Consolidation of soft soil by means of vertical drains: field and laboratory observations

I. B. Gratchev[1], C. Surarak[2], A. Balasubramaniamand[3], and E. Oh[3]

[1]Griffith School of Engineering, Gold Coast Campus, Griffith University, Parklands Drive, Southport, QLD, 4222, Australia; PH (61-7) 555-27686; FAX (61-7) 555 28065; email: ivangratchev@gmail.com
[2]Formely Doctoral Student, Griffith School of Engineering, Gold Coast Campus, Griffith University, Parklands Drive, Southport, QLD, 4222, Australia
[3]Griffith School of Engineering, Gold Coast Campus, Griffith University, Parklands Drive, Southport, QLD, 4222, Australia

ABSTRACT

Prefabricated vertical drains (PVD) in combination with pre-loading have become a popular method of soil improvement in Australia as it provides an effective and low cost solution to the problems of soft soil. A few large-scale trial embankment tests have been performed in the Brisbane and Sunshine Coast areas in the past decades to explore the feasibility of using PVD techniques for construction of high speed motorways on soft soil foundations in Queensland. Although satisfactory performance was observed in several trials, the effectiveness of vertical drains was not fully assessed as the varying geologic conditions as well as the design features of the embankment trial, which may have affected the integrity of the field data, were not controlled for. This paper seeks to provide laboratory data that can be used for assessment of the effectiveness of ground improvement methods, which may reduce the cost of large-scale field projects. The experimental program was designed to study the effect of vertical drains on settlements of soil under different stress levels. It was found that the process of consolidation occurred more rapidly when vertical drains were installed, however it can vary depending on the size of drain and the smear effect. In addition, data from a large-scale trial at the Sunshine Coast Motorway were reviewed to provide a better understanding of the effect of PVDs on the improvement of soft soil characteristics.

Keywords: prefabricated vertical drains, soft clay, Rowe Cell, settlement, ground improvement

1 INTRODUCTION

In recent years, the rapid increase in population of coastal Australia has resulted in the need to develop infrastructure in areas with undesirable ground conditions such as soft clays. Being extremely compressible, 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.

To solve this problem, a good deal of research has been conducted in the past few decades to develop effective methods of soil improvement. Several techniques have been proposed, including sand drains and stone columns, however the combination of preloading method with prefabricated vertical drains seems to have received the most attention from the geotechnical community (Balasubramaniam et al. 1984, Hansbo 1979, Tan et al. 1987, Bergado et al. 2002) as it provides a low cost solution for improving the performance of thick deposits of soft clays.

Although a few analytical solutions and computer codes to predict settlements of soft soil with PVDs have been developed and refined in the past few decades (Indraratna et al. 2003), 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 variables including geologic conditions, spacing between PVDs, 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. 2010a). For example, Wijeyakulasuriya et al (1999) presented the results of trial embankments on soft sensitive marine clays constructed along the eastern coast of Queensland. The authors reported that the use of drains in these soil conditions was not effective and suggested that such a soil improving technique should only be used with caution for soils with similar geotechnical properties. Recently, Ameratunga et al. (2010b) analysed the results from large-scale trail tests at the Port of Brisbane, Queensland, where different drain spacing from 1.0 m to 1.4 m was used, 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 when the drains were closely spaced.

To avoid such undesirable results, the effectiveness of PVDs needs to be assessed for different site conditions, a challenging task that would involve a number of costly and time-consuming field trials. In contrast, relatively inexpensive laboratory tests, including oedometer and large-scale consolidation experiments, can be considered 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. In addition, a few researchers have used laboratory tests to study the smear effect due to installation of PVDs. For example, Bergado et al. (1991) used a large-scale consolidation test apparatus with an inner diameter of 45.5 cm and the height of 92 cm to study the effect of smear zone due to installation of a PVD on settlement of soft soils. Indraratna and Redana (1998) employed a large-scale consolidation apparatus with a diameter of 45 cm and the height of 95 cm to study the behavior of soft clay with a sand drain. Almeida et al (2001) developed a special oedometric consolidation cell with the sample diameter of 12.5 cm to study the effect of vertical drains of different size on the settlement of soft clay. Although the aforementioned studies have provided useful insights into the process of soil consolidation, it still remains unclear whether laboratory tests can be used to assess the effectiveness of ground improvement techniques. This study seeks to shed light on this matter by providing laboratory data obtained from a series of Rowe Cell tests regarding the performance of PVDs during soft soil consolidation.

