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Generalized Assessment of Long-term Settlement of Quasi-overconsolidated Pleistocene Clay Deposits in Osaka Bay Using Elasto-viscoplastic finite element procedure

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Synopsis

The compression modeling for the quasi-overconsolidated Pleistocene clays proposed by the authors has been implemented into the finite element procedure in which an elasto-viscoplastic deformation is assumed to occur even in the quasi-overconsolidated region (p_0<p<p_c). One-dimensional finite element analysis is adopted for assessing the settlement of Sakishima and Yumeshima Reclaimed islands, whereas the plane-strain finite element analysis is carried out for investigating the deformation of the Pleistocene deposit beneath the sheet-pile composite revetment at Maishima Reclaimed Island. Based on the comparison to the measured data, the predictive accuracy of the proposed procedure is verified for assessing the long-term settlement at the reclaimed islands in Osaka Port.

Keywords: Time-dependent behavior, Quasi-overconsolidated Pleistocene clay, Elasto-viscoplastic finite element analysis, Long-term settlement, Revetment

1. Introduction

Long-term settlement at the reclaimed area and islands in Osaka Port caused by the time-dependent compression of the Pleistocene clays has been a serious issue for the few decades (Kiyama, 1991, Mimura et al., 2003a). It is true that those Pleistocene clays clearly exhibit slight overconsolidation with OCR equal to be 1.1 to 1.4, but the geological findings show that they did not undergo the definite mechanical history of overconsolidation (Kobayashi et al., 2001). In the sense, those Pleistocene clays can be regarded as so-called normally consolidated aged clays with seeming overconsolidation that may arise from the effect of diagenesis, such as aging and/or cementation. Tanaka et al. (1999) pointed out that the mineral components of those Pleistocene clays are almost identical for all clay layers, which means that the origin of those sediments has not been changed through 1 million years in Osaka Bay. It is also very important that the experimental results show that the consolidation properties for the Pleistocene clays in Osaka Bay are not so different from those for Holocene clays although the development of structure is predominant for the Pleistocene clays. Mimura et al. (2003b) proposed a new procedure to assess the compression characteristics of the Pleistocene clays in Osaka Bay in which the yield stress, p_c derived from conventional consolidation tests 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. Based on the fact that the Pleistocene clays deposited in Osaka Bay are normally consolidated from the viewpoint of soil mechanics, behavior in the region less than p_c is assumed to be elasto-viscoplastic with time dependency that is clearly different from the framework of the conventional procedure that assumes the behavior less than p_c is instantaneous and elastic. The compression modeling for the Pleistocene clays by using the elasto-viscoplastic constitutive model for normally consolidated clays (Sekiguchi, 1977) is supported by the fact that the properties of the Pleistocene clays are rather similar to those of normally consolidated Holocene clays except the developed structure that the Pleistocene clays clearly have. The validity of this procedure was discussed by comparing with the in-situ measured data of long-term compression for each Pleistocene clay layer at Maishima Reclaimed Island (Mimura et al., 2003b).

In this paper, a series of one-dimensional elasto-viscoplastic finite element analyses is performed to assess the long-term settlement for Sakishima Reclaimed Island and Yumeshima Reclaimed Island in Osaka Port. The calculated increasing processes of vertical effective stress and the gain in vertical strain are discussed for each Pleistocene clay layer. The procedure proposed by the authors is verified how it can function to assess the in-situ behavior of the reclaimed Pleistocene clay deposits by comparing the measured records at Sakishima and Yumeshima Reclaimed Islands. Compression of the top Pleistocene clay layer, Ma12 was independently monitored at Sakishima Reclaimed Island. On the other hand, only the total settlement of the Pleistocene deposits has been measured at Yumeshima Reclaimed Islands. The effect of the construction sequence is also discussed because that for each reclaimed island of Osaka Port is clearly different. The mode of time dependent compression is seriously affected when the rate of loading or consolidation period is different even if the final stress remains less than p_c. Fortunately, we have a variety of construction sequence for the reclaimed islands of Osaka Port discussed in the present paper. Finally, the proposed framework is extended to the deformation analysis for the revetment of Maishima Reclaimed Island. Two-dimensional finite element analysis is carried out to assess the deformation of the reclaimed foundation of the sheet pile composite revetment. In this analysis, the mode of stress distribution generated in the clay foundation due to reclamation load is highlighted and the calculated settlement for each Pleistocene clay layer at revetment are discussed by comparing with in-situ measurement. On the basis of the above-mentioned discussion, the ability of the proposed procedure to assess the long-term deformation of the reclaimed marine Pleistocene deposits in Osaka Port is verified.

2. Outline of Osaka Reclaimed Islands

Osaka Bay is a heart of Kansai economy along which the urban business cities such as Osaka and Kobe are located. Urbanization has been progressed in Japan associated with the development of coastal area as well as offshore-reclaimed islands. In Osaka Bay, reclamation for harbor constructions was started from 1950s for development of Osaka Port and the three major reclaimed islands have been constructed. The plan view of the latest Osaka Bay area is shown in Fig. 1 together with the depth 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 the seabed level is O.P. (=Osaka Pail: the standard unit of elevation in Osaka) ±0 to -10m as shown in Fig. 1. The data of settlement discussed in this paper have been measured at point A for Sakishima, B for Maishima and C for Yumeshima respectively as shown in Fig. 1.

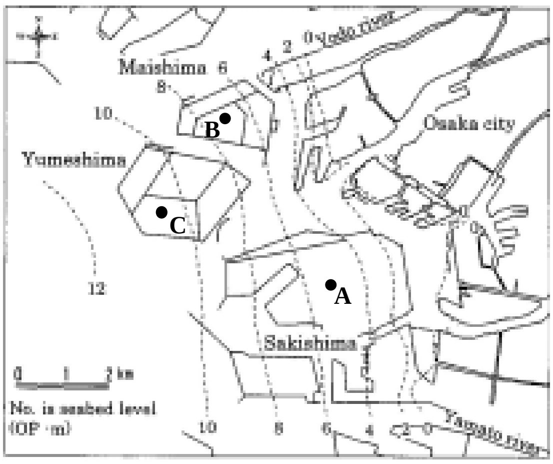


Fig. 1 Distribution of Osaka reclaimed islands

Figure 2 shows the soil profile for each reclaimed island determined on the basis of the Geo-database (Research Committee of Seabed Deposits in Osaka Bay 2002). As is seen Fig. 2, the subsoil layers of the three sites are almost similar. Ma13 is the Holocene clay layer and deposited near the seabed whereas the rest of those clays overlain by Ma13 are the Pleistocene origin. The detailed soil characteristics for each site are published already (Research Committee of Seabed Deposits in Osaka Bay 2002). The process of construction is also very similar for the reclaimed islands of Osaka port. Vertical drains were installed into the Holocene clay layer after a sand mat was formed on the seabed, and then the dredged soils delivered by pump dredger were dumped into the sea to reclaim the seabed. The filling was launched following the improvement of the dredged layer.

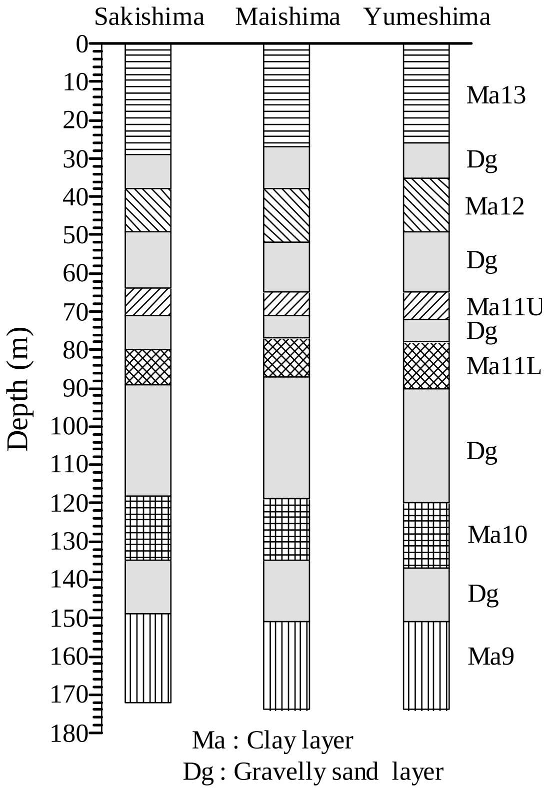


Fig. 2 Soil profile for each reclaimed island deposited in Osaka Port

3. Proposed Compression Model for the Pleistocene Clay Deposits

As is already mentioned, the Pleistocene clays in Osaka Bay can be regarded as normally consolidated based on the history of sedimentation although they exhibit the apparent overconsolidation with OCR of 1.1 to 1.4 due to ageing effect. 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 et al. (2003b) proposed a new procedure to assess the compression characteristics of the Pleistocene clays in Osaka Bay. Figure 3 shows the proposed concept for the compression modeling by comparing with 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, while an elastic behavior is assumed to occur in this region for the conventional compression model as shown in Fig. 3 (b). In the proposed compression model, the yield stress, p_c obtained from conventional consolidation test is assumed not to be associated with plastic yielding but the stress 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.3 (a) should be p_c and in the unloading – reloading region, clays exhibit elastic behavior as is conventionally assumed.

