A STUDY ON change of undrained shear strength and co-efficient of permeability of soft CLAY due to installation of PVD

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BY

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May, 2016.

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I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as part of his **Master of Civil Engineering in Soil Mechanics& Foundation engineering studies.**

All information in this document have been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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I hereby recommended that the thesis prepared under my supervision by Bimal Kanti Pal entitled "***A STUDY ON CHANGE OF UNDRAINED SHEAR STRENGTH AND CO-EFFICIENT OF PERMEABILITY OF SOFT CLAY DUE TO INSTALLATION OF PVD***" be accepted in partial fulfillment of the requirements for the Degree of Master of Civil Engineering with specialization in Soil Mechanics & Foundation Engineering from Jadavpur University.

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CERTIFICATE OF APPROVAL*

The foregoing thesis "***A STUDY ON CHANGE OF UNDRAINED SHEAR STRENGTH AND CO-EFFICIENT OF PERMEABILITY OF SOFT CLAY DUE TO INSTALLATION OF PVD***" is hereby approved as a creditable study of an engineering subject carried out and presented in a manner satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve the thesis only for the purpose for which it is submitted.

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ABSTRACT

Clay, primarily, takes very long time to consolidate. Installation of PVD in such a soil reduces the drainage path and the required time of settlement as well. Objective of this study was to investigate the effect of installation of PVD on soft clay in respect of shear strength and permeability characteristics. The investigation was done conducting small scale model tests in the laboratory and commercially available kaolin was used as soft clay.

A tank of diameter 37cm and height of 50 cm was filled up with kaolin water slurry and was subjected to different surcharge loads with and without installed pre-fabricated vertical drain. The samples were collected from the tank to determine permeability and undrained shear strength for both the cases.

It has been observed that the rate of settlement and undrained shear strength has increased and co efficient of permeability has decreased in the case when PVD was installed within the soil indicating improvement of the soft clay in respect of shear strength and compressibility.

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NOTATIONS

a Thickness of vertical drain

B Half width of Unit cell

b Width of vertical drain

b_s Half width of Smear Zone

C_h Coefficient of consolidation in horizontal direction.

C_r Coefficient of radial consolidation

d_w Equivalent Diameter of the vertical drain

d_m Equivalent diameter of the Mandrel

d_s Diameter of the smear zone.

e Void ratio

K_s Horizontal permeability of soil in the smear zone

K_h Horizontal permeability of soil

K k_h/k_s

n Ratio of diameter of soil cylinder and diameter of vertical drain

q_w Discharge capacity of drain

L Length of the drain

r Radial distance

R, r_e Radius of unit cell.

r_w Radius of well

r_s Radius of smear zone

T_h Time factor in horizontal direction\

t Time

s Drain spacing

U Average degree of consolidation

U_h Excess pore pressure in horizontal direction

U_{max} Maximum excess pore pressure in horizontal direction

U_o Initial excess pore pressure in horizontal direction

$\eta =$ r_{e}/ r_w

$\varepsilon =$ m_{vs}/m_v

Chapter 1

INTRODUCTION

1.1General

During the last decades, urbanpopulation has increased many fold. Huge infrastructural activities are taking place all over the worldto accommodate these growth. As a result, engineers are forced to undertake constructionactivitiesonlow-lyingmarshyareas, with highlycompressibleweakorganicandpeatysoilsofvaryingthickness.These softclay deposits exhibitslowbearingcapacityaswellasexcessivesettlementcharacteristics.Therefore,itbecomese ssentialto improve and stabilizethese softsoils beforecommencing any construction.

Preloading with band drain is one of the mostsuccessful and popular groundimprovementtechniques.Sincemostcompressiblesoilsarecharacterizedbylowpermeabi lityof considerablethickness,therefore thetimeneededfortherequiredconsolidationwill be very long,andalsothe

surchargeloadrequiredwill besignificantlyhigh.Thisis difficultdue to time constraints. Installationofverticaldrainscanreducetheconsolidation

periodsignificantlybydecreasingthedrainagepath

in theradialdirection(astheconsolidationtimeisinverselyproportionaltothesquareofthelengthoft hedrainagepath).Applicationofsurchargeloadingwith pre-fabricated vertical draincanfurtheraccelerateconsolidationwithoutanyadverseeffectsonthestabilityofanembankm entbuiltonsoftclay.

1.2PurposeandApplicationofVerticalDrains

Theprefabricatedverticaldrainscanacceleratetherateofprimaryconsolidationbyreducingthelengt hofdrainagepath,hence,increasingtherateofporewaterpressuredissipationintheradialdirection.Significant secondary consolidation is not usually observed for soft clays stabilized by a sufficient number of PVD. Due to the rapid initial consolidation PVD's will increase the stiffness and bearing capacity of soft clay. Sand drains were widely used until the early 1970's, presently, PVDs have almost totally replaced the conventional sand drains throughout the world. Sand drain, which is simply a borehole filled with sand, does not only provide good drainage, but also reinforces the soft foundation.

The filter (sleeve) is made of synthetic or natural fibrous material with a high resistance to clogging. The common band shaped drains have dimensions of100mm x 4mm.

.Figure 1.1 shows schematic diagram of consolidation without vertical drains.

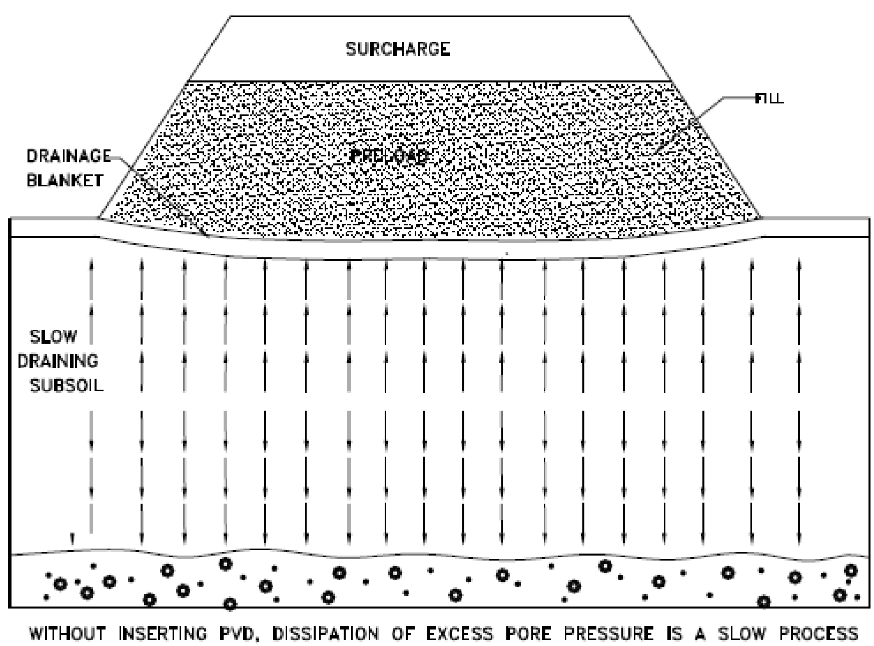


Fig: 1.1 Consolidation Without Vertical Drains

Theverticaldrainscanbeinstalledusingeitherastaticordynamicmethod.Inthestaticprocedure,themandrelispushedintothesoil bymeansofastaticforce.Inthedynamicmethodofinstallation,themandrelisdrivenintothegroundusingavibratinghammeroraconventional drophammer. Theverticaldrainsareparticularlyefficientwheretheclaylayerscontainmanythinhorizontalsandor siltlenses(microlayers).However,ifthesemicro layersarecontinuousinthehorizontaldirection,theinstallationofverticaldrainsmaynotbeeffective, sincerapid drainageofthe pore water out of the soillayers may occur throughthehorizontalmicrolayers.

Figure1.2illustratesatypicalschemeofverticaldrainsinstallationandmonitoringinstrumentsrequiredtomonitortheperformanceofthesoilfoundationbeneathanembankment.Priortoverticaldraininstallation,itisnecessarytoconductgeneralsitepreparation.Thisworkmayincludetheremovalofvegetationandsurficialdebris,establishingsitegradingandconstructingasandblanket.Thepurposeofthesandblanketistoconducttheexpelledwaterawayfromthedrainsandtoprovideasound-workingmat.

