On the Laboratory Testings to Characterize the Smear Zone

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Abstract: Due to its effect on the effectiveness of the PVD performance, the existence of the smear zone is a matter of considerable interest. The objective of this paper is to review the laboratory testing of the previous studies concerning the smear zone. Two main parameters are the focus in this study in order to characterize it, i.e., the extent ratio and the permeability ratio. Differences in the laboratory set-up lead to the ranges of the values of the two main parameters and difficulty to compare their values. It is suggested that a standardized laboratory testing be established to obtain a more accurate and consistent laboratory result.

1 INTRODUCTION

The main parameters proposed for characterizing the smear zone are the extent ratio and the permeability ratio. The extent ratio s or s’ is the ratio of the radius of the smear zone rs to the radius of the drain rw or to radius of mandrel rm. The permeability ratio κ is the ratio of the horizontal permeability k_h at the undisturbed location to that at the disturbed site k_s. The value of these ratios are important in soil improvement planning using PVD and preloading. If the s’ and κ are not planned well, they will result in the incorrect rate and duration of consolidation and thus disrupt the schedule of infrastructure to be built. One method that can be used to measure s’ and κ is by conducting laboratory testing. This method most likely cost less and need shorter time than the method using trial embankment in the field.

Although comprehensive set-up of equipment in the laboratory has not been established, many researchers have used the laboratory testing to obtain the s’ and κ (Bergado et al., 1991; Indraratna and Redana, 1998; Sharma and Xiao, 2000; Indraratna and Rujikiatkamjorn, 2004; Sathananthan and Indraratna, 2006; Fang and Yin, 2006; Shin et al., 2009; Saowapakpiboon et al., 2010; Tran-Nguyen and Edil, 2011; Ghandeharion, et al., 2012; Chai et al., 2013; Rujikiatkamjorn et al., 2014; Indraratna et al., 2015; Joseph et al., 2015; Pajouh et al., 2015; Sengul et al., 2016; Choudhary et al., 2016). Those whose results are compared in this study can be seen in column 2 in Table 1. There is no agreement on the value of s’ and κ resulting from laboratory testing. Therefore, it is important to review set-up laboratory testing that has been used in studying the characteristics of the smear zone and to comprehend the main causes of why the values vary.

2 THE MAIN POINTS OF LABORATORY WORKS

2.1 Laboratory Set-up of Equipment

The laboratory set-up used to determine the s’ and κ values involved at least 6 factors presented in Figure 1. Figure 2 shows an example of a large-scale consolidation apparatus utilized by Indraratna and Redana (1998).
Laboratory Set-Up

<table>
<thead>
<tr>
<th>Dimension and Tank Shape</th>
<th>Type of Soil Sample</th>
<th>Sample Preparation</th>
<th>Preconsolidation and Consolidation Stresses</th>
<th>Mandrel Dimension and Installation Speed</th>
<th>Method of Determination of $s'$ and $\kappa$ values</th>
</tr>
</thead>
</table>

Figure 1. Set Up Testing Equipment at Laboratory

Figure 2. Large-Scale Consolidation Apparatus (Indraratna and Redana 1998)
2.2 Determination of Smear Zone Characteristics in Laboratory

Testing normally starts from the sample preparation stage. The sample preparation and the ensuing determination stage of the smear zone characteristics are presented in Figure 3. Columns 11 - 14 in Table 1 show the results of the 17 previous laboratory studies on the characteristics of the smear zone composed mainly of soft soils.

3 LABORATORY RESULTS

Bergado et al. (1991) concluded using PVD smear effect is an important factor in evaluating the rate of consolidation. Indraratna and Redana (1998) conclude, there is significant decrease of $k_s$ towards SD, where $k'_v$ is soil permeability coefficient in the vertical direction zone. Sharma and Xiao (2000) showed that there are two remedial smear zone, parts located close to PVD and reconsolidated zone that are located between the remoulded zone and the intact zone. Fang and Yin (2006) showed that the buckling effect on PVD will increase the influence of well resistance and decrease rate of consolidation. Indraratna and Rujikiatkamjorn (2004) and Saoawapakpiboon et al. (2010) combines PVD, preloading and vacuum, proposing $s'$ without and using vacuum the same value.

