EXPERIMENTAL STUDY ON EFFECTIVENESS OF VERTICAL DRAINS BY MEANS OF ROWE CELL APPARATUS

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Vertical drains have recently become a popular method of soil improvement in Australia as it provides a low-cost solution for improving the performance of thick deposits of soft clays. The successful application of this method typically depends on the validity of analytical solutions in which settlements of soft deposits are predicted utilizing classical consolidation theories from soil mechanics. However, little has been done to test such theoretical models in practice, where different soil conditions can be encountered, primarily because project deadlines typically do not allow for such time-consuming endeavours. However, lack of reliable field and laboratory data may lead to a situation in which the effectiveness of soil improvement can be significantly below expectations, as recorded in some recent case studies. This research seeks to fill this gap in scientific data by presenting the results of experimental tests in which the behaviour of vertical drains was studied by means of a Rowe Cell apparatus. These tests were designed to investigate the influence of the size of vertical drains, as well as the smear effect, on settlements of soil at different stress levels. It was found that the process of consolidation occurred more rapidly when a drain of a larger diameter was utilized. In addition, similar to the results from large-scale field trials, it was observed that the presence of smear zone can also slow down the rate of settlement in the laboratory tests. Comparisons were made between different laboratory studies in which the performance of sand drains was investigated in a series of Rowe Cell tests. Finally, an attempt was made to compare the performance of vertical drains obtained in the laboratory tests with that which was observed in large-scale field projects.

Keywords: Prefabricated vertical drains, Soft clay, Rowe Cell, Settlement, Ground improvement.

1. INTRODUCTION

Rapid increases in populations along coastal Australia in the last few decades have resulted in the need to develop infrastructure in areas with undesirable ground conditions such as soft clays. Due to its extreme compressibility, these soils present significant challenges for infrastructure design and construction as they have the tendency to sustain high pore water pressures during static loading in the absence of appropriate ground improvement.

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To address this issue, a great deal of research has been conducted in the past few decades, leading to development of different methods of soil improvement, including the combination of preloading method with prefabricated vertical drains (PVDs) (Hansbo, 1979; Tan *et al*., 1987; Bergado *et al*., 2002; Indraratna *et al*., 2003). However, despite significant progress in this field, it still remains a challenging task to select a method of soil improvement that will produce the most desirable outcome for a specific site as there are a few important factors, including geologic conditions and the smear effect, that need to be considered. As a result, there are several case studies in which drains did not perform to expectations, as has been documented in technical papers (Robertson, 1984; Litwiniwicz, 1988; Ameratunga *et al*., 2010). For example, Wijeyakulasuriya *et al*. (1999) noted that the use of drains in sensitive clays along the eastern coast of Queensland was not effective, and suggested that such a soil improving technique should only be used with caution for soils with similar geotechnical properties. Ameratunga *et al*. (2010) analysed the results from large-scale trail tests at the Port of Brisbane, Queensland with different drain spacings ranging from 1.0 m to 1.4 m, and reported that ″a definite reduction in performance was observed for the closer 1.0 m triangular spacing″, mostly due to the greater effect of smear.

From the aforementioned studies, it can be inferred that in order to avoid undesirable outcomes, the feasibility of using PVDs for certain site conditions needs to be assessed beforehand. However, large-scale projects designed for this purpose are typically costly and time-consuming, and thus relatively inexpensive laboratory tests may be considered to some extent as a valid alternative. Although such tests tend to underestimate the consolidation characteristics of soft clays (Balasubramaniam *et al*., 2010), they still produce valuable information about the geotechnical properties of soil within a reasonable time frame. Laboratory tests can also be utilized to evaluate the influence of smear zone due to installation of PVDs on settlement of soft soils (Bergado *et al*., 1991; Indraratna and Redana, 1998; and Almeida *et al*., 2001). Although the above-mentioned studies have provided useful insights into the process of soil consolidation, it is still unclear as to what degree such laboratory tests can be used to predict the performance of vertical drains in the field. This study provides additional laboratory data to clarify the behavior of soft soil with and without vertical drains. Vertical drains of different diameters were utilized to better understand the effect of drain size on the settlement of soil. A special testing procedure was designed to evaluate the effect of smear zone on the time of consolidation. The obtained findings were compared with the data from a laboratory study in which the effect of sand drains was also investigated by means of Rowe Cell tests.

2. EXPERIMENTAL PROGRAM

2.1. *Soil properties*

The dredged mud from a construction site at the Port of Brisbane (PoB) was kindly provided by the PoB authorities. The geotechnical properties of this soil have extensively been studied by Ameratunga *et al*. (2010), who reported that the liquid limit (LL) of this mud can widely range from 40 to 80. The soil samples tested in this work had a liquid limit (LL) of about 62, and a plasticity index (PI) of 29.

