main point of the proposal to perform a construction management by fully utilizing the result of simulations for checking the stability of the foundation during construction.

Keywords: Construction management, soil / water coupled FE analysis, highway embankment, soft clay

INTRODUCTION

In order to construct quality highways in the limited budget, it is necessary to carry out the construction management which systematically utilizes resources, such as time, fund, facility, technique, talented people, and materials. Construction management is one of the total process that unified design, supply and construction.

Construction of the highway embankments on soft clay has so far been carried out with slow banking rate based on the careful observational construction to ensure the stability of the foundation. It is because the geotechnical information available at the design stage may not be fully reliable. Moreover, construction of highway embankment on soft clay has high risks such as embankment failure, long-term settlement and additional deformation after opening to traffic. In order to carry out construction of the embankment guaranteeing safety, quality and life-cycle economy, it is indispensable to predict accurately the stress and deformation behaviour of subsoil and embankment, and to appropriately use these predictions in the construction management.

This paper presents the applicability of soil / water coupled finite element analysis for use in the construction management of highway embankment on soft clay. At the first stage of analysis, the computer simulations of existing highway embankments on soft marine clay are conducted to verify their predictability. The computer simulations of the performance of the embankments are carried out employing a soil/water coupled finite element program called DACSAR originally coded by Iizuka and Ohta (1987) and recently revised by Takeyama et al., (2006). The constitutive model used in the analysis presented in this paper is an elasto-viscoplastic model proposed by Sekiguchi and Ohta (1977). The simulations are based on so-called Class B prediction classified by Lambe (1973) in which the subsoil parameters are modified by pursuing better fitting with prior monitored performance at the site. At the second stage, as case studies, the simulations of construction sequences, for example, with slow to fast banking rates are trialed to find better alternatives.

CLASS B PREDICTION OF DEFORMATION BEHAVIOUR OF HIGHWAY EMBANKMENT

Analyzed Site and Subsoil Properties

Five embankments were constructed 20 years ago as preloaded embankments in Takeo-Kitagata Interchange of Nagasaki Highway, Kyushu, Japan shown in Fig 1 and analyzed by Ohta et al., (1991). The shapes of five embankments and subsoil layers are shown in Fig. 2.

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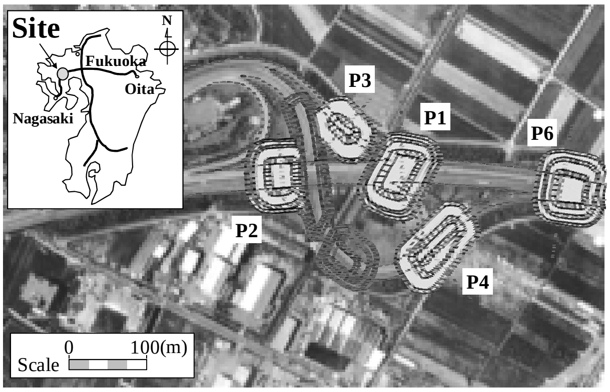


Fig.1 Five preloaded embankments in Takeo-Kitagata Interchange of Nagasaki Highway