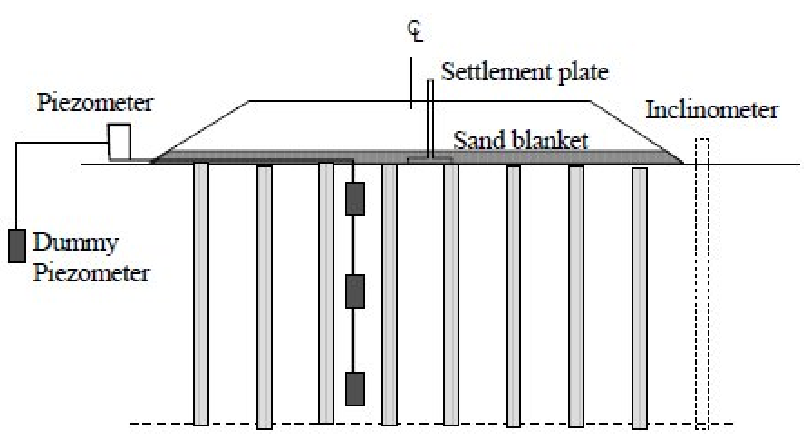


Fig-1.2 Basic instrumentation of Embankment

Severaltypesofgeotechnicalinstrumentationarerequiredtoinstallbeforeandafter construction,inordertomonitortheperformanceoftheembankment.Monitoringis essentialtopreventsuddenfailures,torecordchangesintherateofsettlementandtoverify thedesign parameters.Settlementgauges(e.g.ofhydraulictype)areusedtomeasurethelong-termsettlementsattheoriginalgroundsurfaceandarebeplacedimmediatelyaftertheinstallationofverticaldrains. Settlementplatesaresuitablefor initialreading andarebeinstalled atthebottomofsandblanket,atintermediatedepths,andatthebottomofthecompressiblelayerstomonitoritssettlement.Abenchmarkisusuallysetuponastablegroundatareasonabledistancefromthefill.

Piezometersareusedtomonitor p o r e pressureprofilesandare beinstalledatthebottomofsandblanket,atintermediatedepthsandatthebottomofthecompressiblelayer.
Adummyorremotepiezometershouldalsobeinstalledatanadequatedistancefromtheembankmenttorecordtheoriginalornaturalgroundwaterlevel,andingeneral,theporewaterpressureataparticular depth.Alignmentstakescanbeinstalledparalleltotheembankmentslopepriortotheplacementofthefill.
Thealignmentstakeisasimplemeansofmeasuringthelateraldisplacementofthefoundationduringconstructionoftheembankment.Infact,theycouldprovideanearlywarningofbearingcapacityfailure.Amoresophisticatedequipmenttomeasurelateraldisplacementisaninclinometer,whichisusuallyplacedsetaroundthetoeoftheembankment.

1.3 **The Present Study**

From the review of past works, it has been observed that very little experimental study has been carried out to evaluate the effect of in shear strength and permeability after installation of pre-fabricated vertical drain on soft clay. In order to investigate in improvement of shear strength and permeability properties with installation of PVD, an attempt has been made with the help of a laboratory model study. Soft clay was simulated by commercially available kaolin.

Settlement under the given surcharge was recorded and samples have been extracted for the purpose of measurement of permeability and undrained shear strength at the laboratory.

In this study an effort has been made to find outthe change in shear strength characteristics and coefficient of permeability, due to PVD installation by an experimental study.

CHAPTER 2

LITARATURE REVIEW

2.1General

An attempt has been made in this chapterto review past works of different authors in the relevant fieldThe work on the topic started long back in 1944 by Baron and advancement is being continued till date.It is to be noted that no work could however be come across for about two-three decades since 1948.The past works encountered while reviewing literature in this research area have been presented in a nutshell in chronological order in this chapter.

2.2 Review of Past Work

Barron (1944) gives the first comprehensive theoretical solution to the vertical drain assisted consolidation of soft soil, based on existing solutions for one dimensional vertical consolidation**[** Terzaghi (1925)] . His analysis was based on the following assumptions:

i)Darcy's flow law is valid.

ii) Soil is saturated and homogeneous.

iii) Consolidation displacement is in vertical direction.

iv) Excess pore water pressure at the drain well surface is zero.

v) Soil beyond cylindrical boundary is impervious.

vi) Excess pore water pressure at top boundary of the soil-mass is zero.

vii) No vertical flow at the center cross-section of the soil mass.

Barron assumed a single drain surrounded by single soil cylinder in his analysis. It wasconsidered that the installation process of vertical drain does not affect the soil properties adjacent to the drain, and permeability of the drain well was high enough for well resistance to be neglected.

Barron (1948)included the effect of disturbance coming out installation process in his solution for vertical drain assisted consolidation. He introduced a "zone of smear "with reduced permeability and presumed that arching will redistribute the load so that the vertical strain at a fixed depth become equal, irrespective of the radial distance. Thus no differential settlement will take place. Effect of well resistance on the consolidation process was taken into the consideration, i.e. the drain will have limited capacity to transport pore water entering into the drain.

Barron assumed two different cases to take place

(i) Free vertical strain i.e. surface displacements are non-uniform during consolidation.

(ii) Equal vertical strain i.e. vertical surface stress is non uniform.

In case of equal strain the differential equation of the consolidation process can be written as

$$\frac{\partial u}{\partial t} = C_h \left[\left(\frac{\partial^2 u}{\partial r^2} \right) + \frac{1}{r} \left(\frac{\partial u}{\partial r} \right) \right] \text{.................. (2.1)}$$

Where u is the average excess pore pressure at any point at any given time, r is the redial distance, t is time and C_h is coefficient of horizontal consolidation.

In case of radial drainage only the solution of Barron under ideal condition is

$$U_h = 1 - \exp\left[\frac{-8T_h}{F(n)} \right] \text{.................... (2.2)}$$

Where, $T_h = \frac{C_h t}{D_e}$

$$F(N) = \frac{\quad}{(\quad)} \; n(n) - - + - \text{ ....(2.3)}$$

Hansbo (1981)proposed an approximate solution for vertical drain based on equal strain hypothesis taking both smear and well resistance into account considering that rate of flow of internal pore water can be measured by applying Darcy's law. Hansbo modified the equation developed by Barron by simplifying assumptions of the physical dimensions characteristics of the prefabricated drain and the effect of installations. The modified expression of average degree of consolidation is given as

$$U_h = 1 - \exp\left[\frac{\quad}{(\ )} \right] \text{ . ... (2.4)}$$

And F= F(n)+F_s+F_r. .... (2.5)

Where F is the factor which express the additive effect due to the spacing of the drains f(n).F(s) factor for Smear Effect .F(r) factor for well resistance.

For the typical values of the spacing ratio, of 20 or more, the spacing factor becomes

$$F(n) = \ln\left[\frac{D_e}{D_w}\right] - \frac{3}{4} \text{..................(2.6)}$$

To account for the disturbance during the installation a zone of reduced permeability was assumed. The smear effect factor is given as:

$$F_s = \left[\left(\frac{K_h}{K_s}\right) - 1\right]\ln\left(\frac{d_s}{d_w}\right) \text{.............(2.7)}$$

Where d_s is the diameter of the disturbed Zone and k_h is the co-efficient of permeability in the horizontal direction in the disturbed zone.

Since the PVD s have limited discharge capacity Hansbo introduced a drain resistance factor F_r assuming that the Darcy's law can be applied for flow along the vertical axis of the drain.

Well Resistance factor is given as**:**

$$F_r = \frac{\pi z(L-z)K_h}{q_w} \quad \text{..................... (2.8)}$$

Where z, is the distance from the drainage end of the drain**,**

L is the drainage length when drainage occurs from at both ends,

K $_h$= is the coefficient of permeability in the horizontal directions

q_w is the discharge capacity of the drain at hydraulic gradient of 1.

Hansbo also showed that the process of consolidation for a circular drain and the band drain is almost the same, when the circular drain is assumed do have a circumference equal to that of the band drain **is**

$$d_w = \frac{2(a+b)}{\pi} \qquad \textbf{..................(2.9)}$$

The discharge capacity of the PVD is a function of its filter permeability, cross sectional area, lateral confining pressure & drain stiffness controlling its deformation.

Indraratna et al (1994) analyzed the performance of an embankment constructed on a soft foundation stabilized with vertical band drains, they opined that the effectiveness of the vertical drains could be evaluated by considering the excess pore water pressure, vertical and lateral displacement & the surface settlement profile in relation to the consolidation behavior of the soft clay.

The case study revealed thatfor efficient vertical drains, that the effect of the smear and well resistance is negligible. In the short term the rate of dissipation of pore pressure at the drain soil boundaries controls the drain efficiency, hence the consequent settlement. In the long term (mere than 400 days) the concept of perfect drain seems realistic. The assumption of zero excess pore pressure at the drain boundaries, over estimates the vertical settlements but underestimates the lateral yield. For perfect drains, the prediction of, initial or short term vertical settlement is conservative and lateral movements is under estimated. This is because the propagation of failure surface is mainly a function of the incremental lateral displacement within the upper soft clay.

