LABORATORY EVALUATION OF EXTENT OF SMEAR ZONE DUE TO COLUMNAR INTRUSION FOR COCHIN MARINE CLAYS

ANIL JOSEPH¹, S CHANDRAKARAN², N SANKAR³, BABU T JOSE⁴

ABSTRACT

Cochin is known for its deep deposits of soft marine clays and the soil encountered in this area is highly compressible and prone to settlement problems. Such complexities of the marine clays lead to construction of deep foundations, which is highly expensive and time consuming. Ground Improvement techniques such as band drains, sand piles, stone columns and lime columns are extensively used to overcome the problems arising due to soft clay deposits and to reduce the cost of foundation. The installation of vertical drains by means of a mandrel for displacement system of columnar intrusion causes significant remolding of the subsoil, especially in the immediate vicinity of the mandrel. Thus a zone of smear will be developed around the columnar intrusion on withdrawal of mandrel with reduced permeability and increased compressibility. As remolding retards the permeability, it has to be considered in the analysis and its effect has to be accounted for in the coefficient of consolidation values. This paper presents the results of laboratory studies to determine the extent of smear zone due to vertical sand drain installation on reconstituted Cochin marine clays. The extent of smear zone around a vertical drain was studied using a large scale consolidation apparatus. The soft marine clay used for the study was collected from a site opposite to Vallarpadama container terminal, Cochin. The clay was collected from a depth of about 8 to 9m. River sand was used to form the columnar intrusion. As it was not feasible to obtain one undisturbed sample for the large scale consolidation apparatus, reconstituted marine clays was used to make large samples. The experimental setup consisted of circular steel tanks of 600mm diameter and 600mm height. After the assembling of the tanks, it was filled with soft marine clay with water content very close to liquid limit. The friction along the cell boundary was reduced by placing 1.5mm thick polythene sheet around the internal tank boundary. All the 3 model tanks were subjected to an initial pre-consolidation pressure of 0.05kg/cm² and the settlements were monitored. Once all the model beds were stabilized, in tank no: 02 and tank no: 03, columnar intrusion of sand by displacement method was installed by using a pipe mandrel of 50mm diameter and 2mm thickness. For tank no:03 a second sand compaction pile was driven at the same point by displacement method there by pushing the initially installed sand compaction pile into the smeared zone. After installation of the sand compaction piles in the tank numbers 2 and 3 all the three tanks where subjected to further consolidation and a total overburden of 0.2kg/cm² was applied in 6 stages. Each load increment was retained for consolidation to be completed, which was ensured by time-settlement measurements. After preloading was completed samples were collected from radial distances of 8, 13, 18 and 23cms (1.6D, 2.6D, 3.6D and 4.6D, where D is the diameter of columnar intrusion) from the center of the tank in both horizontal as well as vertical drainage directions from the 3 Zones A (0-20cms), B (20-40cms) and C (40-60cms). The collected samples were subjected to one dimensional consolidation using conventional oedometers in order to study

¹ANIL JOSEPH, Ph D Student, Department of Civil Engineering, N.I.T. Calicut, Kerala, India. E-mail:aniljoseph01@gmail.com
²S CHANDRAKARAN, Professor, Department of Civil Engineering, N.I.T. Calicut, Kerala, India.E-mail: chandra@nitc.ac.in
³N SANKAR, Professor, Department of Civil Engineering, N.I.T. Calicut, Kerala, India.E-mail: sankar@nitc.ac.in
⁴BABU T JOSE, Head of Civil Department & Director, Albertian Institute of Science & Technology, Cochin, Kerala, India. E-mail: babutjose@ymail.com
the variation in soil properties close to and away from the central drain. From the results, the smear zone radius was estimated to be about 130 to 150mm, which was a factor of five to six times the radius of the central drain. The horizontal permeability within the smear zone is about 25 to 30% less than in the undisturbed zone. The incorporation of precise values of permeability will help to predict settlements and assess degree of consolidation more accurately for ground improvements using vertical columnar intrusion.

