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Assessment the Engineering Characteristics of the Smear Zone around PVDs Using Laboratory Tests

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ABSTRACT

Smear zone is usually formed around the prefabricated vertical drains (PVD's) due to mandrel driving. The geotechnical properties of the soil in this zone exhibit significant changes that affect the performance of the PVD's. The most relevant property in this respect is the coefficient of permeability. So far, no serious attention is paid to investigate the effects of shearing under large shear strains on the geotechnical properties of the soft soil in Fao region. In this study, an extensive laboratory testing program was conducted to assess the characteristics of the smear zone with an emphasis on the permeability coefficient of Fao soft soil. The results show that the permeability of the smear zone is about 70% of the horizontal permeability of the intact soil. An attempt was made to estimate the extension of the shearing zone in the direct shear test. The analysis results indicate that thickness of the shearing zone is about (2.4) cm.

Keywords: clay, PVDs, smear effect, soft clay, permeability, shear strength

تحديد الخصائص الهندسية للترب المشوهة حول المبازل العمودية باستخدام الفحوصات المختبرية

الخلاصة

المنطقة المشوهة عادة ما تتكون حول المبازل العمودية بسبب اختراق المكبس للتربة. الخصائص الجوتكنيكية للتربة تظهر تغيرا كبيرا وهذه التغيرات تؤثر على اداء المبزل العمودي. الخاصية الاهم في هذه الحالة هي معامل نفاذية التربة. لغاية الان لا يوجد انتباه حقيقي لدراسة تأثير القص بانفعال قصي كبير على الخصائص الجيوتكنيكية للتربة الناعمة في منطقة الفاو. في هذه الدراسة تم عمل برنامج فحوصات مختبرية موسع لتحديد الخصائص المنطقة المشوهة مع التركيز على معامل نفاية تربة الفاو. النتائج اظهرت بان معامل نفاذية المنطقة المشوهة يعادل حوالي 70% من نفاذية التربة غير المشوشة. تم القيام بمحاولة لتحديد سمك منطقة القص المتكونة من فحص القص المباشر. تحليل النتائج اظهر سمك المنطقة المشوهة يعادل حوالي 2.4 سم.

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1. INTRODUCTION

Preloading with prefabricated vertical drain (PVDs) is widely used improvement technique for the clayey soils. The PVDs improve the clayey soils by accelerating the consolidation rate of the soil deposit under surcharge loading by activating the radial drainage through the PVDs, **Bergado et al., 2002, Kim, et al., 2014, Xu and Chai, 2014**. Installation of the PVDs is usually done by driving a metallic mandrel inside the soft soil. After positioning the PVD inside the mandrel to the required depth in the soil, the mandrel is pulled out, leaving the PVD inside the soil deposit, **Zhou and Chai, 2016**. This process of PVD installation causes significant disturbance (remoulding) to the soil surrounding the mandrel. The zone of the remoulded soil that surrounds the mandrel and later the PVDs is so called the "Smear Zone", **Zhou and Chai, 2016**. This soil zone is characterized by lower value of permeability coefficient than the the intact soil. This reduction of the permeability of the smear zone will significantly affect the performance of the PVDs, **Bergado, et al., 1991, Indraratna and Redana, 1998, Hird and Moseley, 2000, Sharma and Xiao, 2000, Bo, et al, 2003, Basu and Prezzi, 2007, Sathananthan, et al., 2008, Shin, et al., 2009, Sengul, et al., 2016, Zhou and Chai, 2016, Zhou, et al., 2017, and Chai, et al., 2018**. Various results for the extension (thickness) of smear zone have been obtained by several researchers. Most of the research in this respect indicate that the smear zone is ranging between (1.5-5) times the radius of the mandrel **Table 1**. The ratio of the permeability in radial direction of the undisturbed soil (k_h) to the permeability of the smear zone (k_S) varying between (1-11), **Sengul, et al., 2016**. So far, there are no methods for direct measurements (using laboratory or field tests) for the parameters associated with the smear effect which are the diameter of the smear zone and the ratio of the permeability of the natural soil to the permeability of the smear zone. Engineering judgment and indirect analysis methods were suggested to predict these parameters, **Sengul, et al., 2016, and Chai, et al., 2017**.

