

November 2004

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Indraratna, Buddhima and Rujikiatkamjorn, Cholachat: Laboratory Determination of Efficiency of Prefabricated Vertical Drains Incorporating Vacuum Preloading 2004.
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Laboratory Determination of Efficiency of Prefabricated Vertical Drains Incorporating Vacuum Preloading

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Abstract: This paper is mainly concerned with a laboratory study to investigate the effect of vacuum preloading. Two separate series of tests were conducted in a large-scale consolidation apparatus designed and installed at the University of Wollongong, with axial load increments of 30 and 50 kPa. The first series of tests were performed based on the conventional method (i.e. without vacuum preloading). For the second series, a vacuum pressure of 100 kPa was applied during the process of consolidation. The corresponding settlement behaviour was recorded and plotted. The extent of smear zone was examined by the variation of permeability of small specimens obtained from the large-scale consolidometer. The void ratio-permeability relationship was also determined from the small specimens. The test results based on the large-scale laboratory testing confirm the efficiency of vacuum preloading in comparison with the conventional method of surcharge alone.

1 INTRODUCTION

In recent years, prefabricated vertical drains (PVDs) incorporating vacuum preloading have been used widely for accelerating the consolidation of soft ground (Shang *et al.*, 1998). Using this technique, the drainage length is considerably shortened from the full thickness of the soft soil layer to half of the drain spacing in the horizontal direction. The vacuum pressure propagating along the PVDs increases the hydraulic gradient and performs as an additional surcharge load. Therefore, this system accelerates the consolidation process, and the height of the embankment can be reduced to achieve the same degree of consolidation (Mohamedelhassan and Shang, 2002).

In the current research, a large-scale consolidometer (Indraratna and Redana, 1998) was utilized to compare the performance of the PVDs system incorporating vacuum preloading with the conventional method (without vacuum preloading), and to assess the extent of the smear zone around a mandrel driven vertical drain. By collecting the undisturbed soil samples around the vertical drain, the void ratio (e) and permeability (k) of each sample were measured by oedometer test. Permeability of all soils is strongly influenced by the density of packing of the soil particles, which can be simply described through the void ratio that was obtained readily from the ordinary soil moisture content test (Narasimha Raju, *et al.*, 1997). Therefore, the smear zone could be quantified either by measuring the change of permeability of soil samples or the change of void ratio. Finally, the e -log k relationships from this type of soil were proposed in this study.

2 VOID RATIO-PERMEABILITY RELATIONSHIP

The permeability depends on the size, shape, and void distribution. Depending on soil types, the void ratio permeability relationship can be divided into two categories, namely, sands and

clays. For sands, the relationship was proposed by Taylor (1948) and later modified by Samarasinghe *et al.* (1982) as given by:

$$k = C \frac{e^n}{1+e} \quad (1)$$

where, k = permeability, C = a reference permeability indicating the soil characteristics, n = a constant depending on the type of soil and e = void ratio.

Showing the limitations of Eq. (1) for clays, Taylor (1948) proposed an empirical linear relationship between the log k and e . The relationship can be expressed as:

$$\log k = \log k_0 - \frac{e_0 - e}{c_k} \quad (2)$$

where, c_k is a permeability change index, k_0 and e_0 are the *in-situ* values. This type of relationship has been commonly used to describe the variation of the permeability of clays with void ratio. It can be noted that Eq (2) would be generally valid for the range of void ratio in engineering practice (Tavenas *et al.*, 1983).

3 APPARATUS

The schematic illustration of the large-scale radial drainage consolidation apparatus is shown in Fig. 1. The main body of the cell consists of two half sections made of stainless steel (450 mm in internal diameter and 950 mm in height). In order to reduce the friction along the cell boundary, a 1.5 mm thick Teflon sheet was inserted around the internal boundary. The loading system with a capacity of 1200 kN can be applied by an air jack compressor system via a piston. Water and air tightness of piston is achieved by using an O-ring system on its peripheral edge. The LVDT connected with data logger is usually placed at the top of the piston to measure the settlements. For vacuum pressure application, a vacuum pump capable of generating 100 kPa suction pressure is employed at the top of PVD. The cell is also equipped

with a specially designed steel hoist from which a prefabricated vertical drain can be inserted vertically along the central axis of the cell.