*Keywords*: Smear Zone, Soft Clay, Ground Improvement, Compressibility, Permeability
LABORATORY EVALUATION OF EXTENT OF SMEAR ZONE ON COLUMNAR INTRUSION FOR COCHIN MARINE CLAYS

ANIL JOSEPH, Ph D Student, N.I.T. Calicut, aniljoseph01@gmail.com
S CHANDRAKARAN, Professor, N.I.T. Calicut, chandra@nit.ac.in
N SANKAR, Professor, N.I.T. Calicut, sankar@nit.ac.in
BABU T JOSE, Professor, AISAT, Cochin, babutjose@ymail.com

ABSTRACT: This paper presents the results of laboratory studies to determine the extent of smear zone on columnar intrusion by displacement method for Cochin marine clays. The experimental setup consist of 3 circular steel tanks of 600mm diameter and 600mm height. Once the model beds were stabilized, in tank no: 02 and 03, columnar intrusion of 50mm sand by displacement method was installed. After installation of the sand compaction piles, all the three tanks were subjected to a total overburden of 0.2kg/cm² in stages. After preloading was completed samples were collected from various radial distances at different depths and were subjected to one dimensional consolidation using conventional oedometers in order to study the variation in permeability characteristics close to and away from the central drain. From the results, the smear zone radius was estimated to be about 130 to 150mm, which was a factor of five to six times the radius of the central drain. Incorporation of correct variation of permeability values can lead to more realistic prediction of settlements and the time required for assessing the degree of consolidation for ground improvements using vertical columnar intrusions.

INTRODUCTION
Cochin is known for its deep deposits of soft marine clays and the soil encountered in this area is highly compressible and prone to settlement problems. Such complexities of the marine clays require construction of deep foundations, which are highly expensive and time consuming. Ground Improvement techniques such as band drains, sand piles, stone columns and lime columns are extensively used to overcome the problems arising due to soft clay deposits and to reduce the cost of foundation. The installation of vertical drains by means of a mandrel by displacement system of columnar intrusion causes significant remolding of the subsoil, especially in the immediate vicinity of the mandrel. Thus a zone of smear is developed around the columnar intrusion on withdrawal of mandrel leading to reduced permeability and increased compressibility and it has to be considered in the analysis and its effect has to be accounted for in the coefficient of consolidation values. Kjellman (1948) was the first to solve the theory of vertical drains based on “Equal Vertical Strain Hypothesis”. Barron (1948) presented the most comprehensive solution to the problem of radial consolidation by drain wells. Hansbo (1979) introduced a zone of smear in the vicinity of the drain with a reduced value of permeability. The presence of smear zone significantly influences the horizontal consolidation rate and is reported by various researchers. (Onoue et al.,1991; Hird and Moseley 2000; Sharma and Xiao 2000; Basu and Prezzi 2007; A ParsaPajouh and Vincent 2014). According to literature, two main hypotheses are proposed to characterise the disturbed soil surrounding the drain (a) two zones hypothesis (Indraratna and Reddana 1998; Chai and Miura 1999; Rujikiatkamjorn and Indraratna 2009), which divides the surrounding soil into the smear zone and the intact zone and (b) three zone hypothesis (Hawalader and Muhunthan 2002; Basu et al 2006), considering three zones, which are the smear zone in the immediate vicinity of the drain, the transition zone and the undisturbed zone. This paper presents the results of laboratory studies to determine the extent of smear zone due to vertical sand drain installation on reconstituted Cochin marine clays. The extent of smear zone around a vertical drain was studied using a large scale consolidation apparatus. By sampling the soil around the vertical drain in both the horizontal and vertical directions and at different depths, the extent of smear zone could be quantified by the measured changes in permeability.
EXPERIMENTAL SETUP

Materials
Clay
The soft marine clay used for the study was collected from a site opposite to Vallarpad container terminal, Cochin. The clay was collected from a depth of about 8 to 9m. The properties of the soil collected are given in Table 1.

Table 1 Basic Properties of Marine Clay

<table>
<thead>
<tr>
<th>SI No</th>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Natural Moisture Content, %</td>
<td>112</td>
</tr>
<tr>
<td>2</td>
<td>Specific Gravity</td>
<td>2.62</td>
</tr>
<tr>
<td>3</td>
<td>Grain Size Distribution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sand%</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Silt%</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>Clay%</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>Liquid Limit, %</td>
<td>156</td>
</tr>
<tr>
<td>5</td>
<td>Plastic Limit, %</td>
<td>34</td>
</tr>
<tr>
<td>6</td>
<td>Plasticity Index, %</td>
<td>122</td>
</tr>
<tr>
<td>7</td>
<td>Shrinkage Limit, %</td>
<td>10.71</td>
</tr>
<tr>
<td>8</td>
<td>pH</td>
<td>7.53</td>
</tr>
<tr>
<td>9</td>
<td>Coefficient of Consolidation</td>
<td>5.65\times10^{-4}</td>
</tr>
<tr>
<td></td>
<td>(cm²/sec)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Compression Index</td>
<td>0.64</td>
</tr>
<tr>
<td>11</td>
<td>Unconfined Compressive Strength, KPa</td>
<td>4</td>
</tr>
</tbody>
</table>

Sand
The specific gravity, bulk density and grading of the river sand used are given in Table 2.