2.2. *Test Procedure*

A conventional Rowe Cell apparatus with a diameter of 250 mm was employed in this research to study the effect of vertical drains on the consolidation characteristics of soft soil. All the specimens for Rowe Cell tests were prepared from slurry. First, an oven-dry soil was mixed with water to form a uniform slurry with a moisture content of 70%. A vertical drain with a diameter (d_w) of either 8.3 mm or 16.5 mm was placed in the middle of the cell, fixed at the bottom, and kept upright while the soil slurry was poured inside the cell. Such a test procedure (procedure No.1) was believed to produce specimens without smear effect from installation of the vertical drain. The vertical drains used in this study were made of geofabric to provide a path for water flow during testing. Considering that the process of consolidation occurs across the whole specimen with a diameter (d_e) of 250 mm, the n ratio, which is defined as $n = d_e/d_w$, was about 30 and 15, respectively for the tests with vertical drains. Overburden stress was then applied in increments of 12.5, 25.0, 50.0, and 100.0 kPa. The drainage of water was permitted at the top and bottom of the specimen. Each stress increment continued until 90% consolidation was attained.

To study the smear effect, a different test procedure (procedure No.2) described below was used. First, the slurry was placed in the cell, and a load of 12.5 kPa was applied to the sample until 90% consolidation was reached. Then the sample was unloaded, the top plate of the Rowe Cell was removed, and a vertical drain of either 8.3 mm or 16.5 mm in diameter was installed in the middle of the soil sample by using a specially designed mandrel. After that, the Rowe Cell apparatus was assembled again, and the same load of 12.5 kPa was applied and kept for one day before proceeding to the next stress increment.

2.3. *Results of Rowe Cell Tests*

Results from a series of Rowe Cell tests are presented in Figure 1 in the form of time against settlements obtained at a stress level of 25 kPa for three different cases: 1) no vertical drain – a reference test in which no vertical drain was used; 2) a test with a vertical drain of 8.3 mm;

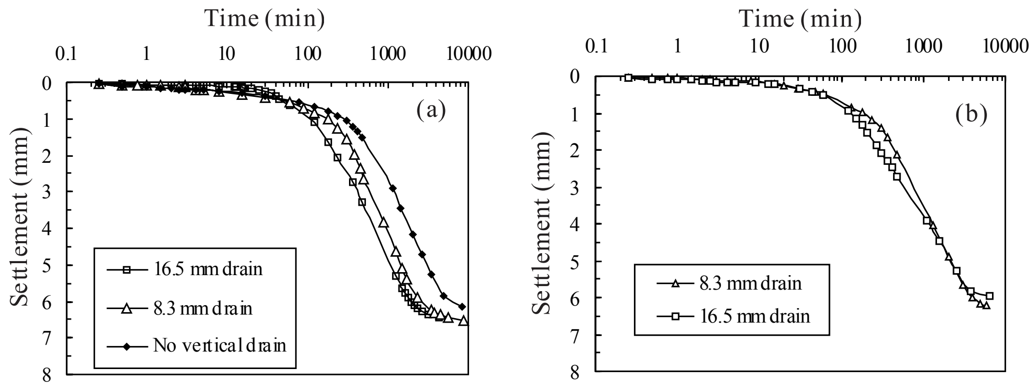

Figure 1. Results of Rowe Cell tests with and without vertical drains plotted as settlement against time at overburden pressures of 25 kPa, using (a) the test procedure 1 (no smear effect), and (b) the test procedure 2 (with smear effect).

and 3) a test with a vertical drain of 16.5 mm. It is evident from Figure 1a that a faster settlement rate was observed for the specimens with the vertical drains compared to that with no vertical drain. Also, a vertical drain with a diameter of 16.5 mm results in more rapid settlements compared to settlements with a vertical drain of 8.3 mm. It is logical to suggest that the drain with a larger diameter would provide a larger area for water flow, and thus produce a greater rate of soil consolidation.

Figure 1b shows the results of laboratory tests in which the vertical drain was installed in the soil specimens by means of a mandrel using the test procedure 2. Comparisons made between the test data presented in Figures 1a and 1b clearly indicate the effect of smear zone on the settlement of soil; that is, the presence of smear zone can slow down the process of consolidation. It is noted that although the drain with a larger diameter (16.5 mm) is still associated with a faster rate of settlement, the difference in performance between these two drains seems to be much smaller compared to the disparity which was observed in Figure 1a.

3. COMPARISONS WITH A LABORATORY STUDY USING SAND DRAINS

The results obtained in this work are compared with the data reported by Prawono (1978), who studied the influence of sand drains on the consolidation characteristics of clay from Bangkok. Prawono (1978) also employed a Rowe Cell apparatus, albeit one with a smaller diameter of 152 mm and a sample height of 25 mm. Sand drains of different diameters, having n-values of 5, 10, 20 and 30, were utilized in those tests to provide a drainage path for water flow.

