On the Laboratory Testings to Characterize the Smear Zone

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Abstract: Due 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, ie 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 standarized laboratory testing be established to obtain a more accurate and consistent laboratory results.

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 r_s to the radius of the drain r_w 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 ratio 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 then 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; Ghandeharioon, 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).

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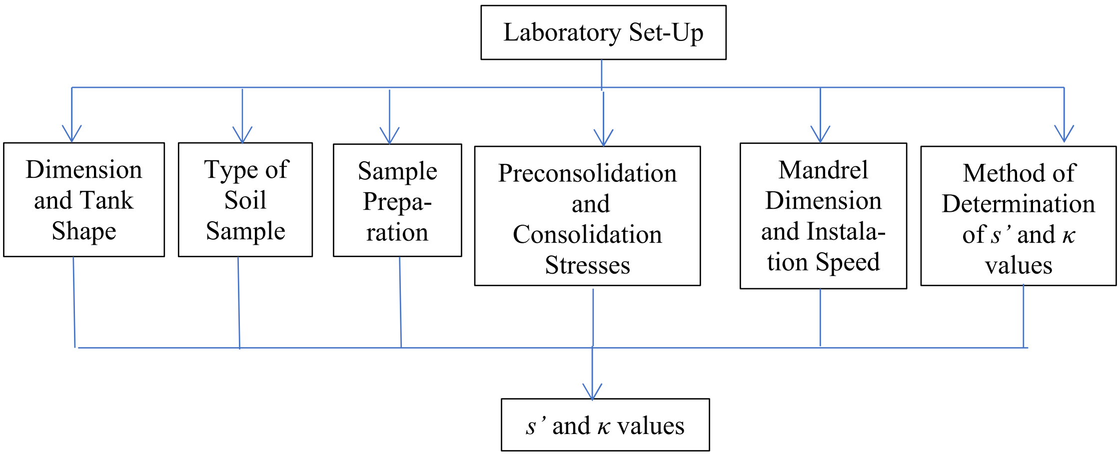

Figure 1. Set Up Testing Equipment at Laboratory

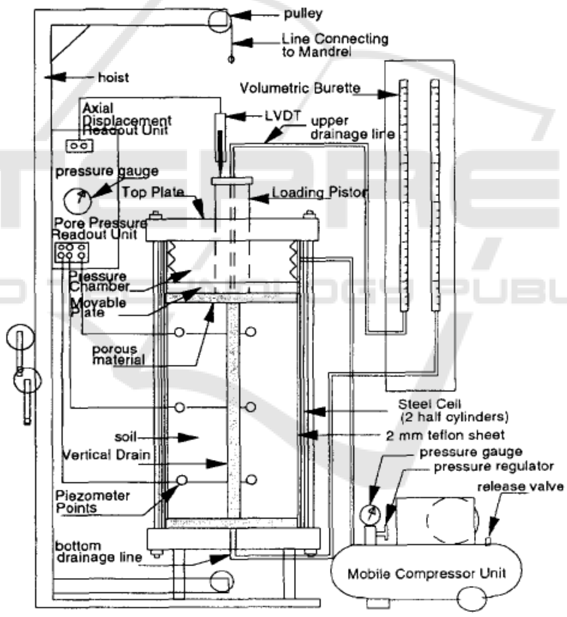

Figure 2. Large-Scale Consolidation Apparatus (Indraratna and Redana 1998)

