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Efficiency of plastic board drain on self-weight consolidation of soft clay

L'efficacité de drain en planche en plastique sur consolidation par poids autonome d'argile douce

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ABSTRACT

A series of centrifuged self-weight consolidation tests of soft clays in which the plastic board drains were installed was carried out to investigate the effect of spacing and width of drain, and the influence of drain deformation caused by following settlement of the clay. Consolidation-time relations of test results were interpreted by current practical solutions. The main conclusions are: 1) the board drain can be converted to the equivalent circular diameter that has the same circumferential length as a board drain, 2) the combined solution of Barron's radial pore water flow and Mikasa's 1-D self-weight consolidation theories well explained the test results.

RÉSUMÉ

Une série de tests de consolidation par centrifugation d'argile douce dans lequel les drains en plastique ont été installés, a été expérimenté pour examiner l'effet d'espacement et la largeur de drain, et l'influence de déformation de drain causée en suivant le règlement de l'argile. Il a été trouvé que drain en planche peut être converti au diamétre circulaire équivalent qui a la longueur circonférentielle pareille comme un drain de planche. Les relations résultantes entre consolidation et temps étaient bien expliquées par une solution combinéé par la théorie de Barron et la théorie de Mikasa de 1-D consolidation par poids autonome.

1 INTRODUCTION

Recently, offshore reclaimed lands in Japan have been constructed by using dredged waste materials from seabed to construct and/or maintain waterways and berths in the port areas and to maintain river mouths. The dredged very soft clayey materials poured or dumped in the enclosed dyke must be consolidated. The vertical drain technique must be used: the plastic board drain (prefabricated vertical drain) is usually used instead of sand drain because the sand drain may not be installed in such a soft soil. Installation of board drains was usually made after the soft soil surface was treated by cement mixing to obtain the trafficability of installation equipment. After installation of board drains, the gradual increase of fill was made to increase consolidation pressure. Recently, the floating type installation equipment is used to install the board drain immediately after the dredged soil was poured or dumped in the dike. This procedure, combined with dewatering the lower pervious sand layer or vacuum loading to increase the consolidation pressure, help the soil volume rapidly reduce, and the more dredged soil can be received (Kiyama et al., 2000 and Kiyama et al., 2002). In this process, the self-weight of the soil exerts predominant consolidation pressure. In such a situation the effectiveness of board drain and the applicability of current time-consolidation prediction, such as Barron's solution, are not yet clarified.

This paper presents test results of a series of centrifuged model test of self-weight consolidation of very soft clay in which board drains were installed, and the interpretation of consolidation-time relation in respect with the spacing and width of drain by current practical consolidation theories.

2 TEST PROCEDURES

The clay used in this study is a plastic clay (w_L = 105 % and w_p = 35 %) dredged from seabed in Kanda, Fukuoka prefecture. It was remolded with seawater to water content of w_0 = 200 %. The remolded clay is poured in a acrylic cylinder with 12 cm in inner diameter and 30 cm in height. Four models were simultaneously tested in the centrifuge having a nominal radius of 2.56 m. The settlement of the clay surface was measured visually to 0.1 mm through a CCD camera with an aid of stroboscope.

Figure 1 shows the arrangement of the drains. All cases are in a square arrangement. Figure 2 shows installation types of the drains. The cylindrical drain in Fig. 2 (1) simulates the circular sand drain, using plastic rigid pipe having many small holes to have pervious condition wound by thin non-woven fabric strip in a spiral manner to reduce skin friction. The board drain in Fig. 2 (2) simulating a plastic board drain is a thick non-woven fabric strip (300 g/m^2). These two types were suspended from the upper lid of the acrylic cylinder not to deform due to settlement of clay during consolidation. This type is called 'suspended type' thereafter. Another board drain in Fig. 2 (3) is a thin non-woven fabric strip (100 g/m^2), and it can deform during the settlement of clay similar to the actual field condition. This type is called 'free type'. The single drainage condition does not allow the bottom drainage and the double drainage condition maintains the water levels at the upper and lower surfaces of the model equal by means of a drainage pipe as shown in Fig. 2 (3).