To evaluate the stability of rapidly built embankment on soft clay, the excess-pore-pressure condition in the drain boundaries must be correctly incorporated in the finite element analysis. The study has shown that unless the un-dissipated excess-pore-pressure along the drain boundaries are correctly accounted for, the vertical settlements and lateral displacement cannot be predicted to an acceptable degree of accuracy. In this respect, additional modification in the pore pressure 'shape function' of the elements along the soil drain boundaries is desirable.

The accurate prediction of lateral displacement requires careful assessment of soil parameters corresponding to the actual stress path response in the field, during embankment loading. The installation and vertical drains curtails lateral displacement substantially, thereby reducing the risk of shear failure. The existence of rigid crust just beneath the embankment can also resist lateral displacement, facilitating construction of higher embankments.

The use of plain strain finite element analysis cannot be regarded superior to a more powerful three dimensional analysis of flow into vertical drains. The analysis is justified in terms of both computational effort and acceptable quality and prediction.

Indraratna and Redana (1997) presented amathematical model to transform the axisymmetric conditions of vertical drain to an equivalent 2D plain Strain finite element model. They included the effect of smear associated with mandrel driven vertical drain in the model. The width of the unit cell was taken as the spacing between the drains and the width of the smear zone and permeability of the smeared soil were converted theoretically into the plain strain parameters.

Figure 2.1 shows about conversion of axisymmetric unit cell into plane strain.

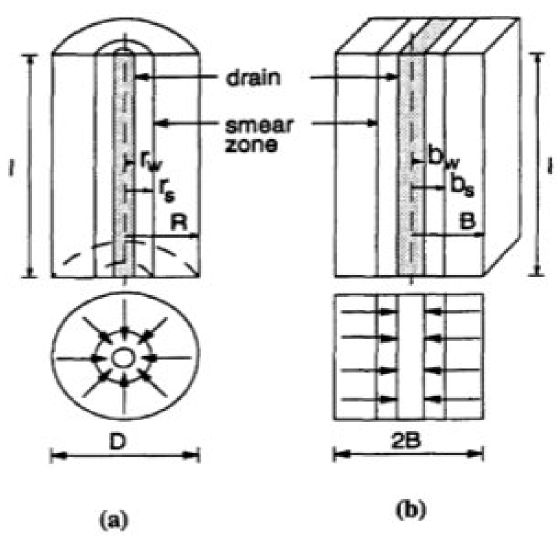


FIG. 2.1 Conversion of Axisymmetric Unit Cell into Plane Strain: (a) Axisymmetric Radial Flow; (b) Plane Strain

(**AfterIndraratna and Redana, 1997)**

Authors tested their model by analyzing an embankment built on soft clay, stabilized with vertical drains. They observed that the introduction of smear effect improves the accuracy of prediction of settlement, and post construction pore pressure dissipation was slower than the predicted.

Indraratna and Redana (1998) studiedalaboratorystudyto investigatethe effectof smear due to vertical drain installation. The extent of the smear zone around a vertical drain was studied utilizing a large scaleconsolidometer. The test results also reveal that a significant reduction in the horizontal permeability takes place toward the central drain, whereas the vertical permeability remains relatively unchanged. The radius of the smear zone was estimated to be a factor of four to five times the radius of the central drain (mandrel), and themeasured ratioof horizontal to vertical permeability approached unityat the drain-soil interface. The laboratory measured settlements are subsequently compared with the predictions basedonthe theory of Hansbo and the finite element method. It is of relevance to note that the inclusion of the correct variation of permeability ratios of the smear zone in the plane strain finite element analysis improves the accuracy of settlement predictions.

Sharma and Xiao (2000) using a large scale laboratory model examined the extent of smear zone. They conducted experiments simulating conditions with smear and no smear. Excess pore water pressure and moisture content was measured at seven different radial locations within the test set up. Several samples for recording moisture content, and void ratio were collected. They observed that the distribution of excess pore pressure due to drain installation gave a clear indication of the extent of smear zone. The effect of reconsolidation of the clay was found to be greater than that of remoulding of the clay.

The extent of smear zone was also confirmed from the change in the void ratio of the clay layer in the smear zone from the moisture content measurement.It was found that the radius of the smear zone is approximately four times the radius of the mandrel.

The alteration of in the properties of the clay layer due to mandrel insertion is caused by reconsolidation due to dissipation of pore pressure and remoulding due to shear applied by outer surface of the mandrel.

Figure 2.2 described excess pore pressures in clay layer during mandrel insertion.

They had proposed that the smear zone to be further divided in two zones –

i. A remolded zone of limited extent close to the drain and

ii. A reconsolidated zone of wider extent between remolded and intact clay.

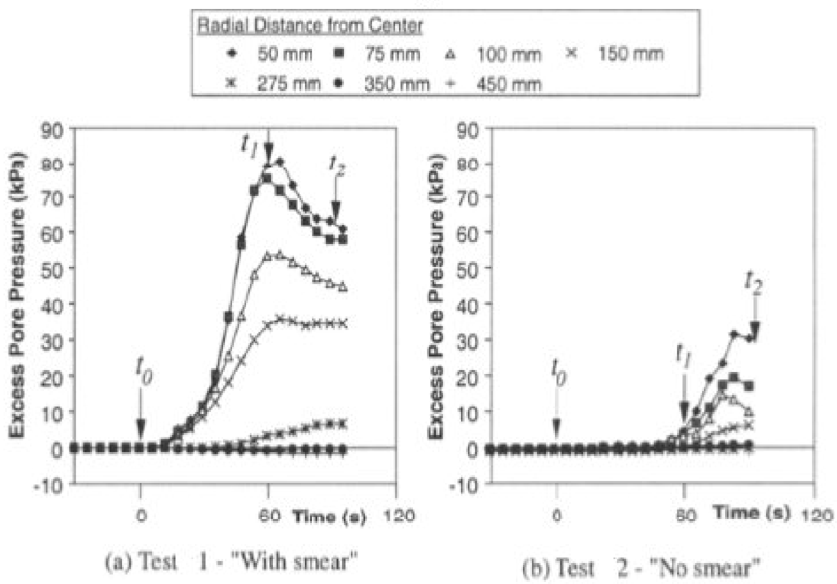


Figure 2.2Excess pore pressures in clay layer during mandrel insertion

(AfterSharma and Xiao ,2000)

Sathananthan and Indraratna (2006),the authors studied about the extent of the smear zone and the reduction of permeability and water content within the smear zone wereinvestigated using a large-scale consolidometer. The extent of the smear zone for Moruya clay New South Wales, Australia) was estimated on the basis of normalized permeability and the reduction of water content by taking undisturbed samples(horizontally and vertically) at different locations. This study reveals that a significant reduction in water content and horizontal permeability takes place towards the drain, whereas the variation in the vertical permeability is negligible. The smear zone for Moruya clay was found to be 2.5 times the equivalent radius of the mandrel with the horizontal permeability varying from 1.09 to 1.64,an average of 1.34 times smaller than that of the undisturbed zone. Finally, a correlation between the permeability decrease and water content reduction within smear zone wasproposed.

Indraratna et al (2007)observed that prefabricated vertical drains with vacuum preloading is an effective way to accelerate consolidation by promoting radial flow.

Key factor influencing the drain efficiency are, occurrence of smear Zone, effect of soil macro fabric, drain instauration and distribution of vacuum pressure. These factors were discussed with an idea of incorporating then in the modern design. An analytical model for soft clay (improved by vertical drain) taking compressibility indices and vacuum preloading into account has been considered. The variation of horizontal permeability co-efficient with the applied stress level and the parabolic loss of permeability in the smear Zone associated with drain installation were considered to represent a realistic field situation.

Cavity Expansion theory was introduced as a tool to predict the extent of smear zone based on the excess pore pressure to effective overburden pressure ratio., which was found to be in agreement with the laboratory data based on permeability and water content approaches.

They observed that Smear Zone is extended up to 3 to 4 times the diameter of mandrel.

The vacuum application increases the rate of pore pressure dissipation due to the increased hydraulic gradient of the drain.

Numerical Analysis confirmed that the occurrence of soil instauration at the drain soil boundary due to mandrel withdrawal and drain installation could retard the pore pressure dissipation .Use of appropriate suction -permeability relationship and revised FEM procedures are important in realistic prediction.

Numerical refinement were also required for using the improved procedures for accurate prediction of the heavily over consolidated surface crust that does not obey either the modified Cam Clay or the Mohr Coulomb theory.

Indraratna (2008) presented an analytical model for soft clay subjected to radial drainage, incorporating compressibility indices (C_c and C_r) and vacuum pressure.