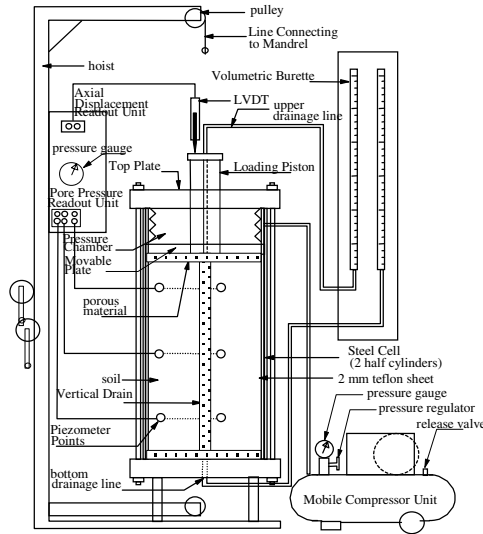


Fig. 1. Large-scale consolidation apparatus (after Indraratna and Redana, 1998)

4 TEST SAMPLE

Reconstituted alluvial clay from Moruya (New South Wales) was used in the apparatus. The clay size particles ($<2 \mu\text{m}$) accounted for about 40% - 50% of the specimen, and particles smaller than silt size ($<6 \text{ mm}$) constituted about 60% of the specimen. Selected geotechnical properties of sample are shown in Table 1. According to the Casagrande plastic chart, the reconstituted clay could be classified as CH (high plasticity clay).

Table 1. Soil properties of reconstituted clay sample.

Soil properties	Reconstituted clay
Water content (%)	45
Plastic limit, w_p (%)	17
Plasticity Index, PI (%)	25
Unit weight, γ_t , (kN/m ³)	17
Initial void ratio (e_0)	1.24
λ (oedometer test)	0.14
κ (oedometer test)	0.05

5 TEST PROCEDURE

Two separate series of tests were conducted in a large-scale consolidation apparatus with axial load increments of 30 and 50 kPa. The first series (Test A) were performed based on the conventional method (i.e. without vacuum preloading). For the second series (Test B), a vacuum pressure of 100 kPa was applied during the process of consolidation. All tests were carried out in three stages: (1) preparation of reconstituted clay, (2) drain installation and (3) collection of oedometer samples. In the first stage, fol-

lowing Burland (1990), the clay specimen was mixed thoroughly with a water content slightly greater than the liquid limit.

Within the large-scale consolidometer cell, the clay was placed and compacted in layers in the apparatus. An initial pre-consolidation pressure of 20 kPa was applied for 5 days before the installation of the vertical drain. In the second stage, the 100 mm \times 3 mm band drain, which equals to 32.5 mm of equivalent drain radius (r_w), was then installed vertically using a steel mandrel. After drain installation, the mandrel was withdrawn by the hoist system, and subsequently, the preconsolidation pressure of 20 kPa was maintained further for the tests. For Test A, the large clay sample was further subjected to loading in increments of 30 kPa and 50 kPa for 16 days and 14 days, respectively. In the case of Test B, the large clay sample was loaded axially in increments of 30 and 50 kPa, together with an application of vacuum pressure of 100 kPa, for 14 days and 20 days, respectively. The corresponding settlement behaviour was recorded and plotted.

After installation of the geosynthetic vertical drain and subsequent testing, vertical and horizontal specimens were collected from different locations within the cell at known radial distances (i.e. Sections A-A and B-B) (Fig. 2). Oedometer tests were performed on these samples to establish the extent of smear zone and the permeability-void ratio relationships close to and away from the central drain.