Test conditions described in the model scale are summarized in Table 1. Since the centrifugal acceleration employed in all cases is 100 g, the unit of length in the prototype scale is expressed by the same digits in meter in the table. Firstly, the models having different diameters of the cylindrical drain (Cases 1 to 7) and the models having different widths of the board drain (Cases 8 to 11) were tested. In this test series, the drains were installed in different spacings. Comparing the consolidation-time curves obtained from cylindrical and board drains installed in the same spacing, discussion is made to estimate the equivalent diameter of the board drain. Secondly, cases of the free type board drain were tested to investigate the influence of drain deformation, the effect of spacing and drainage conditions (Cases 15 to 22). A series of self-weight consolidation tests without drain at different initial water contents was also carried out to compare the consolidation-time curves to those of models with drains. The consolidation characteristics of this soft clay can be obtained from this procedure (Mikasa and Takada, 1985).

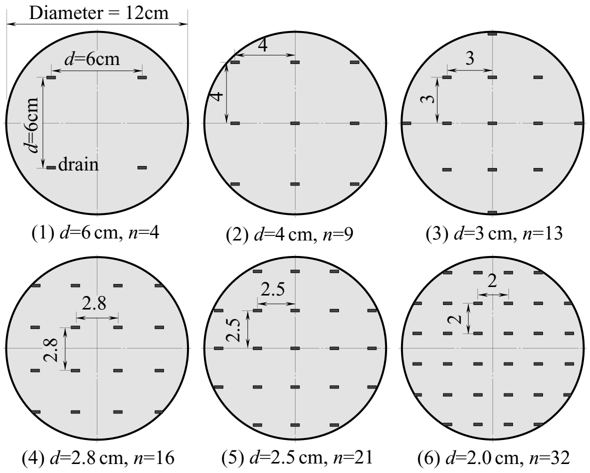

Figure 1. Arrangement of drains (d: spacing, n: number of drains)

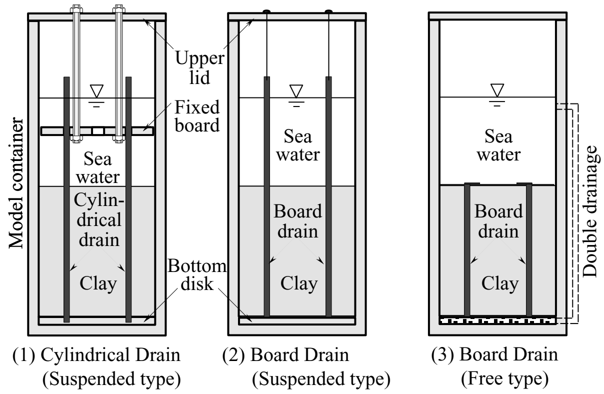

Figure 2. Installation types of drains

Table 1. Test conditions

Test Case	Drain type	d_w(cm) a (cm)	Spacing d (cm)	Drainage condition
1	Cylindrical drain (Suspended type)	0.36	6.0	Single drainage
2			4.0	
3			2.8	
4			2.0	
1		0.36	6.0	
5		0.70		
6		1.04		
7		1.64		
8	Board drain b=0.06 (Suspended type)	0.50	6.0	
9			4.0	
10			2.8	
11			2.0	
8		0.50	6.0	
12		1.04		
13		1.57		
14		2.52		
15	Board drain b=0.02 (Free type)	0.50	6.0	
16			4.0	
17			3.0	
C18			2.5	
19			6.0	Double drainage
20			4.0	
21			3.0	
22			2.5	

d_w: Diameter of cylindrical drain, a: Width of board drain
b: Thickness of board drain (cm)

