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Improvement of Soft Clay by Accelerating Consolidation Using PVD and Vacuum

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***Abstract*—Present investigation is undertaken to study the consolidation of soft saturated Kaolinite clay using PVD (Non-woven geotextile) inserted in a cylindrical sample under hydraulic pressure and also by applying vacuum through the drainage valve using a vacuum pump. An attempt is made to study various consolidation parameters by measuring settlement readings and quantity of water squeezed/expelled with passage of time. At the end of the consolidation through radial drainage, shear strength of Kaolinite clay was found by performing Vane Shear Test. The test was performed in a hydraulically Pressurized Rowe Oedometer 254 mm diameter.**

***Keywords*—Rowe Oedometer, Kaolinite clay, PVD, Vacuum, Settlement, Water Squeezed/Expelled, and Shear strength.**

I. INTRODUCTION

Ground improvement techniques are used to increase the bearing capacity of the soil and reduce its settlement to a considerable extent. Amongst various ground improvement techniques like vibroflotation, compaction with explosive, electro-osmosis, heavy tamping, stone column etc, the technique of preloading or pre-compression used in combination with vertical drains is one of the oldest and most widely used techniques to preconsolidate and strengthen weak compressible cohesive soils in situ. It is used to accomplish two major goals – to eliminate settlements by increasing the effective stress in the compressible stratum prior to construction of the facility and to improve the shear strength of the subsoil by decreasing its void ratio and water content. It is particularly suitable for soils that undergo large volume decreases and strength increases through consolidation; and in instances where there is sufficient time available for the compressions required to occur. The technique has been used successfully to improve foundation soils for buildings, embankments, highways, runways, tanks, and abutments.

Present investigation is undertaken to study the consolidation of soft saturated Kaolinite clay using PVD. The consolidation process under radial drainage through PVD were studied under application of hydraulic pressure and application of vacuum. An attempt is made to study various consolidation parameters by measuring settlement readings and quantity of water squeezed/expelled with passage of time. The test was performed in a hydraulically Pressurized Rowe Oedometer 254 mm diameter. The present investigation gives:

a) Comparison of settlement of all the three tests.
b) Comparison of quantity of water squeezed/expelled of all the three tests.
c) Comparison of average shear strength of Kaolinite clay of all the three tests.

II. TESTING PROGRAM

Total three tests were performed namely- (PVD + Hydraulic pressure loading), (PVD + Vacuum(10 minutes interval i.e. pump runs for 10 minutes and 20 minutes of stoppage of pump for cooling purpose)) and (PVD + Vacuum(20 minutes interval i.e. pump runs for 20 minutes and 40 minutes of stoppage of pump for cooling purpose)).

III. TESTING MATERIAL

- **Soil**-The soil sample is made of soft Kaolinite clay commercially available from the city of Vadodara. It was available in the powdered form having little impurities. The properties of soft Kaolinite clayey soil are shown in **Table-1**.
- **Geotextile**-The PVD used in the present investigation is nothing but the non-woven geotextile which has the following properties as shown in **Table-2**.

TABLE 1-
Properties of soil

1.	Type of clay	Kaolinite
2.	Specific gravity	2.64
3.	Liquid limit	46.12 %
4.	Plastic limit	27.35 %
5.	Plasticity index	18.77 %
6.	Soil classification (as per IS)	CI
7.	MDD	1.39 g/cm^3
8.	OMC	29 %
9.	Free swell index	10 %

TABLE 2-
Properties of non-woven geotextile

SR. NO.	PROPERTY	VALUE/DESCRIPTION
1	Nominal mass	350 g/m^2
2	Thickness at 2 kPa	2.2 mm
3	Physical characteristics	Staple fiber needle punched non-woven geotextile
4	Polymer	100 % polypropylene, UV stabilized
5	UV resistance	> 70 % of strength retention
6	Chemical and biological resistance	High resistance to chemicals in pH range of 2-13 and resistance to biological organisms normally found in the soil
7	Tensile strength	20 kN/m
8	CBR puncture resistance	3600 N
9	Grab strength	1250 N
10	Rod puncture resistance	750 N
11	Trapezoidal tear	475 N
12	Permeability	0.20 cm/s
13	Permittivity	0.9 s^{-1}
14	Colour	white

IV. TEST SETUP

All the three tests were carried out using 254mm diameter and 11cm high oedometer described by Rowe and Barden (1966) and further modified for pore pressure measurement by providing three radial points at 120º each as shown in figure-1. Hydraulic pressure to the sample is given by self compensating mercury control system. Vacuum was applied to the sample through the 0.56 HP light duty vacuum pump connected to top drainage valve through conical flask as shown in figure-2. The vacuum pump had a capacity to create maximum vacuum of 720 mmHg (96 kPa). Throughout the test, 630 mmHg of vacuum was created and maintained i.e. around 85.68 kPa.