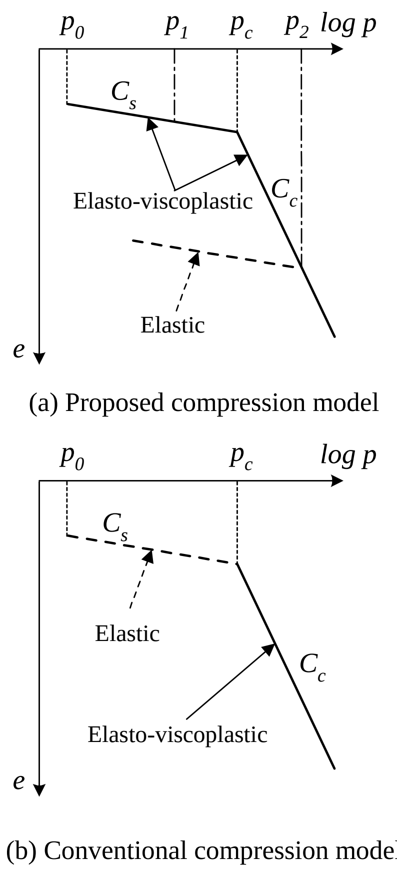


Fig. 3 Compression model for the Pleistocene clay

4. One-dimensional Numerical Assessment of Long-term Settlement at the Reclaimed Islands in Osaka Port

4.1 One-dimensional Elasto-viscoplastic Finite Element Analysis

A series of elasto-viscoplastic finite element analyses is carried out to assess the long-term settlement for Sakishima and Yumeshima Reclaimed Islands in Osaka Port. The finite element analyses are performed with the proposed procedure as well as with the conventional procedure. The constitutive model used in the finite element analysis is the modified plane strain version (Sekiguchi et al. 1982) of the elasto-viscoplastic model originally proposed by Sekiguchi (1977). The reclaimed area is huge enough to assume that the deformation takes place one-dimensionally at the center of the reclaimed island. In addition, the gravelly sand layers sandwiched by the Pleistocene clay layers are thick and continuous enough to regard them as well drained layers (Research Committee of Seabed Deposits in Osaka Bay 2002). In the sense, the one-dimensional analysis is adopted in the present study without considering the effect of permeability loss in those gravelly sand layers. Figure 4 shows the one-dimensional finite element mesh together with the boundary conditions determined based on the Geo-database (Research Committee of Seabed Deposits in Osaka Bay 2002) for Sakishima Reclaimed Island and Yumeshima Reclaimed Island. The thickness of subsurface ground model set for the present analyses is 172m for Sakishima Reclaimed Island and 174m for Yumeshima Reclaimed Island respectively. As Ma9, the bottom of the present ground model is underlain by the thick gravelly sand layer, the bottom boundary is set to be perfect drained. The side boundaries of the gravelly sand layers are assumed to be also perfect drained. The side boundaries of the clay layers are set to be fully undrained as shown in Fig. 4.

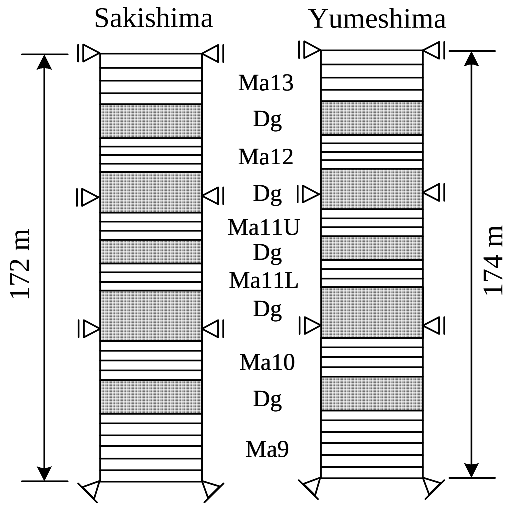


Fig. 4 One-dimensional finite element mesh for Sakishima and Yumeshima Reclaimed Islands

In the present analyses, the above-mentioned proposed procedure in which the elasto- viscoplastic deformation also takes place even in the region less than p_c is adopted. The compression curve in the quasi-overconsolidated region with the inclination of $\kappa = \lambda_{QOC}$ is assumed to have an elasto-viscoplastic component as it is in the NC region (Mimura et al., 2003b). The required soil parameters for the finite element analysis with the proposed procedure were determined rationally based on the prescribed procedure (Mimura et al. 1990, Mimura et al., 2003b). The values of the principal soil parameters adopted for the targeted Pleistocene clay deposits of Sakishima Reclaimed Island and Yumeshima Reclaimed Island are summarized in Table 1 and Table 2 respectively.

As is already described, the construction process and the way of reclamation for two sites are almost similar. The dredged clayey soils, the good quality sandy soils and construction disposals were used for reclamation and filling respectively. Vertical drains were driven into Ma13 and the dredged clay layer with application of dewatering method to promote consolidation. Figure 5 shows a sequence of applied overburden due to reclamation work for Sakishima and Yumeshima Reclaimed Islands. As shown in Fig. 5, the rate of loading for Sakishima Reclaimed Island is relatively mild in the early stage of reclamation followed by the rapid loading with large increase in Δp in a short time. On the contrary, the increase in Δp

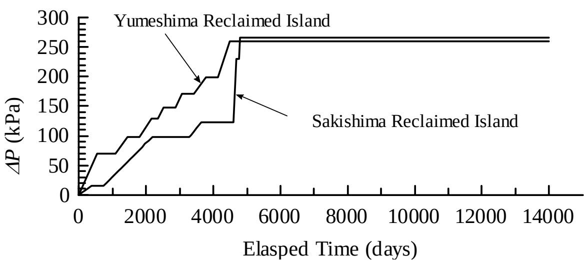


Fig. 5 Sequence of applied overburden due to reclamation for Sakishima and Yumeshima Reclaimed Islands

for Yumeshima Reclaimed Island is relatively steady with time. For both reclaimed islands, the final stress of the upper Pleistocene clay layers such as Ma12 and Ma11 surpasses p_c due to reclamation load, while the final stress becomes close to p_c or remains less than p_c in the lower Pleistocene clay layers such as Ma10 and Ma9. The stress condition at the completion of reclamation is schematically shown in Fig. 6.

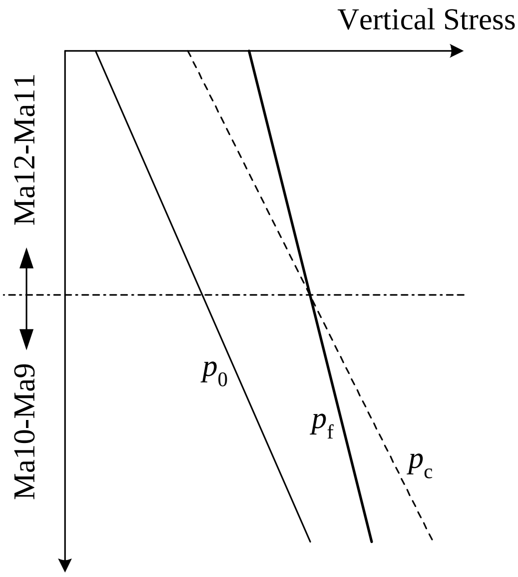


Fig. 6 Schematic final stress condition of the Pleistocene deposits in Osaka Port at the completion of reclamation

4.2 Calculated Results and Discussion for Sakishima Reclaimed Island

Figure 7 shows the calculated increasing processes of the vertical effective stress and the gain in vertical strain for Sakishima Reclaimed Islands. The elements located at the mid-depth are selected as representatives for the individual Pleistocene clay layers. For comparison, the calculated results with the conventional and proposed procedures are shown together for each Pleistocene clay layer. The increasing process of effective stress due to reclamation load with the proposed procedure is almost the same as that with conventional procedure for Ma12. But it can be seen that the calculated compression with the proposed procedure is larger than that with the conventional one. It is noteworthy that the difference in compression appears between both procedures in the quasi-overconsolidated region as shown in Fig. 7(a). The proposed procedure provides the remarkable time-dependent behavior even in the region less than p_c during the period when the stress state halts in the quasi-overconsolidated region from 2000 days to 5000 days, while the conventional procedure gives slight compression during the same period because an elastic deformation is assumed to occur in the quasi-overconsolidated region. The increase in effective stress and compression for Ma11L exhibits almost the same tendency as Ma12 in Fig. 7(b). It is natural that large compression takes place when the stress surpasses p_c as seen for Ma12 and Ma11L, 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 the lower Pleistocene clays, the stress of which remains less than p_c. Figure 7(c) and (d) show the results for Ma10 and Ma9 respectively. Only instantaneous and small elastic compression is calculated with the conventional procedure even after the completion of reclamation work. As soon as the reclamation work is completed, the effective stress becomes almost constant as shown in Fig. 7(c) and (d) since the excess pore water pressure is dissipated rapidly (see Fig. 8(b)). On the contrary, it can be seen in Fig. 7(c) and (d) that the proposed procedure provides the significant time-dependent compression after the completion of reclamation and the effective stress also increases with time.