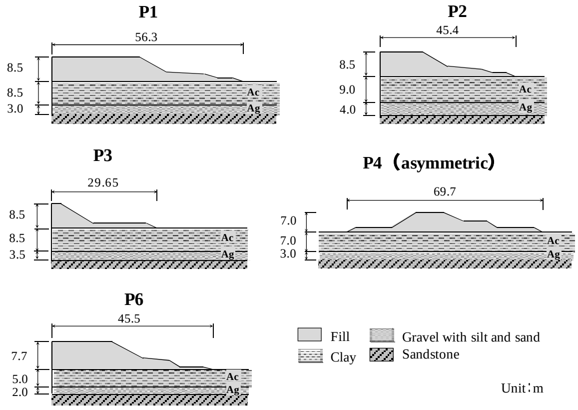


Fig.2 Shapes of five embankments and subsoil layers

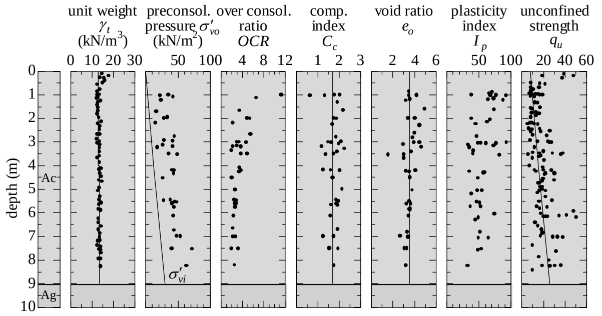


Fig.3 Subsoil properties of soft alluvial clay in Takeo Kitagata Interchange of Nagasaki Highway

The subsoil foundation consists of a soft alluvial clay layer called Ariake clay and gravel bed containing silt and sand underlain by bearing stratum of sand stone. Subsoil properties of soft clay are summarized in Fig.3. Ariake clay is uniform and highly sensitive clay. The layer is an anisotropically consolidated clay whose over consolidated ratio (OCR) is 2-4 and natural water content is 120-180% that is higher than its liquid limit (60-110%). Therefore the clay might be very sensitive. As countermeasure, the paper drains were installed in square pattern in plan with a 0.8m centre-to-centre pitch to accelerate the consolidation settlement due to embankment loading. The sand mat was placed on the ground surface. The counterweight berms, pre-loading fill were trialled. Slow filling by staged loading was also performed with a careful observational method.

Soil / Water Coupled Finite Element Modelling

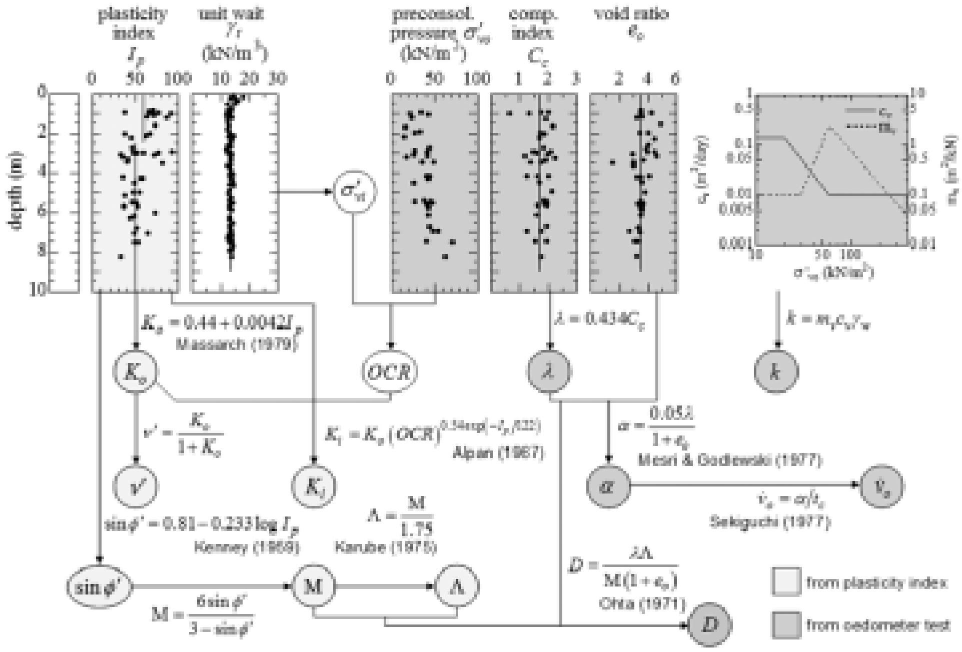
The soil-water coupled FE modelling is conducted during the embankment construction in a form of the so-called Class B prediction classified by Lambe (1973). The application of the Class B prediction may be expected to improve the accuracy of the performance prediction of highway embankment. Because soil parameters and construction sequence of the highway embankment represented by boundary conditions of the numerical model are modified by comparing the results of numerical analysis with monitored data during construction works, it is considered that these calibrations are one of the condition assessments of highway embankments on soft foundations for the uncertainty of ground information. The authors assume that if the analysis can successfully simulate the behaviour during past and on-going construction, the analysis may successfully predict the future settlement and deformation of the highway embankment during operation by extending the boundary conditions to longer time scale.