Accurate Quantification of Lateral displacement and dissipation of pore pressure associated with the radial consolidation are difficult. These may be due to the uncertainties associated withthe evaluation of 1) correctSoil parametersaround PVDs, 2) Correct drain properties And 3)behavior of soil drain interface. Therefore it is essential to use proper laboratory technique to determine these parameters, a large scale testing apparatus can be a preferred tool, it was observed that smear zone is spread over 2 to 3 times the size of the mandrel and the soil permeability of the smear zone will be 1.5 to 2.0 times more than the undisturbed zone.

Accurate modelling of vacuum pre loading requires both laboratory and field studies to specify the nature of vacuum distribution within the drain system.

Rail tracks and highways built on soft saturated clays, stability of which is dependent on lateral movement. PVDs of shorter length canreduce the lateral strain and gain in the shear strength. It can be used under rail tracks to improve track stability by dissipating excess pore pressure and curtail lateral displacement within the critical shallow depth beneath tracks.

Chung et al (2009) proposed a method for estimating, coefficient of radial consolidation, and time of consolidation, that are suitable for 60-90 % degree of consolidation. The method was based on the hyperbolic relationship of settlement versus time and on Barron's solution. The method was applied to well document case studies and results were compared with that obtained in other methods. The observations made were as follows:-

In all cases the estimated co efficient of radial consolidation C_r. Obtained from proposed method are in the range of 1.18 to 2.88 times those obtained from Magnum et al (1983) method, which were, based on the Ashoka Graphical Method. The results of two of the cases were closer to C_v values obtained from in-situ tests. However, in another case where only field test result wereavailable, the estimated Cr values fall within the lower bound of tested values. Such deviations were possibly due to various factors, such as,smear and well resistance, vertical drain type and its finite drainage capacity.

The estimated C_r value was therefore considered to be an approximate value that reflects the actual Ground conditions.

The final settlement estimated from the hyperbolic method were 1.04 to 1.13 times those obtained from the graphical method of Ashoka (1978) which was not consistent with the trend observed in the comparative results of C_r. Values.

The results indicate that the monitored settlement versus time plot for the various cases were governed by the hyperbolic relationship as well as curves obtained from the Barron solution show a different trend from the measured curves.

Rujikiathkamjom and Indraratna (2009)a study was presented by the authors on procedures of design of vertical drain. In this they have extended the earlier methods to include-

a. Linear reduction of lateral permeability in the smear Zone.
b. The effect of overlapping smear zones in a closely spaced drain network.
c. The gain in untrained shear strength due to consolidation.

Basu et al (2009)studied the 2D finite Element analysis of the effect of soil disturbance caused by the installation of a vertical drain on the rate of consolidation. A rectangular pattern of PVD installation was considered. Smear zone a zone of maximum disturbance was assumed to exists on the immediate vicinity of the surrounding the PVD. A transition zone, surrounding the Smear zone, where the effects of disturbance reduce gradually -as the distance from the PVD increases was also considered. The Hydraulic Conductivity in the transition zone is assumed to increase linearly from a low value in the smear zone to the original in situ value in the undisturbed zone.

The extent of the soil disturbance, due to, size of the smear zone, size of transition zone, spacing of the PVD, shape and size of mandrel was investigated. Result of this analysis was compared with that of an experimental study. It was observed that both the results compare reasonably well.

Authors opined that, transition zone has a definite role in slowing the rate of consolidation. neglecting its, effect can lead to faulty estimation of consolidation and settlement.

Error in estimating the degree of consolidation caused by converting the rectangular unit cell to equivalent circles will be less than 5%.Taking into account the disturbance due to installation reduces the error.

The factors relating to drain installation that affects the consolidation most are soil disturbance, extent of the disturbed zone, shape and size of the mandrel.

For a particular degree of consolidation the time factor is related to the ratio of conductivity of the Smear and undisturbed zone.

The transition Zone can be replaced by a equivalent smear zone with increased dimensions. The extent of extra length of the smear zone depends on the degree of disturbance caused by the installation.

Xiao et al (2011)using a large scale model presented a study on the effect of smear on the behavior of radial consolidation with vertical drains. Two tests simulating `smear ’and‘nosmear ‘conducted in a unit cell with extensive instrumentation.

The detrimental effect of smear on the rate of radial consolidation was experimentally demonstrated by the measurements of settlements Vs. time & isochrones of excess pore pressure. The delay in U_h was approximate 10% for the insensitive kaolin clays used, for field with structured and sensitive clays- smear effect is anticipated to be more pronounced.

Gratchev et al (2012)analyzed and discussedthe results from laboratory tests performed by means of Rowe cell apparatus and field data from large- scale experiment at Sunshine Coast Motorway, Queens Land, Australia.

Based on these data authors concluded that, Rowe Cell tests indicates that the rate of settlement may increase when the diameter of the vertical drain increase from 8.3 to 16.5mm. It was found that the smear effect can decrease the rate of Settlement for the both drains used The results from the Rowe cell tests with the data from the Large Scale trial on the basis of N-Values were compared although some similarities were observed, it is not clear whether Laboratory test can predict the performance of vertical drains in the field.Further studies are needed.

Indraratna and Rujikiatkamjom (2012)inthis paper,the authors saidabout vertical drains, vacuum consolidation & preloading. They (2012) analyzed case histories from Australia using schemes that combined PVD and vacuum preloading. He also showed that for these normally consolidated soft clays, the modified Cam-clay parameters are sufficient to predict the settlement, pore pressures and lateral displacements with acceptable accuracy.

They proposed a radial consolidation model using a sophisticated technique to investigate the smear effect in layered soil. The effects of permeability of the penetrating upper layer of soil on the underlying layer are discussed in terms of the degree of consolidation. The intrusion of the upper layer into the underlying layer creates an additional zone where the remoulded permeability of this zone can be increased or decreased depending on the initial permeability of the upper layer. In the intrusion zone located in the lower layer, the change in permeability can be divided into 3 distinct zones, including

(a) A smear zone due to the upper layer of soil being dragged down

(b) A smear zone due to the underlying soil being remoulded, and

(c) An undisturbed lower layer of soil (Fig 2.3).

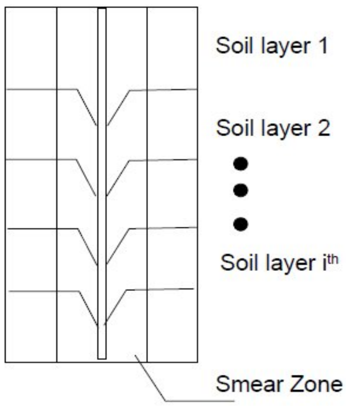


Figure: 2.3down drag effects due to mandrel installation in layered soil

Rajesh et al (2014)in their article described a detail report about the plain strain FiniteElement modelling of an embankment pre-load resting on a soft soil site treated with PVD.

The preloading has been modelled as a stage construction sequence. The pressure of the drains has been modelled by considering the change of permeability of the soil surrounding the drain. The efficiency of the PVD has been illustrated with the aid of comparative Settlement at the center of the embankment in the presence and absence of PVDs.

Application of PVDs helped in the reduction of the excess pore pressure generated at the end of the loading by a significant amount, and resulted in the accelerated dissipation of the accumulated pore pressure. The effect of smear was studied with the aid of varying horizontal to vertical permeability ratio of the soil, which revealed that the in-situ measurement most possibly corresponded to a k_h/k_s magnitude in the range of 3 to 4.

Figure 2.4 shows effect of application of PVD on the excess pore pressure of embankment on soft soil.

Figure 2.5 shows effect of smear zone on time dependent settlement of embankment on soft soil.