The calculated generation-dissipation process of the excess pore water pressure for Ma12 and Ma10 is shown in Fig. 8. For both clay elements, the proposed procedure gives the larger values for overall period of reclamation. In particular, the delay of dissipation after the completion of reclamation is remarkable for the proposed procedure. It is noteworthy that the process of dissipation for Ma10 seriously prolongs for the proposed procedure although the stress of this clay element definitely remains less than p_c. It is very natural that the process of dissipation for the conventional one terminates quickly after the completion of reclamation because of less compressibility associated with high permeability in the quasi-overconsolidated region.

Let us interpret those phenomena by investigating the change in the permeability of the corresponding clay elements. In the present study, the permeability is assumed to change with void ratio, following e-log k relation. It should be emphasized that the time-dependent non-elastic behavior gives rise to serious reduction in the coefficient of permeability in

Table 1 Principal soil Parameters for the foundation of Sakishima Reclaimed Island

MTYP	Quasi-OC region				NC region				M	ν'	p_0 (kPa)	p_c (kPa)	e_0	k_0 (m/day)	λ_k	
	λ_{QOC}	κ_{QOC}	α_{QOC}	$\dot{v}_{0\,QOC}$ (day^{-1})	λ	κ	α_{NC}	$\dot{v}_{0\,NC}$ (day^{-1})								
24	0.069	0.007	1.09×10^{-3}	8.04×10^{-7}	0.694	0.069	1.09×10^{-2}	8.04×10^{-6}	1.3	0.36	285	385	2.20	9.53×10^{-5}	0.694	Ma12
23	0.068	0.007	1.06×10^{-3}	7.89×10^{-7}	0.681	0.068	1.06×10^{-2}	7.89×10^{-6}	1.3	0.36	300	405	2.20	9.53×10^{-5}	0.681	Ma12
22	0.053	0.005	1.00×10^{-3}	7.46×10^{-7}	0.534	0.053	1.00×10^{-2}	7.46×10^{-6}	1.3	0.36	318	429	1.65	9.53×10^{-5}	0.534	Ma12
21	0.024	0.002	4.90×10^{-4}	3.61×10^{-7}	0.239	0.024	4.90×10^{-3}	3.61×10^{-6}	1.3	0.36	336	454	1.45	9.53×10^{-5}	0.239	Ma12
20	—	—	—	—	—	—	—	—	—	0.33	426	—	—	2.16×10^{-2}	—	Sand
19	0.059	0.006	1.14×10^{-3}	9.47×10^{-7}	0.590	0.059	1.14×10^{-2}	9.47×10^{-6}	1.3	0.36	515	670	1.60	2.76×10^{-5}	0.590	Ma11U
18	0.042	0.004	9.50×10^{-4}	7.90×10^{-7}	0.417	0.042	9.50×10^{-3}	7.90×10^{-6}	1.3	0.36	533	693	1.20	2.76×10^{-5}	0.417	Ma11U
17	0.018	0.002	4.40×10^{-4}	3.71×10^{-7}	0.178	0.018	4.40×10^{-3}	3.71×10^{-6}	1.3	0.36	554	720	1.00	2.76×10^{-5}	0.178	Ma11U
16	—	—	—	—	—	—	—	—	—	0.33	611	—	—	2.16×10^{-2}	—	Sand
15	0.059	0.006	1.10×10^{-3}	5.52×10^{-7}	0.590	0.059	1.10×10^{-2}	5.52×10^{-6}	1.3	0.36	667	834	1.70	2.02×10^{-5}	0.590	Ma11L
14	0.045	0.005	9.70×10^{-4}	4.90×10^{-7}	0.447	0.045	9.70×10^{-3}	4.90×10^{-6}	1.3	0.36	685	856	1.30	2.02×10^{-5}	0.447	Ma11L
13	0.013	0.001	3.10×10^{-4}	1.59×10^{-7}	0.126	0.013	3.10×10^{-3}	1.59×10^{-6}	1.3	0.36	712	890	1.00	2.02×10^{-5}	0.126	Ma11L
12	—	—	—	—	—	—	—	—	—	0.33	888	—	—	2.16×10^{-2}	—	Sand
11	0.068	0.007	1.31×10^{-3}	4.06×10^{-7}	0.681	0.068	1.31×10^{-2}	4.06×10^{-6}	1.3	0.36	1061	1326	1.60	4.58×10^{-5}	0.681	Ma10
10	0.08	0.008	1.34×10^{-3}	4.27×10^{-7}	0.799	0.08	1.34×10^{-2}	4.27×10^{-6}	1.3	0.36	1088	1360	1.90	4.58×10^{-5}	0.799	Ma10
9	0.093	0.009	1.45×10^{-3}	4.50×10^{-7}	0.929	0.093	1.45×10^{-2}	4.50×10^{-6}	1.3	0.36	1114	1393	2.20	4.58×10^{-5}	0.929	Ma10
8	0.051	0.005	1.16×10^{-3}	3.61×10^{-7}	0.512	0.051	1.16×10^{-2}	3.61×10^{-6}	1.3	0.36	1139	1424	1.20	4.58×10^{-5}	0.512	Ma10
7	—	—	—	—	—	—	—	—	—	0.33	1228	—	—	2.16×10^{-2}	—	Sand
6	0.043	0.004	1.02×10^{-3}	1.43×10^{-7}	0.430	0.043	1.02×10^{-2}	1.43×10^{-6}	1.3	0.36	1328	1660	1.10	2.96×10^{-5}	0.430	Ma9
5	0.07	0.007	1.41×10^{-3}	1.96×10^{-7}	0.703	0.07	1.41×10^{-2}	1.96×10^{-6}	1.3	0.36	1356	1695	1.50	2.96×10^{-5}	0.703	Ma9
4	0.07	0.007	1.41×10^{-3}	1.96×10^{-7}	0.703	0.07	1.41×10^{-2}	1.96×10^{-6}	1.3	0.36	1384	1730	1.50	2.96×10^{-5}	0.703	Ma9
3	0.063	0.006	1.12×10^{-3}	1.56×10^{-7}	0.625	0.063	1.12×10^{-2}	1.56×10^{-6}	1.3	0.36	1412	1765	1.80	2.96×10^{-5}	0.625	Ma9
2	0.063	0.006	1.12×10^{-3}	1.56×10^{-7}	0.625	0.063	1.12×10^{-2}	1.56×10^{-6}	1.3	0.36	1436	1795	1.80	2.96×10^{-5}	0.625	Ma9
1	0.093	0.009	1.86×10^{-3}	2.59×10^{-7}	0.929	0.093	1.86×10^{-2}	2.59×10^{-6}	1.3	0.36	1455	1819	1.50	2.96×10^{-5}	0.929	Ma9

Table 2 Principal soil Parameters for the foundation of Yumeshima Reclaimed Island

