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Effect of Permeability and Compressibility of Permeable Gravelly Sand Layers on Long-term Settlement of Pleistocene Deposits

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Synopsis

A series of elasto-viscoplastic finite element analyses is carried out to investigate the effect of the permeability and compressibility of the Pleistocene gravelly sand layers on the stress-deformation characteristics of the Pleistocene deposits in Osaka Port. The relevant procedure to evaluate the rigidity of the Pleistocene gravelly sand layers is also introduced. It is found that the estimation of the elastic shear modulus, G_0 as well as permeability of the Pleistocene gravelly sand layers plays a significant role for the settlement prediction of the reclaimed islands in Osaka Port.

Keywords: quasi-overconsolidated Pleistocene clay, Pleistocene gravelly sand layer, coefficient of permeability, excess pore water pressure, elastic shear modulus, elasto-viscoplastic finite element analysis

1. Introduction

Long-term settlement occurring at the reclaimed Pleistocene deposits in Osaka Bay has been a serious geotechnical issue which directly causes the obstacle for superstructures on those reclaimed islands. Far from the case for the Holocene clays, the Pleistocene clays have so-called distinguished structure with relatively high void ratio due to the effect of diagenesis even under the condition of high confining stresses. This high void ratio of the Pleistocene clays easily breaks down by the construction loading, which results in serious large and long-term compression. The authors have reported the measured achievement at the reclaimed islands in Osaka Bay (Mimura et al., 2003). On the basis of the in-situ measured information, the new procedure has been proposed in which a viscoplastic deformation is assumed to occur even in the region less than p_c and the proposed procedure has been found to provide good description for the measured long-term compression of each Pleistocene clay layers at Sakishima, Maishima and Yumeshima Reclaimed Islands in Osaka Bay (Mimura and Jang, 2004, 2005). The thick Pleistocene deposits that consist of alternating marine clay (Ma) and gravelly sand layers (Dg), are overlain by the Holocene clay layer (Ma13) in Osaka Bay. And the horizontal continuity of the gravelly sand layers sandwiched by the Pleistocene clay layers was definitely confirmed in Osaka Port (Research Committee on Ground in Osaka Bay, 2002).

It is true that the modeling of compressibility for quasi-overconsolidated Pleistocene clays is the main factor to describe the long-term settlement of the reclaimed Pleistocene marine foundations, but a due attention should also be paid to the fact that the thickness and the coefficient of permeability, k of the gravelly sand layers are the influential factors to control the process of generation and dissipation of excess pore water pressure in the Pleistocene deposits (Mimura and Sumikura, 2000). A rate of consolidation of the sandwiched Pleistocene clay required for those layers are elastic shear modulus,

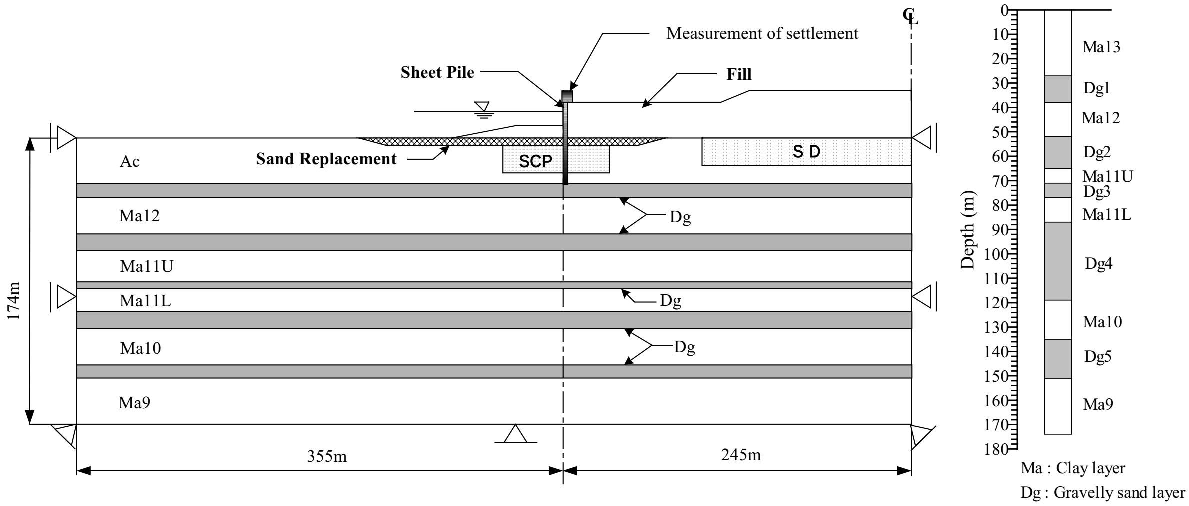

Fig. 1 Model of the foundation ground for finite element analysis

layers is also controlled by the permeability of the Pleistocene gravelly sand layers. The rigidity of the Pleistocene gravelly sand layers is another key factor to evaluate the deformability of the Pleistocene deposits although the contribution to the total settlement is not so large compared to the one taking place in the Pleistocene clay layers. As the parameters controlling the compression of the hard Pleistocene gravelly sand layers have been less concerned, the relevant information of them for detailed numerical analysis is hardly found.