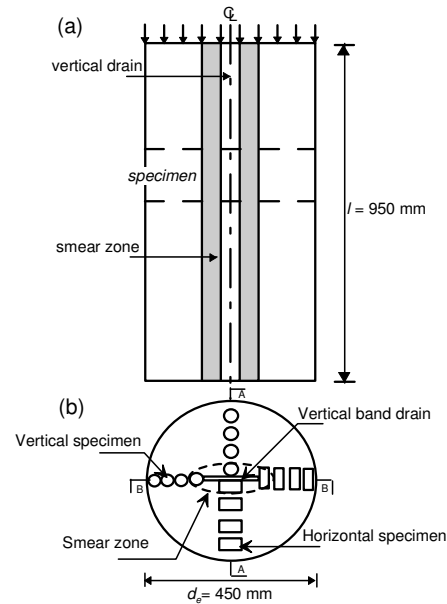


Fig. 2. Schematic Diagram: (a) section of test equipment showing central drain and associated smear; (b) locations of specimens obtained to determine smear zone by employing void ratio and permeability characteristics.

6 TEST RESULTS AND ANALYSIS

In this section, the effect of vacuum preloading in the PVDs system is discussed. The extent of the smear zone associated with the PVD was investigated by evaluating the permeability parameters at different radii. Finally, the void ratio-permeability relationships for both horizontal and vertical direction are established.

The stages of loading for Test A and Test B are shown in Fig. 3a. Figure 3b presents the measured settlements versus time for

Tests A and B. The magnitude of settlement with applied vacuum preloading (Test B) is more than the conventional loading about 1.5 times at the end of the test. It also implies that the rate of settlement for Test B is faster than that of Test A. This clearly shows that (a) vacuum preloading performs as an additional surcharge load (b) the rate of consolidation settlement is accelerated by the propagation of negative pressure along the drain length resulting in higher hydraulic gradient.

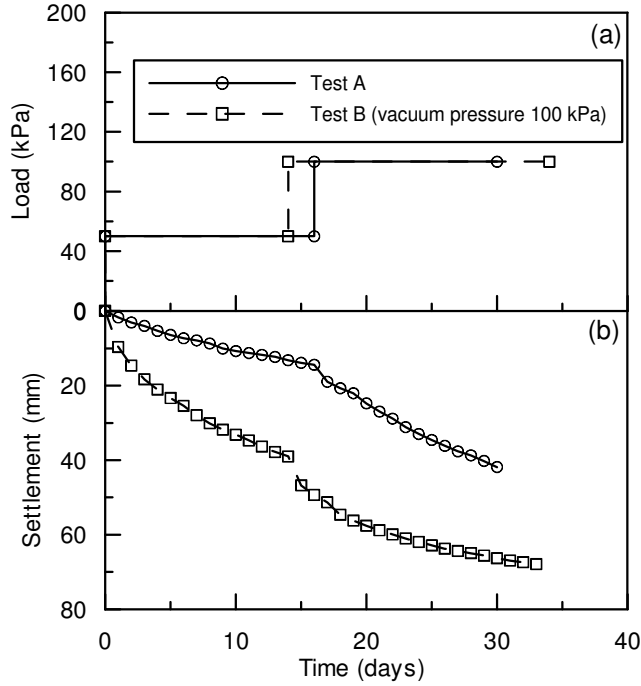


Fig. 3. (a) Loading sequences; (b) Measured settlements.

As mentioned earlier, to investigate the extent of smear zone, small specimens were collected along Section A-A and B-B within unit cell in both vertical and horizontal directions at the end of the test (Fig. 2b). Figures 4 and 5 show the variation of void ratio as well as the horizontal and vertical permeability at the different radial distances for Test A and Test B, respectively. It is observed that the void ratio as well as the horizontal and vertical permeability decrease towards the vicinity of the drain. This verifies that the soil disturbance (smear zone) is highest near the drain boundary. As expected, the final average values of void ratio, horizontal and vertical permeability from Test B is less than Test A due to the effect of vacuum preloading (Table 2). Indraratna and Redana (1998) suggested that a dimensionless ratio k_h/k_v is a proper method in determining the smear zone, because, this method minimizes the error occurring in the determination process of the actual coefficient of permeability. The method of obtaining k_h and k_v is not critical, as long as the same laboratory approach is made consistent for both k_h and k_v . Figure 6 illustrates the ratio k_h/k_v along the radii of the unit cell. Observing the significant drop of k_h/k_v , the radius of smear zone for both tests can be taken to be 80 mm and 120 mm for Sections A-A and B-B, respectively. The variations of k_h/k_v from both tests along the radial distance from the drain are similar. It verifies that there is no effect of vacuum pressure on this parameter. The average radius of smear zone is 100 mm or it is about 3 times the value of r_w , which agrees well with Indraratna and Redana (1998). It can be observed that the variations of void ratio with radial distance also decrease considerably within the smear zone, because, void

ratio relates directly to the permeability (see Figs. 4 and 5). Therefore, the variation of void ratio could be employed as an alternative way to determine the extent of smear zone.