MTYP	Quasi-OC region				NC region				M	ν'	p_0 (kPa)	p_c (kPa)	e_0	k_0 (m/day)	λ_k	
	λ_{QOC}	κ_{QOC}	α_{QOC}	$\dot{v}_{0\,QOC}$ (day^{-1})	λ	κ	α_{NC}	$\dot{v}_{0\,NC}$ (day^{-1})								
24	0.069	0.007	1.08×10^{-3}	4.92×10^{-7}	0.693	0.069	1.08×10^{-2}	4.92×10^{-6}	1.3	0.36	254	343	2.22	1.25×10^{-4}	0.693	Ma12
23	0.098	0.01	1.06×10^{-3}	4.83×10^{-7}	0.980	0.098	1.06×10^{-2}	4.83×10^{-6}	1.3	0.36	274	370	2.22	1.25×10^{-4}	0.980	Ma12
22	0.053	0.005	9.90×10^{-4}	4.51×10^{-7}	0.532	0.053	9.90×10^{-3}	4.51×10^{-6}	1.3	0.36	293	396	1.70	1.25×10^{-4}	0.532	Ma12
21	0.024	0.002	5.50×10^{-4}	2.50×10^{-7}	0.241	0.024	5.50×10^{-3}	2.50×10^{-6}	1.3	0.36	314	424	1.20	1.25×10^{-4}	0.241	Ma12
20	—	—	—	—	—	—	—	—	—	0.33	414	—	—	2.16×10^{-2}	—	Sand
19	0.044	0.004	9.10×10^{-4}	7.57×10^{-7}	0.436	0.044	9.10×10^{-3}	7.57×10^{-6}	1.3	0.36	509	662	1.40	2.29×10^{-5}	0.436	Ma11U
18	0.027	0.003	6.20×10^{-4}	5.19×10^{-7}	0.274	0.027	6.20×10^{-3}	5.19×10^{-6}	1.3	0.36	527	685	1.20	2.29×10^{-5}	0.274	Ma11U
17	0.022	0.002	5.40×10^{-4}	4.55×10^{-7}	0.218	0.022	5.40×10^{-3}	4.55×10^{-6}	1.3	0.36	547	711	1.00	2.29×10^{-5}	0.218	Ma11U
16	—	—	—	—	—	—	—	—	—	0.33	588	—	—	2.16×10^{-2}	—	Sand
15	0.059	0.006	1.08×10^{-3}	3.06×10^{-7}	0.592	0.059	1.08×10^{-2}	3.06×10^{-6}	1.3	0.36	636	795	1.75	2.29×10^{-5}	0.592	Ma11L
14	0.052	0.005	1.09×10^{-3}	3.09×10^{-7}	0.518	0.052	1.09×10^{-2}	3.09×10^{-6}	1.3	0.36	667	834	1.38	2.29×10^{-5}	0.518	Ma11L
13	0.018	0.002	4.40×10^{-4}	1.25×10^{-7}	0.176	0.018	4.40×10^{-3}	1.25×10^{-6}	1.3	0.36	694	868	1.00	2.29×10^{-5}	0.176	Ma11L
12	—	—	—	—	—	—	—	—	—	0.33	872	—	—	2.16×10^{-2}	—	Sand
11	0.073	0.007	1.40×10^{-3}	4.36×10^{-7}	0.730	0.073	1.40×10^{-2}	4.36×10^{-6}	1.3	0.36	1047	1309	1.60	4.66×10^{-5}	0.730	Ma10
10	0.08	0.008	1.35×10^{-3}	4.18×10^{-7}	0.795	0.08	1.35×10^{-2}	4.18×10^{-6}	1.3	0.36	1071	1339	1.95	4.66×10^{-5}	0.795	Ma10
9	0.094	0.009	1.47×10^{-3}	4.55×10^{-7}	0.939	0.094	1.47×10^{-2}	4.55×10^{-6}	1.3	0.36	1098	1373	2.20	4.66×10^{-5}	0.939	Ma10
8	0.05	0.005	1.10×10^{-3}	3.40×10^{-7}	0.504	0.05	1.10×10^{-2}	3.40×10^{-6}	1.3	0.36	1125	1406	1.30	4.66×10^{-5}	0.504	Ma10
7	—	—	—	—	—	—	—	—	—	0.33	1217	—	—	2.16×10^{-2}	—	Sand
6	0.042	0.004	1.01×10^{-3}	1.41×10^{-7}	0.423	0.042	1.01×10^{-2}	1.41×10^{-6}	1.3	0.36	1310	1638	1.10	2.90×10^{-5}	0.423	Ma9
5	0.07	0.007	1.38×10^{-3}	1.93×10^{-7}	0.691	0.07	1.38×10^{-2}	1.93×10^{-6}	1.3	0.36	1342	1678	1.50	2.90×10^{-5}	0.691	Ma9
4	0.07	0.007	1.38×10^{-3}	1.93×10^{-7}	0.691	0.07	1.38×10^{-2}	1.93×10^{-6}	1.3	0.36	1373	1716	1.50	2.90×10^{-5}	0.691	Ma9
3	0.061	0.006	1.09×10^{-3}	1.53×10^{-7}	0.612	0.061	1.09×10^{-2}	1.53×10^{-6}	1.3	0.36	1401	1751	1.80	2.90×10^{-5}	0.612	Ma9
2	0.061	0.006	1.09×10^{-3}	1.53×10^{-7}	0.612	0.061	1.09×10^{-2}	1.53×10^{-6}	1.3	0.36	1425	1781	1.80	2.90×10^{-5}	0.612	Ma9
1	0.091	0.009	1.82×10^{-3}	2.54×10^{-7}	0.910	0.091	1.82×10^{-2}	2.54×10^{-6}	1.3	0.36	1444	1805	1.50	2.90×10^{-5}	0.910	Ma9

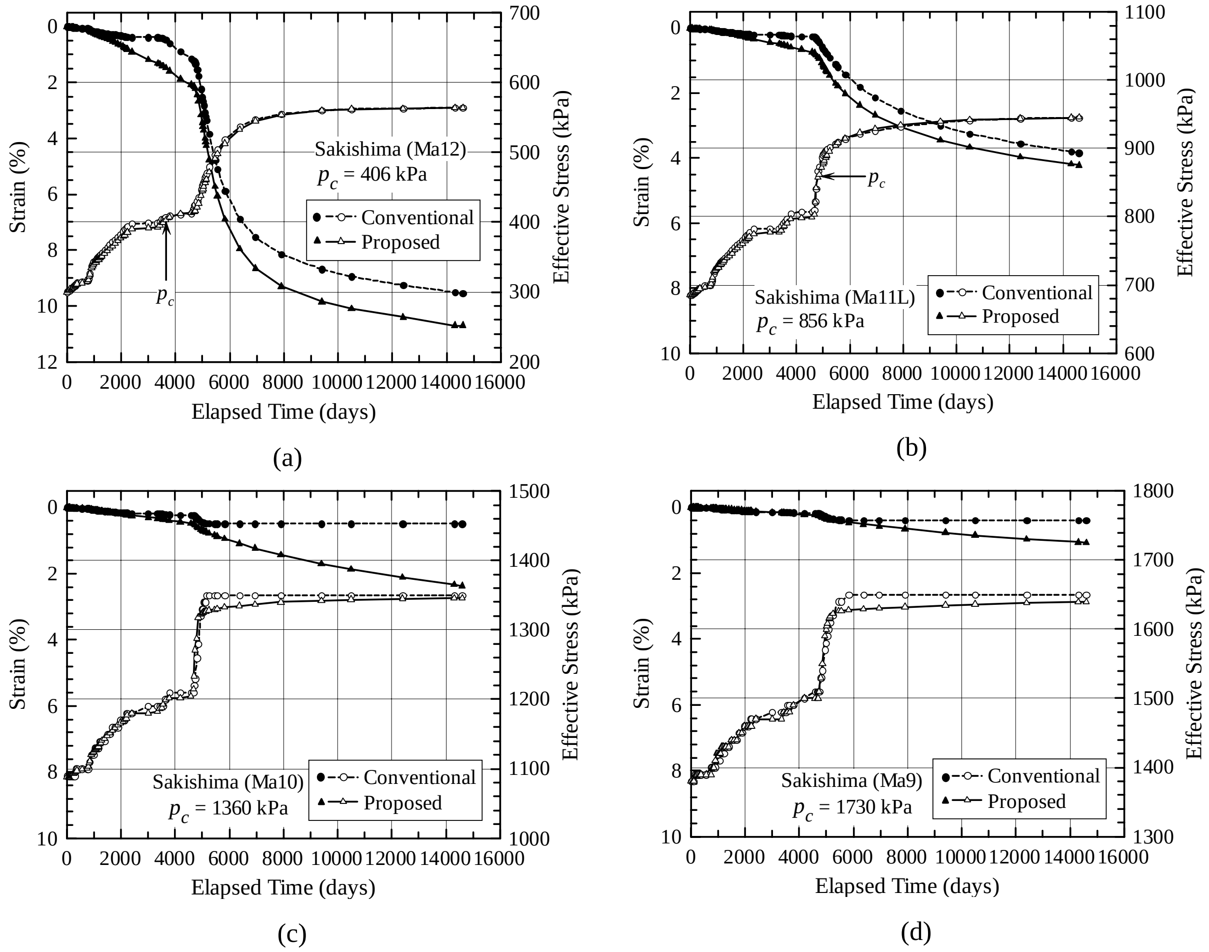


Fig. 7 Increasing processes of effective stress and strain for Sakishima Reclaimed Island

the quasi-overconsolidated region. It is natural that the rate of excess pore water pressure dissipation decreases with reduction in void ratio due to viscoplastic compression because the proposed procedure assumes that the elasto-viscopastic deformation takes place even in the region less than p_c. Figure 9(a) and (b) show the calculated variation of coefficient of permeability k with the decrease in the void ratio for Ma12 and Ma10 respectively. As the proposed procedure gives the larger compression in the quasi-overconsolidated region (4200 days), the reduction in k is also significant compared to the conventional one. This reduction in k due to the elasto-viscoplastic deformation in the quasi-overconsolidated region affects the process of excess pore water pressure dissipation. Because of this effect, the proposed procedure provides the delayed compression of the Pleistocene clays in the quasi-overconsolidated region associated with less dissipation of excess pore water pressure.

The calculated *e*-log *p* relations for the Pleistocene clay layers during reclamation at