This paper presents preliminary results of this study in which a conventional Rowe Cell apparatus with a diameter of 25 cm was employed to investigate the consolidation characteristics of dredged mud. Vertical drains of 8.3 mm and 16.5 mm in diameter were used in these tests to better understand the effect of drain size and spacing on the settlement of soil. A special testing procedure was designed to evaluate the effect of smear zone on the time of consolidation. Finally, the obtained results were discussed in the light of the data from a large-scale trial performed at the Sunshine Coast Motorway, Queensland, where different spacing between PVDs was used.

2 LABORATORY ROWE CELL TESTS

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 been studied by Ameratunga et al (2010a), 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 Experimental procedure

A conventional Rowe Cell apparatus with a diameter of 250 mm was employed in this research to study the effect of vertical drainage 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 an uniform slurry with a moisture content of 70%. A vertical drain with a diameter 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 a 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 $n=d_e/d_w$, for the tests with vertical drains was about 30 and 15, respectively. 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 in which the vertical drain was installed before the soil sample was placed in the Rowe cell (test procedure 1) are presented in Fig.1. In this figure, the data of settlement against time for three different cases are shown: 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 ($n \approx 30$); and 3) a test with a vertical drain of 16.5 mm ($n \approx 15$). It is evident from this plot that a faster settlement rate was observed for the specimens with the vertical drains compared to that with no vertical drain. Also, when the drain of a larger diameter (16.5 mm) was used, the settlement occurred more rapidly than that in the test with a vertical drain of 8.3 mm.

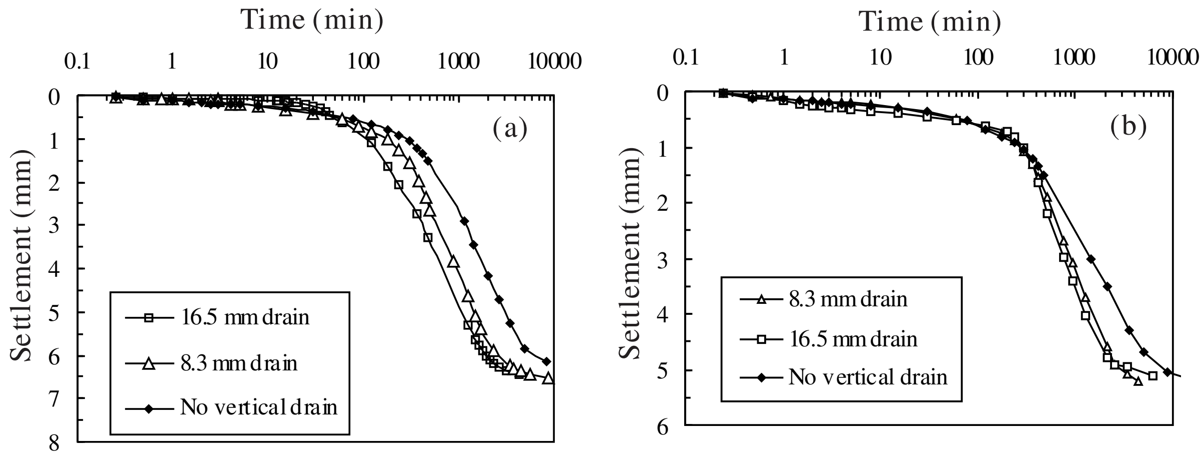

Figure 1. Results of Rowe Cell tests with and without vertical drains plotted as settlement against time at overburden pressures of 25 kPa (a), and 50 kPa (b).