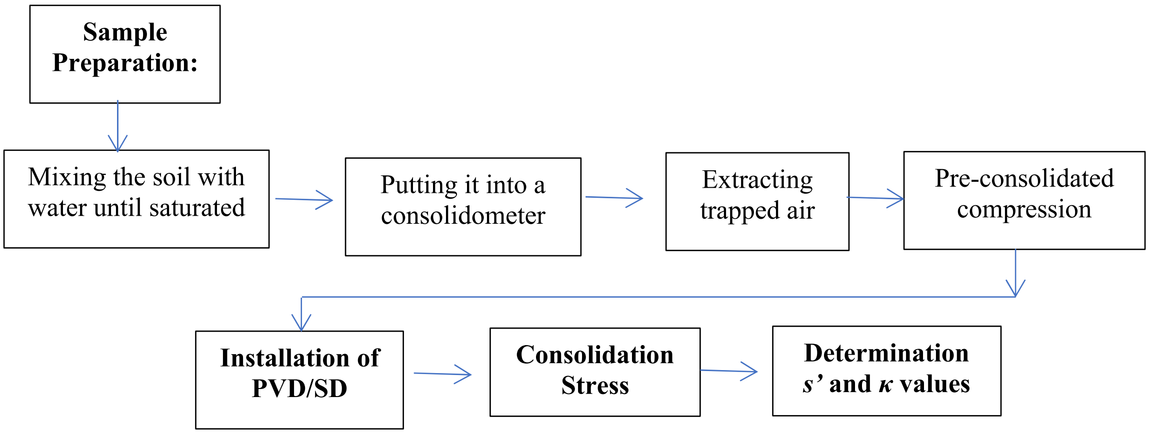

Figure 3. Sample Preparation And Determination Phases of Smear Zone Characteristics in Laboratory

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_h towards SD, where k'_v is relatively unchanged. 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 Saowapakpiboon 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 κ 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≤ s' <4, and **high** : 4≤s'<7. Then the value of s' laboratory test results are mostly in the **moderate** to **high**. The minimum values of κ = 1.03, maximum=3.13, and the averaged= 2.0. The range of κ values can be classified as follow, **low**:1< κ<4, **moderate:** 4≤ κ <7, and **high** 7≤ κ<12. Then the value κ laboratory test results are in the **low** range.

On the other hand, the range of κ value appears to be limited within the low values.

Table 1: Summary results of previous laboratory testings to characterize the smear zone