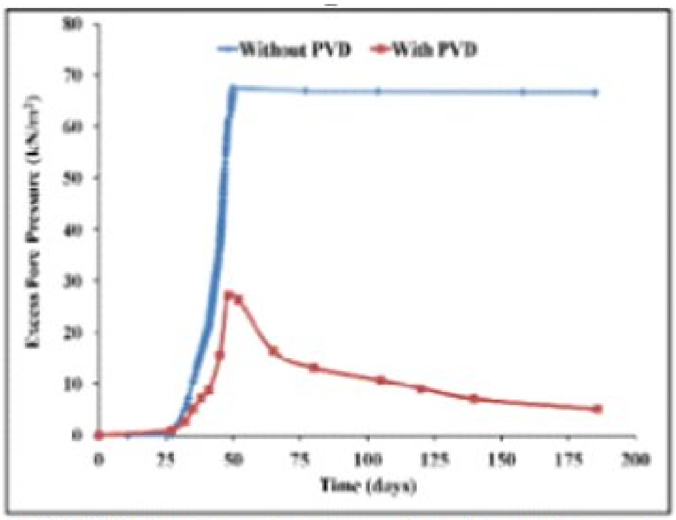


Fig.2.4 Effect of application of PVD on the excess pore-pressure of embankment on soft soil

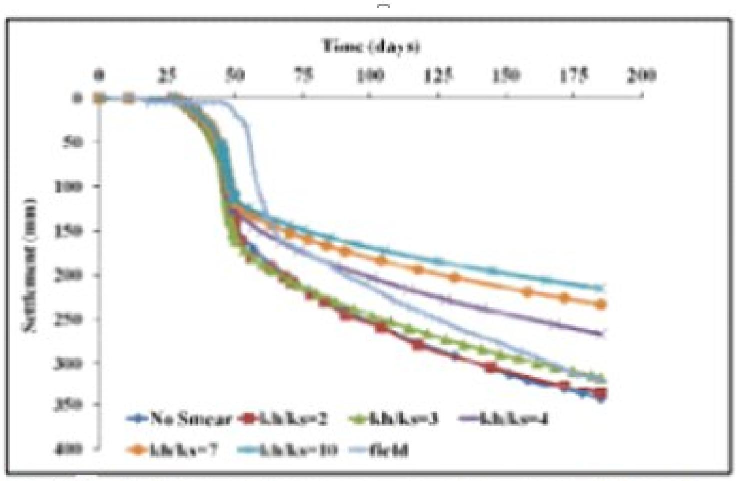


Fig.2.5 Effect of smear on the time-dependent settlement of embankment on soft soil

(After Rajesh et al ,2014)

2.3Outcome of the Literature review:

Based on the literature review, it is observed that the following aspects have-not been well addressed in the literature

1. Number of studies on the smear effect has been made .The results of these studies vary widely .Reason for these variation has not been explained.

2. The coefficient of permeability obtained from standard laboratory tests does not reflect the actual field permeability .Back analysis of field data does not corroborate with and laboratory data.

3. It has been observed that installation of PVD enhances the undrained shear strength of the soil, but quantification of this undrained shear strength has not been studied in detail.

2.4 Need of The Present Study

It has been observed that very little work has been carried out to evaluate the effect of in shear strength and permeability after installation of pre-fabricated vertical drain in soft clay. In this study an effort has been made to find out the change in shear strength characteristicsand coefficient of permeability due to PVD installation.

Chapter 3

OBJECTIVE AND SCOPE OF WORK

3.1 General

In this the objective and scope of work of the current study has been presented.

3.2Objective

To evaluate performance of vertical drain on soft clay to find out the shear strength characteristics and coefficient of permeability, before and after PVD installation.

3.3Scope Of Work

To fulfill the above objective the following scope of work has been considered and outlined below in respect of the present study.

The change in shear strength and permeability has been studied in the laboratory by fabricating a test set up with a small test tank of diameter 37 cm and depth 50 cm. Before theinstallationof PVD, the soil slurry made with kaolin has been consolidated in the tankby surchargeweights for a period of 24 hours. The shear strength and permeability were then found out under different values of surcharge load with and without PVD.

To study the changes in these two soil parameters, after consolidation with PVD, the same surcharge was placed on the soil for equalperiod of time and the soil was allowed to consolidate for a period of 24 hours. The properties were determined after the soil had undergone the process of consolidation. The changes in the properties have been studied for different surcharge loads.

Chapter 4

MATERIALS AND PREFABRICATED VERTICAL DRAINPROPERTIES

4.1General

In this chapter an attempt has been made to describe the materials that has been used to replicatethe soil condition and different components of PVD.

4.2   Soil(kaolin)

The soil used in the present experimental study islocally available kaolin. The main advantages in using kaolin is its commercial availability and existing database of its engineering properties.

4.2.1Properties of Kaolin

Routine laboratory tests on Kaolin soil samples yielded the following properties:

Liquid limit,(W_l)= 58%

Plastic limit, (W_p) = 33%

Optimum moisture content = 20%

Maximum dry density, (γ_d) = 16.24 kN/m^3

Average. Moisture content of compacted soil during testing = 38%

Unit weight of compacted soil during testing = 18.0 kN/m^3

Undrained cohesion, C = 15.0 kN/m^2

Angle of internal friction, $\phi = 7^0$

Grain size: Sand = 0%

Silt = 58%

Clay = 42%

4.3 Components of PVD

There are two components of prefabricated vertical drain a) core and b) filter jacket. By combining the features of both core and filter jacket, pre-fabricated PVC drain system provides effective, fast and reliable performance for soil improvement. Figure 4.1 shows different components of prefabricated vertical drain.

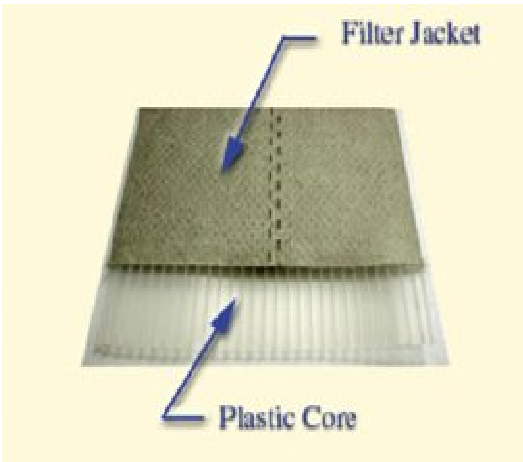


Fig: 4.1 Components of Prefabricated vertical drain

4.3.1 Core

It is also called drain body which is a unique, corrugated, and flexible and made of polypropylene specifically designed to provide high discharge capacity, high tensile strength.

4.3.2 **Filter jacket**

It is strong and durable non-woven, polypropylene fabric wrapped around the core. The fabric is of random texture having high tensile strength, high permeability and effective filtering properties. It acts as a filter to allow passage of ground water into the drain core while eliminating movement of soil particles and preventing piping. It also serves as an outer skin to maintain the cross sectional shape and hydraulic capacity of the core channels.

Figure 4.2 shows the schematic diagram of prefabricated vertical drain.

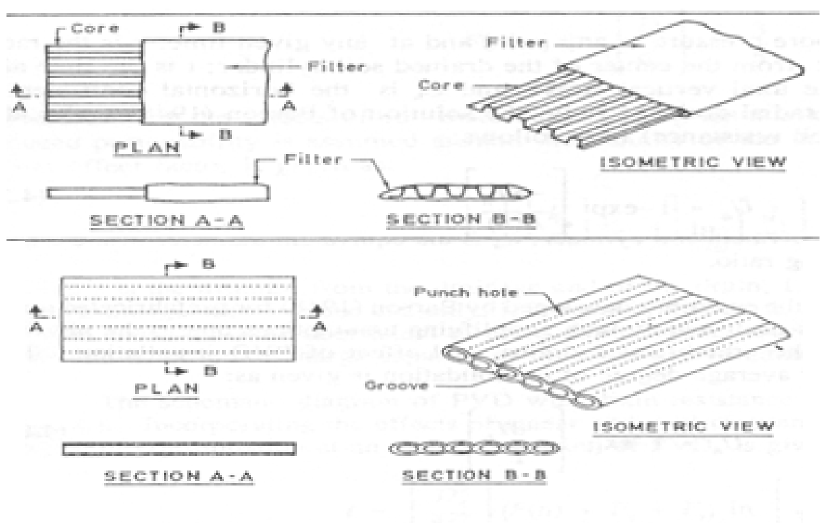


Fig 4.2 Schematic diagram of prefabricated vertical drain

4.3.2.1**Opening Size of Filter Jacket**

Thedrainmaterial(sanddrain)andthefilterjacketofPVDhavetoperformtwobasicbutcontrastingrequirements,whichareretainingthesoilparticlesandatthesametimeallowingtheporewatertopassthrough.Thegeneralguidelineofthedrainpermeabilityisgivenby:

$k_{filter} > k_{2soil}$

4.4 Equivalent drain diameter for band shaped drain

Theconventionaltheoryofconsolidationwithverticaldrainsassumesthattheverticaldrainsarecircularincross-section.Therefore,aband-shapeddrainneedstobeconvertedtoanequivalentcirculardiameter.Hansbo(1981)introducedtheequivalentdiameterforaprefabricatedband-shaped drain, as given in equation

$$d_w = 2\frac{(a+b)}{\pi} \quad \text{Or} \quad r_w = \frac{(a+b)}{\pi} \qquad \text{…………………..} \qquad (4.1)$$

Where,a=thewidthofthePVD

And

b=thethicknessofthePVD

In our study,

a= width of PVD 100 mm   and b= thickness of PVD 4 mm

$$d_w = 2\frac{(100+4)}{\pi} = 66.2 \text{ mm}$$

4.5Properties of Pre-Fabricated Vertical Drain

(As per data supplied by Z-Tech India Private Limited)

Type	CX100
Polymer	PE/PP

4.5.1 Hydraulic Propertiesof PVD

Table 4.1 describes about hydraulic properties of Prefabricated Vertical Drain.