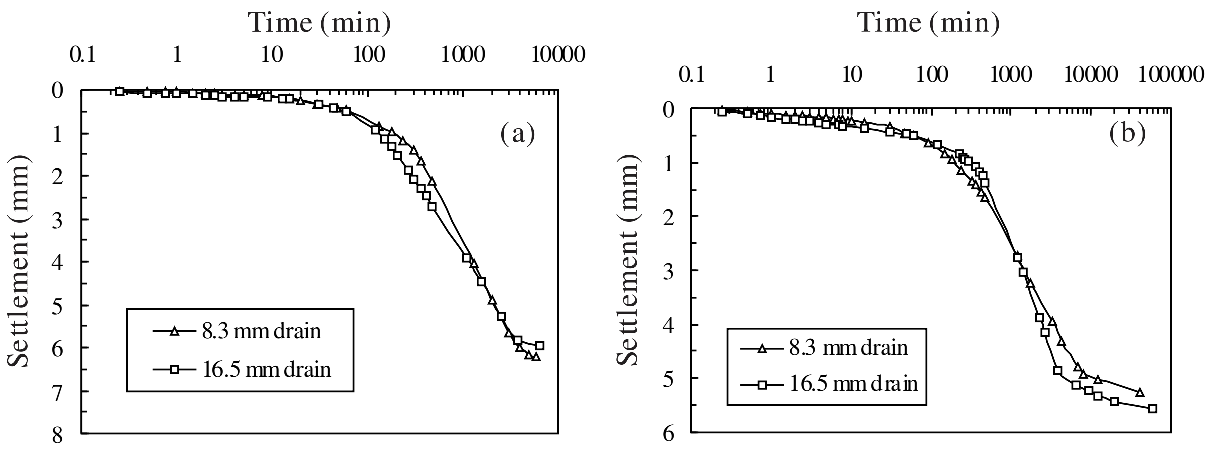

Figure 2. Results of Rowe Cell tests with and without vertical drains plotted as settlement against time at overburden pressures of 25 kPa (a), and 50 kPa (b) (with the smear effect).

Figure 2 shows the results of laboratory tests in which the vertical drain was installed in the soil specimens by means of a mandrel (test procedure 2). Comparisons made between the test data presented in Fig.1 and Fig. 2 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.

3 LARGE-SCALE FIELD TRIAL AT SUNSHINE COAST MOTORWAY, QUEENSLAND

3.1 Site description and soil conditions

It is interesting to compare the results from laboratory experiments with data obtained from field projects to determine how effective the laboratory tests can be in assessing the performance of ground improvement techniques in the field. In this paper, the data from a large-scale experiment at the Sunshine Coast Motorway previously reported by the authors (Surarak 2005, Oh et al. 2007) are reviewed in the light of the laboratory results discussed above.

In 1992, Queensland Department of Main Roads was commissioned to perform and monitor a fully instrumented trial embankment (Fig. 3) in Area 2A of the Sunshine Coast Motorway, South East Queensland, with the purpose of assessing the effectiveness of different ground improvement techniques (Rankine et al. 2005). The site investigation revealed the presence of up to 11 m thick layer of soft, extremely compressible marine clays of high sensitivity (Surarak 2005).The natural moisture content of this clay varied from 80 to 100%, which was significantly higher than its liquid limit (LL) which was approximately 60% (Fig. 4).