In this paper, behavior of excess pore water pressure in the Pleistocene deposits with the permeability of the gravelly sand layers is investigated through tow-dimensional elasto-viscoplastic finite element analyses. Maishima Reclaimed Island is selected for the representative of the reclaimed islands in Osaka Port. Propagation of excess pore water pressure in the gravelly sand layers is discussed. It is very important to know how far the generated excess pore water pressure will propagate in the permeable gravelly sand layers because it directly influences on the subsequent deformation as well as the adjacent structure. The effect of the permeability of the permeable Pleistocene gravelly sand layers on the subsequent settlement process of each Pleistocene clay layer is also discussed. Discussion is extended to the compressibility of the Pleistocene gravelly sand layers. As it is assumed in the present analysis that the Pleistocene gravelly sand behaves as an elastic material, the main parameters G_0 and Poisson's ratio ν. A series of one-dimensional elasto-viscoplastic finite element analyses is carried out to investigate how the estimation of G_0 for the Pleistocene gravelly sand layer influences on the calculated total settlement of the Pleistocene deposits. In general, the values of G_0 for sandy layers have been determined by an empirical relationship in terms of the N_{SPT} value. In this research, two different empirical equations related to N_{SPT} values are selected to determine G_0 of Osaka Pleistocene gravelly sand layers, and the calculated compression of those layers with both procedures is compared. Yumeshima Reclaimed Island where the total settlement of the Pleistocene deposits has been measured from the start of reclamation is selected as the target area for discussion.

2. Permeability of the Pleistocene Gravelly Sand Deposits

2.1 Problems Set up and Parameters

A series of two-dimensional elasto-viscoplastic finite element analyses is performed to investigate the effect of permeability of the gravelly sand layers on the stress-deformation characteristics for the Pleistocene marine foundation. Maishima Reclaimed Island is adopted as the model foundation shown in Fig. 1. The bottom boundary and the sea side boundaries of the gravelly sand layers are assumed to be fully drained. The reclaimed side boundaries of all layers are assumed to be fully undrained considering the geometrical symmetry. The constitutive model used for numerical analysis is the modified plane strain version (Sekiguchi et al., 1982) of the elasto-viscoplastic model (Sekiguchi, 1977). The input parameters of the Pleistocene clay layers and loading sequence for Maishima Reclaimed Island were already described in the reference (Mimura and Jang, 2004). The Pleistocene gravelly sand layers, which are indicated by Dg, are assumed to be linear elastic materials with finite permeability. The comparative analyses with four different coefficient of permeability for gravelly sand layers are performed. The adopted coefficient of permeability, k in the Pleistocene gravelly sand layers for each case is summarized in Table 1. The sensitivity analyses are performed by varying the coefficient of permeability, k. The one extreme condition is introduced with k equal to be infinite as a benchmark (Case 0). Values of k are varied with 10 times larger (Case 1) or smaller (Case 3) from the actual one (Case 2) to check the effect of permeability of the Pleistocene gravelly sand layers on the subsequent deformation. Another extreme assumption is applied to Case 4 with k equal to 1/100 of the actual value that can be seen offshore far from river mouth. In the case the permeable sandy layers are poor with such low permeability, the effect of excess pore water pressure propagation in those layers is remarkable and the rate of dissipation becomes very low. This kind of problem takes place at the offshore reclaimed island of Kansai International Airport (Akai and Tanaka, 1999, Research Committee on Ground in Osaka Bay, 2002).

Table 1 Adopted coefficient of permeability in the Pleistocene gravelly sand layers for each case

	Coefficient of permeability, k (m/day)
Case0	Fully drained
Case1	2.16×10^{2}
Case2	2.16×10^{1}
Case3	2.16×10^{0}
Case4	2.16×10^{-1}