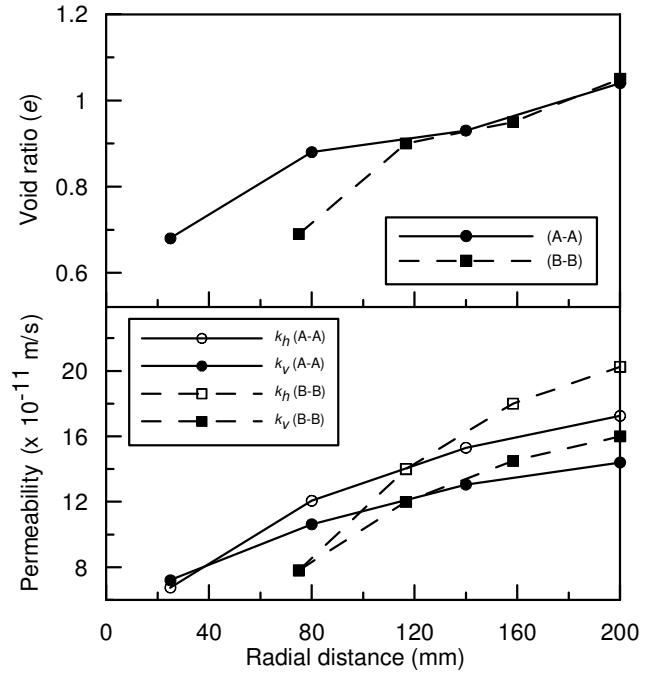


Fig. 4. Void ratio and permeability along radial distance from central drain (Test A).

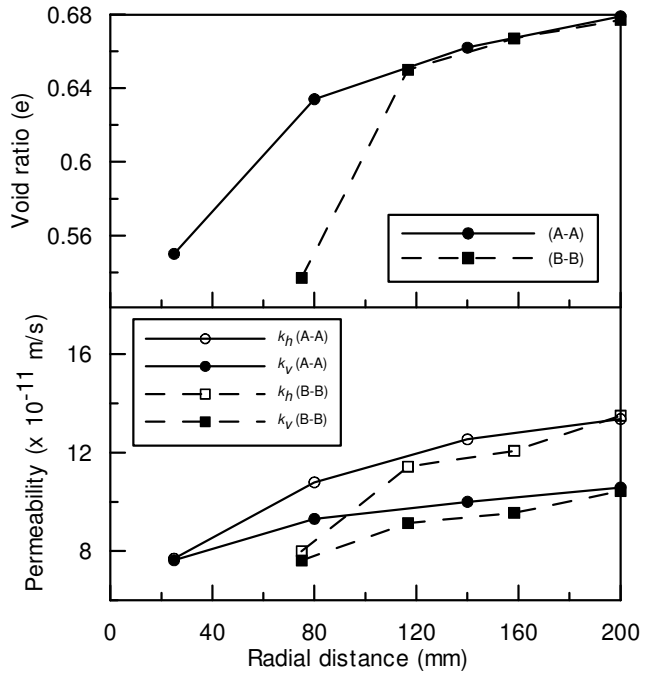


Fig. 5. Void ratio and permeability along radial distance from central drain (Test B).

