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Numerical assessment for long-term settlement of the reclaimed Pleistocene deposits

Évaluation numérique du tassement à long terme de dépôts du Pléistocène gagnés sur la mer

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ABSTRACT

Long-term settlement has occurred at the reclaimed area and islands in Osaka Bay caused by the time-dependent compression of the Pleistocene clays. The authors proposed a new procedure to assess the compression characteristics of the Pleistocene clays in Osaka Bay. A series of one-dimensional elasto-viscoplastic finite element analyses is carried out to evaluate the long-term settlement for Sakishima, Maishima and Yumeshima Reclaimed Islands in Osaka Port. The calculated performance by the elasto-viscoplastic finite element analyses formulated with the proposed procedure is found to well evaluate the long-term settlement of the Pleistocene deposits measured in the reclaimed islands in Osaka Port, whereas the conventional approach is found to exhibit serious underestimation. It is also confirmed that the estimation of elastic shear modulus, G_0 for the Pleistocene gravelly sand deposits plays a significant role for the settlement prediction.

RÉSUMÉ

Des tassements à long terme de terrains gagnés sur la mer et d'îles artificielles se sont produits dans la Baie d'Osaka à cause de la compression influencée par le temps des argiles du Pléistocène. Les auteurs proposent une approche viscoplastique pour évaluer les caractéristiques de compression des argiles du Pléistocène de la Baie d'Osaka. Des analyses unidimensionnelles et élasto-viscoplastiques par éléments finis ont été effectuées pour évaluer les tassements à long terme des terrains gagnés sur la mer de Sakishima, Maishima et Yumeshima, dans le Port d'Osaka. Les résultats montrent un bon accord avec les tassements à long terme des dépôts du Pléistocène mesurés sur les sites considérés, alors que l'approche conventionnelle conduit à une sous-estimation importante de ces tassements. L'étude confirme aussi que l'estimation du module de cisaillement, G_0, des dépôts de sable graveleux du Pléistocène joue un rôle significatif dans les prédictions de tassement.

1 INTRODUCTION

Along Osaka Bay, the problem related to long-term settlement was recognized in the Port Island where the unforeseen settlement advanced at the time when the reclaimed ground appeared above the sea level in 1971. Mikasa and Takada (1977) confirmed that the unforeseen settlement was attributed to the compression of the Pleistocene clay layers based on the in-situ measurement. Kiyama (1991) pointed out that the serious long-term settlement had continued at the reclaimed islands in Osaka Bay, such as Osaka South Port (Sakishima Reclaimed Island) and Rokko Island with the contribution of compression of the Pleistocene clay layers. Mimura et al. (2003) reported on the basis of the in-situ measured records that the reclaimed islands in Osaka Port have suffered from remarkable long-term settlement due to the serious time dependent compression of the Pleistocene clays for a long time although they do not undergo plastic yielding. Those Pleistocene clays in Osaka Bay have been called "quasi-overconsolidated clays" (Akai and Sano 1981).

In this paper, a series of elasto-viscoplastic finite element analyses is carried out to assess the long-term deformation occurring at the reclaimed islands in Osaka Port. A new procedure for the compression of the Pleistocene clays was proposed and incorporated in the finite element code (Mimura and Jang, 2004) on the basis of the fact that the quasi-overconsolidated Pleistocene clays can be regarded as normally consolidated from the sedimentation environment of Osaka Bay (Kobayashi et al., 2001). The calculated performance is verified by comparing with the long-term measurement of settlement in the reclaimed islands followed by the description of the characteristic performance of this new procedure. Based on those discussions, the validity and superiority of the present procedure is interpreted. 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 sand layers encountered in Osaka Bay because of their large thickness. 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.