The soil-water coupled FE code used in this analysis is DACSAR coded by Iizuka et al. (1987) and Takeyama (2007), which is based on the consolidation theory proposed by Biot (1951) together with the formulation developed by Akai and Tamura (1978) and Takeyama (2007). Two-dimensional FE modelling is used in this analysis. In this case study of class B prediction during construction period, embankment construction is modelled by adding elements to the mesh and the loading rate and the thickness of fill are assumed identical with those in the actual staged construction works. The level of underground water is set ground surface. The buoyancy to act under the fill body is also considered in this modelling.

The constitutive model employed in this analysis is an incremental elasto visco-plastic models developed by Sekiguchi and Ohta (1977). The yield function of the elasto-plastic model is defined by

$$f = MD \ln \frac{p'}{p'_0} + D\eta^* - \varepsilon_v^p = 0 \qquad (1)$$

The flow function of elasto-viscoplastic model is defined by



Layer	Depth(m)	γ_t (kN/m^3)	OCR	I_p	M	Λ	D	K_0
Fill		20.0	E = 25000 kN/m^2					
Ac1	0.0-1.0	13.0	E = 5000 kN/m^2					
Ac2	1.0-2.5	13.0	4.0	60	1.4	0.8	0.094	0.69
Ac3	2.5-4.0	13.0	3.5	50	1.4	0.8	0.094	0.65
Ac4	4.0-5.0	13.5	3.0	50	1.4	0.8	0.094	0.65
Ac5	5.0-7.0	13.5	2.5	50	1.4	0.8	0.094	0.65
Ac6	7.0-9.0	13.5	2.5	50	1.4	0.8	0.094	0.65
Ag		16.0	E = 60000 kN/m^2					

Layer	Depth(m)	K_i	ν'	λ	e_0	α	$\dot{v}_0$	k (m/day)
Fill								10.0
Ac1	0.0-1.0							1.44X10^{-3}
Ac2	1.0-2.5	1.31	0.41	0.74	3.51	8.18X10^{-3}	1.64X10^{-5}	1.44X10^{-3}
Ac3	2.5-4.0	1.02	0.39	0.74	3.51	8.18X10^{-3}	1.64X10^{-5}	1.44X10^{-3}
Ac4	4.0-5.0	0.91	0.39	0.74	3.51	8.18X10^{-3}	1.64X10^{-5}	1.44X10^{-3}
Ac5	5.0-7.0	0.88	0.39	0.74	3.51	8.18X10^{-3}	1.64X10^{-5}	1.44X10^{-3}
Ac6	7.0-9.0	0.85	0.39	0.74	3.51	8.18X10^{-3}	1.64X10^{-5}	1.00X10^{-3}
Ag								1.00X10^{-3}