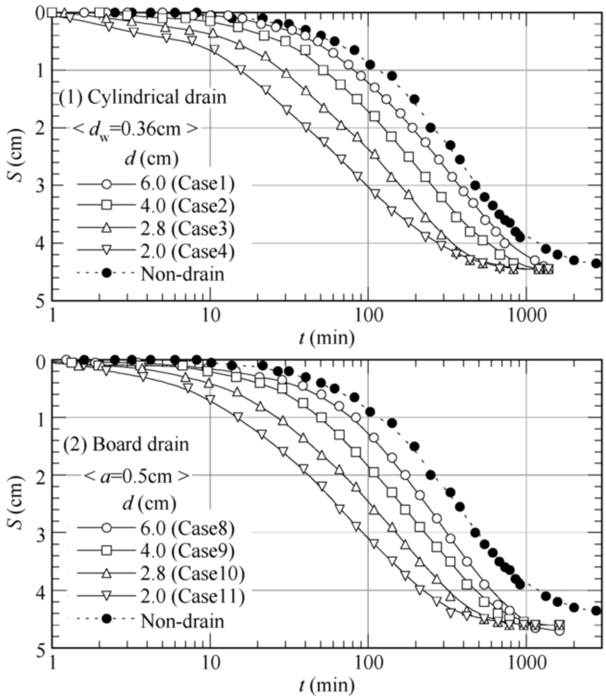

Figure 3 Effect of drain spacing of cylindrical and board drains

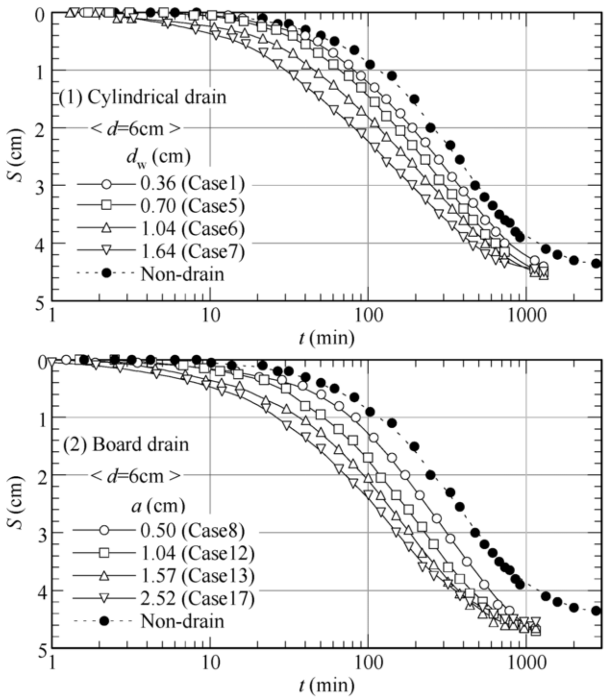

Figure 4. Effect of diameter and width of cylindrical and board drains

3 CONSOLIDATION-TIME CURVES BY CYLINDRICAL AND BOARD DRAINS

Figures 3 (1) and (2) show consolidation-time (S–log t) curves in the cases of the cylindrical drain with a diameter, d_w, of 0.36cm and the board drain with a width, a, of 0.5 cm, respectively, with different drain spacings, d, under the single drainage condition together with the case of non-drain for comparison. Apparently, the cases having smaller d show more rapid consolidation process. Figures. 4 (1) and (2) show S–log t curves in the cases of the cylindrical drain of diameter of d_w = 0.36, 0.70, 1.04, and 1.64 cm and the board drain of width of a = 0.5, 1.04, 1.57, 2.52 cm, respectively, under the common drain spacing of d = 6 cm. The larger d_w and a generate the more rapid consolidation process.