Figure-1 Photograph of Rowe Oedometer

Figure-2 Arrangement Showing Vacuum Pump Connection with Rowe Type Oedometer through Conical Flask

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V. METHOD OF SAMPLE PREPARATION

The Kaolinite soil in powder form was mixed with tap water having quantity double the liquid limit to ensure full saturation. The slurry was transferred into the Oedometer after it had been lightly coated with a thin layer of silicon grease to minimize side friction. The sample was then preconsolidated under a gradually applied static load of 10 kPa so that the normal consolidation could be achieved.

VI. INSTALLATION OF PVD

The axial hole was formed with a thin walled rectangular mandrel inserted into the sample after trimming the surface. The width of the band drain = 32 mm and thickness of the band drain = 6 mm which is equivalent to cylindrical drain diameter 24.19 mm as per Hansbo's formula. The PVD was placed in the rectangular mandrel after removal of the soil from the mandrel (figure-3). A proper care of the complete removal of the clay from the bore hole is to be assured so as the clay does not stick the band drain and block the drainage path during consolidation. It should be noted that before inserting the PVD, it was completely wetted and then it was inserted.

Figure-3 Photograph Showing Installation of Band Drain

VII. PROCEDURE FOR TESTING

After the static pressure of 10 kPa was applied till the complete consolidation at this pressure was achieved, the soil sample in the oedometer was sealed by rubber gasket (figure-4) covered with the top plate. Settlement dial gauge was connected at the central rod connected to the rubber gasket. Hydraulic pressure was applied initially of 20 kPa and settlement reading were taken till the settlement was complete. During that time interval the quantity of water squeezed through the central drainage valve was measured. Similarly the readings were taken at the pressure of 40 kPa, 80 kPa, 160 kPa, and 320 kPa.

After the completion of loading, the set-up was dismantled and readings of vane shear strength was taken at three radial points in the soil sample.

The second and third test were conducted by applying vacuum at the top drainage valve (central rod). In the second test, the soil sample was prepared exactly similar to first test and then the vacuum was applied at the interval of 10 minutes followed by 20 minutes rest period for cooling of the pump. The cycle of giving vacuum for 10 minutes having magnitude 85.68 kPa and 20 minutes rest period were continued till there is no further settlement or squeezing of water from the sample. During the entire vacuum period the measurement of settlement and quantity of water squeezed were recorded. Similarly in the third test, the vacuum was applied for 20 minutes followed by 40 minutes rest period. During all the three tests, the initial condition of the specimen was same.

Figure-4 Photograph of The Rubber Gasket

VIII. RESULTS AND ANALYSIS

For plotting the theoretical curve of degree of consolidation for radial drainage versus time factor for radial drainage(figure-5), it is required to determine the 'n' value i.e. ratio of radius of oedometer to the radius of drain. We have, b = 32 mm = width of the PVD, t = 6 mm = thickness of the PVD. Equivalent drain diameter (d_w) by the Hansbo's equation is 24.19. Further to calculate the degree of consolidation and time factor for radial drainage, the following formulae for time factor and degree of consolidation for radial drainage given by Barron are used:

$$\mathbf{n} = \frac{r_e}{r_w} = \mathbf{10.50}$$

$$\mathbf{U_r = 1 - exp}\left(\frac{-8T_r}{F(n)}\right)$$

$$\mathbf{T_r} = \frac{\mathbf{C_r.t}}{d^2}$$

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$$F(n) = \frac{n^2}{n^2-1}\ln(n) - \frac{3n^2-1}{4n^2} = 1.63$$

Where,

U_r = Degree of consolidation for radial drainage, T_r = Time factor for radial drainage, C_{vr} = C_r = Coefficient of consolidation for radial drainage, t = Time rate of consolidation for radial drainage, d = Drainage path