2 COMPRESSION MODEL FOR QUASI-OVERCONSOLIDATED PLEISTOCENE CLAYS

As already stated above, the Pleistocene clays in Osaka Bay can be regarded as normally consolidated based on the history of sedimentation, whereas they exhibit the apparent overconsolidation with an OCR of 1.1 to 1.4. The in-situ measured data show that the long-term settlement has actually taken place at the reclaimed islands of Osaka Port even in the Pleistocene clay layers that do not undergo plastic yielding. On the basis of those findings, Mimura and Jang (2004) proposed a new procedure to assess the compression characteristics of Pleistocene clays in Osaka Bay. Figure 1 (a) shows the proposed concept for the compression modeling compared to the conventional compression model. The Pleistocene clays are assumed to exhibit an elasto-viscoplastic behavior even in the quasi-overconsolidated region ($p_0 \leq p \leq p_c$) because they can be regarded as normally consolidated aged clays, while an elastic behavior is assumed to occur in this region by the conventional constitutive model as shown in Fig. 1 (b). In the proposed compression model, the yield stress, p_c derived from conventional consolidation test is assumed not to be the one associated with plastic yielding but the one changing the phase of deformation due to fading the structural effect. But once those clays undergo additional loading surpassing p_c, the corresponding total stress, p_2 in Fig.1 (a)

should be p_c and in the unloading - reloading region clays exhibit elastic behavior as is conventionally assumed.

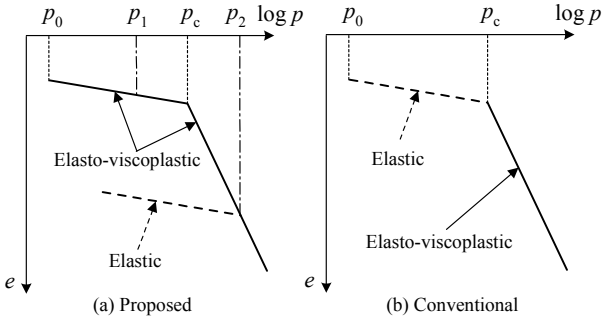


Figure 1. Compression model

3 OUTLINE OF RECLAIMED ISLANDS AT OSAKA PROT AND ELASTO-VISCOPLASTIC FINITE ELEMENT ANALYSIS

In Osaka Port, reclamation for harbor constructions was started from 1950s and the three major reclaimed islands have been constructed. Figure 2 shows the plan view of the latest Osaka Bay area together with the depths of the sea. Sakishima was constructed from 1958 to 1980, Maishima from 1973 to 1990, and Yumeshima has been constructed since 1988. There is also a plan for construction of a new reclaimed island in the offing of Yumeshima. Each island was constructed in the region where seabed level is O.P. (=Osaka Pail: the standard unit of elevation in Osaka) ±0 to -10m as shown in Fig. 2. The clayey soils dredged for the seabed and those waste disposals were used to construct these three islands. The load due to reclamation is about 150 to 250kPa. The data of settlement discussed in this paper have been measured at A for Sakishima, B for Maishima and C for Yumeshima respectively as shown in Fig. 2.