Tran-Nguyen and Edil (2011) reported there were two identifiable zones around PVD in the soil mass after PVD installation. Ghandeharioon, et al (2012) may present a variety of excess pore pressures at different locations during PVD installation and mandrel withdrawal. Pajouh et al. (2015) found a slight increase in the decrease after excess pore pressures dissipated in each of the loading stages that may be associated with the creep phenomenon. Sengul, et al. (2016) indicates that there are three soil zones adjacent to PVD namely smear zone, transition zone and undisturb zone. Choudhary et al. (2016) evaluates the characteristics of the smear zone based on changes in the hydraulic gradient derived from excess pore water pressure data measured in the radial direction.

Rujikiatkamjorn et al. (2014) stated that the soil will significantly lose its structure after the installation of PVD, especially in locations close to PVD. Indraratna et al. (2015) reported the degree of disturbance in soil in the field can be higher when the installed PVD is longer, and the disturbance in the soil is greater towards PVD. With reference to the results of previous studies it is found that the extent ratio $s'$ values vary between 2.0 - 6.3, and permeability ratio $k$ values from 1.03 - 3.13. The minimum values of $s'=2.0$, the maximum=6.0, and the average=4.0. The range of the $s'$ values can be classified as follows, low: $1<s'<2$, moderate: $2\leq s'<4$, and high: $4\leq s'<7$. Then the value of $s'$ laboratory test results are mostly in the moderate to high. The minimum values of $k=1.03$, maximum=3.13, and the averaged= 2.0. The range of $k$ values can be classified as follow, low: $1<k<4$, moderate: $4\leq k<7$, and high $7\leq k<12$. Then the value $k$ laboratory test results are in the low range.

On the other hand, the range of $k$ value appears to be limited within the low values.
Table 1: Summary results of previous laboratory testings to characterize the smear zone

<table>
<thead>
<tr>
<th>No.</th>
<th>Researchers</th>
<th>Dimension</th>
<th>Basic Soil Properties</th>
<th>Sample Preparation</th>
<th>Stress</th>
<th>Dimension</th>
<th>Speed of Installation</th>
<th>Smear Zone</th>
<th>Estimation</th>
<th>Estimation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bergado et al. (2019)</td>
<td>10 x 13</td>
<td>Reconstituted Kaolinite Clay</td>
<td>Samples are placed in cell consolidation tank and compacted using consolidometer cell.</td>
<td>100 x 3.5</td>
<td>Rectangular</td>
<td>1.0</td>
<td>Small 2.5</td>
<td>1.0</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>Feng and Sharma et al. (2018)</td>
<td>13 x 14</td>
<td>Reconstituted Kaolinite Clay</td>
<td>Samples are mixed with water up to w = 1.45, put into consolidation tank and be compacted using consolidometer cell.</td>
<td>200 x 3.6</td>
<td>Rectangular</td>
<td>1.0</td>
<td>Small 2.5</td>
<td>1.0</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>Indraratna and Joseph et al. (2015)</td>
<td>14 x 15</td>
<td>Reconstituted Kaolinite Clay</td>
<td>The sample is taken into a cell consolidation tank and be compacted using consolidometer cell.</td>
<td>250 x 3.6</td>
<td>Rectangular</td>
<td>1.0</td>
<td>Small 2.5</td>
<td>1.0</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>Choudhary et al. (2016)</td>
<td>17 x 18</td>
<td>Reconstituted Kaolinite Clay</td>
<td>The sample is taken into a cell consolidation tank and be compacted using consolidometer cell.</td>
<td>300 x 3.6</td>
<td>Rectangular</td>
<td>1.0</td>
<td>Small 2.5</td>
<td>1.0</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 2: Summary results of previous laboratory testings to characterize the smear zone (continued)

