Soil disturbance associated with mandrel-driven prefabricated vertical drains: field experience

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Abstract
It has been widely known that load-settlement behaviors of cast-in placed bored piles are determined not only by the soil properties alone but also by the construction methods. This paper discusses the performances of (6) instrumented test piles of various diameters (80; 100 and 120 cm) and constructed using different techniques i.e. mud-water, polymer slurry and full-casing under relatively uniform subsurface condition that consisting of very stiff silty clay in West Jakarta. Each test pile was instrumented by vibrating wire strain gauge (VWSGs) and loaded to near ultimate load (2.5 times design load) with objective to obtain the loadtransfer characteristics of the test pile. Variation in pile diameters and construction methods that may affect the concrete modulus, load-settlement and load transfer behaviors are observed and discussed.

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SOIL DISTURBANCE ASSOCIATED WITH MANDREL-DRIVEN PREFABRICATED VERTICAL DRAINS: FIELD EXPERIENCE

Darshana Perera¹, Buddhima Indraratna² and Cholachat Rujikiatkamjorn³

ABSTRACT: It has been widely known that load-settlement behaviors of cast-in place bored piles are determined not only by the soil properties alone but also by the construction methods. This paper discusses the performances of (6) instrumented test piles of various diameters (80; 100 and 120 cm) and constructed using different techniques i.e. mud-water, polymer slurry and full-casing under relatively uniform subsurface condition that consisting of very stiff silty clay in West Jakarta. Each test pile was instrumented by vibrating wire strain gauge (VWSGs) and loaded to near ultimate load (≈ 2.5 times design load) with objective to obtain the load-transfer characteristics of the test pile. Variation in pile diameters and construction methods that may affect the concrete modulus, load-settlement and load transfer behaviors are observed and discussed.

Keywords: Instrumented test pile, load transfer

INTRODUCTION

The use of prefabricated vertical drains (PVD) has become a very popular ground improvement method in recent times. The vertical drain is inserted to the ground using a steel mandrel and this mandrel driving process alters the structure of the clay and creates a disturbed region known as smear zone. Vertical permeability and compressibility are altered in this region, therefore an accurate estimation of the extent of this smear zone and the reduction of the horizontal permeability within, is very important to predict the consolidation response.

First comprehensive governing mathematical solutions for vertical drains were derived by Barron (1948) and then later they were extended by Hansbo(1981) to incorporate the effects of smear and well resistance. The extent of the smear zone and the ratio between the horizontal permeability of the smear zone and undisturbed zone are the two main aspects used to characterise the smear zone (Chai and Miura 1999). Using reconstituted clay, Indraratna and Redana (1998) found that the radius of the smear zone is about 4 to 5 times of the equivalent radius of the drain and permeability ratios between vertical and horizontal directions is approached unity close to the drain within the smear zone. Sathananthan and Indraratna (2006) investigated the characteristics of the smear zone formed by mandrel driven PVDs and concluded that the extent of the smear zone is about 2.5 times of the equivalent mandrel radius based on the water content and horizontal permeability reduction. According to the Rujikiatkamjorn et al. (2013) most of the smear zone studies performed based on the reconstituted clay and scaled down mandrels indicating a smear zone extent of 2-4 times of the equivalent diameter of the mandrel used.

When the soil is remolded, the in situ structure of the soil is completely destroyed and it behaves differently to its undisturbed behaviour (Leroueil and Vaughan 1990). In the field, speed of drain installation is considerably higher than the speeds used in experimental studies. Therefore smear zone characteristics derived in the laboratory conditions may not provide the accurate picture of the soil disturbance associated with the mandrel driven drain installation in the field. In this study, using the in-situ samples extracted around a mandrel driven PVD, smear zone characteristics were investigated and a more accurate method of calculating the extent of smear zone is proposed based on variation of the

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coefficient of horizontal permeability, water content and the degree of disturbances

PVDS INSTALLATION AND SAMPLE EXTRACTION

Clay samples for this study were obtained from the site in Ballina, North NSW, Australia, which is situated on a low lying flood plain. Typically uniform soil profile has been observed in the area and it comprises highly compressible, saturated soft clay up to a depth of 15m. Natural water content (w) of the soil is measured as 94.7% and the liquid limit (LL) is 98%. Plasticity index (PI) is 66% and soil is classified as high plasticity clay according to the Unified soil classification system.

Wick drains (100mm wide, 3mm thick) were installed in 1.2m spacing in a square pattern to a depth of 15m. Steel mandrel (120mm x 60mm) was used with rectangular shoe (140mm x 90mm) attached to the drain to anchor it. Immediately after the drain installation, extraction of samples for laboratory testing was conducted. Location plan of the samples collected around the drain is shown in Figure 1a and Figure 1b. Total number of 10 samples was collected for one dimensional consolidation tests as well as for moisture content tests to obtain the smear zone parameters. Gap of at least 300mm was maintained between the adjacent sampling locations in order to minimise the disturbance when collecting the samples.