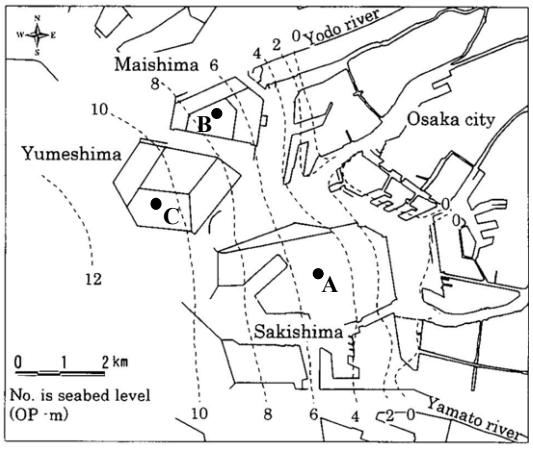


Figure 2. Plan view of Osaka Bay

A series of elasto-viscoplastic finite element analyses is performed for the above-mentioned three reclaimed islands in Osaka Port. The constitutive model used in the finite element code is the modified plane strain version (Sekiguchi et al., 1982) of the elasto-viscoplastic model proposed by Sekiguchi (1977). As the reclaimed area is huge enough to assume that the deformation takes place one-dimensionally, in addition the gravelly sand layers sandwiched by the clay layers are thick and continuous enough to regard them as perfectly drained layers (Research Committee of Seabed Deposits in Osaka Bay 2002), one-dimensional analysis is adopted in the present paper without considering the effect of permeability loss in those gravelly sand layers.

Figure 3 shows the subsurface foundation model for each reclaimed island determined based on the Geo-database (Research Committee of Seabed Deposits in Osaka Bay 2002). As is definitely seen, the subsoil conditions of three sites are almost similar. The construction sequence and the way of reclamation are also the same for all sites, namely, the dredged clayey soils, the good quality sandy soils and construction disposals were used for reclamation and filling respectively. The vertical drains with a dewatering method were used to promote consolidation for Ma13 and the dredged clay layer. In the present analyses, the above-mentioned proposed procedure is adopted, namely, the compression curve in the quasi-overconsolidated region with the inclination of $\kappa=\lambda_{QOC}$ is assumed to have a viscoplastic component as same as in the NC region (Mimura and Jang, 2004). The soil parameters required for the input to the finite element code were determined rationally based on the prescribed procedure (Mimura et al., 1990).

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 paper, the value of G_0 is determined by the empirical procedure with N_{SPT} values (Okura et al., 1996). The values N_{SPT} of and ν' of Osaka Pleistocene gravelly sand layers are assumed to 60 and 0.33 respectively (Research Committee of Seabed Deposits in Osaka Bay, 2002).

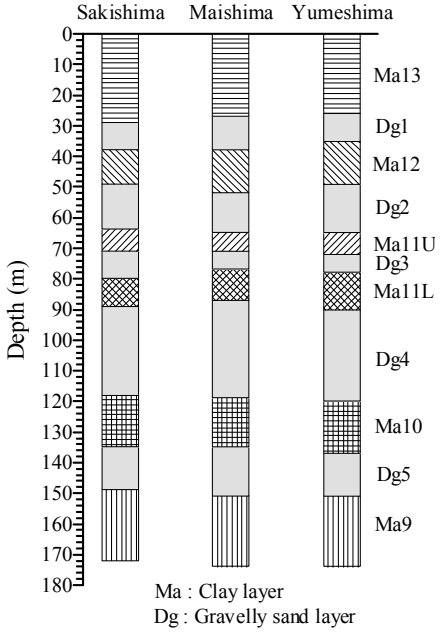


Figure 3. Subsurface foundation model

4 RESLUTS AND DISCUSSION

The calculated increasing process of vertical stress and the gain in vertical strain are shown in Fig. 4 for Sakishima Reclaimed Island. For comparison, the performances by both the conventional and proposed procedure are shown together for each Pleistocene clay layer. It is natural large compression occurs when the stress surpasses p_c as seen for Ma12 and 11L, but a due attention should be paid to the fact that the proposed procedure provides the gain in strain even in the region less than p_c. This behavior is more clearly seen for Ma10 the stress of which remains below p_c. The serious long-term compression is calculated by the proposed procedure whereas the strain by the conventional model remains instantaneous and small. As is clearly shown in Fig. 4, the calculated performance with the proposed procedure provides larger and time-dependent compression both in the case the stress due to reclamation surpasses p_c or remains less than p_c.