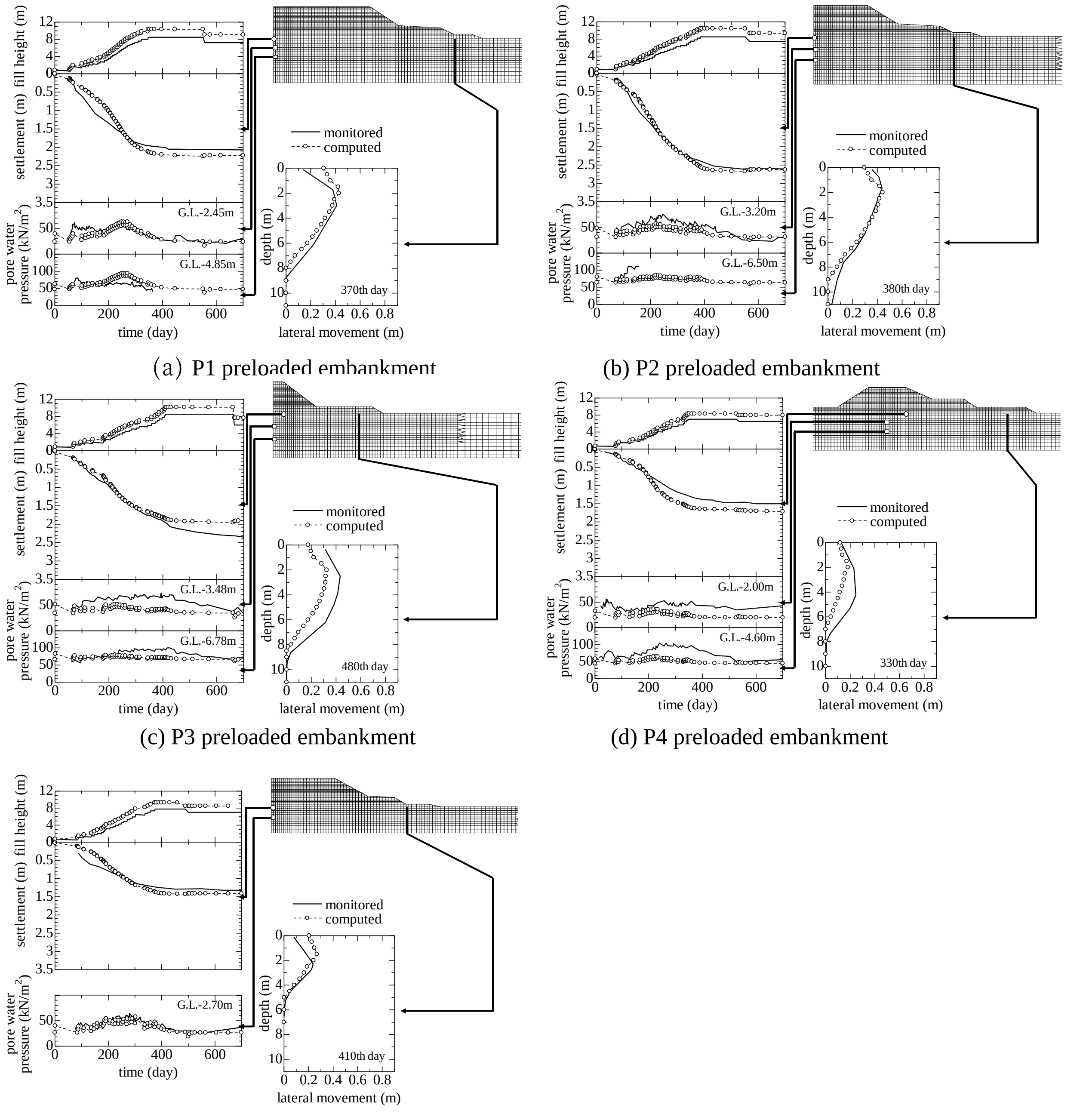
Fig.4 Input parameter determination of subsoil

$$F = \alpha \ln\left\{1 + \frac{t}{t_0}\exp\left(\frac{f}{\alpha}\right)\right\} - \varepsilon_v^p = 0 \qquad (2)$$

where M = critical state parameter; D = coefficient of dilatancy proposed by Shibata (1963); p'= mean effective stress; p'_0 = preconsolidated mean effective stress; $\eta*$ = generalized stress ratio proposed by Sekiguchi and Ohta (1977); ε_v^p = viscoplastic part of volumetric strain; α= coefficient of secondary compression proposed by Sekiguchi and Ohta (1977); t = time; t_0 = initial time. Sekiguchi-Ohta model (The S-O model) was developed based on a set of assumptions totally different from the original Cam-clay model (The OCC model) by Roscoe et al (1963), but the final mathematical form is essentially same as the OCC model. The S-O model can also describe the induced anisotropy, creep and relaxation characteristics of soils. In this analysis, clay layer is assumed an elasto visco-plastic model. However the surface crust is assumed a linearly elastic model. Because the value of unconfined strength is relatively high, (see Fig. 3) compacted fill material, and gravel layer are also assumed linearly elastic models.