In this study, a laboratory testing program was conducted, mainly by using the direct shear apparatus and the one dimensional consolidation test (oedometer test) to assess the characteristics (i.e. permeability and thickness) of the remoulded zone. The soil used in this study was obtained from the Fao region which is located in the extreme South of Iraq. Fao region is very important and its importance comes in view of the fact that it is the unique marine front in Iraq. Many oil exporting facilities, ports and other infrastructures are planned to be constructed in this region. This study is therefore devoted to assessing the significant changes that commonly occur on the values of permeability coefficient upon shearing under large shear strain condition and extension of the shearing zone in the direct shear box.

Table 1. Extents of the smear zone, **Rujikiatkamjorn, et al., 2013**.

Authors	Equivalent radius of smear zone, rs
Hansbo, 1981	$1.5r_{m,eq}$ ($r_{m,eq}$=equivalent radius of mandrel)
Bergado, et al., 1991	$2r_{m,eq}$
Sharma and Xiao, 2000	$4r_{m,eq}$
Sathananthan and Indraratna, 2006	$2.5r_{m,eq}$
Ghandeharioon, et al., 2010	$3.1r_{m,eq}$
Sengul, et al., 2016	(2.3-3.3) $r_{m,eq}$

Indraratna and Redana, 1998	(4–5)r_w (r_w=radius of central drain)

2. EXPERIMENTAL WORK

The soft clayey soil in the Fao region is characterized by top layer of silty clay that its thickness is about 20m below natural ground level (NGL). The ground surface is almost flat and the ground water table is close to the (NGL), **Al-Mufty, 1990**. Undisturbed soil samples were brought from a depth of about 3 m. As shown in **Plate 1**, an open pit was initially performed by an excavation machine to about 2 m depth then by manual excavation for the last meter to avoid sample disturbance, as much as possible. Then thin wall metallic cylinders were pushed by hand inside the soil. The dimension of each cylinder is (0.2 cm) in thickness and (20 cm x 25 cm) is the diameter and height of the cylinder. After pushing the cylinders through the soil, the soil surrounds the cylinders were manually removed. That means a block undisturbed soil inside the cylinders and it is ready to be collected from the pit. The collected samples were then carefully sealed and transported to Baghdad. All the laboratory tests were carried out at the Laboratories of the Department of Civil Engineering / University of Baghdad.

The experimental work consists of two main phases, identifying the main geotechnical properties of the intact soil was done in the first phase. The second phase was devoted to assessing the effects of soil shearing and smearing on the characteristics of the Fao soft clay.