Table-4.1 Hydraulic Properties of PVD

Flow Capacity(350Kpa)	140×10^{-6} m^3/s
Flow Capacity(200Kpa)	45×10^{-6} m^3/s

4.5.2 Mechanical PropertiesOf PVD

Table 4.2 describes about mechanical properties of Prefabricated Vertical Drain.

Table-4.2 Mechanical Properties of PVD

Tensile Strength	2.5 KN
Elongation at 1.0KN	3%
Strength at 10%elongation	1.5%
Grab Strength	2000N
Trapezoidal Fear Strength	680N
Puncture Strength	600N

4.6 Factors Influencing the Vertical Drain Efficiency

4.6.1 Smear zone

Theinstallationofverticaldrainsbymeansofamandrelcausessignificantremouldingofthesubsoile speciallyintheimmediatevicinityofthemandrel.Thus,azoneofsmearw i t h reducedpermeability andincreasedcompressibility develops around the mandrel.Barron(1948) thedrivingandpullingofthecasing (mandrel)would distortandremouldtheadjacentsoil.Barron(1948)suggestedtheconceptofreducedpermeability,w hichisequivalenttoloweringtheoverallvalueofthecoefficientofconsolidation.Hansbo(1979)alsoi ntroducedazoneofsmearinthevicinityofthedrainwithareducedvalueofpermeability.

Jamiolkowskietal. (1981)proposedthat thediameterofthesmearzone (d_s)andthe crosssectionalareaofmandrelcanberelatedasfollows

$$d_s = \frac{(5 to 6) d_m}{2} \qquad \text{…………………(4.2)}$$

Where$d_m$isthediameterofthecirclewithanareaisequaltothecrosssectionalareaofthemandrel. BasedontheresultsofHoltzandHolm(1973)andAkagi(1979)Hansbo(1987)proposedanotherrel ationshipasfollows

$$d_s = 2d_m \qquad \text{…………………(4.3)}$$

Indraratna&Redana(1998)proposedthattheestimatedsmearzoneisabout3-4timesthecross-sectionalarea ofthemandrel.The degree of disturbance in the soil increaseswiththe size (crosssectionalarea) of the mandrel and roughness of the material used.

Chapter 5

EXPERIMENTAL STUDY

5.1 <u>General</u>

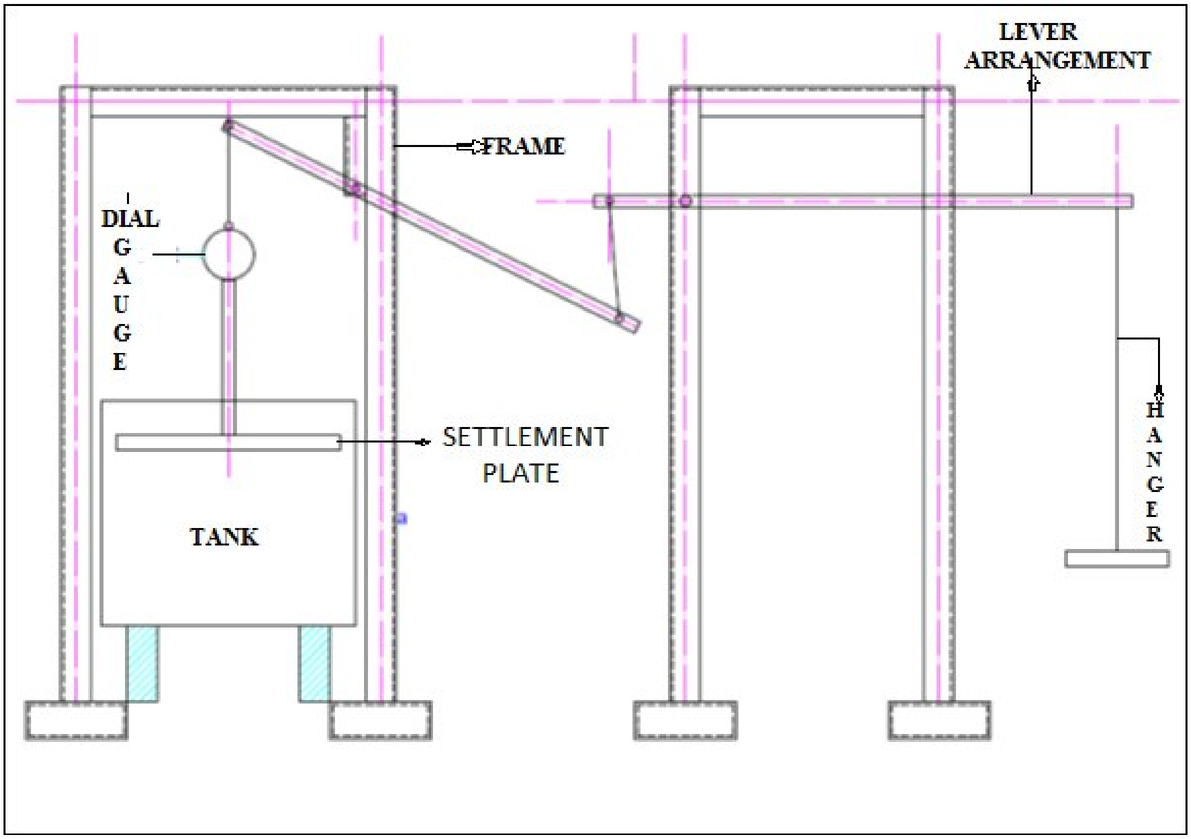
In order to study the change in properties of soft clay before and after installation of PVDan experimental set up was fabricated in the laboratory. An attempt has been made in this chapter to present the description of equipment and test set up with its different components and test procedure.

5.2 <u>Test Set up, Test Program andTest Procedure</u>

A laboratory test apparatus for the investigation of consolidation of clay around vertical drains has been fabricated at the Soil Mechanics laboratory of Jadavpur University. The apparatus consists offour main components:

- a consolidation tank
- lever mechanism
- mandrel
- Instrumentation.

Due to its large size, it is possible to conduct realistic unit cell experiments that simulate the field situation of clay consolidation around vertical drains with minimum boundary effects. The test set up is shown in fig 5.1.



<u>Fig 5.1 Schematic Diagram of Test Set Up</u>

Fig 5.2 Photograph of Test Set Up

5.2.1Consolidation Tank

The cylindrical consolidation tank is made of gun metal with 12 mm thick PVC(polyvinyl chloride)lining and has a37 cm internal overalldiameter.The composite wall thickness of the tank is 18 mm and height is 50 cm. The inside surface of the tank hasPVC(Polyvinyl chloride) coating of 12 mm to minimize friction between the soil sample and consolidation tank. The consolidation tank was made water leak proof.Small circular holes were madeat different depths of the tank. The piezometric pipes have been inserted into the tank through these holes to measure pore pressure of water .To prevent kaolin from seeping out through the circular holes and clog these pipes, small pieces of cloth have been fixed around these openings as a filter.

Fig 5.3: Photograph of Consolidation Tank

5.2.2 Loading Frame

A loading frame was designed& fabricated and a lever arrangement was made to apply the required load on the soil sample.

The loading frame consists of 2 platform made with M.S.Steel.A lever arm arrangement has been made in the loading frame. Load amplification factor of the lever system was 12.

5.2.3 Mandrel

The prefabricated vertical drainhas been inserted into the sample with help of amandrel. The mandrel is a rectangular boxsection, made of 3 mm thick mild steel plate. Overall dimension of this mandrel is 110 $\times$25mm. and when inserted into the testing sample, it can beeasily withdrawn with minimum disturbance and the pre-fabricated vertical drain can be placed into the sample.

The common installation procedureis by closed-end mandrel. Thus, the amount of soil disturbance caused byinstallation is depends on the size and shape of the mandrel, as well as by thedimensions and shape of the detachable shoe or anchor located at the mandrel tip.

The shoe may be a small piece of sheet metal bentinto a V shape, orsometimes a small piece of drain. While the mandrel is still up about 300-400 mm above the ground surface, some drain is pulled out of it, wrapped round a short tube and either stapled or tucked-up into the mandrel.

