Long-term Deformation of the Reclaimed Pleistocene Foundation of the Offshore Twin Airport

Déformations à long terme d'une fondation de remblai pléistocène récupéré sur mer pour un projet d'aéroport jumelé

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ABSTRACT: A series of elasto-viscoplastic finite element analyses is performed to assess the long-term deformation including the interactive behavior of the reclaimed Pleistocene foundation due to the adjacent construction of the offshore twin airport. Attention is paid to the modeling of permeability for the Pleistocene sand gravel layers considering the sedimentation environment. The concept of "mass permeability" is introduced to model the actual process of dissipation of excess pore water pressure in the field. It is regarded as the macroscopic capability of permeability for the individual Pleistocene sand gravel layers by evaluating the permeability not of each element but of the whole layer in one body. The mechanism for the propagation of excess pore water pressure due to construction of the adjacent reclamation is discussed through the numerical procedure using the concepts of "mass permeability". The concept of "mass permeability" for the individual Pleistocene sand gravel layers is found to well function to assess the long-term deformation including the interactive behavior in the reclaimed Pleistocene foundation.

RÉSUMÉ : Les déformations à long terme d'un remblai pléistocène en mer sont évaluées a partir d'une série d'analyses élasto-viscoplastiques par éléments finis. Les interactions dues aux travaux d'aménagement d'aéroport jumelé sont aussi prises en compte. On vise plus particulièrement à modéliser la perméabilité du sable/gravier pléistocène en considérant la sédimention du milieu. La dissipation des surpressions interstitielles in-situ est calculée à partir d'une perméabilité massique de l'ensemble des couches sable/gravier. Les mécanismes de propagation de surpressions interstitielles induites par le remblai voisin sont déterminés par modélisation numérique faisant appel au concept de perméabilité massique. L'application de ce concept semble être commode pour évaluer les déformations à long terme des couches sable/gravier pléistocène en interaction avec d'autres ouvrages voisins.

KEYWORDS: elasto-viscoplastic finite element analysis, mass permeability, standard hydraulic gradient

1 INTRODUCTION

The development of coastal areas accomplished in Japan has been outstanding. Kansai International Airport (KIX) was constructed in Osaka Bay as two man-made reclaimed islands to minimize noise and pollution in residential areas as well as to meet the increasing demand for air transportation. Such a large-scale offshore reclamation in Osaka Bay is accompanied with large and rapid settlement of deep Pleistocene clay deposits (Mimura et al., 2003). Long-term settlement of the Pleistocene marine foundations due to huge reclamation load has been of great concern in this project. The seabed deposits of Osaka Bay have been formed due to the soil supply from the rivers and the alternating deposits of KIX have been formed due to sedimentation of clayey soils during transgression and of sandy to gravelly soils during regression on the sinking base of Osaka Bay. The Pleistocene clay deposited in Osaka Bay exhibits the behavior of the quasi-overconsolidated clay without definite mechanical overconsolidation history. Itoh et al. (2001) summarized on the basis of the data from elastic wave exploration and in-situ boring logs that the Pleistocene sand gravel deposits are not always distributed uniformly in thickness, consistently and that the amount of fine contents included in them is significant. The most serious problem originating from these sand gravel deposits is the "permeability" that controls the rate of consolidation of sandwiched Pleistocene clays. In the sense, the modeling for the quasi-overconsolidated Pleistocene clay and the evaluation of permeability for the Pleistocene sand gravel deposits are the significant factors to assess the long-term behavior of the reclaimed Pleistocene foundation due to the reclamation of the offshore twin airport. Mimura and Jang (2004) proposed a concept of compression in which viscoplastic behavior is assumed to occur even in the quasi-overconsolidated region less than p_c for the Pleistocene clays in Osaka Bay. The procedure has been found to be versatile and allows for the long-term settlement monitored in the reclaimed islands in Osaka Port to be described (Mimura and Jang, 2005a). In the present paper, the numerical procedure to assess the long-term behavior of the Pleistocene deposits at KIX in terms of elasto-viscoplasitc FEM is proposed by introducing the concept of "mass permeability" and "standard hydraulic gradient" for the Pleistocene sand gravel layers. The validity of the procedure is carefully discussed by comparing the performed results with in-situ measurements.

