Numerical and Experimental Investigations of the Effect of PVD and Vacuum Pressure on the Degree of Saturation

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ABSTRACT

Soft clays are generally characterized by low shear strength, low permeability and high compressibility. An effective method to accelerate consolidation of such soils is to use vertical drains along with vacuum preloading to encourage radial flow of water. In this research numerical modeling of prefabricated vertical drains with vacuum pressure was done to investigate the effect of using vertical drains together with vacuum pressure on the degree of saturation of fully and saturated-unsaturated soft soils. Laboratory experiments were conducted by using a specially-designed large consolidometer cell where a central drain was installed and vacuum pressure was applied. All tests were conducted with a vacuum pressure of 40 kPa applied for a period of 30 days where a degree of soil consolidation of 90% was attained. At the end of the test period fifteen samples were taken from different locations distributed along the depth and radially to measure the water content. Consolidation settlements were recorded with time for all tests. The results showed that using vacuum pressure with vertical drains is a very effective method to accelerate consolidation of soils. As the thickness of unsaturated top layer increases, the settlement of soil surface decreases. The water content decreased after 30 days of application of the vacuum pressure.

Key words: degree of saturation, PVD, vacuum, and degree of consolidation.

تحليل نظري وعملي لتأثير أعمدة الصرف الطولية وضغط التفريغ على درجة التشبع

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الخلاصة

تتكون الترب الرخوة في مناطق ترسيب الأنهار أو البحار أو البحيرات. تتكون هذه الترب على شكل طبقات تتداخل مع طبقات من الرمل والغرين التي تعرضت الى حالات الجفاف والترطيب بصورة دورية قرب السطح. ولغرض دراسة سلوك التربة الرخوة بإستخدام أعمدة التصريف الطولية والمفرغ تم تصميم وإنشاء خلية إنضمام خصيصا لهذه الدراسة. تم إجراء فحوصات مختبرية بتسليط ضغط سالب مقداره 40 kPa لمدة لاتقل عن ثلاثين يوم. بالإضافة الى الدراسة العملية أجريت دراسة نظرية بالإعتماد على طريقة العناصر المحددة بإستخدام برنامج ABAQUS بإصداره 6.13 لدراسة تأثير أعمدة الصرف الطولية والمفرغ على درجه تشبع الترب المشبعة وغير المشبعة حيث أظهرت النتائج كفاءة هذه الطريقة في تحسين التربة وتقليل الزمن اللازم للوصول الى إنضمام عالي داخل التربة. وأظهرت النتائج تقارب كبير بين الفحوص العملية والتحليل النظري .

الكلمات الرئيسية: درجة التشبع، وأعمدة الصرف الطولية، والمفرغ، و درجة الإنضمام.

1. INTRODUCTION

Large areas covered with thick deposits of soft clay layers which are not suitable for construction of many infra structures. The growing need for infrastructures in urban and the lack of sites suitable for development increased land prices dramatically. Accordingly, lands having poor geotechnical properties (low shear strength and high compressibility) were utilized as construction sites. Prefabricated Vertical Drains, PVDs, together with vacuum pressure have been widely used to accelerate the consolidation of soft soils **Indraratna, and Rujikiatkamjorn, 2004, and AL-Shammarie, 2013**. This technique shortened the horizontal drainage path to half of the drain spacing. Moreover, propagation of vacuum pressure along the PVD increases the hydraulic gradient and creates an additional surcharge load. The concept of drainage through vertical drains was initially developed in the 1920s. The property of sand being more permeable than clay silty soil was utilized by creating sand columns in lesser permeable soils and these sand columns functioned as drains. The first prefabricated vertical drain was developed by **Kjellman, 1940** (as cited by Indraratna, et al, 2005). Several other types of PVDs have been developed since then such as Geodrain, Alidrain, and Mebradrain. PVDs consisted of few channels imprinted into a stiff card board core **Indraratna, et al., 2003.**

The basic idea of the PVD depends upon the radial consolidation of soils since the PVD provides a lateral path and facilitates dissipation of pore-water pressure during the loading process, thus, accelerating the consolidation process. **Barron, 1948** analytically solved radial consolidation for free- and equal-strain conditions. **Indraratna, et al., 2005** developed a radial consolidation formula that involves compression indices. Their derivation was based upon several assumptions among them is that the relationships void ratio-effective stress and void ratio-horizontal coefficient of permeability can be found from:

$$e = e_o - c_c \log \frac{\sigma'}{\sigma'_i} \qquad (1)$$

and

$$e = e_o + c_k \log \frac{k_{hp}}{k_{hi}} \qquad (2)$$

where c_c, compression index, c_k, permeability index, e, void ratio, e_o, average void ratio corresponding to the initial in-situ effective stress, k_{hi}, initial coefficient of horizontal permeability of undisturbed soil, σ', vertical effective stress, and σ'_i, initial effective vertical stress.