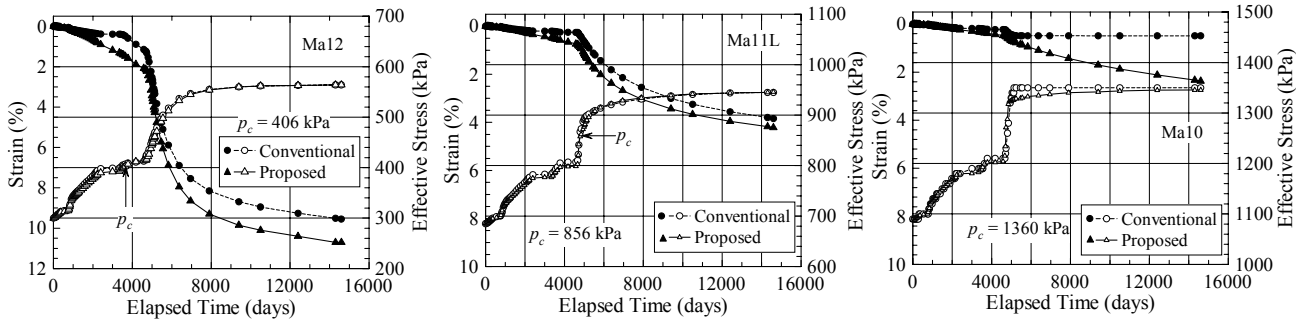


Figure 4. Calculated increasing process of vertical effective stress and vertical strain (Sakishima Reclaimed Island)

The calculated settlement is compared with the in-situ measured data for Sakishima in Fig. 5. At Sakishima, the compression of Ma 12 can only be discriminated because differential settlement gauges were set for this layer. For Ma 12, the stress of which surpasses far beyond p_c (see Fig. 4), the calculated compression with the proposed procedure definitely traces the measured data. It should be noted that the discrepancy between the proposed and the conventional model is not so large because the settlement of Ma12 took place by the contribution of normally consolidated compression components, whereas the difference between both procedures is mainly caused by the time-dependent compression occurring in the region less than p_c. However, the rate of settlement with time is better predicted by the proposed procedure. The superiority of the proposed procedure is more clearly shown in the comparison for the layers below Ma11. The calculated performance with the proposed procedure can describe the measured settlement below Ma11 much better than the conventional one because of the consideration of the viscoplastic behavior in the region less than p_c. Then, as for the total settlement of the Pleistocene deposits, the proposed procedure can predict the in-situ behavior almost perfectly.

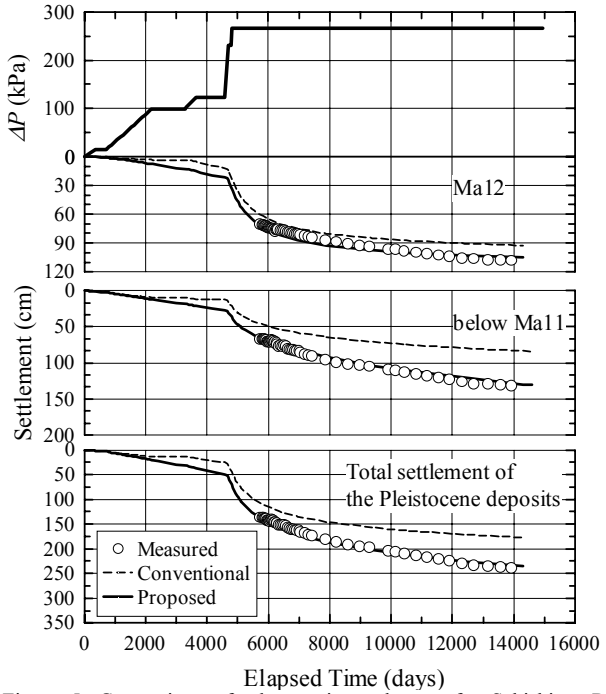
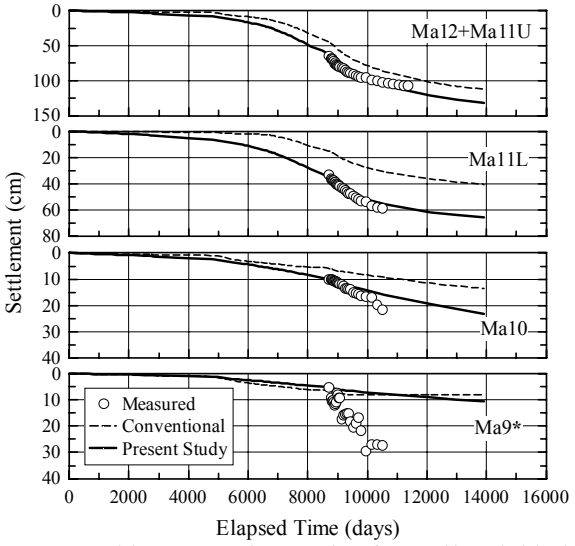