Input Parameter Determination

The input parameters needed in the S-O model should primarily be determined through the triaxial test, oedometer test and permeability test which are not practical enough to carry because of the time and cost required. Actually, these laboratory tests were not performed prior to the actual construction works. Consequently, the procedure of input parameter determination of clay follows the flow charts shown in Fig. 4 proposed by Iizuka and Ohta (1987) based primarily on the conventional soil testing methods and the plasticity index. The procedures are based on laboratory and field tests together with a set of correlations proposed by many research workers. The



(e) P6 preloaded embankment

Fig.5 Monitored and computed performance of five pre-loading embankments

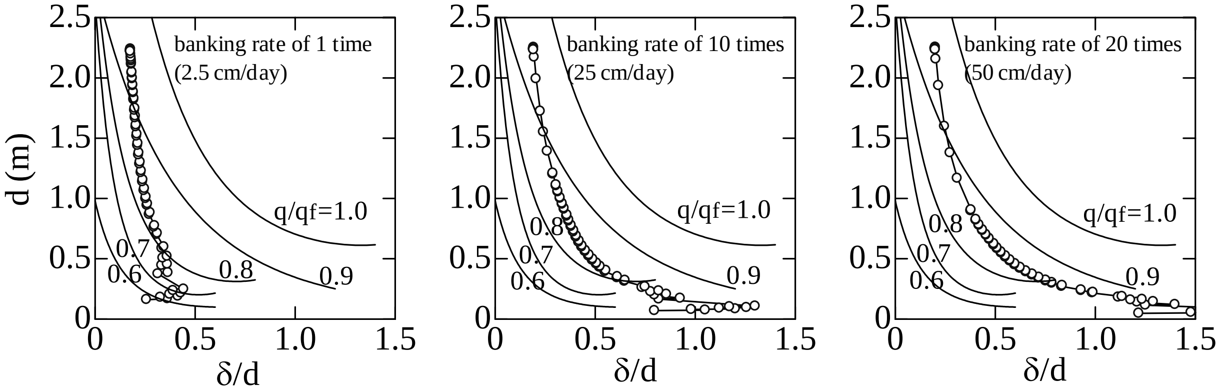
permeability of clay layer is assumed to change during the process of consolidation by the relationship between permeability coefficient and void ratio after Taylor (1948).

At the site investigated, the paper drains were installed to accelerate the consolidation settlement due to embankment loading. The installation of paper drains resulted in 30% of reduction of coefficient of consolidation *Cv* due to disturbance. Adopting the method proposed by Yoshikuni (1979), the apparent increase in coefficient of consolidation due to the shortening of drainage length is estimated in such a way that 50% of consolidation time both of Barron's horizontal-radial water flow and Terzaghi's one dimensional vertical water flow become to coincide.

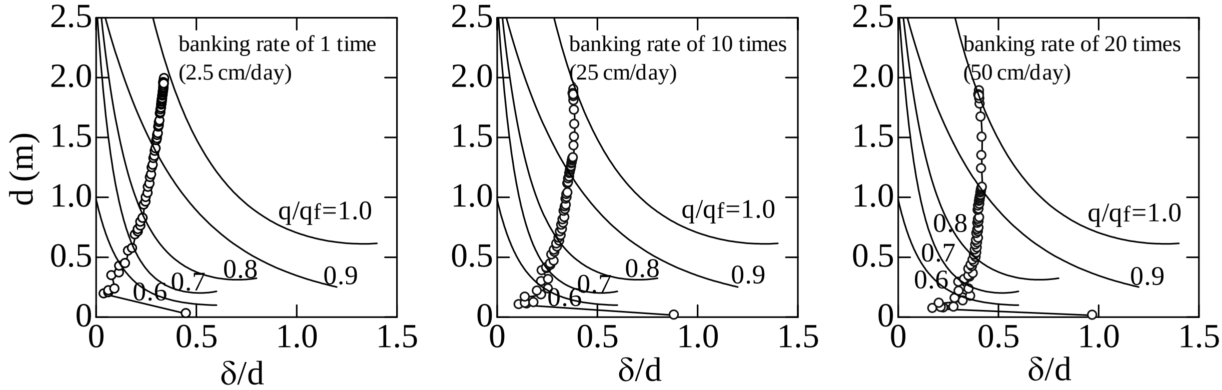
The deformation parameters of compacted fill material, gravel layer and surface crust are assumed by reference to the author's past experiences. The estimated parameters are summarized in Fig.4.