The results of this research are summarized in Figure 2 in terms of time against the degree of consolidation. It is clear from this figure that an increase in the diameter of sand drain (that is, a decrease in the n-values) leads to a faster rate of soil settlements, a finding that is similar to the one obtained for vertical drains used in the present study.

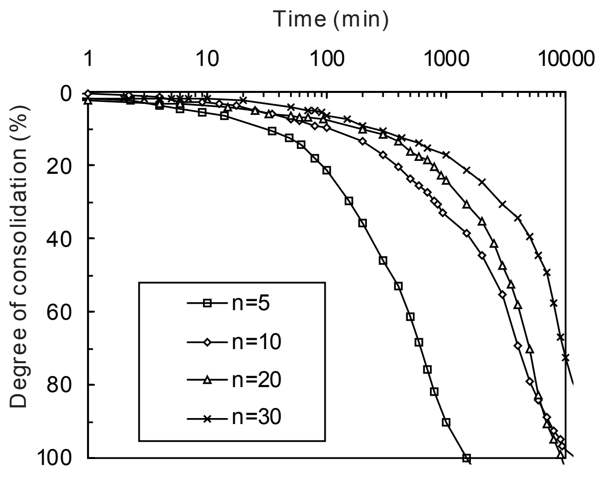

Figure 2. The effect of sand drain diameter on the rate of consolidation of Bangkok clay (after Prawono, 1978).

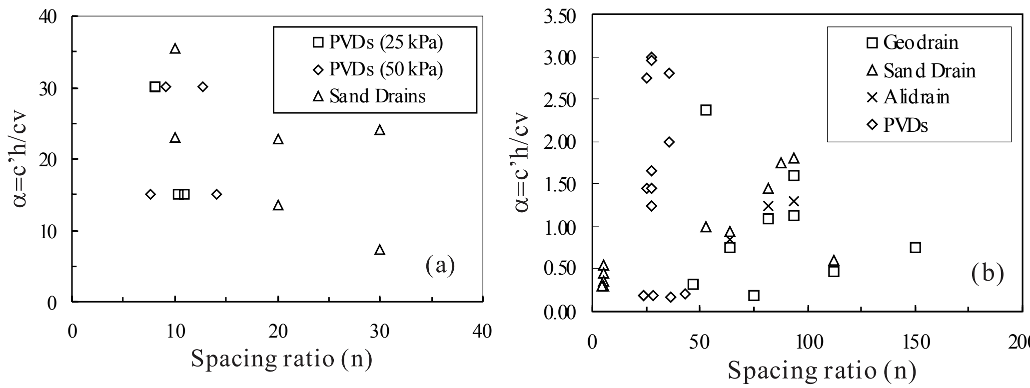

Figure 3. Summary of laboratory test results (a), and data from large-scale field trials (b) plotted as α against the spacing ratio (n).

4. COMPARISONS WITH LARGE-SCALE FIELD PROJECTS

An attempt was made to compare the performance of vertical drains obtained in the laboratory with that which has been observed in large-scale field tests over the past several years. The parameter $\alpha = c'_h/c_v$ (*where* c'_h - the coefficient of consolidation in horizontal direction obtained for soft soil with vertical drains, and c_v - the coefficient of consolidation in vertical direction before installation of vertical drains) was used as a criterion for such comparisons, following the work of Takeuchi *et al*. (1988), as it can be easily measured for both: laboratory and field experiments. The relevant data from several field projects, covering different types of drains, different ranges of drain spacing (up to 4 m), and different locations, were derived from the available literature (Takeuchi *et al*., 1988; Hansbo, 1992a,b, Indraratna *et al*., 2011). Figure 3a shows the summary of the laboratory tests discussed in the previous chapters plotted as α against the spacing ratio (n) while Figure 3b presents the analysis of data from the field experiments. It is evident from Figure 3 that the c'_h/c_v ratio in the laboratory tests is significantly greater (about 10 times) than the one that was back-calculated from the field projects.

5. CONCLUDING REMARKS

In this paper, the data from laboratory Rowe Cell tests on soft soil using vertical drains of different diameters were presented and discussed. Based on the obtained results, the following conclusions can be drawn:

– Results of Rowe Cell tests indicate that the rate of settlement may increase when the diameter of vertical drains increases from 8.3 to 16.5 mm. However, it was also found that the smear effect due to drain installation can decrease the rate of settlement for both of the drains used.
– The results of this work seem to be in agreement with data from previous laboratory studies in which sand drains were used to provide the path for water flow.

– Comparisons made between the results of laboratory studies and large-scale field trials suggest that laboratory tests tend to overestimate the performance of vertical drains compared to that which is typically observed in field projects.

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