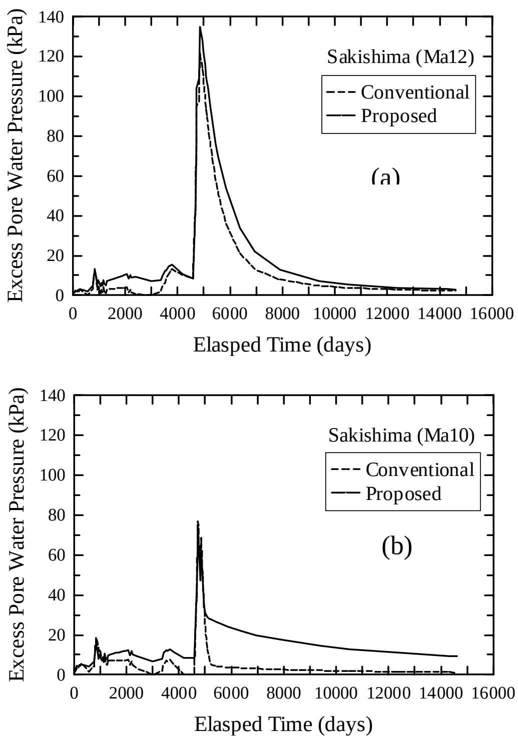


Fig. 8 Generation-dissipation process of excess pore water pressure

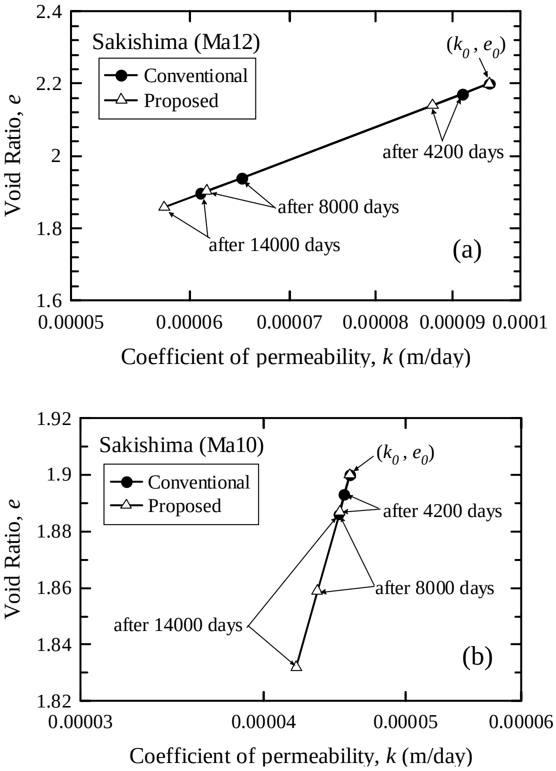
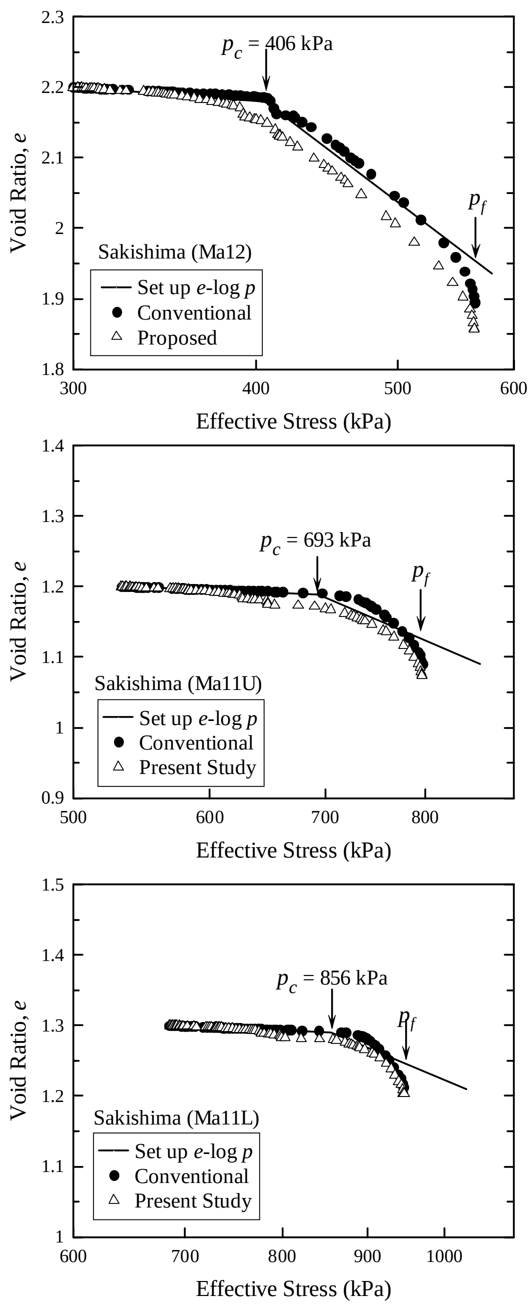


Fig. 9 Variation in coefficient of permeability with the decrease in void ratio

Sakishima Reclaimed Island are shown in Fig. 10 together with the set up compression curves. In all figures, the set up compression curve is illustrated by the solid lines, the results by the conventional and the proposed elasto-viscoplastic analysis are plotted by the pull circles and open triangles respectively. For Ma12, Ma11U and Ma11L that the stress state remains in the quasi-overconsolidated region for a long time, the calculated compression curves by the conventional elasto-viscoplastic analysis move on the set up *e* - log *p* in the quasi-overconsolidated region, and the time-dependent behavior appear only after p_c. On the other hand, in the compression curves by the proposed procedure, it can be clearly seen that the delayed compression is provided not only in the NC region but also in the quasi-overconsolidated region. Ma10 in Fig. 10 is a representative of those layers that the final stress becomes close to p_c and Ma9 in Fig. 10 is a representative of those layers that the final stress remains less than p_c respectively. In both cases, the calculated compression curves with the proposed procedure move a slightly lower than the set up *e* - log *p* curves whereas those by the conventional procedure are almost move on the set up *e* - log *p* curves. It is natural that the time-dependent behavior such as shown in Fig. 10 takes place because the proposed procedure assumes that the time-dependent behavior occurs even in the quasi-overconsolidated region.

The calculated settlement of the Pleistocene deposits is compared with the in-situ measured data for Sakishima Reclaimed Island in Fig. 11. At Sakishima, the compression of Ma 12 can only be discriminated because differential settlement gauges were set only for this layer. For Ma 12, the stress of which surpasses far beyond p_c (see Fig. 7(a)), the calculated compression with the proposed procedure definitely traces the measured data. It should be noted



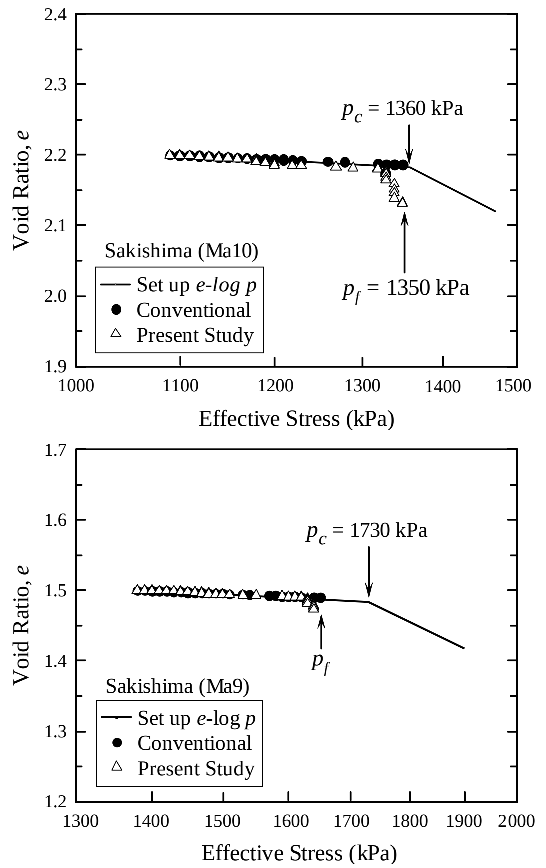


Fig. 10 Calculated e - log p relations for the Pleistocene clay elements

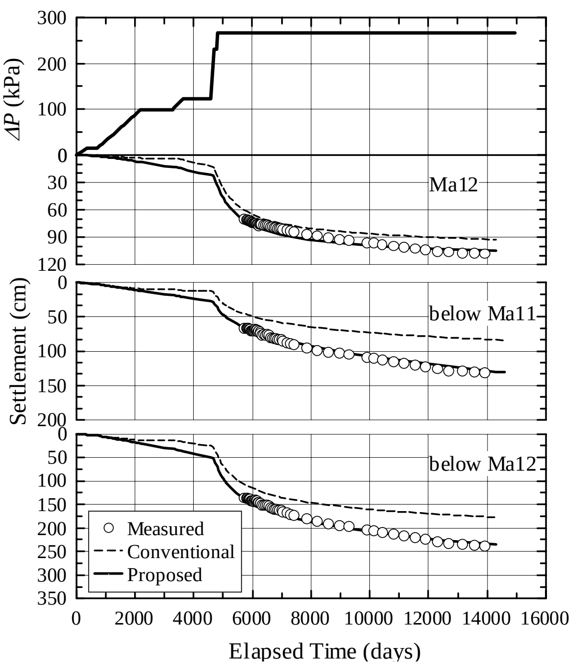


Fig. 11 Comparison of the calculated settlement with the measured settlement for Sakishima Reclaimed Island

that the discrepancy between the proposed and the conventional model is not so large because the settlement of Ma12 took place mainly by the contribution of normally consolidated compression components. The slight difference between both procedures is caused by the time-dependent compression occurring in the region less than p_c. The rate of settlement with time is better predicted also 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 elasto-viscoplastic behavior in the region less than p_c. As a result, for the total settlement of the Pleistocene deposits, the proposed procedure can predict the in-situ behavior almost perfectly.