Figure 5. Comparison of advance in settlement for Sakishima Reclaimed Island

Figure 6 shows the comparison for Maishima Reclaimed Island. More detailed differential settlement was monitored at Maishima, namely, the compression of Ma12+Ma11U, Ma11L and Ma10 were separately measured. Therefore, discussion for the quality of prediction by the models can be critically discussed. The compression of Ma12+Ma 11U, Ma11L and Ma10 are discriminated. Except below Ma9, the calculated compression with the proposed procedure can better describe the measured one for all cases than the conventional model. Particularly, for the deeper Pleistocene clays, such as Ma11L and Ma10, the quality of prediction with the proposed procedure is found to be much better than the conventional model. The settlement shown in Fig. 7 is derived by summating all compression in Fig. 6. It is natural that the proposed procedure provides better coincidence with the measured total settlement of the Pleistocene clay deposits at Maishima.



* Measured data : Summated compression of Ma9 and its underlying layers

Figure 6. Comparison of advance in settlement of each Pleistocene clay layer for Maishima Reclaimed Island

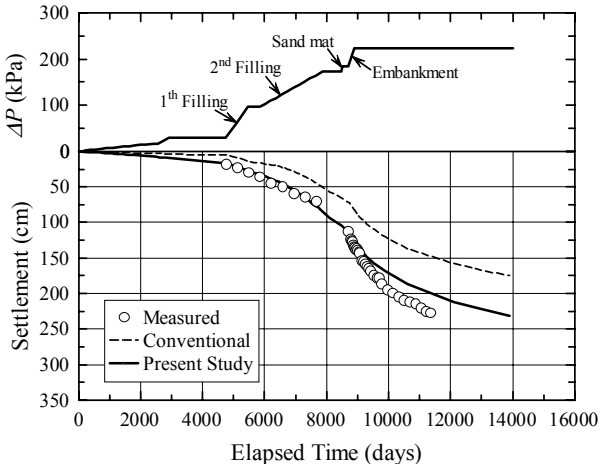


Figure 7. Comparison of advance in total settlement for Maishima Reclaimed Island

The calculated settlement for Yumeshima Reclaimed Island is compared with the in-situ measured data in Fig. 8. Here, it should be emphasized that the total settlement of the Pleistocene deposits has been monitored from the beginning of the reclamation only at Yumeshima. It is true as discussed above that the proposed procedure can provide better description both for Sakishima and Maishima, but the comparison was done only for the limited period of overall reclamation. The validity of the procedure can be discussed by comparing the total compression of the Pleistocene deposits from the beginning of reclamation at Yumeshima. As is seen in Fig. 8, the calculated performance with the proposed procedure also shows a better agreement with the in-situ measurement although the construction is not completed yet. The conventional model definitely underestimates the actual settlement also at Yumeshima site. From those findings discussed for the three reclaimed islands, the proposed procedure is evaluated to have better descriptive accuracy for the long-term settlement of the quasi-overconsolidated Pleistocene clay deposits in Osaka Port.