Fig 5.4: Installation Of Pre-fabricated Vertical Drain

5.3 Test Program

The test program is presented in Table 5.1

Table-5.1: Test Program

SL NO	Surcharge Load	Without/ With PVD	Settlement (cm)	Vane shear (KN/m^2)	Co efficient Of permeability (mm/sec)
T- 1 A	520 kg	Without PVD	Yes	Yes	Yes
T- 1 B	650Kg		Yes	Yes	Yes
T- 2 A	520kg	With PVD	Yes	Yes	Yes
T- 2B	650kg		Yes	Yes	Yes

5.4Test Procedure

A typical test in the present study was carried out in three stages as follows.

1. Preparation of sample

2. Installation of PVD

3. Collection of samples for permeability test, vane shear test.

5.4.1Preparationof Sample

Initially the kaolin was mixed with water by a soil mixer, which wasdeveloped in Jadavpur University Geotechnical laboratory. The amount of water was approximately two times the liquid limit of kaolin. The mixed kaolin was poured into bucket for 24 hours, to remove air bubbles trapped inside the slurry.

After 24 hours, the mixed kaolin was slowly poured in the consolidation tank in layers. The kaolin poured into tank, wasstirred again, to remove the air bubbles. Alayerof geo-jute was placedon the top surface of the slurry and a perforated perspex coverwas also placed on the top of thegeo-jute. Load was applied with the help of leaver arrangement to remove any excess water from top of the kaolin mix.

An initial pressure of80kg i.e.0.78KN was applied for 24 hours to prepare the sample for the test. Some amount water was seen to come out from the surface of perspex sheet and the piezometric pipes.

5.4.2 Testing of Soil Bed

5.4.2.1Test 1A And1B (Tests without PVD)

After 24 hours, a consolidation pressure of 180 kg i.e. 1.765 KN was appliedby the loading frame. The settlements of the sample were recorded. After 15 min a consolidation pressureof 130 kg i.e.1.274 KN was applied and the settlement was measured. This was done for 2 more times. So the test was carried out under surcharge load of ($180+130\times3+80=650$ kg) i.e. 6.37 KN and settlement was recorded for 1 hour after the entire load was placed on the sample.

After 24 hours,the water was seen coming outthe sample and the same wascarefully removed. The total settlement was recorded. The loads were removed and samples were collected for permeability and vane shear test.

Similar test was repeated for a surcharge load of 520 kg i.e. 5.1 KN.

5.4.2.2 Test 2A And2B (Tests with PVD)

Initial load of 80 kg wasapplied for preparation of soil sample.The PVD was carefully installed into the samples with the help of mandrel. After placing the PVD into the desired depth, the mandrel was carefullywithdrawn from the sample.

After 24 hours, a consolidation pressure of 180 kg i.e. 1.765 KN was applied through the loading frame. The settlements of the sample were recorded. After 15 min a consolidation pressure of 130 kg i.e.and 1.274 KN the settlement was measured. This was repeated 2 times. The test was performed under the total load of $180+130\times3+80=650$ kg i.e. 6.37 KN and settlement was recorded for 1 hour after the entire load was placed on the sample.

After 24 hours, the lager quantity of water was seen coming out from the sample. The water was carefully removed. The total settlement was recorded. The loads were removed and samples were collected for permeability and vane shear test.

Kaolinwas again mixed with water with the help of soilmixer.The processwith PVD wasrepeated and surcharge load on the sample was changed to 520 kg i.e. 5.10 KN.

5.5 Presentation of Test Results

The study consists of six set of tests out of which three are without PVD and other three are with PVD.

The test results have been presented in Table 5.2.

Table 5.2: Presentation of Test Results

SL NO	Surcharge Load	Without/ WithPVD	Settlement (mm)	Vane shear (KN/m^2)	Co efficient Of permeability $\times 10^{-6}$(mm/sec)
T- 1 A	520 kg	Without PVD	11.9	16.2	11.53
T- 1 B	650Kg		24.9	19.8	8.12
T- 2 A	520kg	With PVD	14.81	20.4	6.44
T- 2B	650kg		31.59	23.7	3.76

Chapter 6

DISCUSSION ON TEST RESULTS

6.1 General

In this chapter an attempt has been made to interpret the results obtained from laboratory tests. As mentioned earlier the change in shear strength and permeability characteristics have been obtained by carrying out appropriate tests before and after PVD installation. Further to understand the status of consolidation and change of rate of consolidation time, the plot of Time vs.Settlement has been studied for both the cases, i.e., before and after PVD installation.

6.2 Time VS Settlement

Time-settlement graph with and without PVD has been plotted and has been shown in figure 6.1.

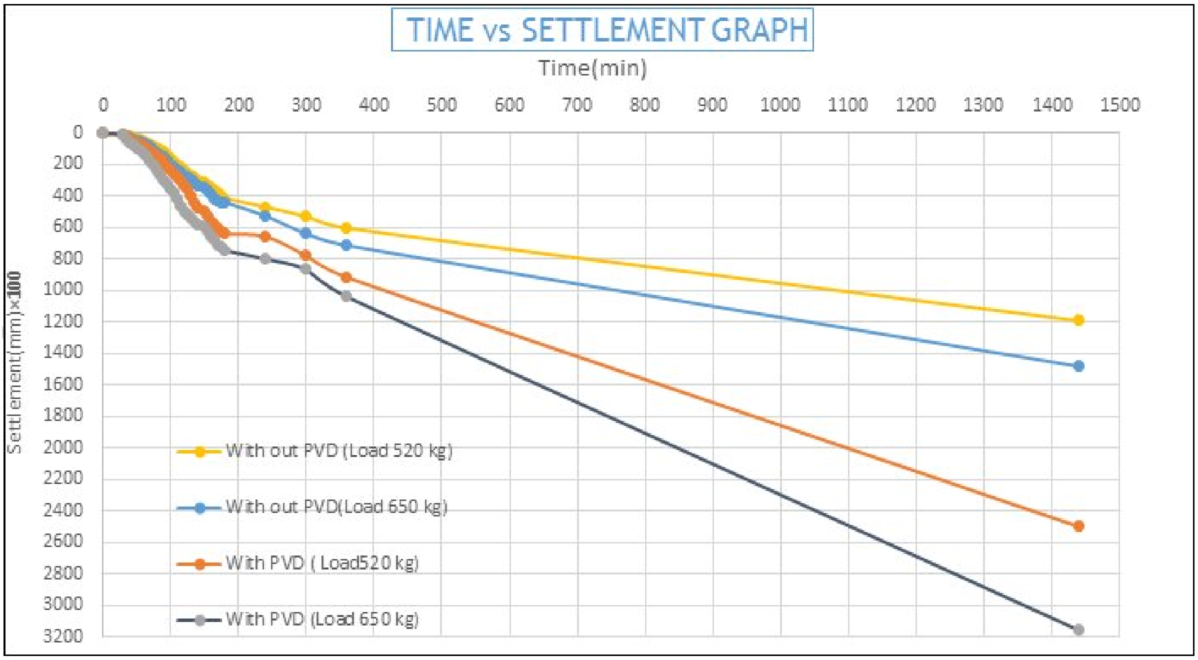


Fig: 6.1 Time vs. Settlement graph

The time-settlement graphs clearly indicate that the primary consolidation is not complete under the loads applied and within the time duration allowed for the consolidation. However, the effect of changes in shear strength and permeability characteristics can be obtained to some extent to understand the effect of PVD installation.

From the graph it is seen that in every case the settlement is increasing with respect to time.

The settlement increases with the increase in super imposed load. It is further noticed that the settlement is accelerated with the introduction of PVD. The settlement increases by 24% and 26% for loads of 5.1KN and 6.37 KN respectively with the installation of PVD.

From the above result it can be seen the settlement increases with the induction of PVD. The reason being the introduction of PVD accelerates the consolidation process with radial drainage. The above observation is corroborated by the fact that there was substantial accumulation of water on the top of settlement plate.

6.3Shear Strength VS Surcharge load

Change in undrained shear strength with and without PVD under same super imposed load has been shown fig 6.2.