2 CONCEPTS OF "MASS PERMEABILITY" AND "STANDARD HYDRAULIC GRADIENT"

Mimura and Jang (2005a) reported when the permeability of sand gravel layers is considered perfectly drained, one-dimensional analysis only considering the characteristic of clayey soil can be adopted for the consolidation problem without considering the effect of permeability loss in the those sand gravel layers. However, the sand gravel layers sandwiched by the Pleistocene clay layers at KIX were recognized not to function as perfect drainage layers through the in-situ measurement of excess pore water pressure. Therefore, the two or three-dimensional analysis that considers the permeability of the Pleistocene sand gravel layers is required to assess the long-term behavior of the reclaimed Pleistocene foundation. The influential factors to evaluate the permeability of sand gravel layers are the thickness, the horizontal continuity and the fine contents of them. The permeability of them is different with places even if they are categorized as the identical ones. But, it is impossible to evaluate the permeability of sand gravel layers at every point. It is also very difficult to confirm how the sand gravel layers under the Pleistocene marine foundation are distributed in practice. The concept of "mass permeability" is proposed to evaluate the permeability not of each element but of the whole layer in one body. It is regarded as the macroscopic capability of permeability for the individual sand gravel layers by considering the horizontal continuity, the change in thickness and the degree of fine contents of them. Mimura and Jeon (2011) evaluated the mass permeability of the Pleistocene sand gravel layers using the simple foundation model as shown in Fig.2. The distribution of sand gravel layers not only in the loading area but also in the area that can rule out the effect of the hydraulic boundary condition should be considered to assess the mechanism of the propagation/dissipation of excess pore water pressure in the coupled stress-flow analysis. In the sense, on the basis of the assumption that the hydraulic gradient derived in the representative foundation model having the horizontally even layer with constant thickness is regarded as the standard one for the individual Pleistocene sand gravel layers, the evaluated mass permeability can be the representative of the capacity of permeability for the individual Pleistocene sand gravel layers at KIX. The standard hydraulic gradient is hence applied to the geologically genuine foundation model that has been developed to consider the actual stress level not only of the monitoring point but also of the considered area for the numerical analysis. Due attention should be paid to the fact that this assumption is only considered in horizontal position for the individual Pleistocene sand gravel layers.

3 FOUNDATION MODEL AND HYDRAULIC BOUNDARY

The differential settlement of the individual Pleistocene clay layers as well as the excess pore water pressure at various depths, both in the clay and the sand gravel layers, have been measured at a lot of points of KIX. Figure 1 shows the plan view of KIX together with the location of representative monitoring points on the 1st phase island. A series of elaso-viscoplastic finite element analyses is carried out along the representative section shown by A-A' at monitoring point 1 in Fig.1. Figure.2 shows the representative foundation model assumed to be horizontally even layer that have a constant thickness and continuous layer based on the boring data at the monitoring point 1. Figure.3 shows the geologically genuine foundation model having the inclined base and layers that is constructed based on the soil exploration and geological survey data (Kitada et al, 2011). The clay layers increase in thickness towards the offing and the sand gravel layers drastically change in thickness horizontally. The continuity of the individual layers is still guaranteed even for the geologically genuine foundation

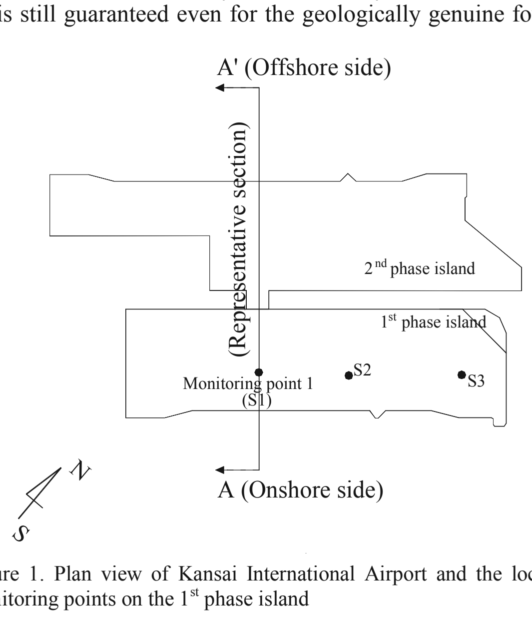


Figure 1. Plan view of Kansai International Airport and the location of monitoring points on the 1st phase island

model in the present study. Here, Ma and Ds denote marine clay

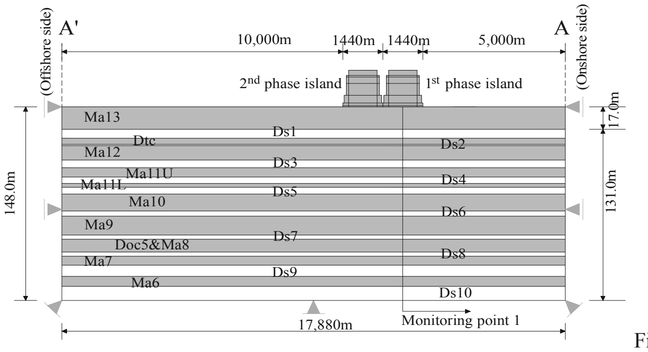


Figure 2. Representative foundation model of KIX for finite element analysis at representative section