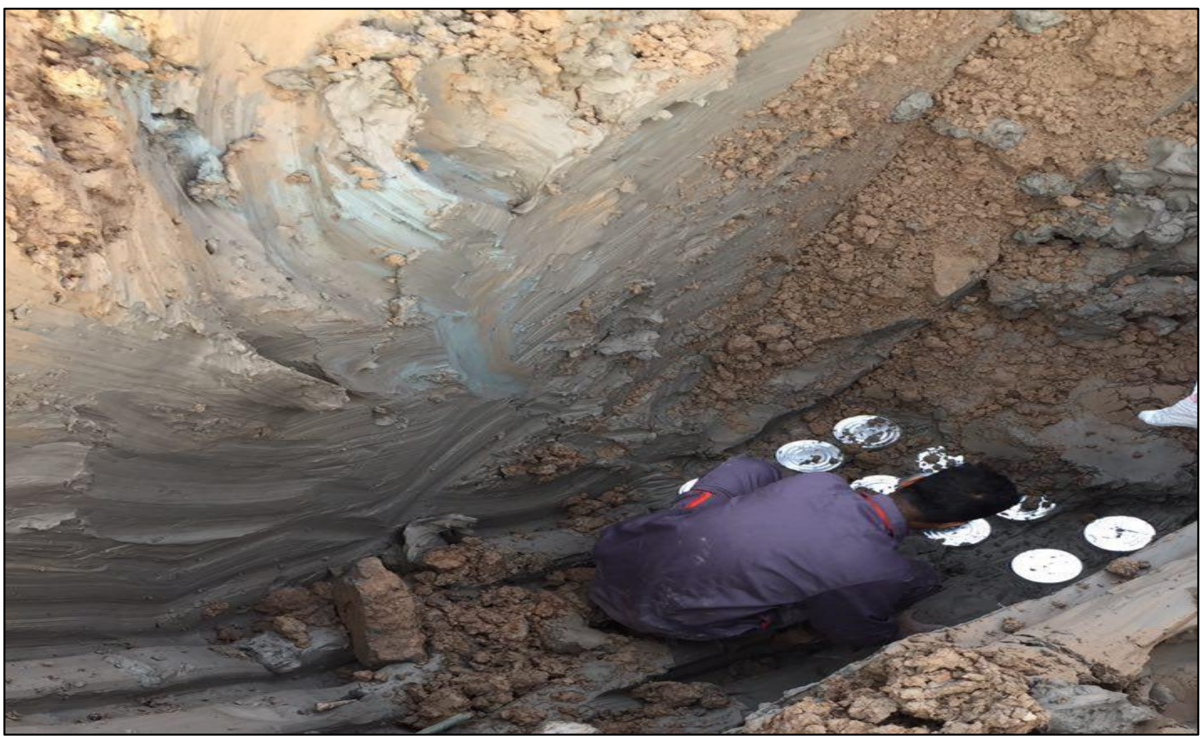

Plate 1. Undisturbed soil samples from an open bit.

2.1 Undisturbed Soil Properties

This phase comprises the tests that are used to identify the geotechnical properties of the intact soil, that are, the physical, chemical and mechanical properties.

Table 2 displays the physical properties of the intact soil following ASTM designation. It is clear that the soil is lean clay with a natural water content of about 0.36 and about 100% saturation. The liquid limit is about 48 and the plasticity index is 21. The specific gravity of the soil is about 2.75. The gained results are almost compatible with, **Al-Mufty, 1990**.
Table 3 shows the chemical composition of the natural soil. It can be noticed that the percent of organic matters is about 4.2%. The value of pH which is about 8.04 indicates a weak base nature of the soil.

Table 2. The physical properties of the virgin soil.

Type of tests	Results and Description of averaged value	ASTM designation
Liquid limit	48%	D4318
Plastic limit	27%	
Specific gravity	2.756	D854
Sieve Analysis	99 % passing sieve no. 200	D6913
Hydrometer test	70% is the percentage of clay, while 29 % is the percentage of silt, and 1% is the percentage of sand.	D7928
Water content	36 %	D2216
Bulk Unite weight	18.4 kN/m^3	D7263
Void ratio	0.99	D2435
Porosity	0.497	Physical relationships
Degree of saturation	100%	
Unified soil classification	CL (clay with low plasticity, very soft clay)	D2487

One dimensional consolidation test (oedometer test) was used to assess the compressibility characteristics of the virgin soil. Both vertical and horizontal coefficients of consolidation were assessed following ASTM designation 2435. Lateral undisturbed soil specimens were used to evaluate the coefficient of the horizontal consolidation.

Table 3. Chemical tests results.

Chemical Compound	Value as Percentage
Total SO_3	0.475
Total soluble salt T.S.S	1.4

Organic content	4.2
Total Cl%	0.38
pH value	8.04

Table 4 shows the values of the vertical and horizontal coefficient of consolidations and vertical and horizontal coefficient of permeability. The vertical and horizontal coefficients of consolidations were obtained from the oedometer test by using two load increments. Ϭv represent the vertical pressure used in oedometer test. It is worthy mentioning that the soil samples that were used to measure the horizontal permeability were obtained by inserting the relevant molds into the undisturbed soil blocks in the lateral direction. The vertical and horizontal coefficient of permeability were evaluated from Eq. (1) and (2) respectively, **Head, 1994**. It is clear that coefficient of horizontal consolidation is slightly higher than the coefficient of vertical consolidation. The coefficient of horizontal permeability is therefore slightly higher than that in the vertical direction. That may be due to the soil structure which is more permeable in the radial direction. It could be noticed that the coefficient of vertical consolidation is about 0.002 cm^2/sec while the coefficient of horizontal consolidation is about 0.0025 cm^2/sec. The soil possesses low permeability therefore low rate of consolidation would be expected. The coefficient of horizontal permeability is about 3.356 x 10^{-9} m/sec while the coefficient of vertical permeability is about 2.89 x 10^{-9} m/sec. These results are compatible with, **Al-Alusi, 1977, and Al-Mufty, 1990.**

$$kv = C_v \times m_v \times \gamma_w \qquad (1)$$

Where:-

K_v = coefficient of vertical permeability in m/sec

C_v = coefficient of vertical consolidation in m^2/sec

m_v = coefficient of volume change in m^2/kN

γ_w = unit weight of water in kN/m^3

$$K_h = C_h \times m_v \times \gamma_w \qquad (2)$$

Where:-

K_h = coefficient of horizontal permeability in m/sec

C_h = coefficient of horizontal consolidation in m^2/sec

m_v = coefficient of volume change in m^2/kN

γ_w = unit weight of water in kN/m^3

Table 4. Vertical and Horizontal coefficient of consolidations.