<table>
<thead>
<tr>
<th>No.</th>
<th>Researchers</th>
<th>Dimension</th>
<th>Basic Soil Properties</th>
<th>Sample Preparation</th>
<th>Stress</th>
<th>Dimension</th>
<th>Speed of Installation</th>
<th>Smear Zone</th>
<th>Estimation</th>
<th>Estimation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ghandeharioon et al. (2019)</td>
<td>11 x 12</td>
<td>Reconstituted Alluvial Clay</td>
<td>Samples are mixed with water up to w = 1.47, put into consolidation tank and be compacted using consolidometer cell.</td>
<td>200 x 3.5</td>
<td>Rectangular</td>
<td>1.0</td>
<td>Small 2.5</td>
<td>1.0</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>Chai et al. (2020)</td>
<td>11 x 12</td>
<td>Reconstituted Alluvial Clay</td>
<td>The sample is taken into a cell consolidation tank and be compacted using consolidometer cell.</td>
<td>200 x 3.6</td>
<td>Rectangular</td>
<td>1.0</td>
<td>Small 2.5</td>
<td>1.0</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>Joseph et al. (2015)</td>
<td>13 x 14</td>
<td>Reconstituted Alluvial Clay</td>
<td>The sample is taken into a cell consolidation tank and be compacted using consolidometer cell.</td>
<td>250 x 3.6</td>
<td>Rectangular</td>
<td>1.0</td>
<td>Small 2.5</td>
<td>1.0</td>
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</tr>
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<td>4</td>
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<td>14 x 15</td>
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</tr>
</tbody>
</table>

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4 DISCUSSION

4.1 Shape and Ratio of H/Diameter of Tank

Tank soil in the laboratory is typically cylindrical and box. Researchers variously designed dimensions of consolidometer tank cylinder. In column 3 of Table 1, the diameter of the tank (d) varies from 300 mm-700 mm, the height (h) varies from 400 mm-1,000 mm, and the h/d ratio varies from 0.4 to 2.11. There is no agreement whether the ratio h/d > 1, h/d =1 or h/d <1. Generally the tank used has a ratio h/d > 1. However Joseph et al. (2015) used the ratio h/d=1, while Sharma and Xiao (2000), Indraratna et al. (2015), and Choudhary et al. (2016), used a h/d ratio of <1. The tank-shaped box was made by Tran-Nguyen and Edil (2011), and further developed by Sengul et al. (2016).

4.2 Basic Soil Properties Tested

Soil stiffness depends on basic properties of the soils. According to Sengul et al. (2015), and Sathananthan and Indraratna (2015) the $r_s/r_m$ and $r_t/r_m$ ratios depend on the soil stiffness. For a more stiff soil the ratio is larger than for a less stiff soil. When compared to the soil characteristics data in column 4 of Table 1, the sample water content $w$ values vary between 40%-112%, liquid limit $LL$ between 42%-102%, plastic limit $PL$ between 17%-34%, specific gravity $G_s$ between 2.56-2.76 and unit weight $γ$ between 14.7 kN/m$^3$-18.5 kN/m$^3$. The inheritance properties of the soil tested resulted in differences in stiffness, the $r_s/r_m$ and $r_t/r_m$ ratios generated.

4.3 Preparation of Soil Sample

The sample preparation data can be seen in column 5 of Table 1 of. In the disturbed sample, $w$ when mixing varies from the natural w in the field up to 2 times the LL of soil. Saturation time varies from a few days to 6 months. The technique of removing the air trapped in the soil during mixing also varies. Some use the technique of compressing, vibrating, or vacuum. The similar conditions occur in undisturb samples. Large and intact samples were taken from the field for testing on consolidometer cells with small samples taken for oedometer testing. Different preparation of soil samples resulted in different $s'$ and $κ$ ratios being generated.

4.4 Pre-consolidated Stress $P_o$

This Stress represents the amount of existing stress acting on the soil. Referring to column 6 of Table 1 the magnitude varies from 5 kPa-1,100 kPa. This difference results in the difference in $s'$ and $κ$ values generated.