Table 2 Properties of River Sand

<table>
<thead>
<tr>
<th>SI No</th>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Specific Gravity</td>
<td>2.6</td>
</tr>
<tr>
<td>2</td>
<td>Bulk Density (kg/m3)</td>
<td>1460</td>
</tr>
<tr>
<td>3</td>
<td>Fine particles less than 0.075mm (%)</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>Sieve Analysis</td>
<td>Zone II</td>
</tr>
</tbody>
</table>

Preparation of Reconstituted Bed for Columnar intrusion

Fig. 1 Experimental Setup for Large Scale Consolidation Tests

The coefficient of permeability in horizontal and vertical directions, for the undisturbed samples retrieved using specially designed samplers was assessed by back calculation using the Terzaghi one dimensional consolidation theory. As it was not feasible to obtain an undisturbed sample for the large scale consolidation apparatus reconstituted marine clay was used to make large samples. The experimental setup consisted of circular tanks of 600mm diameter and 600mm height. The tanks were made in such a way that it can be removed into 6 pieces, so that the cross section could be inspected visually at any depth and to extract samples from various depths to determine the permeability and shear strength characteristics in horizontal as well as vertical directions. After the assembling of the tank by stacking the 6 pieces one over the other with keys tightened for locking, it was filled with soft marine clay with water content very close to liquid limit. The friction along the tank walls was reduced by placing 1.5mm thick polythene sheet around the internal tank boundary. Care was taken to ensure that no air bubbles are trapped in the clay mass. The water content of the clay at this stage was checked to ensure that it remained as a constant percentage of the liquid.
limit. A thin central drain of sand, 20mm in diameter, was formed with filter paper at centre of all beds to allow radial drainage.

Test Procedure
All the 3 model tanks were subjected to an initial pre-consolidation pressure of 0.05kg/cm² and the settlements were monitored. Once all the reconstituted beds were stabilized, in tank no:02 and tank no:03, columnar intrusion of sand was installed by using a pipe mandrel of 50mm diameter and 2mm thickness. Mandrel was driven vertically into the clay by a hammer of 2.6 kg falling from a height of 30cm ensuring the verticality throughout the intrusion. River sand was poured into the mandrel and rodded at every 10cm layer. The mandrel was then slowly withdrawn carefully maintaining the verticality while applying light vibration to the pipe as well as compacting the inner sand using a rod. The vertical drain thus formed can be regarded as a sand compaction pile.

It has been observed from field studies that multiple driving at the same point will enhance the performance of columnar intrusions, since the material of columnar intrusion will be pushed into the smear zone formed during the initial installation process. One of the major limitations of columnar intrusion is the smear zone generated due to the relative movement of the mandrel and the soil around. This leads to lower capabilities within the smear zone. It is expected that some of this disadvantages could be overcome by the forceful penetration of the intrusion material into the smear zone of the soft clay and the enhancement of permeability will lead to accelerated consolidation settlements. For tank no:03 a second sand compaction pile was driven at the same point thereby pushing the initially introduced sand compaction pile into the smear zone.

After installation of the sand compaction piles in the tank numbers 2 and 3, all the three tanks were subjected to further consolidation and a total overburden of 0.2kg/cm² was applied for both tanks in 6 stages. Each load increment was retained for consolidation to be completed, which was ensured by time-settlement measurements. After the placement of final load it is again left to consolidate for a period of 2 weeks. After preloading was completed samples were extracted from tank number 1(model bed tank) and 2 (tank with single sand compaction pile), in horizontal as well as vertical direction and the permeability of the samples was assessed using conventional oedometer test.

Soil Sampling and Testing
To study the consolidation properties and to arrive at the permeability characteristics of the soil bed in model tank and the tanks with columnar intrusions, the whole plan area of the tanks was divided into 4 annular zones and reconstituted bed was divided into 3 zones as shown in Figure 2.

Fig. 2 Sample Locations

The samples were collected from radial distances of 8, 13, 18 and 23cms (1.6D, 2.6D, 3.6D and 4.6D, where D is the diameter of columnar
intrusion) from the center of the tank in both horizontal as well as vertical drainage directions from the 3 Zones A(0-20cms), B(20-40cms) and C(40-60cms). The samples collected were subjected to one dimensional consolidation using conventional oedometers in order to study the variation in soil properties close to and away from the central drain. It is postulated that the compressibility and permeability characteristics of the smear zone near the sand drain would be significantly different from rest of the clay unaffected by the installation of the sand compaction pile.