Coefficients of vertical consolidation (C_v) in cm^2/sec		Coefficient of horizontal consolidation (C_h) in cm^2/sec	
σ_v=12.5 kPa	σ_v=25 kPa	σ_v=12.5 kPa	σ_v=25 kPa
0.002	0.00185	0.0025	0.00241
Coefficients of Vertical permeability (kv) in m/sec		Coefficients of Horizontal permeability (kh) in m/sec	
σ_v=12.5 kPa	σ_v=25 kPa	σ_v=12.5 kPa	σ_v=25 kPa
2.89×10^{-9}	1.55×10^{-9}	3.356×10^{-9}	1.78×10^{-9}

The direct shear test was used to assess the shear strength of the intact soil following the **ASTM designation 3080-04** and the recommendations presented by **Bro, et al., 2013**.
Table 5 presents the results of the undrained shear strength from the direct shear test. It could be noticed that the undrained shear strength of the undisturbed soil is about 15.26 kPa while the undrained shear strength of the remoulded soil is about 8.18 kPa. The direct shear test was performed on the undisturbed and remoulded soil in their natural water content which is about 0.36. These results are compatible with, **Al-Mufty, 1990**.

Table 5. Shear strength of the virgin soil.

Type of test	Undrained Shear Strength (S_u) in kPa		Water content %	ASTM Designation
	undisturbed soil	remoulded soil		
Direct Shear test "Normal load equal to 12.5 kPa"	15.26	8.175	35.86	D3080-04 and **Bro et al. (2013)**

2.2 Characteristics of the Smear Zone

This phase of laboratory tests was to identify the properties of the soil in the smear zone that affect the performance of the PVDs. These properties are the permeability coefficient and the thickness of the shear concentration zone.
In this study, the smear zone was created using special technique through the direct shear apparatus to simulate the mandrel entrance and advancement through the soil. There are some differences in the arrangement of the components of the shear box between the smearing technique that used to assess the permeability of the smear zone and the smearing technique used to assess the extension of the smear zone.

2.2.1 Permeability of the smear zone

This smearing technique was used to simulate the smearing caused by mandrel entrance and advancement inside the clayey soil to construct the prefabricated vertical drains PVD's. After shearing the samples under large shearing strains, the permeability of the sheared zone was measured by using the odometer test. This technique also enables the assessment of the remoulded shear strength of the soil in direct contact with the mandrel (i.e. remoulded soil). However, the steps below explain this smearing technique:-

- The direct shear apparatus was used to generate a smear zone in soil specimen of dimensions (6cm x 6cm x 2cm).
- As known, the shear box of the direct shear apparatus consists of two parts, the upper part is fixed while the lower part is movable forward and backward. A steel plate was fitted in the top of the lower part of the shear box (**Plate 2**) in direct contact with the soil specimen in the bottom face of the upper part of the shear box. The contact surface between the steel plate and the soil specimen was the same usual shear surface in the common direct shear tests. That was only to simulate the mandrel (which was represented by the steel plate) inside the soil in the field.
- The soil specimen was set in the shear box to make the shear surface at the bottom face of the soil specimen. After the placement of the soil specimen, the other components of the shear box were fitted. Then the normal load (7.15 kPa) was applied.
- Moving the lower part of the shear box means moving the steel plate which is in direct contact with the normally loaded soil specimen above it. That would cause remoulding for the particles of the soil specimen.