2.2 Distribution of Excess Pore Water Pressure

Figure 2 shows the calculated contours of excess pore water pressure ratio ($\Delta u/\Delta p$) for each case at the completion of reclamation and after 20 years form the completion of reclamation. The applied load, Δp is different between at the inside of reclaimed island and the revetment. In this paper, to compare the distribution mode of the excess pore water pressure for each case, 224 kPa is adopted as Δp, which is the applied load at the inside of reclaimed island. So, the presented values of $\Delta u/\Delta p$ around the revetment in Fig. 2 are a little less than the actual calculated ones. As shown in Fig. 2, the distribution of excess pore water pressure for the three cases, Case1, Case2 and Case3 are almost the same with the one for Case0 in which the gravelly sand layers are assumed to be fully drained. Although in the untreated Holocene layer (12m to 27m in depth), a large amount of excess pore water pressure remains at the completion of reclamation, the excess pore water pressure in the Pleistocene gravelly sand layers has already been dissipated at the completion of reclamation. It can also be seen that the excess pore water pressure in the Pleistocene clay layers is almost dissipated after 20 years in those cases. On the other hand, for Case4 in which k of the gravelly sand layer is assumed to be 2.16×10^{-1} m/day, the distribution of excess pore water pressure is quite different form other cases. As shown in Fig. 2, a large amount of excess pore water pressure in the upper layer (10m to 82m in depth) remains at the completion of reclamation. In particular, the excess pore water pressure of the gravelly sand layer (Dg1) overlying the Pleistocene clay layer Ma12 is significant. Because of the poor permeability of the gravelly sand layer, relatively larger excess pore water pressure is distributed in the Pleistocene clay deposits than those of the other three cases. It is noteworthy that a remarkable excess pore water pressure remains not only in the upper Pleistocene clay layer such as Ma12 and Ma11 but also in the gravelly sand layer (Dg1) even after 20 years from the completion of reclamation.

It is also very interesting to know the mode of propagation of excess pore water pressure in the gravelly sand layers due to reclamation. Mimura and Sumikura (2000) explained the mechanism of excess pore water pressure propagation in the poorly permeable sandy layers that can be seen at the Pleistocene deposits, southern Osaka. As it is shown in Fig. 2, a significant propagation of excess pore water pressure does not occur in the gravelly sand layers toward the sea side for Case1, Case2 and Case3, not to mention for Case0. On the contrary, for Case4, the excess pore water pressure generated in Dg1 and Dg2 propagates toward the sea side significantly. It is found that the poor permeable gravelly sand layers provides a serious propagation of the excess pore water pressure in them even if they have sufficient thickness.