No.	Researchers	Tank Dimension	Basic Soil Properties	Sample Preparation	Stress (kPa)	Dimension PVD mm	Mandrel mm	Speed of Installation mm/s	Determination Smear Zone	Extent Ratio r_s/r_m	Extent Ratio r_t/r_m	Permebility Ratio k_h/k_s	Permebility Ratio k_h/k_t
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Bergado et al. (1991)	*h*=920 mm *d*=455 mm *h/d*=2.02	Reconstituted Soft Bangkok Clay γ=14.7 kN/m^3, *Cc*=0.80, *Cs*=0.13,*e*=2.3	Samples are placed in cell consolidation layer by layer. Sand of 5 cm thick is given on the surface.	Po=10.2 ΔP=47.8	40x6	60x60 recta- ngular	-	Small sampels	2.0	-	1.5-2.0	-
2	Indraratna and Redana (1998)	*h*=950 mm *d*=450 mm *h/d*=2.11	Reconstituted Allivial Clay, Sydnay *w*=40%,*LL*=70%,*PL*=30%, G_s=2.6,γ=17.0 kN/m^3	Samples are mixed with water, placed in a consolidometer cell and compacted layer by layer.Surface is given sand 5 cm.	Po=20 ΔP=200	SD diam.46	diam.50 circular	-	Small sampels	4.0-5.0	-	kh/kv= 1.15	-
3	Sharma and Xiao (2000)	*h*=400 mm *d*=1.000 mm *h/d*=0.40	Reconstituted Kaolinit *w*=65%, *LL*=70%,*PL*=40%, e=1.4,Gs=2.61	Kaolinite is mixed water up to *w* = 2 x *LL*, put into consolidation tank and be vacuumed for stress at 90 kPa for several days.	Po=100 ΔP=1,102	SD diam.50	diam.50 circular	5.0	Small sampels	4.0xr_w	-	1.30	-
4	Indraratna and Rujikiatkamjorn. (2004)	*h*=950 mm *d*=450 mm *h/d*=2.11	Reconstituted Allivial Clay, Moruya *w*=45%,*LL*= 42%, *PL*=17%, G_s=2.6,γ=17.0 kN/m^3	Samples are mixed with water up to w slightly larger than LL, placed in a coating, compacted using consolidometer cell.	Po=20 ΔP=30+50	100x3	125 x 25 recta- ngular	-	Small sampels	3.0xr_w 3.0xr_w (+v)	- -	kh/kv= 1.17-1.20	- -
5	Sathananthan and Indraratna (2006)	*h*=1040 mm *d*=650 mm *h/d*=1.60	Reconstituted Allivial Clay, Moruya *w*=45%, *LL*= 42 %, *PL*=17%, *Gs*=2.6,γ =17.0 kN/m3	Clay is mixed with water, kept on container for several days, placed in coating consolidometer cell (150 mm/Layer), and compacted.	Po=20 ΔP=200	100x3	125 x 25 recta- ngular	8.3	Small sampels	2.5	-	1.34	-
6	Feng and Yin (2006)	*h*=450 mm *d*=300 mm *h/d*=1.50	Reconstituted Hongkong Marine Clay, *w*=85,6 %, *LL*= 51.1 %, *PL*=26.1 %, *Gs*=2.58.	Clay is mixed with water and stored in container for several days, placed in coating consolidometer cells (150 mm/ layer) and compacted.	Po=20 ΔP=80	50x5	60x13 recta- ngular	-	Direct at cell consoli- dation	2.0	-	2.00	-
7	Shin et al. (2009)	*h*=1000 mm *d*=700 mm *h/d*=1.43	Reconstituted Busan Clay *w*=56 %, *LL*= 46.4 % *PL*=24.1 %, *Gs*=2.64	The test sample passed the sieve No.40. is mixed with water up to w = 2 x *LL*. The trapped air is removed by vacuum during mixing.	Po=50 ΔP=200	85x6.4	100x50 recta- ngular	20.0	Direct at cell consoli- dation	4.0-4.2 (l) 3.3-3.4 (s)	- -	- -	- -
8	Saowapakpiboon et al. (2010)	*h*=500 mm *d*=305 mm *h/d*=1.64	Reconstituted Soft Bangkok Clay *w*=113%,*LL*= 102%,*PL*=40%, G_s=2.66,γ=14.7 kN/m^3.	The sample is taken into 3-4 m from the ground surface and placed in the cell consolidometer coating.	- ΔP=100	100 x 3.5	-	-	Back- Calcula- *tion*	2.0 2.0 (+v)	-	*2.70* 2.50	-
9	Tran-Nguyen and Edil (2011)	*h*=530 mm *w*= 350 mm *t* = 130mm	Reconstituted HRK, *LL*=49 %, *PL*=24 %, *Gs*=2.59. Reconstituted CID *LL*=49 %, *PL*=20-25 %,*Gs*=2.71	Sample with *w* equal to the field is placed on the box. Placed in SZM instrument coating, compressed with vibrator.	Po=25 ΔP=Gradien. hydraulic i=20-30	100 x 3.2	15x120 recta- ngular	1.0-2.5	Directly at SZM instrument	3.0 (HRK) 4.2 (CID)	- -	1.03 1,25	- -