4.3 Calculated Results and Discussion for Yumeshima Reclaimed Island

The calculated increasing processes of the vertical effective stress and the vertical strain for Yumeshima Reclaimed Islands are shown in Fig. 12. As is seen in the figures, the qualitative tendency of the increase in effective stress and the compression for each Pleistocene clay layer are almost the same as the results for Sakishima Reclaimed Island. However, it is noteworthy in Fig. 12 that the difference of the performance in the quasi-overconsolidated region between both procedures is not so definite for Ma12, compared to the case of Sakishima Reclaimed Island. No serious creep deformation is provided even by the proposed procedure because the effective stress steadily increases and surpasses p_c for Ma12 due to reclamation load at Yumeshima Reclaimed Island (see Fig. 5). Although there is no significant compression difference in the quasi-overconsolidated region between both procedures due to effect of loading sequence, the calculated final compression of Ma12 with the proposed procedure becomes larger than that with the conventional one. This difference is caused by the fact that the states of the corresponding clay elements are already different between both procedures when the stress reaches p_c. The accumulation of the viscoplastic components in the quasi-overconsolidated region ($p_0<p<p_c$) makes the clay element weaker for the proposed procedure, which leads to more strains in the subsequent stage in

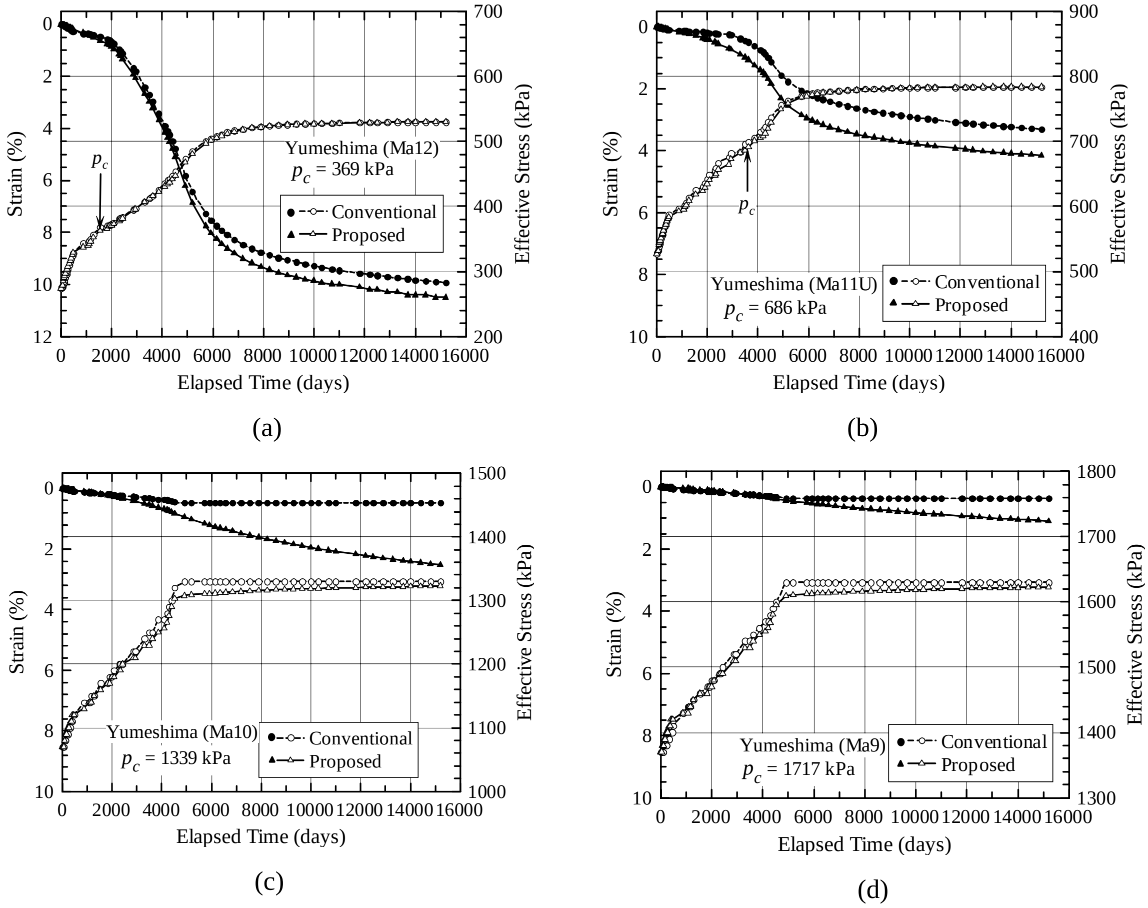


Fig. 12 Increasing processes of effective stress and strain for Yumeshima Reclaimed Island

the normally consolidated region.

Figure 13 shows the comparison of the calculated settlement with the conventional and proposed procedures for each Pleistocene clay layer of Yumeshima Reclaimed Island. The calculated settlement with the proposed procedure is larger than that with the conventional one. In particular, for Ma10 and Ma9 that the final effective stress remains less than p_c, the proposed procedure provides the remarkable time-dependent settlement with time, while only elastic instantaneous settlement is calculated with the conventional procedure. From those results, it is confirmed that the calculated performance with the proposed procedure provides the larger and time-dependent compression irrespective of the stress condition.

The calculated settlement for Yumeshima Reclaimed Island is compared with the in-situ measured data in Fig. 14. Here, it is important that the total settlement of the Pleistocene deposits has been monitored from the beginning of the reclamation work only at Yumeshima Reclaimed Island. It is true as discussed above that the proposed

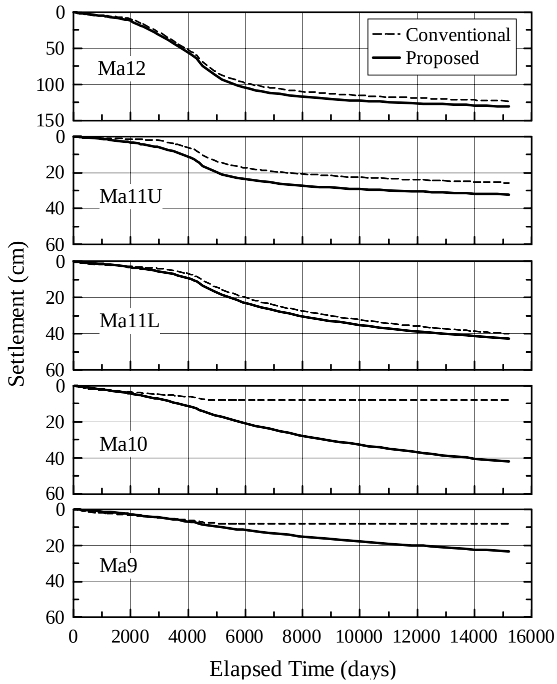


Fig. 13 Comparison of the calculated settlement for each Pleistocene clay layer of Yumeshima

procedure can provide better description both for Sakishima and Maishima Reclaimed Islands, but the comparison was done only for the limited period of overall reclamation. The validity of the procedure can be quantitatively discussed by comparing the total compression of the Pleistocene deposits from the beginning of reclamation at Yumeshima Reclaimed Island. As is seen in Fig. 14, the calculated performance with the proposed procedure also shows better match with the in-situ measurement although the construction is not completed yet. The conventional procedure definitely underestimates the actual settlement also at Yumeshima site. From those findings discussed for Osaka reclaimed islands including Maishima Reclaimed Islands (Mimura et al., 2003b), 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.

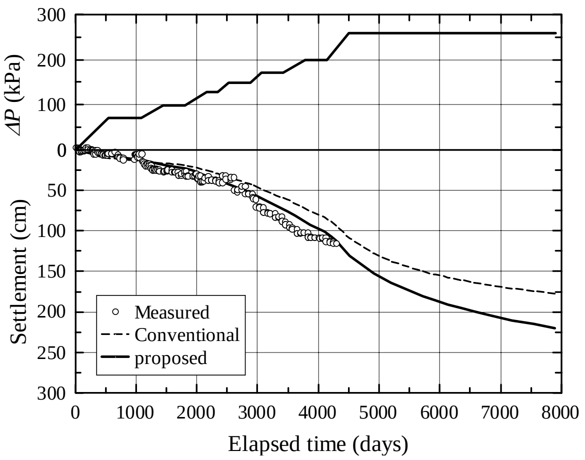


Fig. 14 Comparison of the calculated total settlement of the Pleistocene deposits with measured settlement for Yumeshima Reclaimed Island

5. Two-dimensional Numerical Analysis of Long-term Settlement for the Reclaimed Foundation at the Revetment of Maishima Reclaimed Island

5.1 General Conditions of Maishima Reclaimed Island

Figure 15 shows the plan view for Maishima Reclaimed Island. The settlement for each Pleistocene clay layer has been measured at point B and D located inside the island. Along the southern revetment, called C revetment, the total settlement of the Pleistocene deposits has been observed. The long-term settlement for the inside of reclaimed area has been evaluated by one-dimensional elasto-viscoplastic finite element analysis with the proposed procedure already (Yamamoto et al., 2004, Mimura et al., 2003b). In this section, the two-dimensional elasto-viscoplastic finite element analysis is carried out along the section shown by A-A’ in Fig. 15 to evaluate the time-dependent settlement of the reclaimed foundation at C revetment

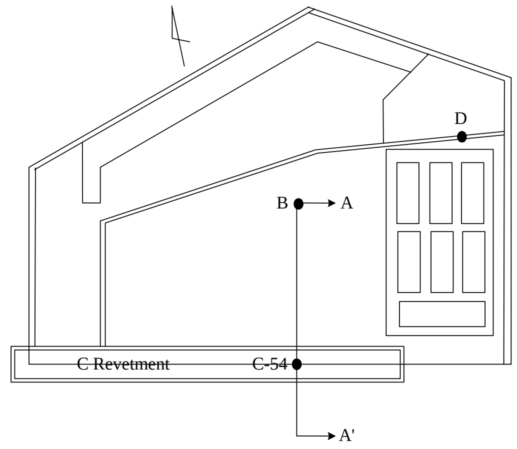


Fig. 15 Plan view of Maishima Reclaimed Island

of Maishima Reclaimed Island.