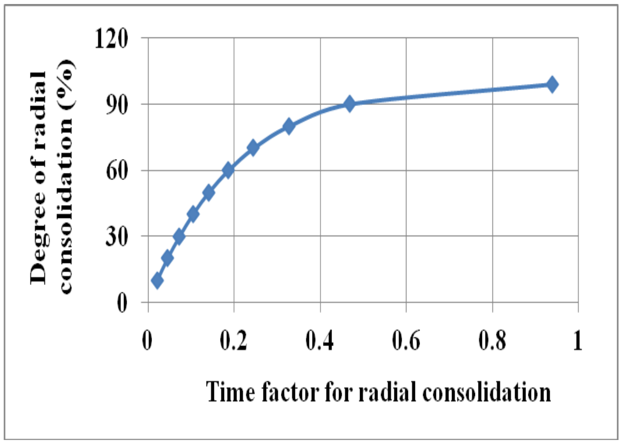

Figure 5 Degree of consolidation versus time factor characteristics for consolidation of Kaolinite clay through radial drainage

a) Characteristics Under PVD and Hydraulic Pressure:

Figure **6 and 7** shows **settlement versus logt characteristics of soft Kaolinite clay** for the normal pressure of **20 kPa**, and **320 kPa** respectively. All the curves indicate typical logt characteristics of the consolidation process. The curves have same nature as that of one dimensional consolidation. 50% of primary consolidation is achieved at 1350 min for 20 kPa pressure which reduces with the increase of normal pressure; it is 1025 minutes for 320 kPa normal pressure. While the Cvr value increased from **2.81×10^{-4} cm²/s** at **20 kPa** to **3.69×10^{-4} cm²/s** at **320 kPa**.

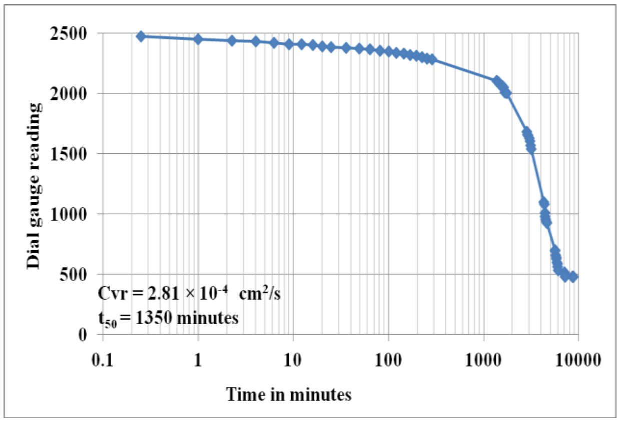

Figure 6 Settlement versus log t characteristics of soft Kaolinite clay during consolidation through radial drainage (Hydraulic pressure 20 kPa)

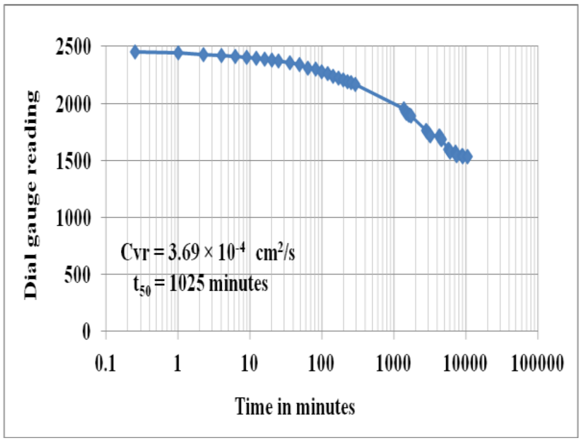

Figure 7 Settlement versus log t characteristics of soft Kaolinite clay during consolidation through radial drainage (Hydraulic pressure 320 kPa)

Figure **8** shows the curve for the quantity of water squeezed versus time for the pressure **20 kPa**. As the time increases the quantity of water increases and at a time **4200 minutes** the quantity of water squeezed was **285 ml** and thereafter the water did not get squeezed.