Average degree of consolidation can be expressed in terms of excess pore-water pressure or strain as follows:

$$U_p = 1 - R_u \tag{3}$$

or

$$U_s = \frac{\rho}{\rho_\infty} \tag{4}$$

where U_p, average degree of consolidation calculated from pore-water pressure, R_u, average excess pore water pressure ratio, U_s, average degree of consolidation calculated from strain, ρ, settlement at any time, and ρ_∞ settlement at effective stress equal to initial effective stress plus the additional load.

2. THEORETICAL ANALYSIS

The effect of using PVD and vacuum pressure on the degree of saturation of fully saturated and saturated-unsaturated soils was investigated by using ABAQUS software version 6.13. Five different cases were investigated including fully saturated, and partially saturated (50% degree of saturation) with different depths of unsaturated layer namely 1/8 L, 1/4 L, 3/8 L, and 1/2 L thick lay on a fully saturated layer, where L is the total depth of the soil sample. A half-unit cell 0.35 m in diameter and 0.8 m deep was analyzed by using ABAQUS software. **Fig. 1** shows the geometry of the five different cases together with the mesh. In the analysis it was assumed that the soil element is eight nodded and axi-symmetric, quadrilateral, biquadratic displacement, bilinear pore-water pressure, and reduced integration were adopted, abbreviated as CAE8RP. The soft soil was analyzed as elasto-plastic material obeying Modified Cam-Clay Model, MCC. The input data to the MCC were: slope of normal consolidation line, λ, 0.18; slope of the critical-state line, M, 1.2; initial yield surface, a_o, wet surface size, ξ, and flow stress ratio, k, both assumed to be 1. The input data to the porous elastic model included: slope of over consolidationed line, κ, 0.08, and Poisson's ratio, υ, 0.3. The unit weight and permeability of the soil were 18 kN/m^3

and $2.11*10^{-8}$ m/sec, respectively. The PVD was assumed to behave as an elastic material with Young's modulus, E, equal to 1800 kPa and Poisson's ratio equal to 0.4. In order to define the unsaturated element in ABAQUS, the sorption effect should be included since ABAQUS depends upon soil-water characteristic curve to define the degree of saturation of soil. **Fig. 2** shows the soil-water characteristic curve, SWCC, based upon results obtained from the plate-pressure method.

3. APPARATUS of EXPERIMENTAL WORK

In this research, a cylindrical steel container (consolidometer cell) was specially designed and manufactured to be used for the investigation of the improvement of the behavior of soft soils by using PVD. The cell was designed to be air and water tight with removable top and bottom flanges. The cell contained seven openings to insert the wires; four of them were used to insert the piezometers and the remaining three to insert the pressure cells. **Fig. 3** is a schematic representation of the consolidometer used in this research and shows the distribution of the openings along the wall of the cell. The cap of the model contained an opening to connect the vacuum pump; an opening to insert a point gauge; and a circular glass window for inspection. The base of the model contained a drainage hole; 5 mm in diameter and provided with a valve.

4. TEST PROCEDURE

Five separate series of tests were conducted, the first series involved applying a vacuum pressure of 40 kPa at the top of a fully saturated soft-soil while the other series of tests involved applying a vacuum pressure of 40 kPa at the top of an unsaturated soil with different depths (1/8L, 1/4 L, 3/8 L, and 1/2 L thick, and 50% degree of saturation) laid on a fully saturated soft-soil layer, where L is the total depth of the soil placed in the cell. The testing procedure involved three main steps namely preparation of reconstituted clay, installation of the drain, and collection of oedometer samples.

The preparation of reconstituted clay was done according to the procedure suggested by **Burland, 1990** (as cited by Indraratna, et al, 2005), where the clay specimen was mixed thoroughly with distilled water at water content slightly greater than the liquid limit. The clay was placed and tamped in layers in the consolidometer cell; the unsaturated layer was then placed on the top of the saturated soft soil with a thickness equal to 1/8, 1/4, 3/8, and 1/2 the total depth of the soil sample. Then a 25 mm × 3 mm band drain was inserted through the total depth of the soil by using a steel mandrel. During the placement of the soil in the cell four piezometers were placed at 19, 35, 50 and 80 cm from the top of the soil. A vacuum pressure of 40 kPa was applied for 30 days and the corresponding settlement and pore-water pressure were measured. **Table 1** shows the physical and chemical properties of the natural soft-soils brought from AL-Basrah city south of Iraq. At the end of the test period for fully and saturated-unsaturated soft soil, fifteen samples were taken from different locations distributed along the depth and radially to measure the water content.