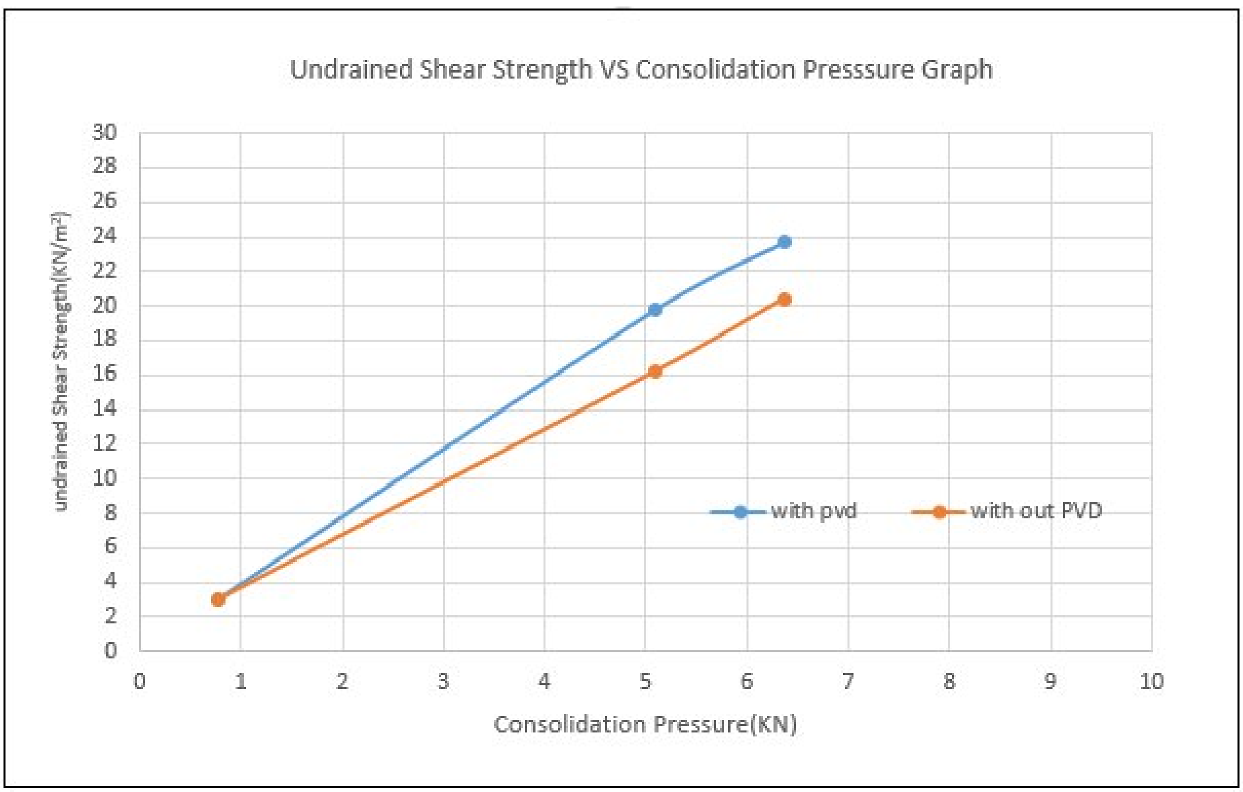


Fig 6.2: Changes of Undrained Shear Strength vs. Consolidation Pressure

The figure indicates that the variation ofundrained shear strength (C_u)withconsolidation pressure (q) in both the cases, prior to and after PVD installation. It is observed that cu varies almost linearly with q, as it should be for the normally consolidated soil.

From the figure it can be observed again that without PVD underthe loadof .78KNto 5.1 KN and 5.1 KN to 6.37 KN, undrained shear strength has increased from 3.02 KN/m^2 to 16.2 KN/m^2 and to further20.04KN/m^2respectively.

With the installation of PVD for the same load condition the undrained shear strength has increased to 19.8KN/m^2 to 23.7 KN/m^2 respectively.

An additional gain in shear strength of about 22 % more for a surcharge of 5.1 KN.

Similarly for surcharge of 6.37 KN an additional gain in shear strength of 16% has been achieved with the introduction of PVD.

Due to the fact that soil has gained strength at an accelerated rate with the installation of PVD, which has accelerated the consolidation with radial drainage.

6.4 Change in Coefficient Of Permeability

Values of coefficient of permeability(K) have been plotted with surcharge load for both thecases, with and without PVD installation in fig.6.3.

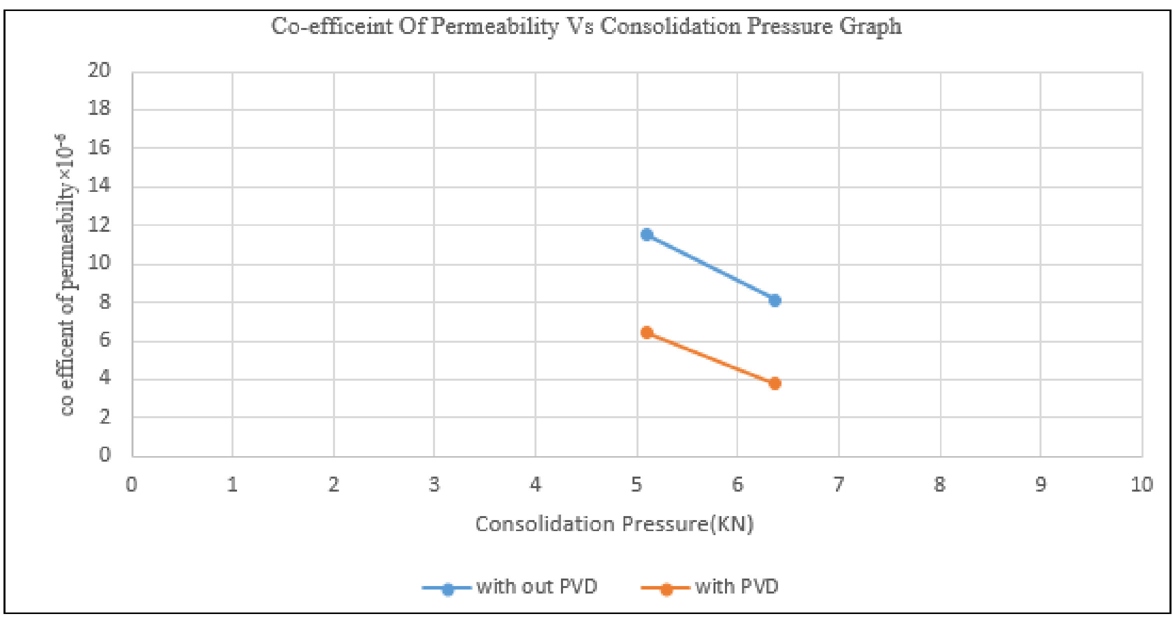


Fig 6.3: Changes of co efficient of permeability vs. Consolidation pressure

It is observed that permeability reduces with surcharge load for both the case, although the values are higher in case of without PVD installation. This is due to the fact that PVD installation accelerates the consolidation process resulting in decrease of void ratio. It is further noticed that even without PVD installation or with the same, coefficient of permeability decreases with higher surcharge load indicating that the consolidation has proceeded further with same surcharge load under similar condition of drainage.

With the introduction of PVD under the surcharge load of 5.1 KN the co efficient of permeability has been observed to be reduced from 11.5×10^{-6} mm/sec to 6.44×10^{-6} mm/sec, that is 44 % less.Similarly, for a surcharge load of 6.31 KN, the co-efficient of permeability reduces from 8.12×10^{-6} mm/sec to 3.76×10^{-6} mm/sec, that is 53% less.

Chapter 7

Summary, Conclusion and Scope of Further Study

7.1 Summary

In order to investigate the improvement of the soft clayey soil in respect of shear strength and permeability properties with installation of PVD, an attempt has been made to carry out a laboratory model study. Soft clay was simulated by commercially available kaolin.

A loading mechanism has been fabricated to apply surcharge load on the soil and a tank has been modified for the purpose of carrying out tests.

Settlement under the given surcharge was recorded and samples have been extracted for the purpose of measurement of permeability and undrained shear strength at the laboratory. Time settlement data have been obtained and values of undrained shear strength and permeability have been measured for both the cases of consolidation with and without PVD.

7.2 Conclusions

Based on the results of laboratory tests of the present study, the following conclusions may be drawn .

1. Settlement increases with the increase in consolidation pressure. Installation of PVD increases the settlement by 24 % and 26 % for surcharge loads of 5.1 KN and 6.37 KN respectively.

2. The shear strength increases when surcharge load is increased. Installation of PVD accelerates the process, with surcharge load of 5.1 KN the gain in undrained shear strength is 22% and with surcharge load of 6.37 KN the gain in undrained shear strength is 16%

3. Co efficient of permeability decreases when surcharge load is increased. The change in co efficient of permeability is 44% and 53 % for surcharge of 5.1 KN and 6.37KN respectively after installation of PVD.

7.3 Scope of Further Study

Future research may be directed in the following directions:

a) The smear effect for PVD installation may be studied with determination of ratio of horizontal to vertical permeability.

b) Field study may be carried out with laboratory model study to develop design charts.

c) Numerical modelling may be done to analyze the effect of PVD installation in respect of improvement of soft ground by adopting appropriate technique.

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