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Figure **9** shows the curve for the quantity of water squeezed versus time for the pressure **320 kPa**. The nature of curve is curve-linear-curve-linear. Initially, it is curve. As the time increases the quantity of water squeezed was increased and at a time **10620 minutes** the quantity of water squeezed was **87 ml i.e. 69.47% less than that for pressure 20 kPa** and after **10620 minutes,** the water did not get squeezed.

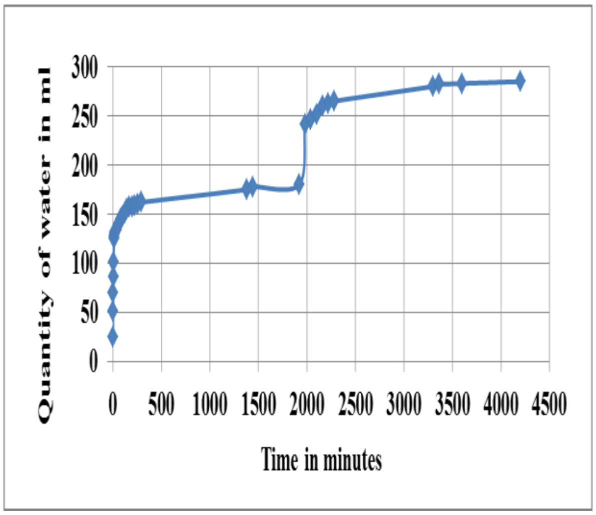

Figure 8 Quantity of water squeezed versus time characteristic during consolidation of Kaolinite clay through radial drainage (Hydraulic pressure 20 kPa)

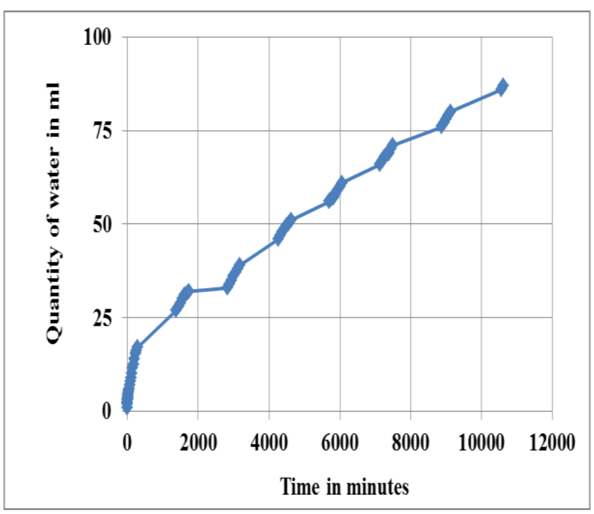

Figure 9 Quantity of water squeezed versus time characteristic during consolidation of Kaolinite clay through radial drainage (Hydraulic pressure 320 kPa)

Figure **10** show the curve for void ratio versus pressure. As the pressure increases, the void ratio decreases and then remains almost constant at **320 kPa load**. Initially the void ratio is **1.93 at 20 kPa** and finally the void ratio is **1.21 at 320 kPa**. The decrease in void ratio is about **62.69 %** as compared to void ratio at **20 kPa.**

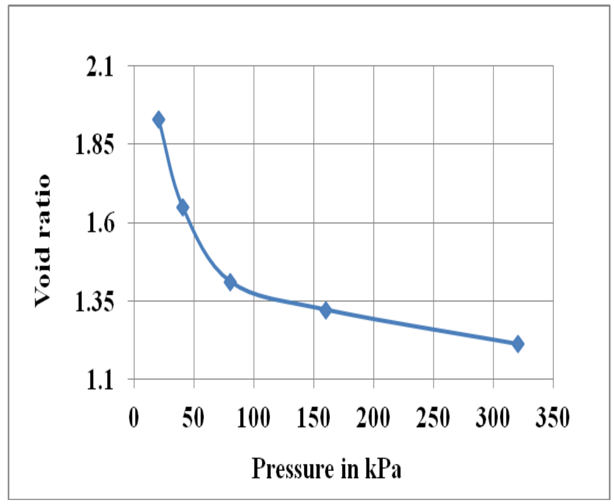

Figure 10 Void ratio versus pressure curve for Kaolinite clay during consolidation by radial drainage

Figure **11** shows the curve for the radial distance versus shear strength. As the radial distance increases, the shear strength of the soil decreases. The shear strength at radial distance **r1 = 25.4 mm**, **r2 = 71 mm**, and **r3 = 110 mm** from the centre is **33.33 kPa**, **27.36 kPa**, and **25.26 kPa**.