Table 2. Soil properties at the end of the test

	Test A	Test B
Average void ratio	0.89	0.63
Average horizontal permeability ($\times 10^{-11}$ m/s)	13.92	11.17
Average vertical permeability ($\times 10^{-11}$ m/s)	11.84	9.28

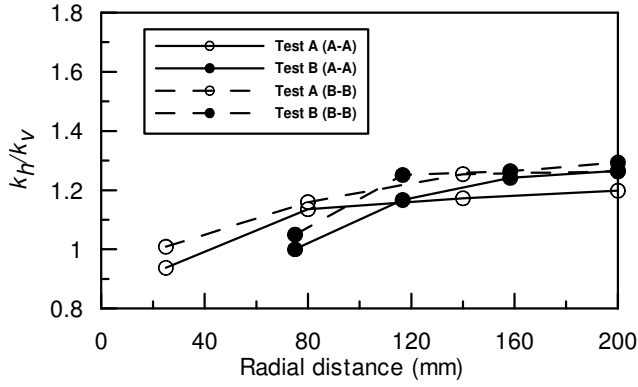


Fig. 6. Ratio of k_h/k_v along the radial distance from central drain

Figures 7 and 8 show the relationships of void ratio-vertical permeability (e - $\log k_v$) and void ratio-horizontal permeability (e - $\log k_h$), respectively. Based on linear regression analysis, For vertical permeability:

$$\log k_v = 0.59e - 10.45 \quad (3)$$

For horizontal permeability:

$$\log k_h = 1.10e - 10.83 \quad (4)$$

Once again, it can be seen that there is no effect of vacuum pressure on the soil permeability during the test. According to Eq. (2), the initial vertical permeability (k_{v0}) and initial horizontal permeability (k_{h0}) can be back calculated based on Eqs. (3), (4) and initial void ratio (e_0). The corresponding values are shown in Figs. 7 and 8. The initial horizontal permeability is about 2.5 times the initial value along the axial direction.

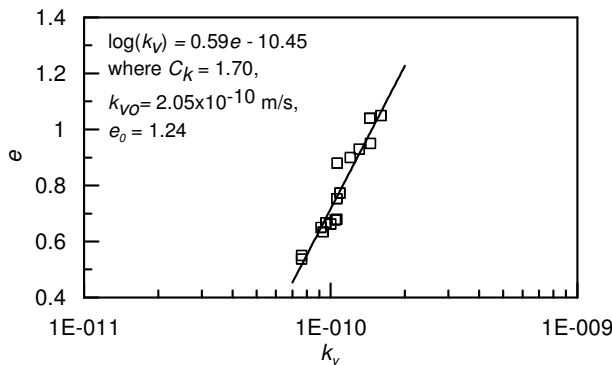


Fig. 7. Void ratio-vertical permeability relationship

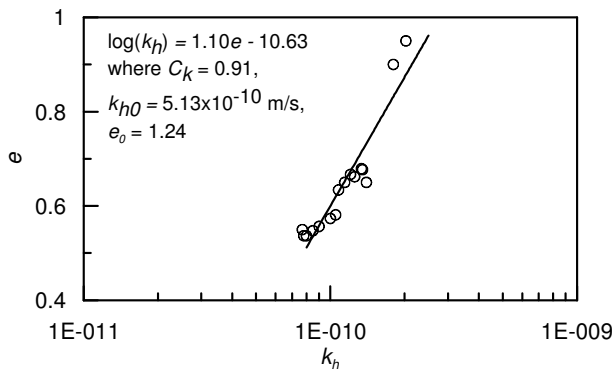


Fig. 8. Void ratio-horizontal permeability relationship

7 CONCLUSION

The performance of prefabricated vertical drain incorporating vacuum preloading was investigated in the laboratory test, using a large-scale consolidometer. Comparing with the conventional method, it shows that the vacuum application performs as an additional surcharge load and accelerates the consolidation process. By measuring the variation of the horizontal and vertical permeability at the different radial distances in the unit cell, the extent of smear zone could be determined. The smear zone radius was approximately 100 mm for tests with and without vacuum pressure, showing that the size of smear zone is not influenced by the vacuum application. It is also found that void ratio which relates directly to soil permeability can also be employed as a simple tool to determine the extent of smear zone around a mandrel driven vertical drain.

ACKNOWLEDGMENTS

Writers would like to thank Mr. T. Dimovski and Mr. T. Cadden, who are former undergraduate students from University of Wollongong for their assistance during the laboratory testing. The second writer gratefully acknowledges the financial support from University of Wollongong.

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