4.5 Consolidation Stress $ΔP$

Referring to column 6 of Table 1 the consolidation stress varies from 80 kPa-1,102 kPa. Sengul, et al. (2016) concluded the decrease of $k_s/k_t$ and $k_a/k_t$ in smear and transition zone is affected by the increased of the consolidation stress. Sharma and Xiao (2000), and Sathananthan and Indraratna (2006) concluded that $κ$ decreases with the increasing pressure of consolidation on the ground. Indraratna and Redana (1998) concluded that smear effects are limited within short to medium term consolidation. The difference in consolidation stress causes the variation in $s'$ and $κ$ ratios.

4.6 Use of Reconstituted Soil Samples

Tran-Nguyen and Edil (2011) who used reconstituted samples reported that the extent and permeability ratios measured in their laboratory study were at the lower limit reported in the literature. This is due to the fact that soils were very disturbed and had no structure, thus less susceptible to disturbance. The laboratory testing using undisturbed soil samples was done by Rujikiatkamjorn et al. (2014) who found that permeability reductions were almost twice as much as those using disturbed soil. On the other hand Bo et al. (2003) suggested that the smear zone could become larger in undisturbed soils due to the destruction of the soil structure. Nevertheless the condition of the soil in the field is typically intact, leading to the higher values of $s'$ and $κ$ ratios. Tests that use reconstituted and undisturb samples are indicated in column 4 of Table 1.

4.7 Mandrel Shape and Dimensions

The PVD installation in the laboratory is performed using a mined mandrel of unequal shape and size as presented in column 8 of Table 1 of. Sathananthan and Indraratna (2015) said the $s'$ ratio depends on the dimensions of mandrel used. Tran-Nguyen and Edil (2011) suggested the size and shape of mandrel is an important factor affecting $s'$. Shin et al. (2009) denoted a non-spherical shape of the smear zone but the ellip with a greater range on the longer mandrel.
side compared to the short side. These differences in mandrel shape and dimensions cause the resulting $s'$ and $\kappa$ values to be different.

### 4.8 Speed of PVD Installation

Due to the absence of a standardized speed, the researchers used varied between 0.5 mm/s-20 mm/s as presented in column 9 of Table 1. Sathananthan and Indraratna (2006) said the $s'$ ratio value depends on the installation speed. If the installation speed is faster, the disturbance on the ground will increase and thus the permeability ratio $\kappa$ will increase. The existence of the speed difference affect the value of $s'$ and $\kappa$ generated.

### 4.9 Determination Method of Smear Zone Characteristics

There are three ways to determine the characteristics of smear zone in the laboratory use of small diameter samples, back calculation and direct measurements in large-diameter consolidation cells. Using small diameter samples was performed by sampling small diameters of large diameter consolidation cells for oedometer testing. The determination of value is done using Terzaghi 1-D consolidation theory. With the measured distance of sampling to PVD and $k$ value, the changes of $k$ value to PVD distance can be detected and the smear zone characteristics can be determined. The method of back calculation of laboratory testing data to determine the value of consolidation coefficient in horizontal direction $c_h$ based on the Asaoka method [1978] and Hansbo [1987] is done by adjusting the time-settlement curve, then obtaining $s'$ and $\kappa$. Measuring directly in SZM (Smear Zone Model) intruments, cell Rowe and consolidation cells was also performed by researchers. The methods of determination of smear zone characteristics are presented in column 10 of Table 1.

### 5 CONCLUSIONS

There are no standards established to be used as references in laboratory testing. The resulting smear zone parameter values are various due partly to different set up of laboratory equipment. With reference to the results of the previous studies it is found that the extent ratio $s'$ values varies between 2.0 - 6.3 and the permeability ratio $\kappa$ values from 1.03 - 3.13.

### ACKNOWLEDGEMENTS

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### REFERENCES


Ghandeharioon, A., Indraratna, B., and Rujikiatkamjorn, C., 2012 “Laboratory and finite-element investigation of...
soil disturbance associated with the installation of mandrel-driven prefabricated vertical drains”, *J Geotech Geoenviron Eng* 138(3) pp 295–308.


ASTM D 2435-96 Standard Test Method for One-dimensional Consolidation properties of Soils