Figure 5 shows the comparison of consolidation processes of the cylindrical drain of d_w = 0.36 cm and the board drain of a = 0.5 cm under different drain spacings d in which the axis of ordinate is expressed by degree of consolidation, U, defined by using final settlement reading because the final settlement readings slightly scatter as shown in Figs. 3 and 4. Both curves are in good agreement in each spacing. Therefore, the board drain with a = 0.5 cm corresponds to d_w = 0.36 cm of the cylindrical drain. Comparison of U–log t curves in the cases of the cylindrical drain having different diameters and in the cases of the board drain having different widths under the common drain spacing of d = 6 cm is presented in Fig. 6. Although the consolidation processes in the cases of board drain tend to be slightly faster than those in the cases of cylindrical drain, the processes in the cases of a = 0.5, 1.04, 1.57, 2.52 cm of board drain fairly coincide with the processes in the cases of d_w = 0.36, 0.70, 1.04, and 1.64 cm of cylindrical drain, respectively, and the corresponding cases having different drain types are regarded to have equivalent drain diameters. This concludes that the equivalent diameter of the board drain is calculated by the following equation.

$$d_w = \frac{2(a+b)}{\pi} \qquad (1)$$

where b is the drain thickness. This equation describes that the circumferential lengths of drain of both types are the same. In the current design method, one-half of the width of plastic board drain has been regarded as the equivalent diameter. Above conclusion shows that the current design procedure is too safe side in respect with the consolidation time.

4 EFFECTIVENESS OF BOARD DRAIN

4.1 *Estimation of consolidation process*

The consolidation process of the clay having vertical drains is practically estimated by using the Barron's solution. In this estimation, the 1-D consolidation component occurring at the top and bottom of the layer is superposed by the following manner (Carrillo, 1942), although 1-D component is usually neglected when the clay layer is thick.

$$U(t) = 1 - \left(1 - U_z(t)\right)\left(1 - U_r(t)\right) \qquad (2)$$

where $U(t)$ is the combined degree of consolidation, $U_z(t)$ is the degree of consolidation calculated by 1-D consolidation theory and $U_r(t)$ is the Barron's radial pore water flow solution.

When the clay is very soft, the effect of self-weight of clay is very strong on the consolidation process. In this paper, the consolidation process expressed by $U_z(t)$ in Eq. (2) is calculated by Mikasa's 1-D non-linear consolidation theory numerically, considering self-weight of the clay and the change in the coefficient of consolidation, c_v, during consolidation process (Mikasa and Takada, 1984). The calculation of consolidation process in the cases of the board drain employs the equivalent diameter described by Eq. (1) and effective model diameter is regarded as 1.13d considering square drain arrangement. The horizontal coefficient of consolidation, c_h, used in the Barron's solution was given 11 cm^2/d (Oshima et al., 2002). The value c_h is determined empirically as the same value of c_v as the average value at initial and final water content.

4.2 *Effect of spacing and width of board drain*

Figure. 7 shows the comparison of experimental and calculated U–log t curves with different drain spacings d under the common board drain width of a = 0.5 cm. The calculated curves are expressed by the model scale in accordance with the similarity rule of centrifuge model. Mikasa's solution for the case of non-drain is also shown in the figure, which coincides well with the experimental U–log t curve. The Barron's solutions as shown Fig. 7 (1) underestimate the consolidation rate and overestimate the effect of drain spacing. On the other hand, the combined solutions calculated by Eq. (2) as shown Fig. 7 (2) successfully explain the experimental curves. Thus the Eq. (2) is applicable to the consolidation of very soft clay having vertical drains.

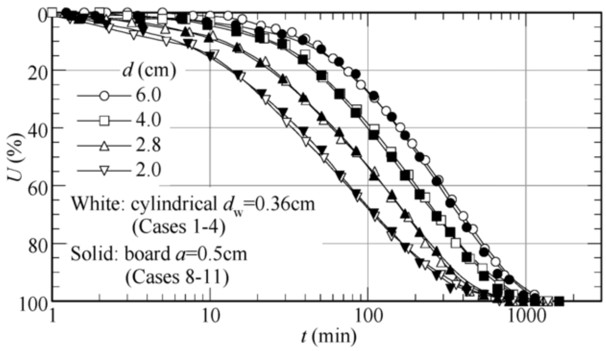

Figure 5. Comparison of cylindrical and board drains with different spacings

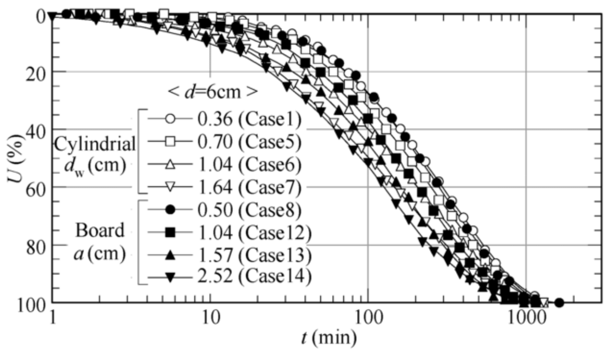

Figure 6. Comparison of cylindrical and board drains with different diameters and widths