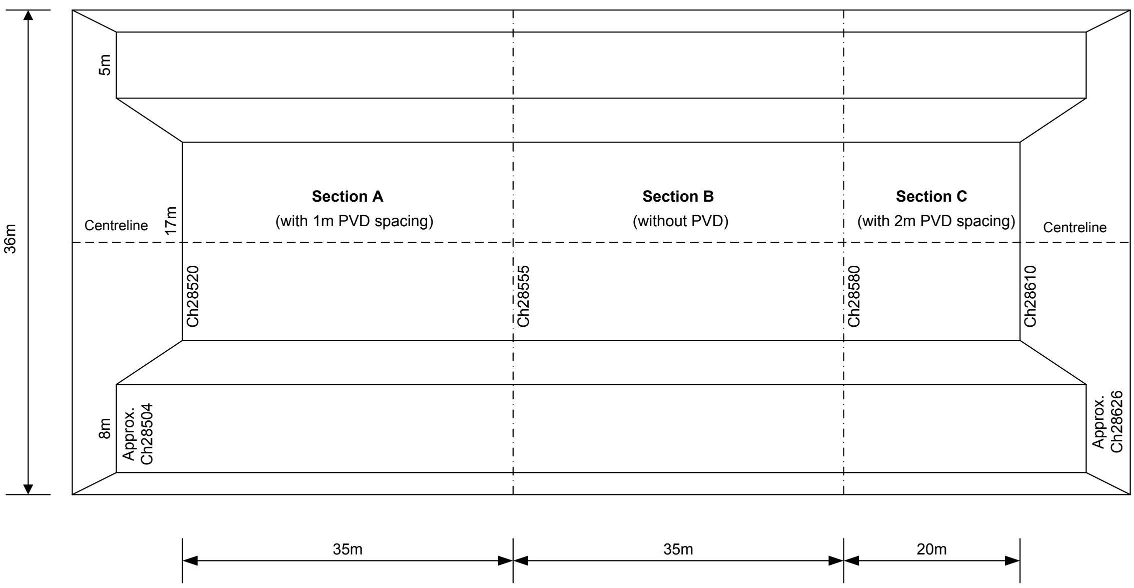

Figure 3. A schematic plan of trial embankment at the Sunshine Motorway (from Surarak 2005).

The trial embankment which was approximately 90 m long and 36 m wide included three sections, namely A, B, and C as shown in Fig. 3. In Sections A and C vertical drains were installed in a triangular grid pattern but with different spacing: 1 and 2 m, respectively. Section B was designed to study the settlement of soft clay without ground improvement (without PVD).

3.2 Settlements at different sections

The process of consolidation was monitored for a long period of time, and data of settlement and pore water pressure were recorded for each section. Figure 5 shows the rate of settlement for Sections A (with 1-m PVD spacing), and B (without PVD). It is evident from this figure that the rate of settlement was greater for Section A, where PVDs were used. Although no settlements were measured at Section C, the data of pore water pressure were obtained for all Sections, and analysed by Surarak (2005), and Oh et al (2007). Oh et al (2007) reported that the pore pressure dissipation in Section A occurred more rapidly than that in Section C. Also, the rate of pore pressure dissipation was faster in Section C compared to Section B.

3.3 Discussion

Considering that for the spacing of 1m and 2 m in field-scale projects the n-values shall be about 15 and 30, respectively, comparisons can be made between the Sunshine Coast Motorway trial data and the laboratory results from the Rowe cell tests. Using the n-value as a criterion, some similarities in the performance of vertical drains in the field and laboratory tests can be observed. For the both cases, a higher rate of settlements was associated with a lower n-value (n=15). From this analysis, it seems that laboratory tests can provide to some extent an indication of the performance of vertical drains in the field. However, it is noted that this study is still at the preliminary stage, and further investigation is necessary to address different aspects regrading the comparison between laboratory and field data. It is clear that more laboratory results and field data from various large-scale projects need to be analysed to determine whether laboratory tests can be effective in assessing the performance of vertical drains in the field.