The representative soil profile of Maishima Reclaimed Island for the finite element analysis is the same as already shown in Fig. 2. Figure 16 shows the foundation ground model and its boundary condition for the present analysis. The region selected for the analysis is 600 m long and 174 m deep into the Pleistocene clay layer Ma9. Ma13 represents the Holocene clay layer underlain by the alternating Pleistocene marine clay (Ma) deposits and gravelly sand layers (Dg). The thick gravelly sand layers, Dg are assumed as partially drained elastic material with finite permeability. Sand drains (SD) with 40 cm in diameter were installed in a rectangular arrangement with 3.5 m intervals in the reclaimed area to promote consolidation for the Holocene clay layer. The ground improvement was performed by densely compacted sand column (SCP) with a replacement ratio of 50% followed by sand replacement at the revetment foundation. Here, the replaced sand and driven sand piles cause the increase in unit weight of the improved soils. For the numerical analysis, the increase in unit weight of $\Delta\gamma = 5$ kPa for the replaced sand and $\Delta\gamma = 2.5$ kPa for SCP are taken into account.

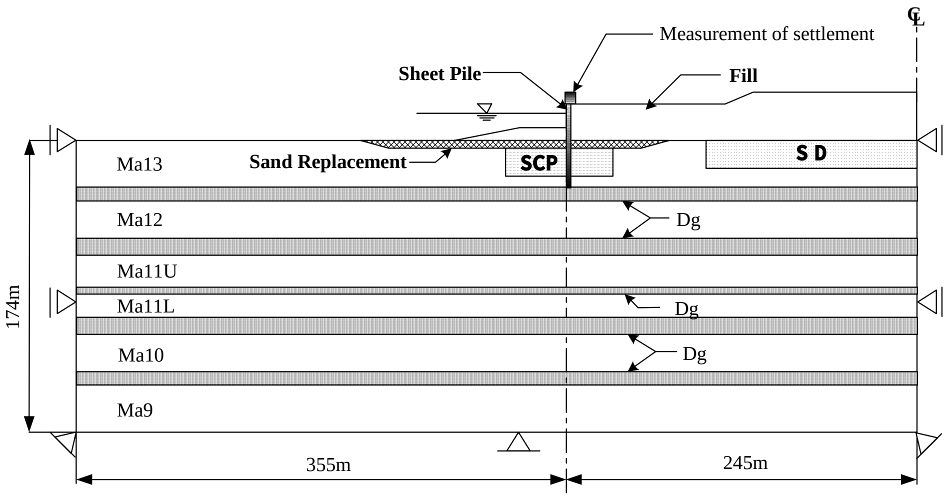
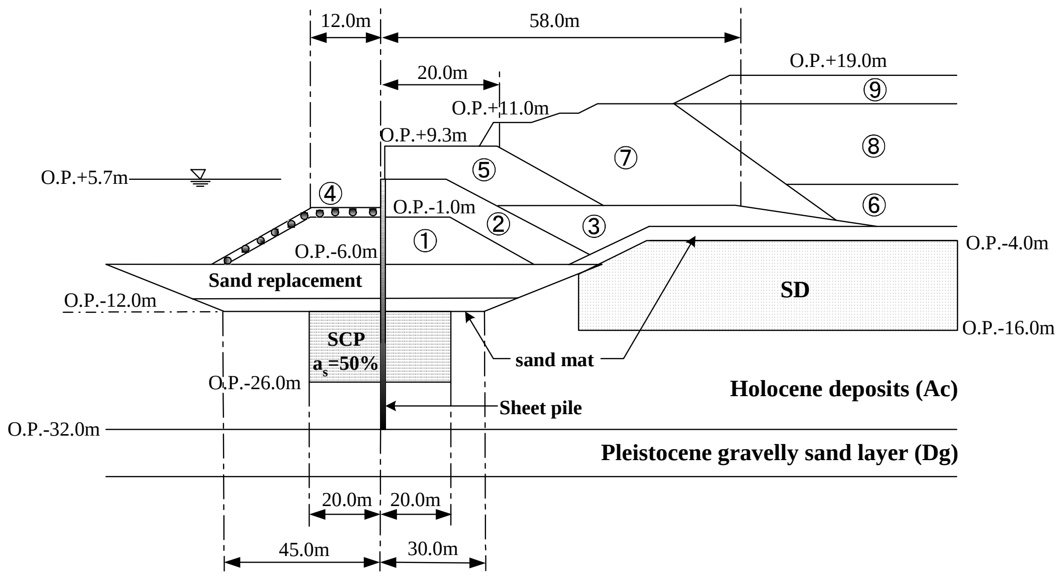


Fig. 16 Model of the foundation ground for finite element analysis



① Sand mound: 1974
② Bacfilling: 1975
③ Bacfilling: 1975
④ Armor-stone: 1976
⑤ Bacfilling: 1976
⑥ 1th Reclamation: 1979
⑦ Bacfilling: 1981
⑧ 2nd Reclamation: 1982
⑨ Embankment: 1989

Fig. 17 Completed cross-section of Maishima Reclaimed Island with the process of construction

The modeling of the water flow by SD and SCP is modeled by the macro-element method (Sekiguchi et al., 1986). Sheet piles were driven into the gravelly sand layer beneath the Holocene clay layer. As is shown in Fig. 16, the settlement of the revetment has been measured at the top of the sheet pile. Therefore, the measured settlement means the contribution of the Pleistocene deposits. The bottom boundary is assumed to be perfect drained as same as the case of one-dimensional analysis. The seaside boundaries of the gravelly sand layers are assumed to be perfectly boundary. The seaside boundaries of the clay layers and the reclamation side boundaries of all layers are assumed to be fully undrained. As for the soil parameters set up for the elasto-viscoplastic finite element analysis with the proposed procedure at

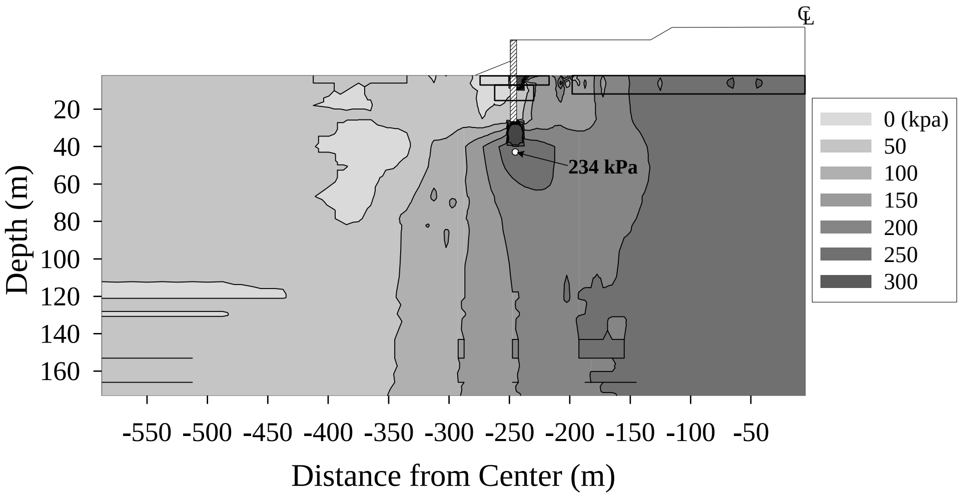
Maishima Reclamation Island, refer to Mimura et al. (2003b).

The completed cross-section of the reclaimed Island is shown in Fig. 17 together with the construction sequence. Sand mound was formed in 1974 up to O.P. –6.0 m following the completion of the ground improvement in the Holocene deposits, and then, backfilling was performed in 1975. Reclamation was initiated in 1979, and the final embankment was completed in 1990 with the height of O.P. +19.0 m.