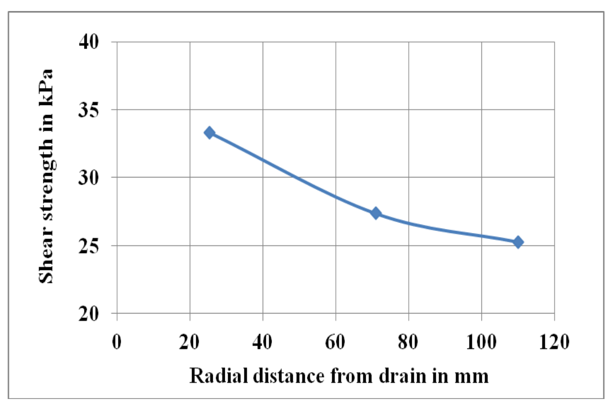

Figure 11 Radial distance versus shear strength curve for Kaolinite clay during consolidation by radial drainage

b) Characteristics Under PVD and Vacuum:

Figure **12** shows the time versus settlement characteristics of soft Kaolinite clay undergoing consolidation through radial drainage using PVD and vacuum (10 minutes interval). Initially the settlement increases with the time but attains a constant value after the time **1040** minutes. The curve is similar in nature as of that one dimensional consolidation curve.

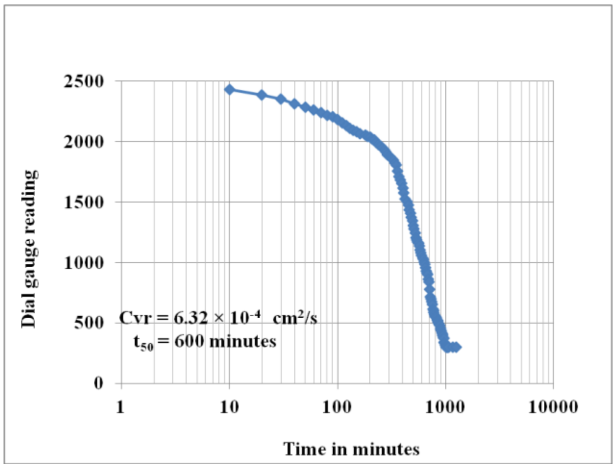

Figure 12 Settlement versus log t characteristics of soft Kaolinite clay during consolidation through radial drainage using Vacuum (Vacuum 85.68 kPa, 10 minutes interval)

Figure **13** shows the quantity of water expelled versus time. The curve is linear initially in nature but somewhat curvature is also there. As the time increases, the quantity of water extracted from the sample increases and at time **1040 minutes**, the water does not get expelled. Total amount of water expelled is **100.3 ml**.

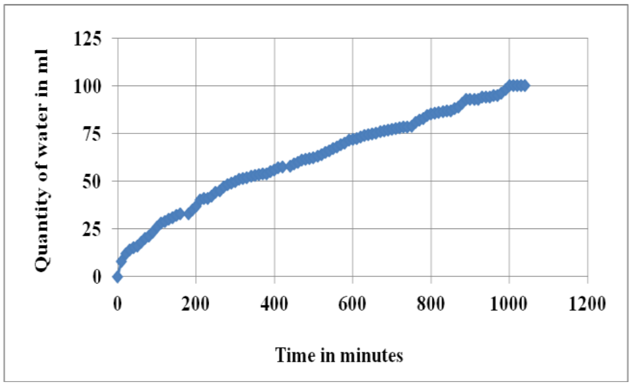

Figure 13 Quantity of water expelled versus time characteristic during consolidation of Kaolinite clay through radial drainage using Vacuum (10 minutes interval)

Figure **14** show the **void ratio versus time characteristics curve**. As the time increases, the void ratio decreases and attains a constant value of **1.512 at time 1040 minutes**. Initially the void ratio is **1.73**. The void ratio decreases about **12.60 %** as compared to initial void ratio.