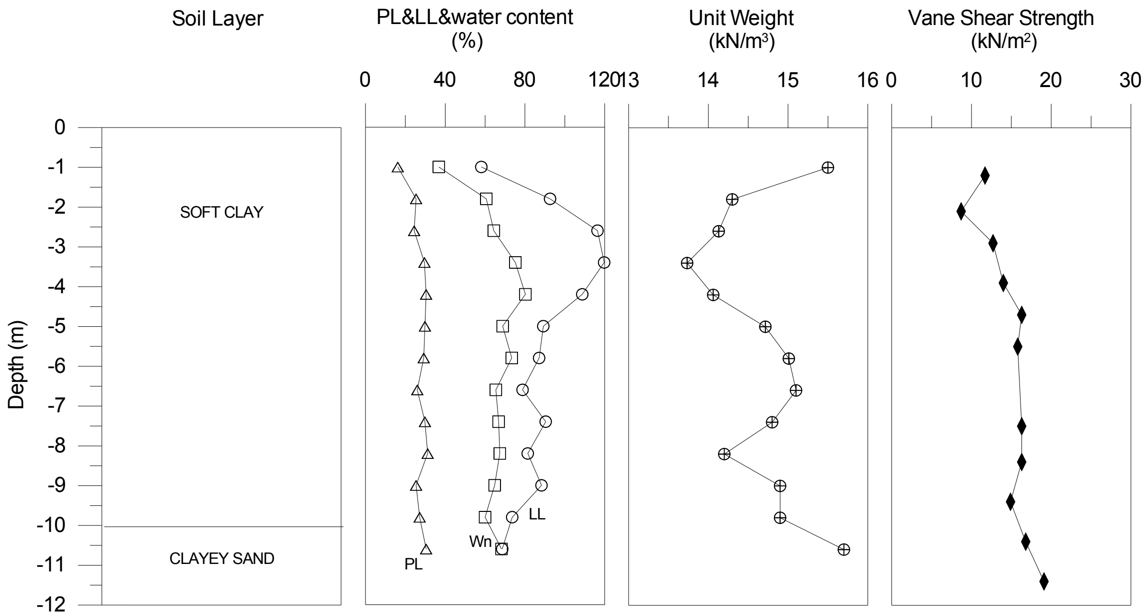

Figure 4. Geotechnical properties of soft clay at the trial embankment. PL-plastic limit; LL-liquid limit. (from Surarak 2005, Oh et al. 2007).

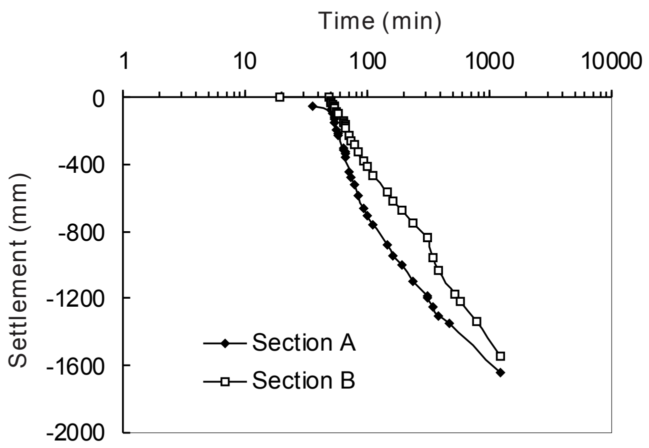

Figure 5. Variation of settlements with time along the centreline observed for Sections A and B.

4 CONCLUDING REMARKS

In this paper, the results from laboratory tests performed by means of Rowe Cell apparatus and data from a field large-scale experiment at the Sunshine Coast Motorway, Queensland, Australia, were analyzed 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. It was also found that the smear effect can decrease the rate of settlement for the both drains used;
- An attempt was made to compare the results from the Rowe cell tests with the data from the Sunshine Coast Motorway large-scale trial on the basis of n-values. Although some similarities were observed, it is still unclear whether laboratory tests can predict the performance of vertical drains in the field. Decidedly, further studies in this area are needed.

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