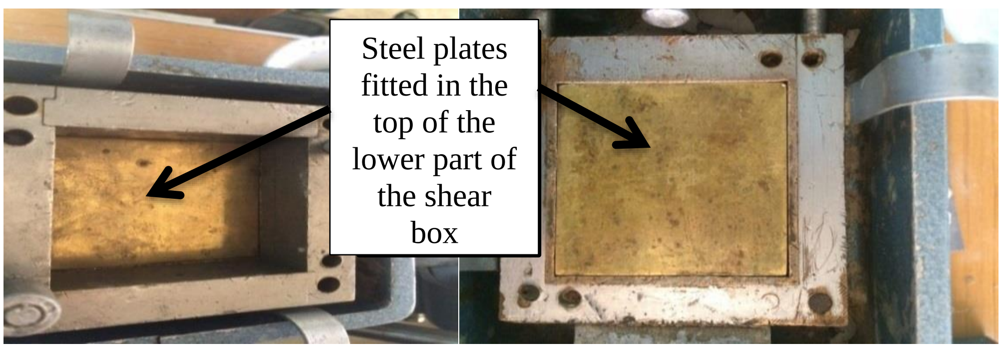

Plate 2. Steel plate fitted on the top of the lower part of the shear box.

- Moving the lower part of the shear box for 16 mm forward and backward (i.e. cycle) for more than 7 cycles to ensure that the smearing was took place.
- The remoulding was assured by recording the same shear strength at the 5^{th}, 6^{th} and/or 7^{th} cycle of remoulding.

- After doing the direct shear test for creating the smear zone. The permeability of that smeared sample was calculated from the oedometer test. That was accomplished by inserting the consolidation ring inside the smeared soil specimen. After that caring out the oedometer test on that smeared specimen inside the consolidation ring.

2.2.2 Extension of the smear zone

While the mandrel advancing through the soil, a thin film of soil particles will stick in the face of the mandrel. These adhered particles will fully surround the embedded length of the mandrels. Because of these adhered particles, the smear surface will be between soil particles which are the adhered soil particles on the face of mandrel and the particles of the intact soil. The following steps were adopted to clarify the above mentioned idea:

1. The direct shear apparatus was used to generate a shearing zone in the soil specimen of dimensions (6cm x 6cm x 2cm and 6cm x 6cm x 4cm).
2. After placing the soil specimen inside the shear box, smearing (remoulding) was starting at the middle height of the specimen (10 mm or 20 mm) by shearing the sample and that had been done by moving forward the lower part of the shear box for at least 15mm then moving backward to the initial position. This could be considered as a cycle of remoulding or shearing. By repeating this process for at least seven cycles to be assured that the remoulding between the soils particles in the smearing surface had been occurred. The remoulding was assured by recording almost same shear strength at the 5^{th}, 6^{th} and 7^{th} cycle of shearing.
3. The remoulding was assured by recording the same shear strength at the 5^{th}, 6^{th} and 7^{th} cycle of remoulding.
4. After that the smeared soil specimen was moved out from the shear box. Then by using the consolidation ring, the soil specimen was trimmed from the smeared soil specimen for the one dimensional consolidation test to find the permeability of the smeared soil specimen (i.e. smear zone).
5. To start the one dimensional consolidation test on the smeared soil specimen (i.e. remoulding or shearing at the middle height of the soil specimen), the controlling of the position of the smear surface at the middle height of the smeared soil specimen inside the ring was monitored. The thickness of the smear zone and the thickness of the soil layer above the smear zone were indicated through the relationship between the changes in t_{90} with the change of sample thickness.

3. RESULTS AND DISCUSSION

3.1 Permeability of the shearing strain concentration

After smearing by steel plate and maintaining the smear surface in the bottom face of the smeared soil specimen, one dimensional consolidation was carried out to assess the permeability of the specimen. **ASTM D2435** was followed through the execution of the odometer test. The same relationships that used to assess the permeability of the undisturbed soil were also followed to assess the permeability of the smeared specimen.

Table 6 details the values of permeability. Ϭv represent the vertical pressure used in oedometer test. More than 5 tests were done to reach results consistency for each the tests. It can be noticed that the permeability of the smear zone is about 2.33 x 10^{-9} m/sec. **Fig. 1** shows a bar chart for the permeability of the undisturbed soil in vertical and horizontal directions and the permeability within the shearing zone.

Table 6. Values of the soil permeability at the shear concentration zone.