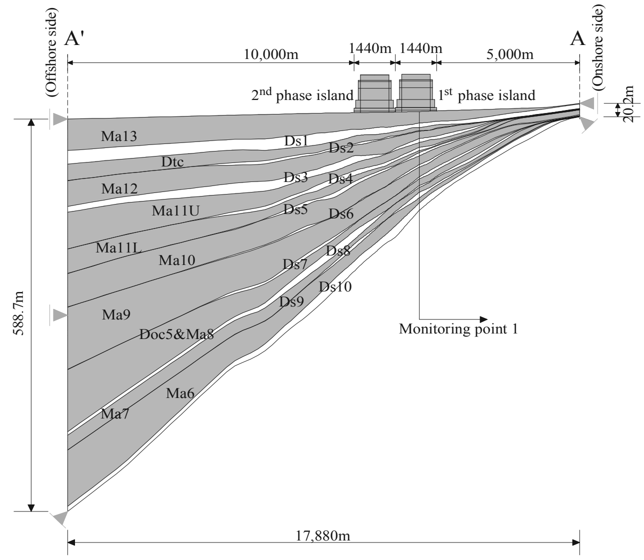


Figure 3. Geologically genuine foundation model of KIX for finite element analysis at representative section

and Pleistocene sand gravel layer respectively. Ma13 is the Holocene marine clay whereas others are the Pleistocene origin. For the Holocene clay deposit, Ma13, sand drains are driven in a rectangular configuration with a pitch of 2.0 to 2.5 meters to promote consolidation. The lateral boundary of the clay layers is assumed to be undrained while the one of the sand gravel layers is assumed to be fully drained. Mimura and Jang (2005b) reported that when the distance to the boundary is set to be about 10 times of the loading area, the effect of the hydraulic boundary condition can be ruled out. Based on the findings, the same condition is satisfied even for the foundation models used in the present study. The distance to the offshore and onshore boundary is set to be 10,000m and 5,000m respectively. The present two foundation models are divided into finite element mesh consisting of 8,580 nodal points and 8,378 elements.

4 LOADING CONDITION AND SOIL PARAMETERS

The prescribed final overburden due to airport fill construction amounts to about 430kPa at the 1st phase island and about 530kPa at the 2nd phase island respectively. The 2nd reclamation is started after about 13years from the 1st reclamation. In the present analysis, the permeable capability evaluated from the concept of "mass permeability" for the Pleistocene sand gravel layers is applied for the present finite element analysis. On the basis of the findings by Itoh et al. (2001), the relatively high permeable capability are assumed for Ds1,3 10 because they have been evaluated as gravelly, horizontally continuous and having enough thickness. On the other hand, very low permeable capability is assumed for Ds6 and 7 that have been evaluated to have insufficient thickness with high degree of fine contents and poorly continuous. The other layers have been evaluated as the ordinary permeable capability. The used all soil parameters for analysis are also exactly the same with that used by Mimura and Jeon (2011).

5 RESULTS AND DISCUSSIONS

The calculated distribution of excess pore water pressure before and after the construction of the 2nd phase island is shown in Fig.4 for two foundation models respectively. As shown in Fig.4, the similar distribution tendency of excess pore water pressure can be seen for two foundation models. It should be noted that a large amount of excess pore water pressure still remains undissipated in the middle Pleistocene clay layers, Ma10, 9 and Doc5&Ma8 as well as sand gravel layers, Ds6 and 7 before the construction of the 2nd phase island because of poor permeability of sand gravel layers, Ds6 and 7. In contrast, the excess pore water pressure in the upper and lower Pleistocene layers such as Dtc, Ma12,11,7,6 and Ds1,3,9,10 is monotonically dissipated with time because of high permeability of sand gravel layer, Ds1,3 and 10. At the completion of the 2nd reclamation, a large amount of excess pore water pressure is concentrated in the upper and middle Pleistocene layers such as Ma12, 10, 9 and Doc5&Ma8 beneath the foundation of the 2nd phase island. Here, a due attention should also be paid to the fact that the increased excess pore water pressure beneath the foundation of the 2nd phase island is propagated to that of the 1st phase island. Since the permeability of the upper and lower Pleistocene sand gravel layers is higher than the one of the middle layers, a larger amount of excess pore water pressure in the upper and lower Pleistocene layers is propagated compared to the one in the middle layers of the foundation of the 1st phase island.