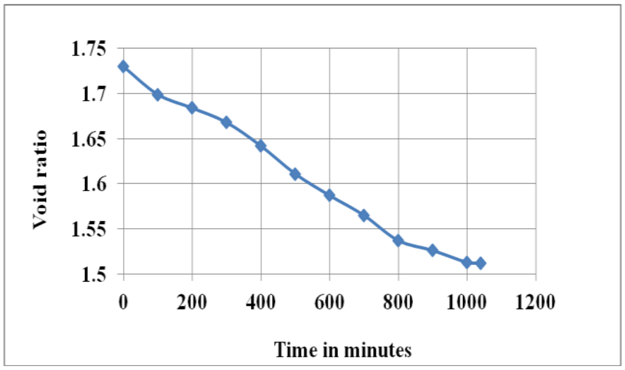

Figure 14 Void ratio versus time curve characteristic during consolidation of Kaolinite clay through radial drainage using Vacuum (10 minutes interval)

Figure **15** shows the curve for the radial distance versus shear strength. As the radial distance increases, the shear strength of the soil decreases. The shear strength at radial distance **r1 = 25.4 mm**, **r2 = 71 mm**, and **r3 = 110 mm** from centre was **6.32 kPa**, **4.56 kPa**, and **3.86 kPa**.

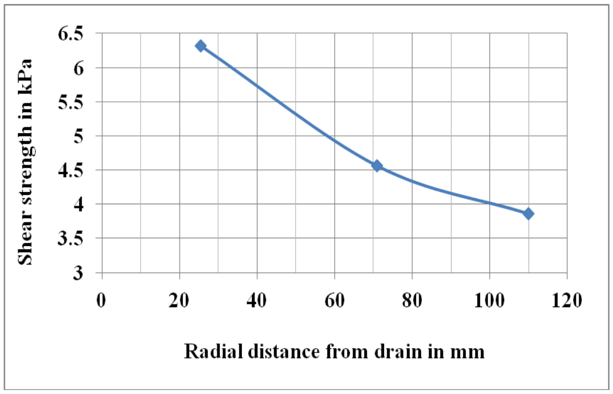

Figure 15 Radial distance versus shear strength curve for Kaolinite clay during consolidation by radial drainage using Vacuum (10 minutes interval)

Figure **16** shows the time versus settlement characteristics of soft Kaolinite clay undergoing consolidation through radial drainage using PVD and vacuum (20 minutes interval). Initially the settlement increases with the time but attains a constant value after the time **1160 minutes**. The curve is similar in nature as of that one dimensional consolidation curve.

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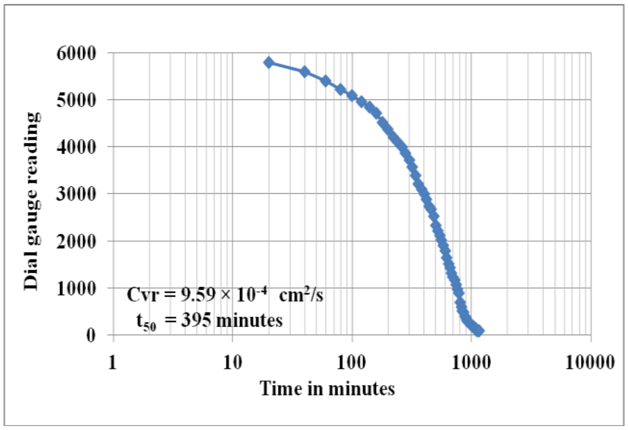

Figure 16 Settlement versus log t characteristics of soft Kaolinite clay during consolidation through radial drainage (Vacuum 85.68 kPa)

Figure **17** shows the quantity of water expelled versus time. The curve is initially curvilinear in nature. As the time increases, the quantity of water also increases and at time **1160 minutes,** the water did not get expelled. The total quantity of water expelled was about **165.20 ml**.