Test No.	Permeability of the shear strain concentration zone in m/sec	
	Ϭv=12.5 kPa	Ϭv=25 kPa
1	2.36 x 10^{-9}	1.54 X 10^{-9}
2	2.34 X 10^{-9}	1.56 X 10^{-9}
3	2.10 X 10^{-9}	1.41 X 10^{-9}
4	2.15 X 10^{-9}	1.44 X 10^{-9}
5	2.71 X 10^{-9}	1.77 X 10^{-9}
Average	2.33 X 10^{-9}	1.54 X 10^{-9}

Fig. 2 illustrates the percentage of the permeability reduction in vertical and horizontal directions due to smearing. The reduction of permeability in horizontal direction is about 30% while the reduction of permeability in vertical direction is about 20%. This reduction in permeability may be due to the destruction of the soil particles skeleton upon remoulding. The particles arrangement is thought to be changed from flocculated to dispersed system. These results are consistent with, **Onoue, et al., 1991, Sharma and Xiao, 2000, Indraratna and Redana, 2000, Sathananthan, et al., 2008, Rujikiatkamjorn, et al., 2013, and Sengul, et al., 2016.**

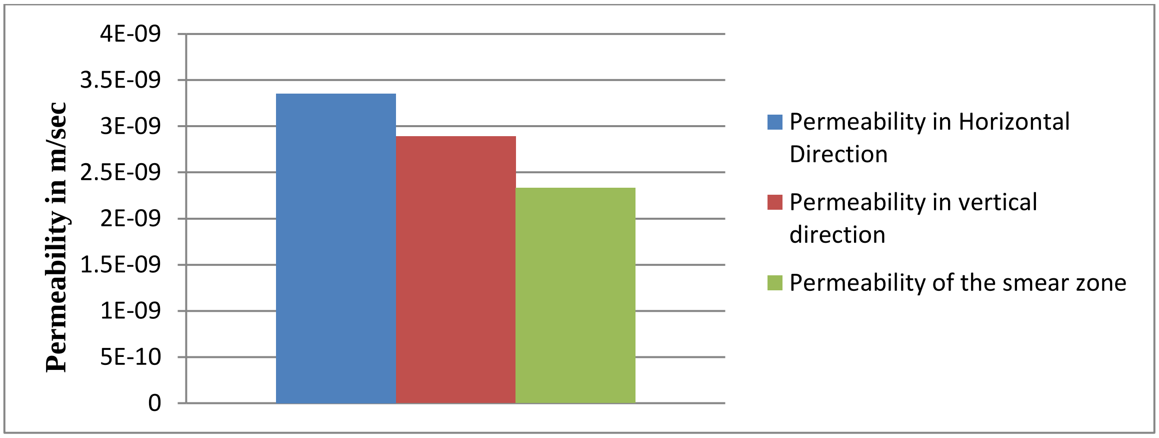

Figure 1. Permeability in the Horizontal, Vertical directions and Smear zone.

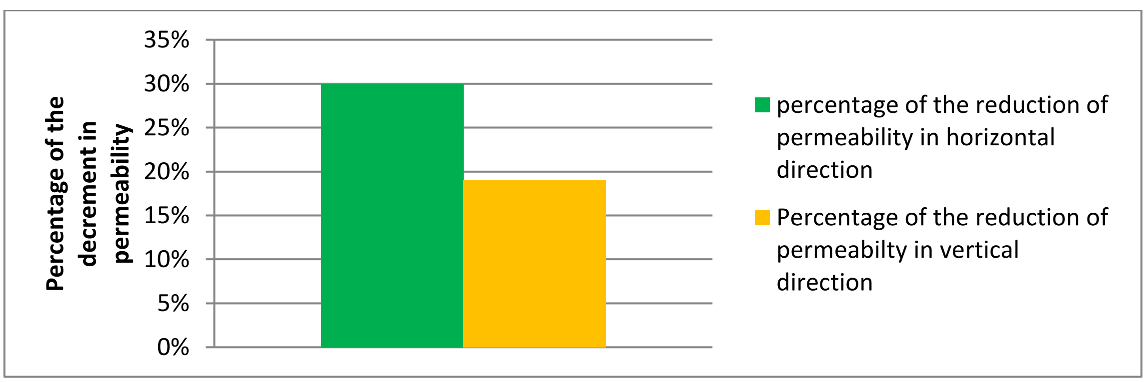

Figure 2. Percentage of the reduction in permeability of the smeared zone compared with virgin soil.