The calculated horizontal distribution of excess pore water pressure in the representative Pleistocene sand gravel layers (Ds3, 6, 10) are shown in Fig. 5 at the time before and after the construction of the 2nd phase reclamation for both foundation models. In the present study, the identical permeable capability for the individual Pleistocene sand gravel layers in two foundation models is applied by considering the concepts of "mass permeability" and "standard hydraulic gradient". However, in Fig.5, it should be noted that the distribution of excess pore water pressure near the 1st phase island almost shows a good match for two foundation modes by applying the concept "standard hydraulic gradient" whereas the one of the other region shows the discrepancy distribution with the stress level. The stress level beneath the foundation of the 1st phase island is almost the same for two foundation models because the representative model was developed based on the monitoring point 1 whereas the one beneath the foundation of the 2nd phase island is different each other due to change in thickness of geologically genuine foundation model. It is noteworthy that

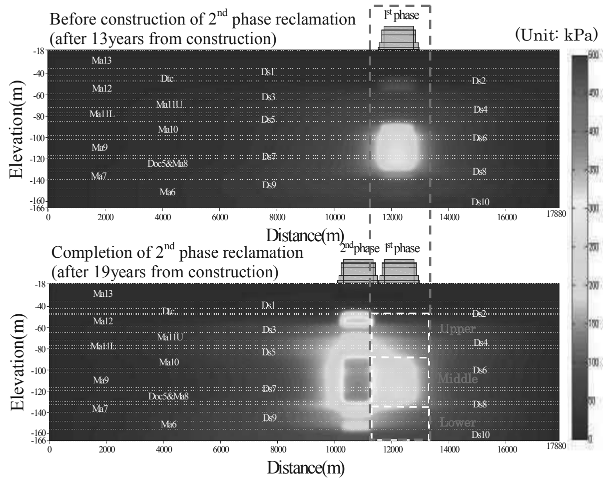


Figure 4(a). Contour of excess pore water pressure for representative foundation model at before and completion of 2nd phase reclamation

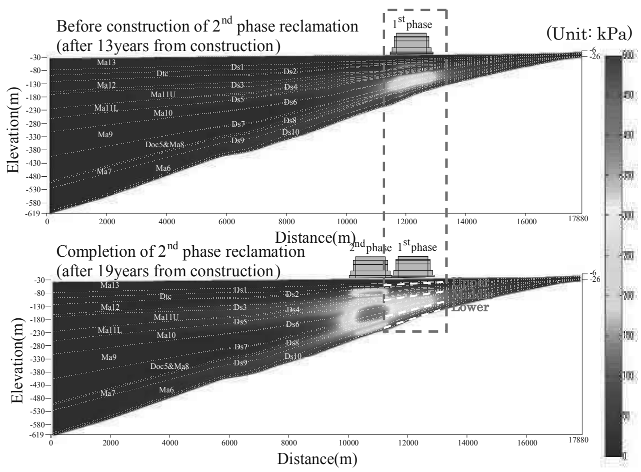
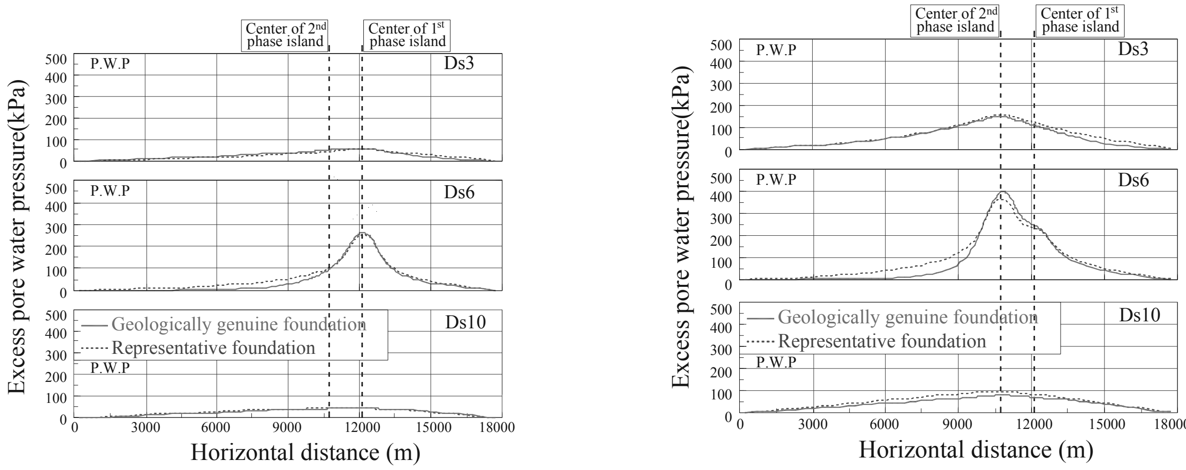