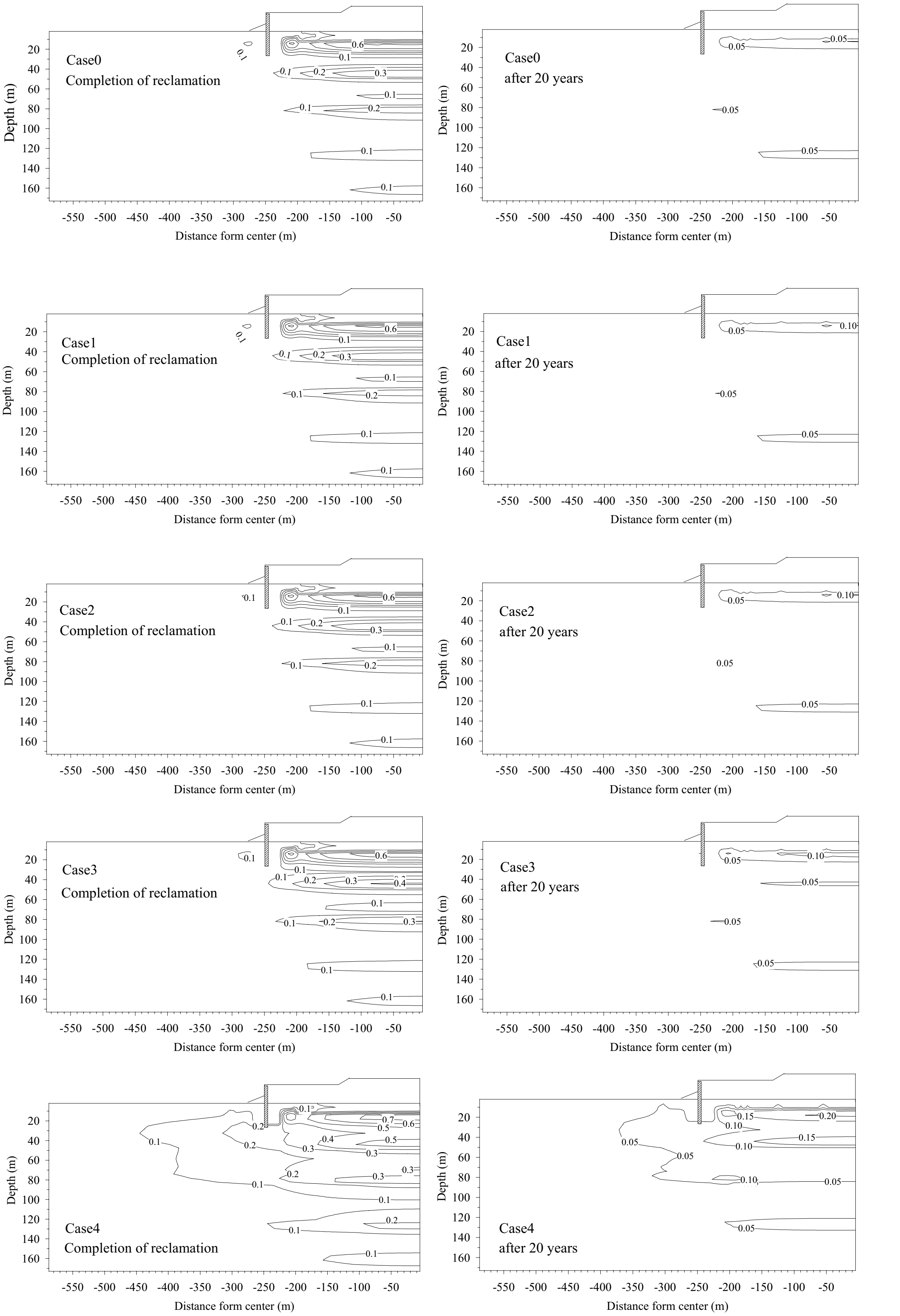

Fig. 2 Contour of Calculated excess pore water pressure ratio

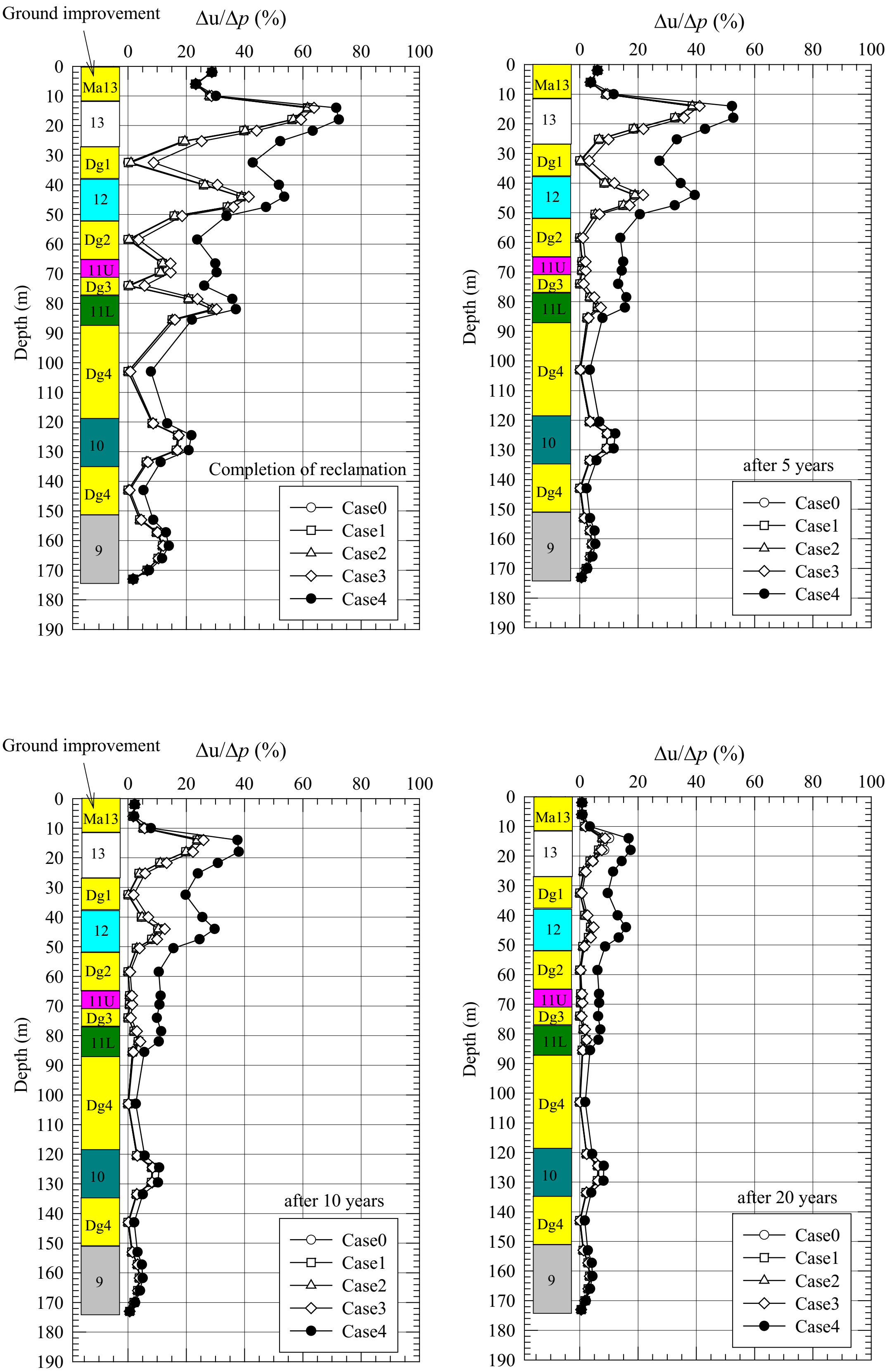

Fig. 3 Profiles of excess pore water pressure ratio with depth

Figure 3 shows the profiles of excess pore water pressure ratio with depth at the centerline of the ground model. It is natural that the profile of excess pore water pressure for Case0 exhibits the jagged shape with a value of zero in the gravelly sand layers, because the gravelly sand layers are assumed to be fully drained for Case 0. Although the gravelly sand layers are assumed as partially drained with finite permeability for Case 1 and Case 2 as shown in Table 1, it can be seen that the calculated profiles of excess pore water pressure ratio are almost the same with that of Case 0. It is true the excess pore water pressure ratio is slightly larger at the completion of reclamation for Case 3 than those for Case1 and Case2 in the upper layer (10m to 82m in depth), but that is almost the same with Case1 and Case2 in the lower layer (below 82m). After 5 years form the completion of reclamation, the excess pore water pressure ratio for Case3 becomes the same with Case1 and Case2. As it is excess pore water pressure contour in Fig. 2, much larger excess pore water pressure ratio is derived for Case4 at the Pleistocene clay layers as well as at the gravelly sand layers due to poor permeability of the gravelly sand layers. Attention should be paid to the fact in Case4 that the process of excess pore water pressure of the gravelly sand layers such as Dg1, Dg2 and Dg3 is very similar for the Pleistocene clay layers overlain by each gravelly sand layers. This mode of excess pore water pressure distribution can be seen in the marine deposits at Kansai International Airport (Akai and Tanaka, 1999), where they have the thinner, less continuous, poorly permeable Pleistocene gravelly sand deposits in the Pleistocene alternating layers. Based on the discussion, it is confirmed that the dissipation of excess pore water pressure could prolong when the quality of permeable layers is poor even if they have sufficient thickness.

2.3 Comparison of Long-term Settlement in the Pleistocene Clay Deposits