3.2 Extension of the Shear Strain Concentration Zone

Assessing the thickness of the shearing zone is important in many practical problems. In order to estimate the thickness of this zone, a smear zone was created according to the steps briefly explained in the paragraph (2.2.2). The thickness of shearing zone could be indicated by obtaining the change in slope of relation between (t_{90}), (from the one dimensional consolidation test) and the square of the sample thickness. The theoretical background of this approach can be clarified by the following:

- By considering the coefficient of volume change (m_v) is a constant value for a certain loading level, the coefficient of permeability will be in a linear proportion relation with the coefficient of consolidation (C_v), **Eq. 2.**
- Making use of the following relation for one dimensional consolidation test:

$$Cv = \frac{Tv \times H^2}{t_{90}} \quad (3)$$

and for 90% consolidation with two- way drainage condition, the time required to reach 90% consolidation will be linear proportion to the square of drainage path. This means that for a certain value of (Cv) there is a certain slope for the relation between (t_{90}) and (H^2).
- By attempting different thicknesses of the sheared soil specimens, the thickness of the shear concentration zone can be figured out from the above-mentioned relation.

Table 7 displays the values of (t_{90}) from three consolidation tests of soil specimens with each thickness, starting from 0.4 cm up to 3 cm. The results of this table are shown in **Fig. 3** as solid squares. To deal with the slight scattering in the obtained results, a solid line that represents the best fitting curve is plotted on the same Figure. It is clear that there is an initial trend of variation of (t_{90}) with (H^2) that is different from the final trend of variation. This implies that at a certain value of (H) beyond which a certain change has taken place in the value of (C_v).

Table 7. Values of t_{90} for sheared soil specimens with different thicknesses.

Thickness of soil sample in cm^2	t_{90} (min)		
	Ϭv=12.5 kPa		
	Test 1	Test 2	Test 3
0.16	0.9604	1	1.96
0.36	1.96	1.44	1.5625
0.64	3.425	3.5344	3.3124
1	4.84	4.84	4.84
1.44	5.29	6.76	6.25
1.96	9.61	10.1124	7.29
2.56	10.15	12.29	8.29
3.24	10.89	14.8225	12.84
4	16.19	15.0825	11.56
4.84	20.16	16.81	18.49
5.76	20.5	23.2	21.5
6.76	23.11	24.4	25.26
7.84	24.23	25.59	26.81
9	29.51	25.86	27.49

In order to specify this value of the thickness (H), **Fig.4** is presented with an adjustment for the best fitting line. The initial trend of variation is represented by a straight best fitting line and the final trend of variation is represented by another line of different slope. The intersection of these two lines may give a clear value of the thickness of the soil specimen that exhibits significant change in the value of (C_v). This value is about 2.4 cm. For the sheared soil specimens of thickness less than 2.4 cm, the parameter Cv and then the permeability coefficient has a certain value. Beyond this thickness, the slope of the relation between (t_{90}) and H^2 has changed in a manner that indicates a more rapid consolidation or higher coefficient of permeability. This means that the specimen thickness exceeds the thickness of the shear concentration zone.

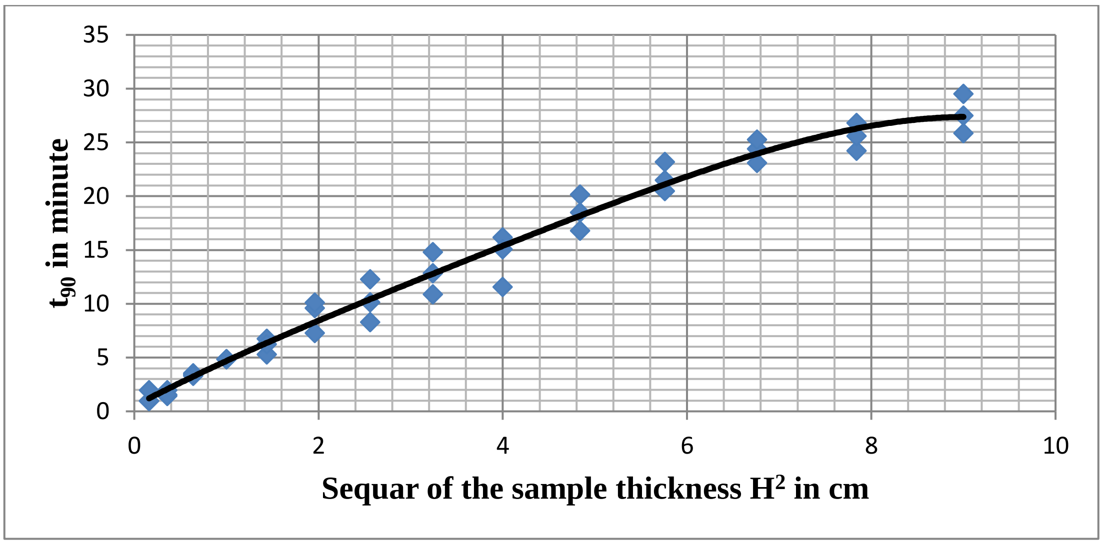

Figure 3. The values of t_{90} for sheared soil specimens with different thicknesses.