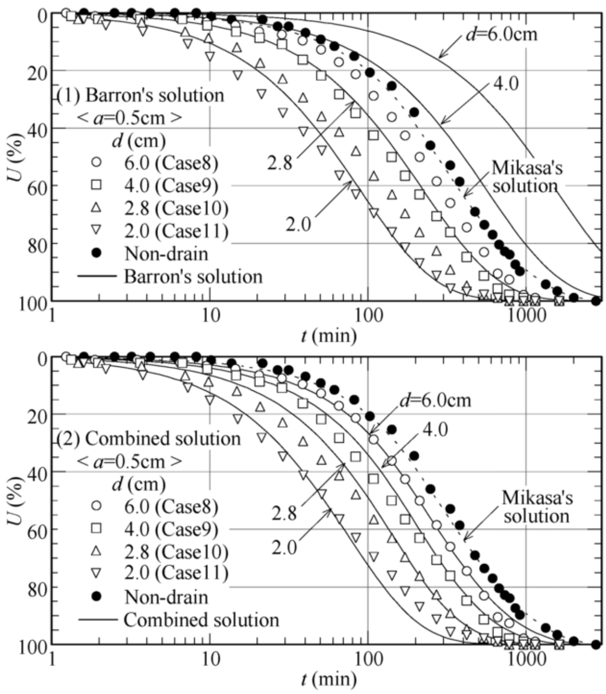

Figure 7. Comparison of experimental and calculated U–log t curves with different drain spacings

Figure 8 shows the comparison of experimental and calculated U–log t curves with different widths of board drains a under the common spacing of d = 6 cm. The Barron's solutions as shown Fig. 8 (1) underestimate the consolidation rate, although the spacing d = 6 cm (d = 6 m in prototype) in these cases are extreme ones. On the other hand, the combined solutions as shown Fig. 8 (2) produce more appropriate estimation, although these solutions slightly underestimate the effect of the drain width. This underestimation is because the Barron's solution that much underestimates the consolidation rate affects the combined estimation.

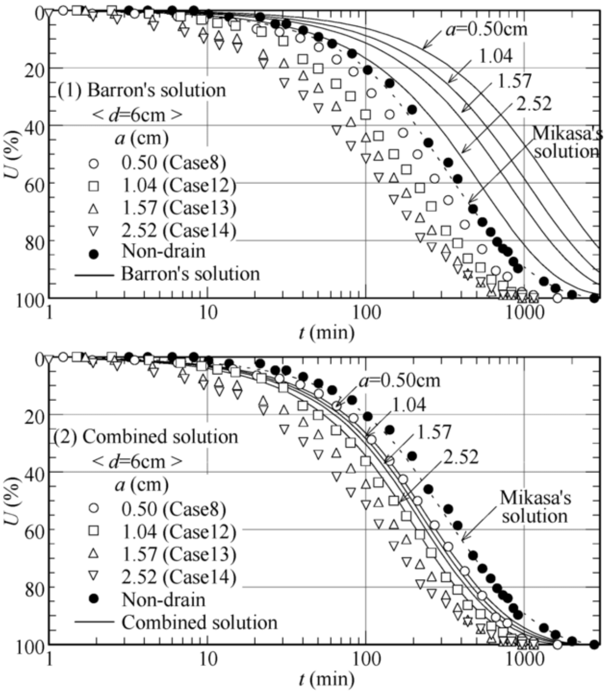

Figure 8. Comparison of experimental and calculated U–log t curves with different widths of drain