Shelby tubes (50mm diameter and 450mm long) were used to extract the samples. The tubes were in accordance with the recommendations made by Hvorslev(1949). The parameter of area ratio (Ca), the outside clearance ratio (Co) and the inside clearance ratio (Ci) are defined as follows:

\[
Ca = \frac{D_o - D_f}{D_f} \quad (1)
\]

\[
Co = \frac{D_w - D_f}{D_f} \quad (2)
\]

\[
Ci = \frac{D_i - D_e}{D_e} \quad (3)
\]

where, \(D_o\) and \(D_f\) are inside and outside diameter of the tube above the cutting edge respectively. \(D_w\) is the outside diameter of the cutting edge that enters to the ground and \(D_e\) is the inside diameter. In the tubes used, Outside diameter was 49.4mm while the inside diameter was 47.8mm. For a good quality sample extraction inside clearance ratio between 0% and 1.5% and outside clearance ratio between 0% and 3% are recommended by Hvorslev(1949). For the tubes used, both these values were 0%. Increasing area ratio creates more disturbances when sampling the soil and the area ratio should be less than 10% as per...
Hvorslev (1949). The area ratio of the sampler used was 6.88% and it is clearly within the allowable limits.

High plastic dark grey estuarine clay samples were extracted from the depth between 2.5m and 2.95m below the ground surface. Firstly the holes were pre-bored till 2.5m and then Shelby tubes were carefully pushed to the ground using hydraulic force ensuring continuous steady insertion of the tube to the ground. The tube was kept for few minutes and then slowly rotated and pushed up in uniform speed to minimise any disturbance. As soon as a tube was extracted from ground it was cleaned and both sides of the tube was sealed using the paraffin wax to prevent any loss of moisture. After that plastic caps were attached to either end and of the tube and wrapped with shock absorbing bubble wrap. Sample tubes were stored in a humidity room under 100°C temperature and 95% humidity to minimise the moisture loss before testing process commenced.

TESTING PROGRAMME

Variation of the moisture content along the radius of the drain can be used to characterise the extent of the smear zone. Therefore immediately after the samples were arrived to the laboratory, moisture content was measured. Plastic cap of the bottom end of the each of the tube was removed and about 3cm of the soil from the bottom were discarded. From each sampling tube three moisture tests were conducted and average of them were taken for the analysis.

One dimensional consolidation tests on both vertical and horizontal samples were performed. Variation of compressibility parameters was obtained using the consolidation tests using vertical samples and variation of lateral permeability was found using the tests conducted on horizontally extruded samples. For vertical sample tests with 20mm thick specimen was cut from the tube and then it was directly fitted to the oedometer ring. Pipe cutter was used to cut the tube along the surface as it did not create any heat during cutting the samples. Firstly the pipe was firmly secured in horizontal direction and then perimeter steel tube was carefully cut using the pipe cutter. Soil was trimmed using a thin wire. For the horizontal samples it is necessary to take the sample out of the tube before trimming it. Due to the relatively small diameter and adhesion between the sample and the tube wall, extruding the whole length is not suitable, as it would create more disturbances. Therefore sample was cut using the previous method mentioned, to a length of approximately 80mm before the extraction process. Diameter of the horizontal sample was 42.1mm. After preparing the each sample they were fitted to an oedometer ring and were set up in a consolidation apparatus. 3.4 kPa of initial pressure was applied to the samples and then that value was doubled at after 24 hours until it reached 218.7 kPa.

TEST RESULTS AND ANALYSIS

Permeability and water content:

Water content variation along the radial distance is presented in Figure 2. In situ moisture contents obtained in the same depth, away from the area where drains were installed, were between 93% and 95%. It is observed that from the vicinity of the drain to 400mm along the radius water content increased from about 70% to 90% and after that it remained relatively constant. This variation of water content is in accordance with the observations of Sathananthan and Indraratna (2006) and Rujikiatkamjorn et al. (2013).

The effective dimension of the mandrel used was 140mm x 90mm and its equivalent diameter was 126.6mm. This gives a ratio of 6.3, between the diameter of the disturbed zone due to installation of vertical drains and the equivalent diameter of the mandrel. Sathananthan and Indraratna (2006) have reported this value to be 2.5 for the reconstituted Moruya clay (Mew South Wales) tested in 650mm diameter large scale consolidometer. In laboratory testing of the undisturbed 345mm diameter Bullai clay (NSW) sample, Rujikiatkamjorn et al. (2013) found that the smear zone diameter is to be 3.7 times of the equivalent diameter of the scaled down mandrel used. Even though these previous studies gives the same trends in water content along the radius, the smear zone obtained is considerably smaller to the value of 6.3, which is obtained in this study.