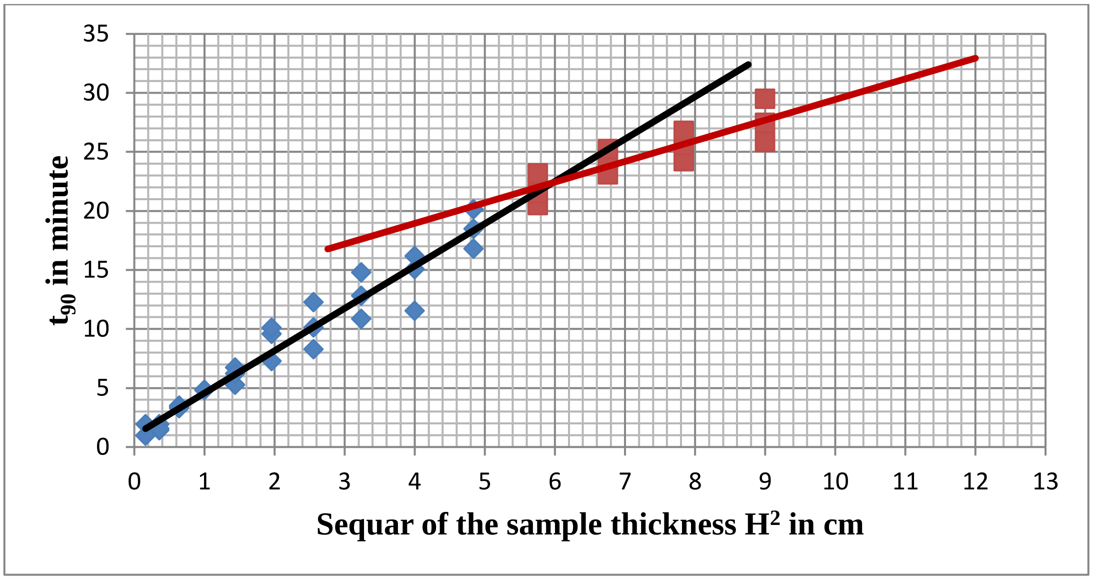

Figure 4. Changes of t_{90} with changing thickness of the sheared soil specimens.

4. CONCLUSIONS

1. The shearing of soft soil under large shear strain causes a pronounced decrease in the soil permeability at the shearing concentration zone. The percentage of reduction is almost 30%. This zone which is called the smear zone, will inversely affect the performance of the PVDs by increasing the time required to reach the designed degree of consolidation through the use of PVDs.
2. The thickness of the affected zone due to specimen shearing only, is about (2.4) cm. The effects of soil radial displacement due to the mandrel inserting into the soil was not considered in this paper.
3. The time required to reach 90% consolidation increases almost linearly with increasing the square of thickness of the soil specimen. The change in slope of this relation may indicate a change in the coefficient of consolidation or the permeability coefficient of the soil specimen.

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NOMENCLATURE

ASTM	= american society for testing and materials.
T.S.S	= total soluble salts.
Tv	= a constant dimensionless time factor.
H	= length of the path drainage of the consolidated specimen.
	= undrained shear strength.
S_u	= water content.
W.C. %	= required time to reach 90% degree of consolidation.
t_{90}	= coefficient of vertical permeability in m/sec.
K_v	= coefficient of vertical consolidation in m^2/sec.
C_v	= coefficient of volume change in m^2/kN.
m_v	= unit weight of water in kN/m^3.
γ_w	= Coefficient of horizontal permeability in m/sec.
K_h	= coefficient of horizontal consolidation in m^2/sec.
C_h	= radius of central drain.
r_w	= equivalent radius of mandrel.
$r_{m,eq}$	= equivalent radius of smear zone.
rs	= vertical pressure.
σ_v	