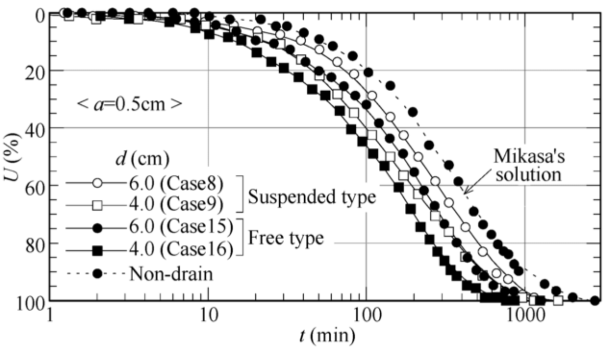

Figure 9. Comparison of suspended and free types of drain

4.3 *Effect of drain deformation*

In the previous sections, discussion is made on the cases of 'suspended type' drain in which the drains do not deform during the consolidation of clay. In this section, the test results in the cases of 'free type' drain is presented, which exhibit more realistic behavior. Figure 9 shows U–log t curves in the cases of free type drain with the drain width of a = 0.5 cm under different spacings together with the cases of suspended type drain presented for comparison. The free type drain shows the slightly higher consolidation rate than the suspended one. Since the drain deforms in the shape of a sine curve, the higher

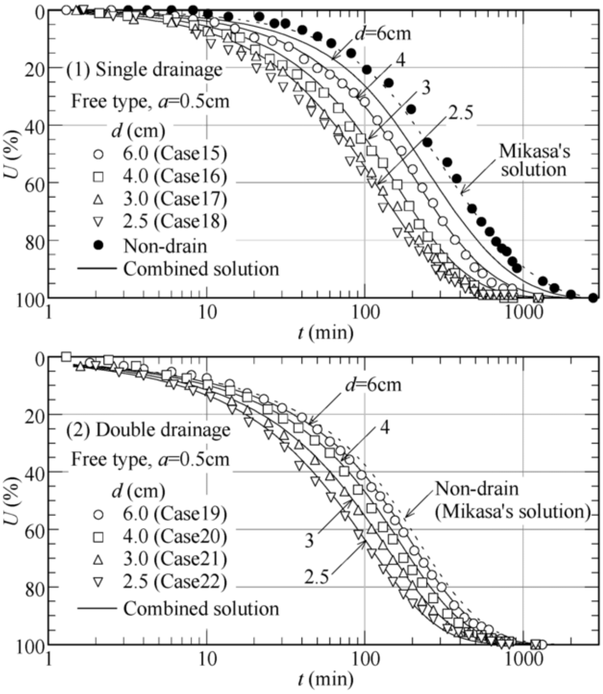

Figure 10. Comparison of experimental and combined U–log t curves with different drainage conditions

consolidation rate may be generated by shortening the radial drainage distance.

Figure. 10 show U–log t curves in the cases of free type drain with a = 0.5 cm under different spacings. In the single drainage cases in Fig. 10 (1), calculated curves show the smaller consolidation rate in the cases of larger drain spacing. In the double drainage cases as shown in Fig.10 (2), calculated estimations well coincide with the experimental curves. Since the component of 1-D consolidation in the combined solution under the double drainage condition is larger than the single drainage condition, the effect of drain spacing on the consolidation rate is less under the double drainage condition.

5 CONCLUSIONS

The consolidation-time relations of the very soft clay having installation of plastic board drain are discussed both by experiment and theoretical calculation. Main conclusions are:

1) Barron's solution cannot applicable to the very soft clay where the effect of 1-D self-weight consolidation is not neglected.
2) The plastic board drain can be converted to the equivalent diameter of circular drain that has the same circumferential length as the board drain.
3) The combined solution of Barron's radial pore water flow theory and Mikasa's 1-D self-weight consolidation theory well explains the experimental test results.
4) The drain deformation like a sine curve caused by following settlement of the clay generates the slightly higher consolidation rate.

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