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

No.	Researchers	Tank Dimension	Basic Soil Properties	Sample Preparation	Stress (kPa)	Dimension PVD mm	Dimension Mandrel mm	Speed of Installation mm/s	Determination Smear Zone	Extent Ratio r_s/r_m	Extent Ratio r_t/r_m	Permebility Ratio k_h/k_s	Permebility Ratio k_h/k_t
1	2	3	4	5	6	7	8	9	10	11	12	13	14
10	Ghandeharioon et al. (2012)	*h*=900 mm *d*=650 mm *h/d*=1.38	Reconstituted Lucustrin *LL*= 55 %, *PL*=27 %, *e*=1.46	Sample is mixed with water until *w* = 1.1 x *LL*, placed in cell consolidometer layer by layer, and compacted.	Po=20 ΔP=50	*100 x 4*	-	-	Small sampels	2.65	5.8	kh/kv= 1.2-1.6	*kh/kv=* *1.6-1.8*
11	Chai et al. et al.(2013)	*h*=700 mm *d*=450 mm *h/d*=1.56	Reconstituted Soft Bangkok Clay *w*=113%,*LL*=104%,*PL*=45%, G_s=2.66,γ=14.7 kN/m^3	Samples are placed in cell consolido-meter layer by layer.	Po=50 ΔP=100	*50 x 3.5*	81.9x18.2 recta- ngular	-	Back- Calcula- *tion*	2,0	-	*3.0*	-
12	Rujikiatkamjorn et al.(2014)	*h*=561 mm *d*=345 mm *h/d*=1.60	Undisturb Bulli Clay *w*=41%, *LL*= 50%, *PL*=25%, *Gs*=2.62,γ=18.5 kN/m^3	The soil around the sample is dug and cut from base, wrapped to prevent loss of *w*, stored in a humidity-controlled room, and placed into cell consolidometer.	Po=20 ΔP=200	*w=50*	55x5 recta- ngular	-	Small sampels	3.7	5.5	1.33-2.85	*1.11-1.33*
13	Indraratna et al (2015)	*h*=25,4 mm *d*=63,5 mm *h/d*=0.40	Undisturb Ballina Clay *w*=94,7%,*LL*=98%,*PL*=32%, *Gs*=2.58,*e*=2.44,γ=16.5 kN/m3	Samples for Oedometer testing are collected from around the PVD installed in the field. A series oedometer testing is performed.	- ΔP=200	*100x3*	120x60 recta- ngular	-	*Oedometer* *test*	6.3	-	2.7	-
14	Joseph et al. (2015)	*h*=600 mm *d*=600 mm *h/d*=1.00	Reconstituted Cochin Marine Clay *w*=112%,*LL*= 156%, *PL*=34%,G_s=2.62	Sample is placed into the tank consolidometer, with *w* = *LL* layer by layer.	Po=5 ΔP=120	SD. diam.46	diam.50 circular	hammer w=2.6 kg h=30 cm	Small sampels	5.0-6.0	-	1.3-1.4	-
15	Pajouh et al.(2015)	*h*=200 mm *d*=250 mm *h/d*=0,80	Reconstituted Kaolinite, bentonite *w*=120%,*LL*=67-87%,*PL*=27-34% *PI*=40-43%	Samples are mixed with water to *w*=(1.4-1.8) *LL*, placed into Rowe cell, and given stress cell =110 kPa,back pressure = 100 kPa for saturation.	Po=20 ΔP=200	SD. *diam.22*	diam.25 circular	-	Directly at cell Rowe	3.0xr_w	-	4.0	-
16	Sengul et al. (2016)	*h*=530 mm *w*= 350 mm *t* = 130mm	Reconstituted HRK,*LL*=51%, *PL*=26%,*IP*=25%,G_s=2.60 Reconstituted CID,*LL*=51%, *PL*=30%,,*IP*=21%,*Gs*=2.76	Samples with *w* equal to the field are placed on the box, placed in SZM instrument coating, and compressed with vibrator.	Po=25 ΔP=hydraulic Head= 50	130x18	120x15 recta- ngular	2-5	Directly at SZM instrument	3.3 2.3-2.4	7.3 5.2-5.8	2.0 2.86-3.13	1.21 1.75
17	Choudhary et al. (2016)	*h*=450 mm *d*=650 mm *h/d*=0.69	Reconstituted Balina Clay *w*=94%, *LL*= 98%, *PL*=32%, *Gs*=2.6	Clay is taken 2 m below ground surface, mixed with distilled water with *w* = 1.4 *LL*, placed into cell consolidometer and given a light vibration.	Po=20 ΔP=Additional end load	100x4	115x10 recta- ngular	-	Directly at cell Consoli- dation	2.5	-	1.3	-

h = high	r = radius	*Po* = Pra-consolidatiion stress	(+v) = With PVD + vacuum preloading
d = diameter	HRK = Hydrite R Kaolinite	*ΔP* = Consolidation stress	k_t = Permeability of soil at transition zone
w = wide	CID = Craney Island Dredgings	*i* = Gradient hydraulic	r_t = Equivalent radius of transition zone
t = thickness	SZM = Smear Zone Model	(l),(s)=Mandrel long and short axis	SD = Sand Drain

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. Refering 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

Refering 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_h/k_s and k_h/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 undistub 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 κ 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 κ will increase. The existence of the speed difference affect the value of s' and κ 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 κ. 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 laborary 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 κ values from 1.03 - 3.13.

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