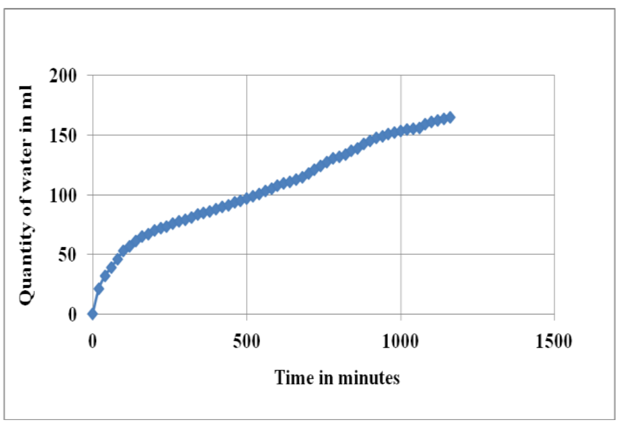

Figure 17 Quantity of water expelled versus time characteristic during consolidation of Kaolinite clay through radial drainage using Vacuum(20 minutes interval)

Figure **18** show the **void ratio versus time characteristics curve**. As the time increases, the void ratio decreases and attains a constant value of **1.44 at time 1160 minutes**. Initially the void ratio is **1.84**. The void ratio decreases about **21.74 %** as compared to initial void ratio.

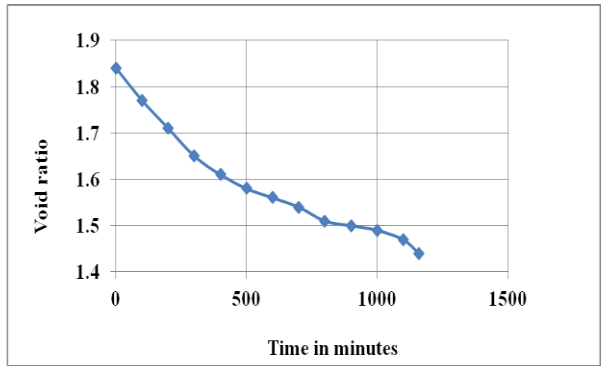

Figure 18 Void ratio versus time curve characteristic during consolidation of Kaolinite clay through radial drainage using Vacuum (20 minutes interval)

Figure **19** shows the curve for the radial distance versus shear strength. As the radial distance increases, the shear strength of the soil decreases. The shear strength at radial distance **r1 = 25.4 mm**, **r2 = 71 mm**, and **r3 = 110 mm** is **22.21 kPa**, **18.91 kPa**, and **16.67 kPa**.

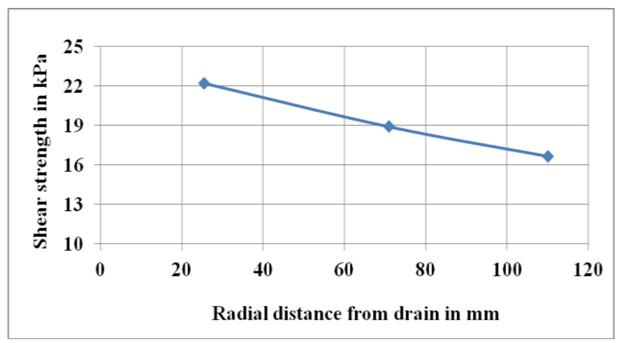

Figure 19 Radial distance versus shear strength curve for Kaolinite clay during consolidation by radial drainage using Vacuum (20 minutes interval)

IX. COMPARISON OF THREE TESTS

Figure **20** shows the comparison of the settlement of all the three tests. The settlement in case of (PVD + Vacuum (10 minutes interval)) test is about **20.42 %** of settlement of (PVD + hydraulic pressure loading) test and the settlement in case of (PVD + Vacuum (20 minutes interval)) test is about **47.01 %** of settlement of (PVD + hydraulic pressure loading) test.

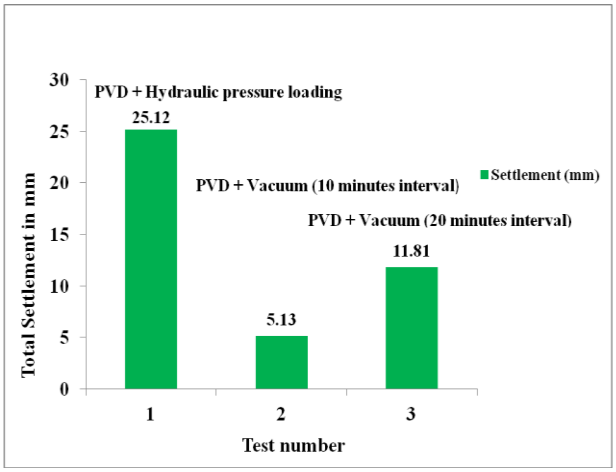

Figure 20 Comparison of total settlement during consolidation of Kaolinite clay through radial drainage using Hydraulic pressure loading and Vacuum

Figure **21** shows the comparison of the quantity of water squeezed/expelled in ml of all the three tests. The quantity of water expelled in (PVD + Vacuum (10 minutes interval)) test is about **10.61%** of quantity of water squeezed in (PVD + hydraulic pressure loading) test and about **17.48%** in case of (PVD + Vacuum (20 minutes interval)) test.