Computed Results

The computed results of five preloaded embankments performed by using a set of input parameters estimated in Fig.4 are shown in Fig.5 (a) through (e) respectively for five embankments P1, P2, P3, P4 and P6 being



(a) P1 embankment



(b) P3 embankment

Fig.6 Simulation results plotted in the diagram for construction control of highway embankment proposed by Matsuo and Kawamura (1977)

compared with monitored performance at site. In each of these figures, the mesh in the vicinity of the embankment is shown at the upper right. The region of mesh formation actually used in analysis is larger than these figures in order to eliminate the influence of the boundary on computed results. The graph at the upper left shows the input and the monitored fill height. The average filling speed of each five embankments is about 2.5 cm/day. The other graphs compare the computed results with monitored data of settlement, pore water pressure and lateral movement at the positions shown in figure of mesh.

The computed results of settlement agree well with the monitored one except that the final settlement value of computed one is less than monitored one. The computed pore water pressures well agree with the monitored value except in P3 and P4. The computed results of lateral movement relatively well with actual one except in P3 and P4. The reason of difference between computed and actual one in P3 and P4 may be a different estimation of permeability coefficient in clay layer, especially modification of the effect of paper drain. The shapes and size of P3 and P4 embankment are similar. The authors presume that the effect of paper drain may be influenced by the shape and size of embankment.

SOIL/WATER COUPLED ANALYSIS FOR USE IN CONSTRUCTION MANAGEMENT

Relevant construction schedule is extremely important when planning distribution of management resources. In construction of the embankments on soft foundations, in many cases, it is carried out at a slow banking rate in order to reduce the risk of foundation failure with a careful observational method. However, construction at the possibly fastest banking rate after securing the stability of the foundation gets advantageous economically in geotechnical engineering practices.

In this section, as case study, it is investigated using the class B prediction result in soil/water coupled analysis whether it was possible to have carried out a banking rate fast. The analyses are performed on the largest fill width of P1 embankment and on the narrowest fill width of P3 embankment comparison is made by performing the simulation of three cases where the banking rate of 1 time (banking period of 350days, 2.5 cm/day, actual rate,), 10 times (banking period of 35days, 25cm/day), 20 times (banking period of 17.5days, 50cm/day).

The pre-loaded periods are the same as three cases. The subsoil parameters are the same as shown in Figs.4.

The simulation results arranged by the diagram for construction control of highway embankment proposed by Matsuo and Kawamura (1977) are shown in Figs. 6. This diagram is the failure forecast method often used for the construction management of embankments on soft grounds in Japan, and is investigated based on the past actual examples of failure. This method focuses its attention to the settlement of ground surface at the centre of the embankment (d), and the lateral movement at the toe of the embankment (δ).

The curves in a figure are isopleth lines of (q/qf) from arbitrary filling loads (q) and the load at the time of failure (qf), and a failure reference line is a curve of (q/qf)=1.0. (q/qf)=0.8-0.9 is considered to be a guidepost when evaluating the risk of failure under construction according to the past experiences, since cracks occur at the top of filling in (q/qf) around 0.9.

According to Figs. 6, it can be concluded that the case where the banking rate of 20 times of p3 embankment has a high risk of failure since q/qf is over 1.0. However, in other cases, q/qf is lower than 1.0. Therefore, the authors assume that it would also be possible to have actually carried out a faster banking rate in construction of this site. However, q/qf of a construction process also gets severe as a filling rate gets fast, that is, the risk of failure also increases.

CONCLUSIONS

This paper presents the applicability of soil / water coupled FE analysis for use in construction management of highway embankment on soft clay.

Owners and contractors can recognize mutually risks of being concerned with embankment construction on soft clay based on a class B analysis result in advance. And making decisions securing the balance of economical efficiency and a risk will bring a great contribution to realization of the optimal construction management.

It is a main point of the proposal to perform a construction management by fully using the result of simulations for checking the stability of the foundation during construction of highway embankment on soft clay.

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