Figure 4 (b). Contour of excess pore water pressure for geologically genuine foundation model at before and completion of 2nd phase reclamation



(a) Before the 2nd phase reclamation

(b) Completion the 2nd phase reclamation

Figure 5. Horizontal distribution of excess pore water pressure for the representative Pleistocene sand gravel layers (Ds3, 6, 10) in a horizontal position

although the identical permeable capability for the individual Pleistocene sand gravel layers was applied, the calculated results of excess pore water pressure could show the difference with the stress level. The calculated excess pore water pressure – time relations for two foundation models are shown in Fig. 6 together with the measured results for the representative Pleistocene sand gravel layers at the monitoring point 1. It is noteworthy that the excess pore water pressure in the upper (Ds3) and lower (Ds10) Pleistocene sand gravel layers is increased but the one of the middle layer (Ds6) is not increased due to the construction of the 2nd phase island. The long-term settlement associated with the phenomenon of propagation of excess pore water pressure is another serious problem for KIX. When the excess pore water pressure increases or the dissipation of excess pore water pressure is hindered due to the construction of the 2nd phase island, the settlement is also retarded or slight upheaval can happen (see Fig.7). It is also found that the calculated performance at the monitoring point 1 shows a good match for two foundation models by applying the concept of "standard hydraulic gradient" and can also well describe the whole process of deformation.

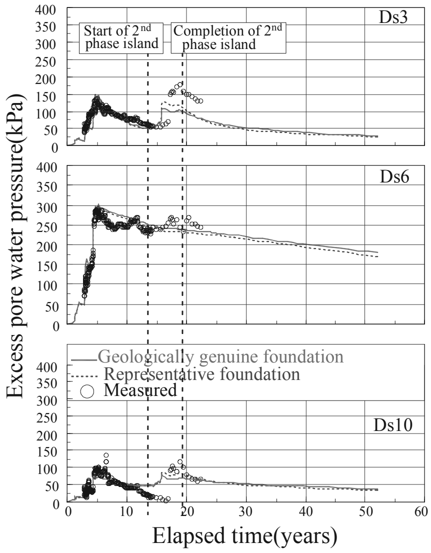


Figure 6. Comparison of measured and calculated excess pore water pressure with time for the representative Pleistocene sand gravel layers

6 CONCLUSIONS

The long-term deformation of the reclaimed Pleistocene foundation of the offshore twin airport was numerically evaluated through the elasto-viscoplastic finite element analyses considering the concepts of "mass permeability" and "standard hydraulic gradient" for the Pleistocene sand gravel layers. The concept of "mass permeability" was evaluated as the representative permeable capacity of sand gravel layers of KIX. The representative permeable capacity of sand gravel layers was applied to the geologically genuine foundation model by introducing the concept of "standard hydraulic gradient" for the coupled stress-flow analysis. The concept of mass permeability for the sand gravel layers was found to well function to assess the process of excess pore water pressure generation/ dissipation/propagation and long-term settlement in the reclaimed foundations of KIX. The concept of standard hydraulic gradient was also found to well reproduce the representative permeable capacity by comparing the calculated results for two foundation models. The validity and objectivity of the proposed concepts will be investigated by applying them to the additional review sections including the monitoring points S2 or S3 shown in Fig. 2.

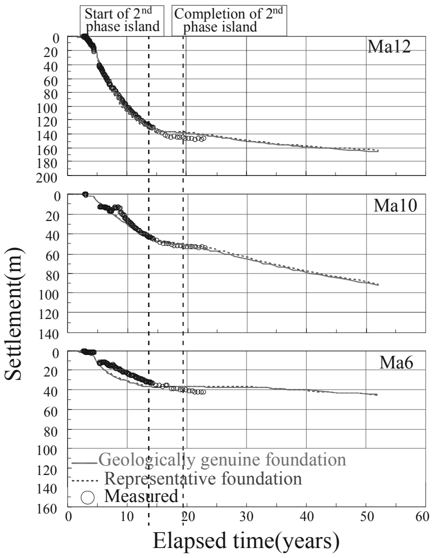


Figure 7. Comparison of measured and calculated settlement with time for the representative Pleistocene clay layers

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