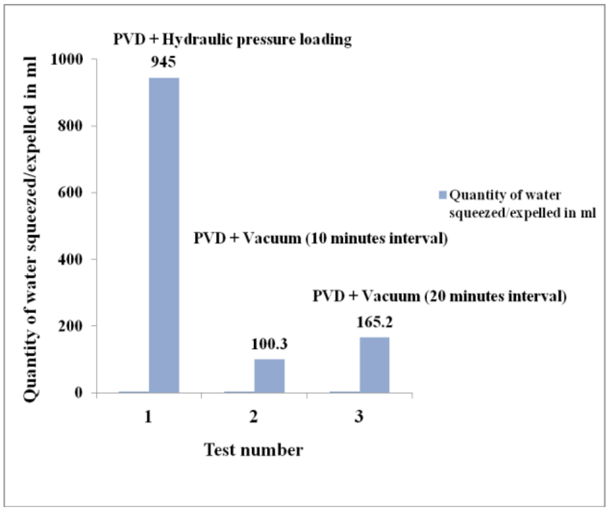

Figure 21 Comparison of Quantity of water squeezed/expelled during consolidation of Kaolinite clay through radial drainage using Hydraulic pressure loading and Vacuum

Figure **22** shows the comparison of the average shear strength of Kaolinite soft clay all the three tests. The average shear strength of Kaolinite soft clay in case of (PVD + Vacuum (10 minutes interval)) test is about **17.14 %** of shear strength of (PVD + hydraulic pressure loading) test and in case of (PVD + Vacuum (20 minutes interval)) test is about **67.23 %** of shear strength of (PVD + hydraulic pressure loading) test.

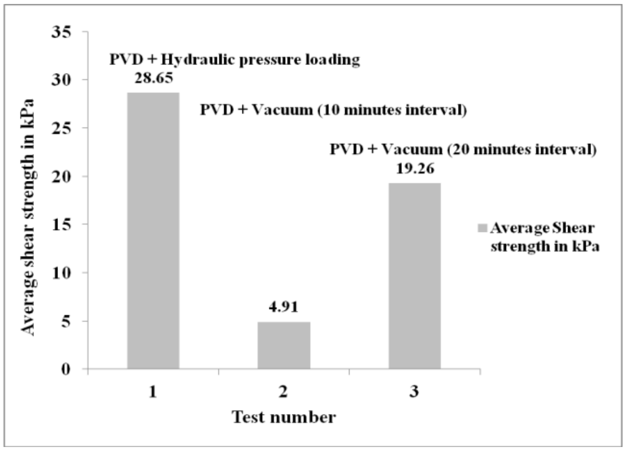

Figure 22 Comparison of Average shear strength during consolidation of Kaolinite clay through radial drainage using Hydraulic pressure loading and Vacuum

X. Conclusions

In the present investigation, Consolidation achieved is **better** in case of (PVD + hydraulic pressure loading) test, as compared to (PVD + Vacuum (10 minutes interval and 20 minutes interval)) test. The coefficient of radial consolidation (C_{vr}) increases from pressure **20 kPa to 320 kPa** in case of (PVD + Hydraulic pressure loading) test. The average shear strength is **higher** in case of (PVD + hydraulic pressure loading) test, whereas the average shear strength is **least** in case of (PVD + Vacuum (10 minutes interval)) test. The above study indicates that the (PVD + Hydraulic pressure loading) test is more effective than the (PVD + Vacuum (10 minutes interval)) and (PVD + Vacuum (20 minutes interval)) test. It can be concluded that (PVD + Vacuum) tests are least effective but if accompanied by hydraulic pressure loading than the results can be improved much better. Above findings will also give an idea to the field engineer for best selection, which will give more benefit in gaining shear strength of soft clays in shortest time.

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