The calculated time-settlement relations at the centerline for each Pleistocene clay layer with different permeability of the gravelly sand layers are compared in Fig. 4. First, let us discuss about Ma10 and Ma9 layers whose final stresses remain less than p_c. The generated excess pore water pressure ratio of those layers is less than 20% at the completion of reclamation (see in Fig. 3). As the calculated settlement for those Pleistocene clay layers is developed by the decrease in void ratio not due to dissipation of excess pore water pressure but mainly strain rate dependent behavior without dissipation of excess pore water pressure, it is natural that the settlement process of all cases for Ma10 and Ma9 is almost the same irrespective of the permeability of the gravelly sand layers. On the other hand, the calculated settlement for the upper Pleistocene clay layers such as Ma12, Ma11U and Ma11L in Case4 is smaller than that of other three cases. This difference is caused by the dissipation process of excess pore water pressure influenced by the permeability of the gravelly sand layers. For example, as it is known in Fig. 3, 40% of the maximum excess pore water pressure can be seen in Ma12 even after 10 years form the completion of reclamation for Case4, whereas only 20% of the maximum excess pore water pressure remains for other four cases. Consequently, this difference in effective stress due to dissipation of excess pore water pressure induces the difference in settlement between case4 and other four cases. It should be emphasized that the calculated settlement of the upper Pleistocene clay layers (Ma12 and Ma11) for Case1, Case2 and Case3 is almost the same with the one for Case 0. In other words, the settlement inside the reclaimed island is not affected

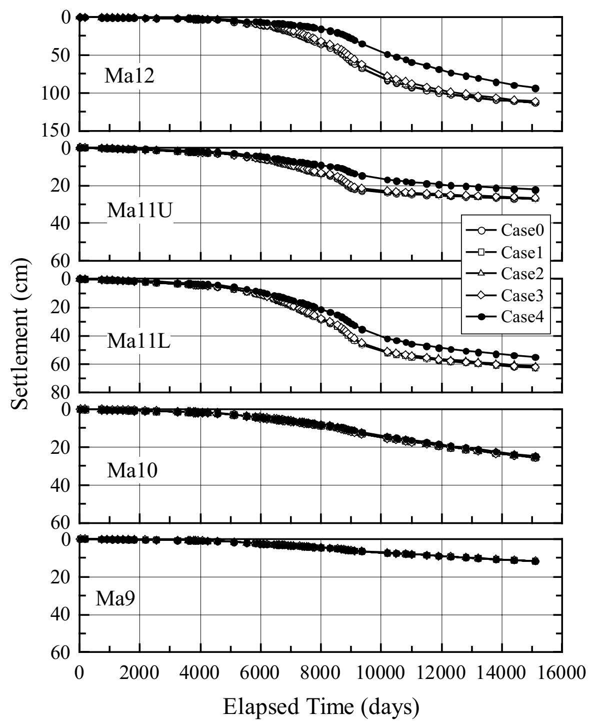

Fig. 4 Comparison of calculated settlement for each Pleistocene clay layer with permeability of the gravelly sand layer

by the permeability of the gravelly sand layers, as far as the coefficient of permeability of those layers has more than 10^0 m/day such as the Pleistocene deposits in Osaka Port. It is noteworthy to find that the calculated settlement of the Pleistocene deposits in Osaka Port is not influenced by the difference in permeability of the sandwiched Pleistocene gravelly sand layers if the value of the coefficient of permeability, k exceeds 10^0 m/day. It means that the propagating effect of excess pore water pressure in the Pleistocene gravelly sand layers can be ruled out for stress-deformation analysis for the reclaimed Pleistocene deposits in Osaka Port. These facts guarantee that the present procedure in terms of elasto-viscoplastic finite element analysis certainly provides the consistent calculated settlement even if the values of k for the Pleistocene gravelly sand layers are set to be infinite.