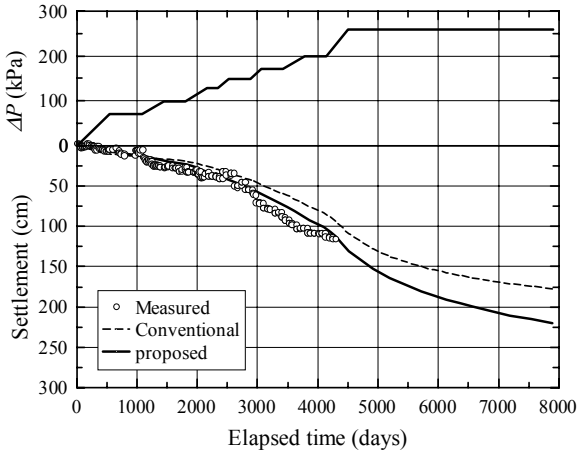


Figure 8. Comparison of advance in total settlement for Yumeshima Reclaimed Island

The elastic rigidity, G_0 for the Pleistocene gravelly sands, Dg is estimated based on the method by Okura et al. (1996) in which it is determined by the monitored in-situ compression of the Pleistocene gravelly sand deposits due to the change in effective stress associated with dewatering in the excavation project. The values derived by this method are trustworthy because of being free from any disturbance associated with sampling.

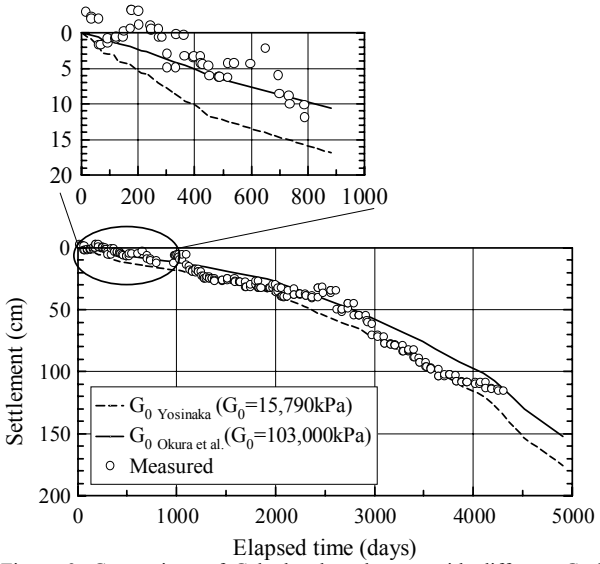


Figure 9. Comparison of Calculated settlement with different G_0 for Yumeshima Reclaimed Island

The calculated settlement of the Pleistocene deposits for Yumeshima Reclaimed Island is compared with the in-situ settlement in Fig. 9. 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 $G_{0\ \text{Okura et al.}}$ can well describe the measured data while that with $G_{0\ \text{Yoshinaka}}$ that is derived on the basis of the relations between N_{SPT} and G_0 for alluvial sands exhibits overestimation.

5 CONCLUSIONS

The predictive accuracy of the proposed compression model for the quasi-overconsolidated Pleistocene clays in Osaka Port is discussed. The assumption that the time-dependent irreversible deformation occurs even in the region less than p_c as well as normally consolidation region is adopted to the proposed compression procedure based on the fact that the quasi-overconsolidated clays in Osaka Bay can be regarded as normally consolidated from the history of sedimentation environment. The calculated performance by the elasto-viscoplastic FE analyses formulated with the proposed procedure is found to successfully describe the in-situ long-term settlement of the Pleistocene deposits measured in the reclaimed islands in Osaka Bay, whereas the conventional framework could not function well. It is also confirmed that the estimation of G_0 for the Pleistocene gravelly sand deposits play a significant role for the settlement prediction especially at early reclamation stage, and the adopted values of G_0 for the firm Pleistocene gravelly sand layers in the present analysis are trustworthy for describing the in-situ compression of the Pleistocene deposits.

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