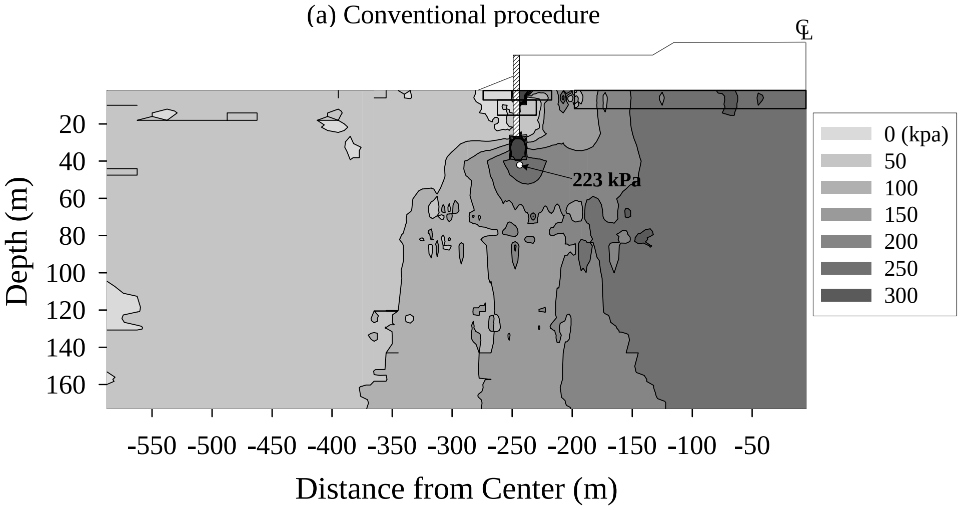
5.2 Calculated Performance of Maishima Reclaimed Foundation

In this section, the calculated performance for the Pleistocene clay deposits at the revetment of Maishima Reclaimed Island is discussed. The calculated performance with the proposed procedure is also compared with the conventional one. Figure 18(a) and (b) show the contours of the total vertical stress increment, Δp due to reclamation load at 14000 days from the start of construction. In general, similar distribution of Δp is derived with the proposed and the conventional procedure although slightly complicated stress distribution in Ma11 is presented for the case calculated with the proposed procedure mainly due to the elasto-viscoplastic deformation occurred in the quasi-oveconsolidated region. It can be seen in both cases that the outstanding stress concentration occurs at the SCP improved Holocene clay layer as well as the place beneath the sheet pile. On the contrary, the relatively uniform stress distribution is derived for all clay layers inside the island. As is shown in Fig. 18(a) and (b), Δp reduces toward the seaside because of the stress dispersion effect. It is noteworthy that the mode of stress distribution is very similar irrespective of the compression modeling.

The calculated settlement with the conventional and proposed procedures for each Pleistocene clay



(a) Conventional procedure



(a) Proposed procedure

Fig. 18 Contour of stress increment at 14000 days from the start of reclamation layer at the revetment (x = –240 m) is shown in Fig. 19. For Ma12, the stress of which surpasses p_c rapidly, the calculated settlement with the conventional and proposed procedures is almost the same until 6000 days. But slightly larger settlement is obtained with the conventional procedure than that with the proposed one after 6000 days because the increment of the total vertical stress associated with the stress distribution beneath the sheet pile is a little larger for the conventional procedure than the proposed one as shown in Fig. 18. For Ma11U and Ma11L that the final stress becomes close to p_c, the calculated settlement with the proposed procedure is much larger from the early stage of reclamation than that with the conventional one, because the proposed procedure provides the time-dependent behavior even in the region less than p_c. The final stress remains within in the quasi-overconsolidated region for Ma10 and Ma9. The calculated compression of Ma10 with the proposed procedure shows the remarkable time-dependency, while only elastic instantaneous settlement is obtained with the conventional one.

It may seem strange that the time-settlement relation with the conventional procedure shows larger settlement at the early stage of the construction and is outstripped by the one with the proposed procedure. The smaller compression at the early stage is

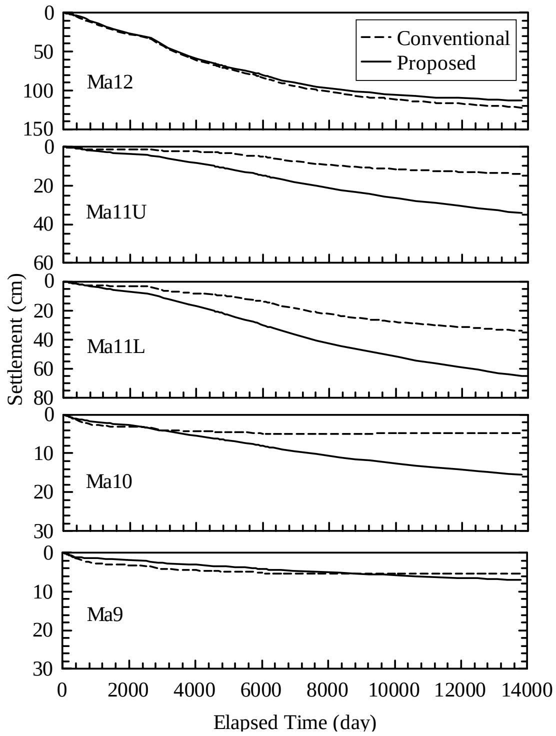


Fig. 19 Comparison of the calculated settlement for each Pleistocene clay layer at the revetment

provided by the proposed procedure because the stress overshoot phenomenon associated with the time-dependent behavior takes place even in the quasi-overconsolidated region whereas instantaneous compression is provided by the conventional one. The same tendency can also be seen for Ma9. The necessary time for outstripping is definitely controlled by the rate of consolidation. As Ma9 is thick with long drainage distance (see Fig. 2), the time-dependent compression of Ma9 advances slowly and it takes long time to outstrip the time-settlement curve derived with the conventional procedure.

Figure 20 compares the calculated total settlement of the Pleistocene deposits at the revetment with the measured data. The calculated settlement with the proposed procedure shows good match with the measured settlement, while the conventional approach provides serious underestimation. From those results, the descriptive accuracy of the proposed procedure has been confirmed also for the complicated improved marine foundation on the quasi-overconsolidated Pleistocene clay deposits in Osaka port.

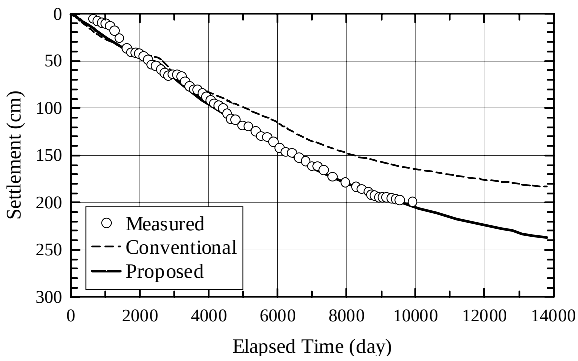


Figure 19 Comparison of the calculated total settlement of the Pleistocene deposits with the measured settlement at the revetment

6. Conclusions

The predictive accuracy of the proposed procedure in terms of elasto-viscoplastic finite element method is discussed for describing the long-term settlement of the quasi-overconsolidated Pleistocene clays in Osaka Port. The assumption that the time-dependent irreversible deformation takes place even in the region less than p_c as well as the normally consolidation region has been adopted to the proposed procedure on the basis of the geological finding that the quasi-overconsolidated Pleistocene clays in Osaka Bay can be regarded as normally consolidated. One-dimensional elasto-viscoplastic finite element analyses are carried out for Sakishima and Yumeshima Reclaimed Islands. In the case that the total stress (p_0+Δp) halts in the quasi-overconsolidated region on the way of reclamation, the proposed procedure provides the remarkable advance in settlement with time whereas the slight compression is obtained with the conventional one. This difference is definitely seen for Ma12 and Ma11 at Sakishima Reclaimed Island. On the other hand, for the case that the effective stress steadily increases and surpasses p_c such as Ma12 in Yumeshima Reclaimed Island, no significant creep deformation in the quasi-overconsolidated region is provided even by the proposed procedure. For Ma10 and Ma9 that the final effective stress remains less than p_c both at Sakishima and Yumeshima Reclaimed Islands, the proposed procedure provides the remarkable time-dependent compression with time, while only elastic instantaneous compression is calculated with the conventional one. The calculated performance by the elasto-viscoplastic finite element analyses formulated with the proposed procedure is found to well evaluate the rate of long-term settlement as well as the total settlement of the Pleistocene deposits measured in the reclaimed islands in Osaka Bay, whereas the conventional framework is found to exhibit serious underestimation.

The proposed procedure has also been extended to the two-dimensional analysis for the C revetment of Maishima Reclaimed Island. It is found that the mode of stress distribution is very similar irrespective of compression modeling. The total vertical stress increment, Δp is distributed uniformly for all clay layers located inside of the reclaimed island, but it reduces toward the sea side due to the stress dispersion effect. Far from the case with one-dimensional analysis, stress concentration due to ground improvement by SCP for the Holocene clay layer influences the condition of stress distribution in the underlying Pleistocene layers. In particular, outstanding stress concentration occurring just beneath the improved area, which directly propagates the underlying Pleistocene deposits. This effect of stress concentration contributes to the compression of the Pleistocene clay layers seriously. The calculated settlement of the Pleistocene deposits with the proposed procedure shows good match with the in-situ settlement measured at the revetment, while the conventional approach is found to underestimate seriously. From these results, the validity and superiority of the proposed procedure is verified for assessing the in-situ time-dependent long-term settlement occurred in the reclaimed islands in Osaka Port.

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弾粘塑性有限要素法による大阪湾擬似過圧密洪積粘土地盤の長期変形挙動の統一的な評価について

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要旨

過圧密領域においても洪積粘土の時間倈存性挙動が発生すると仮定した、著者らによる新たな圧縮モデルを用いて大阪港埋立地である咲洲・夢洲・舞洲における洪積層の長期沈下挙動を１次元及び 2 次元弾・粘塑性有限要素法によって解析し、各埋立人工島で計測された計測結果と比較し、提案している解析手法の妥当性を考察、検証した。その結果、洪積粘土各層別にも、また洪積全層についても、著者らによる提案解析法による長期沈下予測性は実測値を非常に精度よく表現しており、変形予測手法として非常に優れていることが明らかとなった。

キーワード：時間依存性挙動，擬似過圧密洪積粘土，弾粘塑性 FEM，長期沈下，護岸