3. Compressibility of the Pleistocene Gravelly Sand Deposits

3.1 Problems Set up and Parameters

It is self-evident that the compression of the Pleistocene deposits is dominated mainly by the compressibility of the Pleistocene clays, but the instantaneous compression of the intermediate Pleistocene sand layers also contributes to the total settlement even if it is not so significant. Particularly, non-negligible compression can take place in the Pleistocene gravelly sand layers encountered in Osaka Bay because of their large thickness. As they have little construction achievement with measurement related to the Pleistocene gravelly sand deposits, it is very difficult to get the reliable information for evaluating the physical properties of the Pleistocene gravelly sands that are very hard with values of N_{SPT} almost equal to 50 to 60. Undisturbed sampling of those hard Pleistocene gravelly sands is normally associated with disturbance, which results in the serious underestimation of their rigidity derived from laboratory tests. Yoshinaka (1968) suggested the correlation between N_{SPT} and elastic modulus obtained from a borehole lateral load test for the Holocene sand layer as well as clay layer. Sekiguchi et al. (1988) introduced the way determining the elastic shear modulus, G_0 for the intermediate Pleistocene sands of Kansai International Airport foundation ground by using the procedure proposed by Yoshinaka (1968). In the present research, the authors have introduced the procedure on the basis of the field measurement by Okura et al. (1996). Characteristics of compression/swelling for gravelly sand layers including the upper Pleistocene layers with a variation of groundwater level were observed at Osaka Plain (Okura et al., 1996). The value of G_0 for the site was obtained from the relation between the effective stress and occurring volumetric strain due to the variation of groundwater level. The superiority of the procedure by Okura et al. (1996) consists in the fact that the strain was measured in-situ with the change in effective stresses due to changing the ground water level. As the derived rigidity is free from any disturbance associated with sampling, digging holes etc, the values of them are considered much more precise.

A series of one-dimensional elasto-viscoplastic finite element analyses is carried out to investigate the effect of estimation of the rigidity for the Pleistocene gravelly sand layers on the total settlement prediction of the Pleistocene deposits. Yumeshima Reclaimed Island is selected as a target for discussion, because the in-situ total settlement of the Pleistocene deposit including the compression of the Pleistocene gravelly sand layers has been measured there from the start of reclamation. The adopted one-dimensional finite element mesh is shown in Fig. 5 together with the boundary

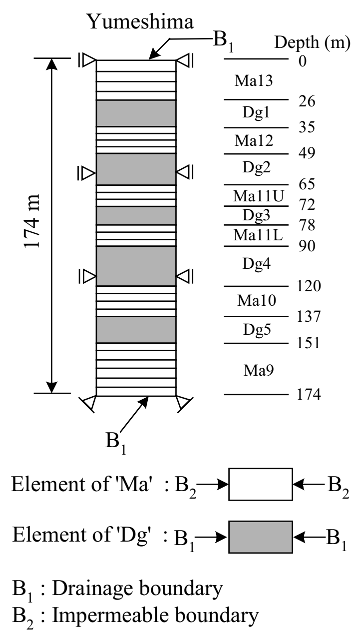

Fig. 5 One-dimensional finite element mesh for Yumeshima Reclaimed Island

Table 2 Determination of elastic shear modulus

Yoshinaka (1968)	Okura et al. (1996)
$G_0\ (\mathrm{kgf/cm^2}) = \frac{7}{2(1+\nu')} N$	$G_0\ (\mathrm{kgf/cm^2}) = \frac{\alpha}{2(1+\nu')} N$, $\alpha = (31\text{-}52)$
G_0 = 15790 kPa	G_0 = 103000 kPa