Change of void ratio along the radius is shown in Figure 3a. It is very similar to the variation of the water contents shown in Figure 2. Figure 3b shows the lateral permeability \(k_h\) variation. Terzaghi’s one dimensional consolidation theory was used to calculate the horizontal permeability and Casagrande’s log time method was used to obtain the coefficient of consolidation in the horizontal direction \(c_v\). It can be clearly observed that lateral permeability was affected by the drain installation. Outside the 400mm smear zone, horizontal permeability remains constant whereas inside the smear zone it is significantly decreased towards the drain. To characterise the smear zone, normalised permeability given by ratio between horizontal permeability \(k_h\) and horizontal permeability of
undisturbed region \( k_{\text{undisturbed}} \) was defined and variation of that along the radius is present in Figure 3c. According to this Figure normalised permeability is significantly reduced towards the drain boundary. In the highly disturbed region next to the drain that the normalised permeability was 0.2 - 0.5 and increased away from the drain and remains close to 1 in the relatively undisturbed region (beyond 400mm). It is also observed that despite different applied pressure, all the curves are congested in a narrow band and the average value of normalised permeability is about 0.6 within the smear zone. According to the test results of water content, void ratio and normalised permeability it is evident that extent of the smear zone is 6.3 times the equivalent mandrel dimension. However this value is higher than the previous values obtained in similar studies using reconstituted soils and model scaled down mandrels used in shallow clay samples. Therefore in the field conditions, soil is subjected to more disturbances due to drain installation than previously assumed based on laboratory experiments. This is due to the longer vertical drains and higher installation speeds used.

Soil compressibility change due to drain installation:

Due to vertical drain installation compressibility parameters are also altered, apart from the changes to the permeability and void ratio. Rujikiatkamjorn et al. (2013) has presented a novel method to capture this effect to the compressibility using the degree of disturbance (DD) which can be quantified as:

\[
DD = 1 - \frac{e_{\text{SD}} - e_{\text{SC}}}{e_{\text{SD}} - e_{\text{id(ICL)}}}
\]  \hspace{1cm} (4)

Where \( e_{\text{SD}} \) is the void ratio of the partially disturbed soil at yield stress, \( e_{\text{SC}} \) is the void ratio of the undisturbed soil at yield stress, and \( e_{\text{id(ICL)}} \) is the void ratio on the isotropic compression line (ICL) at

![Figure 2. Variation of moisture content along the distance away from the drain](image)

![Figure 3. Variations of a) Void ratio; b) Permeability; and c) Normalised permeability along the distance away from vertical drain (Indraratna et. al., 2014)](image)
the intercept of Line AB and the isotropic compression line. Figure 4

Figure 4. Concept to assess the degree of soil disturbance (Indraratna et. al., 2014)

Figure 5a and Figure 5b presents compression curves for vertical samples and horizontal samples respectively. It is evident that compression curves very close to the drain is more disturbed compare to the compression curves from the samples taken further away from the drain. Soil next to the drain (50mm) is almost remolded indicating severe disturbance. The degree of disturbance obtained using equation (4) against radius distance is plotted in Figure 6. Respective void ratio and maximum yield stress along the line AB (Figure 4) was taken from the compression curves shown in Figure 5. It indicates a higher degree of disturbance for the samples taken closer to the drain. The degree of disturbance was 10.4% and 4.1% in the undisturbed region and 89.4% and 82.2% in the smear zone for the vertical sample and horizontal sample respectively. When compared to the results given in Rujikiatkamjorn et al. (2013) these values seems higher indicating higher amount of disturbance due to the longer period of shearing in actual drain installations.

Figure 5. Compression curves for, (a) vertical samples and (b) Horizontal samples(Indraratna et. al., 2014)

Figure 6. Degree of disturbance (DD)

CONCLUSION

Soil disturbance associated with vertical drain installation was investigated using samples extracted from a soft clay site in Ballina, NSW. Extent of the smear zone is established using variation of water content, normalised permeability and soil compressibility. It can be observed that water content was gradually increased within 400mm radial distance from the drain and then remains relatively
constant. Void ratio and lateral permeability also followed the same trend. Degree of disturbance values were indicated that higher disturbance was within the 400mm radial distance from the centre of the drain and it became relatively undisturbed in the outer region. All of these results indicate a smear zone of 6.3 times of equivalent mandrel dimension which is higher than the previously reported values. However most of the previous studies are limited to laboratory experiments and scaled down mandrels, driven to relatively thin soil thickness (less than 1m).

It is evident from this study that soil is subjected to higher amount of disturbance in the field than previously assumed as a result of higher rates of drain installation and longer drains in the field. Smear zone parameters significantly influence the rate and amount of final settlement therefore it is recommended that required parameters should be assessed using undisturbed samples obtained around the vertical drains to obtain a better prediction of settlement and pore water pressure dissipation.

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REFERENCES

Hvorslev, M.J. 1949. Subsurface exploration and sampling of soils for civil engineering purposes: report on a research project. US Army Engineer Waterways Experiment Station, Vicksburg, MS, USA.pp. 521 pp.