TEST RESULTS AND DISCUSSIONS
The extent of the smear zone associated with the vertical sand drain installation was investigated by evaluating the compressibility and permeability parameters close to and away from the vertical drain for the tank no:02 and the results were compared with that of the model tank no:01. Figure 3 shows the variation of horizontal and vertical coefficient of permeability with mean consolidation pressure for the undisturbed samples collected and Figure 4 shows the average variation in Zones A, B and C of horizontal and vertical coefficient of permeability with mean consolidation pressure for the reconstituted bed.

Fig. 3 Variation of $k_h$ and $k_v$ for UDS Samples with Mean Consolidation Pressures

Fig. 4 Variation of $k_h$ and $k_v$ for Reconstituted Bed samples with Mean Consolidation Pressures

Figures 5 and 6 show the average variation in Zones A, B and C of coefficient of horizontal and vertical permeability for various mean applied consolidation pressures with radial distances from the centre of the tank. Figure 7 shows $k_h/k_v$ ratio along the radial distance from the central drain for various mean consolidation pressures.
The values of the coefficient of permeability $k_v$ and $k_h$ are calculated by the Terzaghi consolidation theory. Tavenas et al (1983) have stated that this indirect method of determining $k$ is not accurate because of the assumptions of constant modulus of deformability $(m)$ and constant coefficient of consolidation $(c_v)$ during the reduction of void ratio $(e)$ upon loading. Tavenas et al suggest the determination of permeability using the triaxial or modified oedometer apparatus. However, Indraratna and Redana (1998) point out that the actual magnitude of coefficient of permeability is not critical in determining the extent of smearing. The smear zone is characterized by the significantly decreased permeability towards the drain, in relation to the higher permeability of the soil that is unaffected by the drain installation. The method of obtaining $k_h$ and $k_v$ is not critical, as long as the same laboratory approach is consistently followed for determining both $k_h$ and $k_v$ values.

For the applied consolidation pressure it is observed that the value of $k_h/k_v$ varies between 1.41 to 1.65 for the UDS samples (Figure 3) and from 1.33 to 1.52 for the reconstituted bed (Figure 4). From Figure 5, it is observed that the horizontal permeability on installation of vertical columnar intrusion, decreases towards the central drain, which confirms that the effect of smear is greatest near the drain boundary. From comparison of the results of reconstituted bed tank and the tank with sand compaction pile driven, it is noted that the radius of smear zone extends upto 130 to 150mm or can be estimated to a factor of five to six times the diameter of the drain. The variation of horizontal permeability in the smear zone $(8$cms$)$ to the undisturbed zone $(23$cms$)$ $(k_h/k_v)$ varies from 0.69 to 0.76 for different mean consolidation pressures. The coefficient of vertical permeability in the smear zone $(8$cms$)$ to the undisturbed zone $(23$cms$)$ $(k_v/k_v)$ varies from 0.92 to 0.97 for different mean consolidation pressures. The ratio of $k_h/k_v$ (Figure 7) varies from 1.17 to 1.32 in the smear zone $(8$cms$)$ to 1.46 to 1.64 in the undisturbed zones $(23$cms$)$.

**CONCLUSIONS**

The effect of smear due to the installation of a columnar intrusion (vertical sand compaction pile) was investigated in the laboratory, using a large scale consolidometer. By measuring the variation of the horizontal permeability close to and away from the centrally installed drain, the extent of
smear zone could be determined. The smear zone radius was estimated to be about 130 to 150mm, which was five to six times the radius of the central drain. The horizontal permeability within the smear zone is about 25 to 30% less than in the undisturbed zone. The vertical permeability in the smear zone is about 4 to 7% less than that in the undisturbed zone indicating very low variation. The k_h/k_v value varies from 1.17 to 1.32 in the smear zone to 1.46 to 1.64 in the undisturbed zone. The investigations to understand the effect of multiple driving of columnar intrusion in the behavior and extend of smear zone are in progress. The inclusion of exact variation of the permeability ratio is a more accurate prediction of settlements and the time required for different degree of consolidation in case of ground improvements using vertical columnar intrusions.

REFERENCES

2. Barron RA (1948), Consolidation of fine-grained soils by drain wells. Trans Am Soc Civil Enng 113(1):718-742