conditions determined on the basis of the Geo-database (Research Committee on Ground in Osaka Bay, 2002). The bottom boundary is set to be perfect drained because Ma9 is underlain by the thick gravelly sand layer. The side boundaries of the gravelly sand layers are assumed to be also perfect drained on the basis of the findings that the permeability of the sandwiched Pleistocene gravelly sand layers does not affect the settlement of the Pleistocene deposits as far as the coefficient of permeability, k of the Pleistocene gravelly sand layers exceed 10^0 m/day. The side boundaries of the clay layers are set to be fully undrained as shown in Fig. 5. The adopted soil parameters for the Pleistocene clay deposits and loading sequence of Yumeshima Reclaimed Island were already described by Mimura and Jang (2004). It is assumed that an elastic settlement occurs in the gravelly sand layers, which can be calculated by the elastic shear modulus, G_0 and Poisson's ratio, ν'. In this research, the value of G_0 is determined by the above-mentioned two typical empirical procedures with N_{SPT} values. The used empirical equations and determined G_0 are comparatively shown in Table 2. Here, the values of N_{SPT} and ν' of Osaka Pleistocene gravelly sand layers are assumed to be 60 and 0.33 respectively (Research Committee on Ground in Osaka Bay, 2002). The value of α is assumed to be 40 in the empirical equation suggested by Okura et al. (1996). It can be seen that the determined G_0 is quite different between two empirical equations as shown in Table 2. When the target sand layers are relatively thick encountered in Osaka Port, the total compression gained by the Pleistocene gravelly sand layers can possibly not be ruled out even if the strain level due to elastic deformation is not so large.

3.2 Comparison of Compression for the Gravelly Sand Layers

Vertical strain of the gravelly sand layers calculated by using G_0 that obtained from both empirical equations for Yumeshima Reclaimed Island

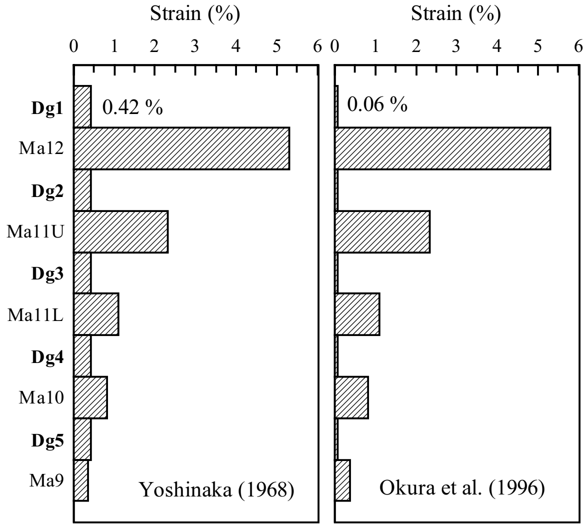

Fig. 6 Calculated vertical strain of the Pleistocene gravelly sand layers

Table 3 Comparison of settlement for the gravelly sand layers

Layer	Settlement of gravelly sand layers (cm)	
	Yoshinaka (1968)	Okura et al. (1996)
Dg1	3.75	0.58
Dg2	6.66	1.02
Dg3	2.50	0.38
Dg4	12.49	1.91
Dg5	5.83	0.89
Total	31.23	4.78

is compared in Fig. 6 together with the vertical strain of the Pleistocene clay layers. As the same N_{SPT} value is assumed for all gravelly sand layers, the vertical strain of those layers is the same irrespective of depth. It is natural that the calculated vertical strain by $G_{0\ \mathrm{Yoshinaka}}$ for the gravelly sand layers is quite larger than that by $G_{0\ \mathrm{Okura\ et\ al.}}$ in Fig. 6, because $G_{0\ \mathrm{Okura\ et\ al.}}$ is much larger than $G_{0\ \mathrm{Yoshinaka}}$. The vertical strain of 0.42 % and 0.06 % are obtained by $G_{0\ \mathrm{Yoshinaka}}$ and $G_{0\ \mathrm{Okura\ et\ al.}}$ in the gravelly sand layers respectively. The calculated settlement of the gravelly sand layers at Yumeshima Reclaimed Island is compared in Table 3. It is noteworthy that the calculated settlement of sandy layer is strongly affected by G_0 values, particularly when the target sandy layers are relatively thick such as the ones encountered in Osaka Port. Introduction of more sophisticated constitutive models for sands has to be considered to describe realistic deformation including non-elastic one in the Pleistocene sand layers. In the present study, the linear elastic deformation is assumed

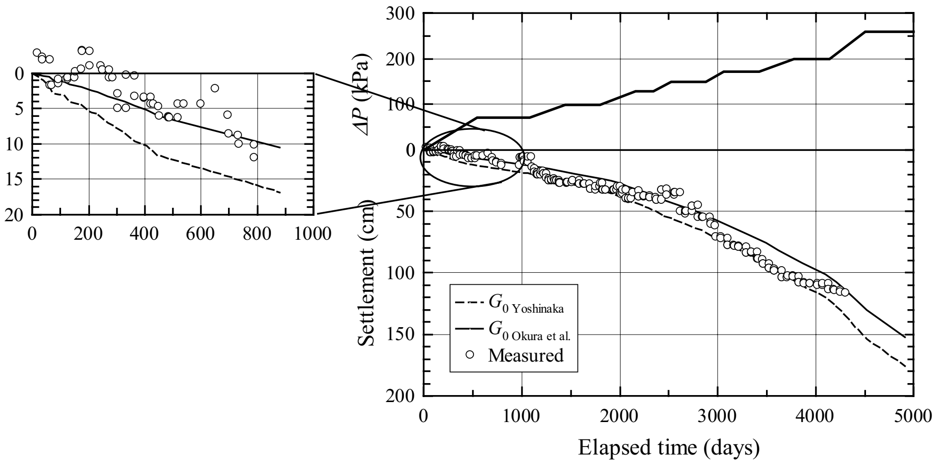

Fig. 7 Comparison of calculated settlement with in-situ settlement for Yumeshima Reclaimed Island

because we only have the information of N_{SPT} values. The sophisticated constitutive models require various soil parameters derived form relevant laboratory tests. Without those reliable values for soil parameters, the calculated results by the sophisticated models cannot guarantee the validity. The use of the sophisticated models should be associated with the relevant subsoil investigations that can provide reliable soil parameters for the models. As the authors consider that the simplified linear elastic behavior is appropriate for the condition that only values of N_{SPT} are available, the linear elastic model with G_0 and ν' is introduced in the present study.

The calculated settlement of the Pleistocene deposits for Yumeshima Reclaimed Island is compared with the in-situ settlement in Fig. 7. The long-term settlement of the Pleistocene clay deposits was already discussed (Mimura and Jang 2005). The instant settlement occurring in the gravelly sand layers is highlighted in Fig. 7. It can be seen in Fig. 7 that the slight settlement took place at the starting stage of reclamation. Scattering of measured data do not merit discussion because of the resolution of measurement. It is noteworthy to point out that the calculated settlement with $G_{0\ \mathrm{Yoshinaka}}$ overestimates the measured settlement while that with $G_{0\ \mathrm{Okura\ et\ al.}}$ can well describe the field data. From those results, it is confirmed that the evaluation of G_0 for the Pleistocene gravelly sand deposits play a significant role for the settlement prediction especially at early reclamation stage, and the values of G_0 for the hard Pleistocene gravelly sand layers should be determined by the procedure by Okura et al (1996).

4. Conclusion Remarks

Sandwiched gravelly sand layers in the Pleistocene deposit function as the permeable boundaries for compressible Pleistocene clay layers. How the capacity of permeability of the Pleistocene gravelly sand layers influences the compression of the Pleistocene deposits is interpreted through the elasto-viscoplastic finite element analyses for Maishima Reclaimed Island in Osaka Port. Because of the large thickness, well horizontal continuity and gravel-based formation, the Pleistocene gravelly sand layers in Osaka Port have high permeability with the coefficient of permeability of 2.16 x 10^1 m/day. On the basis of the calculated performance, it is concluded that the effect of the permeability can be ruled out for the reclaimed islands in Osaka Port as far as the values of the coefficient of permeability, k exceed 10^0 m/day. No serious propagation of excess pore water pressure occurs in the Pleistocene gravelly sand layers during reclamation. The mode of settlement of the Pleistocene deposit in Osaka Port is scarcely affected by the permeability of the sandwiched Pleistocene gravelly sand layers. In the sense, one-dimensional consolidation is permitted to introduce for evaluation of the long-term settlement of the Pleistocene deposits inside the reclaimed islands in Osaka Port.

Compression of the hard Pleistocene gravelly sand layers is less influential than that of the Pleistocene clay layers. As is often the case, the contribution of those gravelly sand layers to the settlement is not taken into consideration. However, the contribution of the Pleistocene gravelly sand layers to the total settlement of the Pleistocene deposits in Osaka Port merits a discussion because of their large thickness. The procedure to evaluate the rigidity of the hard Pleistocene gravelly sand layers is introduced. The superiority of the present procedure consists in the fact that the compression and swelling associated with the change in effective stress due to lowering and recovering of the underground water during excavation project were directly monitored in the field. The in-situ derived values of the rigidity are completely free from disturbance by sampling, stress release and trimming. The calculated performance with the rigidity of the Pleistocene gravelly sand layers derived by the newly introduced procedure for Yumeshima Reclaimed Island shows a good agreement with the measured total settlement of the Pleistocene deposit.

Acknowledgements

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海上埋立による更新統地盤の長期沈下に対する硬質砂礫層の寄与について

張　祐榮・三村　衛

要旨

大阪港では更新統砂礫層が厚く、十分な透水性を有しており、k=10^{-3}cm/s 以上の透水係数であれば、その透水性は更新統粘土地盤の沈下性状にほとんど影響しないことがわかった。埋立初期からの更新統全層の沈下実測結果との比較から，更新統砂礫層の剛性はかなり大きく，地下水位低下に伴う有効応力変化によって生じる更新統砂礫層の圧縮量から算定する大倉らの手法で求めた値がパラメータとして妥当であることがわかった。

キーワード：擬似過圧密更新統粘土，更新統砂礫層，透水係数，過剰間隙水圧，せん断弾性係数，弾粘塑性 FEM