5. RESULTS AND DISCUSSION

A comparison between the settlement of a fully saturated soft soil and that of a saturated soil overlaid by a layer of unsaturated soil whose thickness is 1/8, 1/4, 3/8, and 1/2 of the total soil depth is shown in **Fig. 4**. Settlement of soil was measured by using a point gauge. It is obvious that the presence of an unsaturated layer reduces soil settlement. The degree of consolidation based upon soil settlement was found to be more than 90 % after 30 days of vacuum application (for two-way drainage conditions) while applying a surcharge with same magnitude without a PVD requires more than 93 days to reach 90 % degree of consolidation.

Figs. 5 through 9 show the variation of measured water content with the depth and radial distance as compared with the results obtained from numerical analysis. From these figures, it is obvious that the water content for fully saturated soils decreased after 30 days of application of vacuum pressure. During the experimental test, water started to flow out from the soil after some time and was collected in the vacuum container. Water content at the face of the drain decreased more rapidly than that at the boundary. Due to the insertion of mandrel a disturbed zone near the PVD is formed causing the horizontal permeability to be less than that in the undisturbed zone. Accordingly, the water content would be less at the interface of the PVD than at the boundary of the soil sample. The water content for the unsaturated soil layer increases with time due to the high matric suction in the unsaturated layer. Application of vacuum pressure also accelerates the transmission of water from the saturated layer to the unsaturated layer. Also as the depth of the unsaturated layer increases the time required for water to appear on the soil surface increases. A good agreement was found between the numerical and the experimental work.

6. CONCLUSIONS

The results show that a system of prefabricated vertical drains accompanied with the application of vacuum pressure is an effective method to accelerate the consolidation of soft soils where the degree of consolidation was found to reach more than 90% in 30 days instead of 93 days for two-way drainage conditions. Presence of unsaturated soil reduces soil settlement. The degree of saturation of the fully saturated and saturated-unsaturated soft soil changes by 30 % depending upon the initial moisture content of the soil. A good agreement was found between experimental work and numerical analysis.

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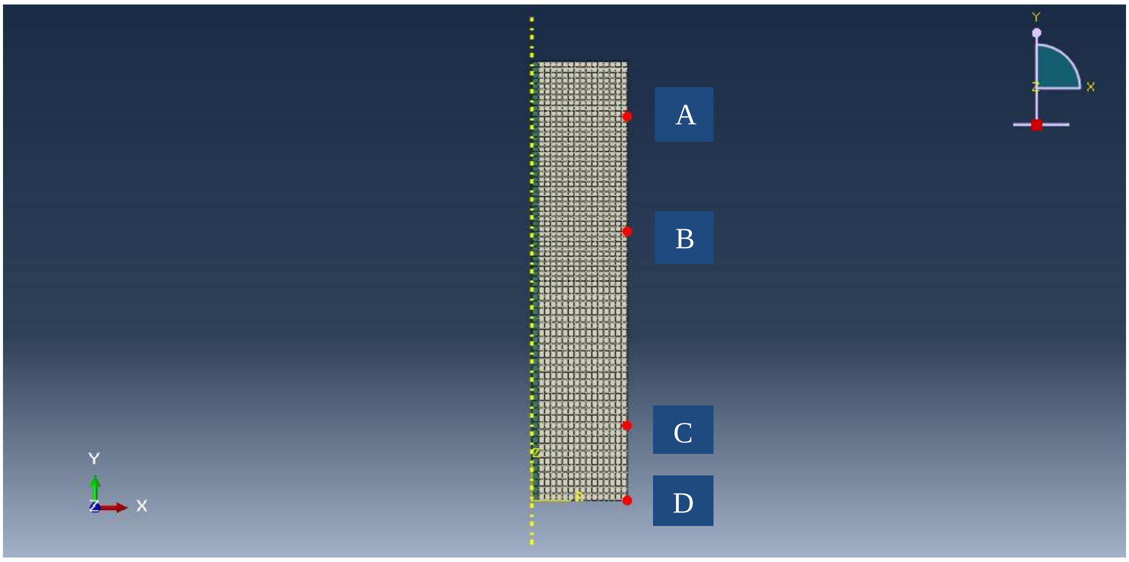
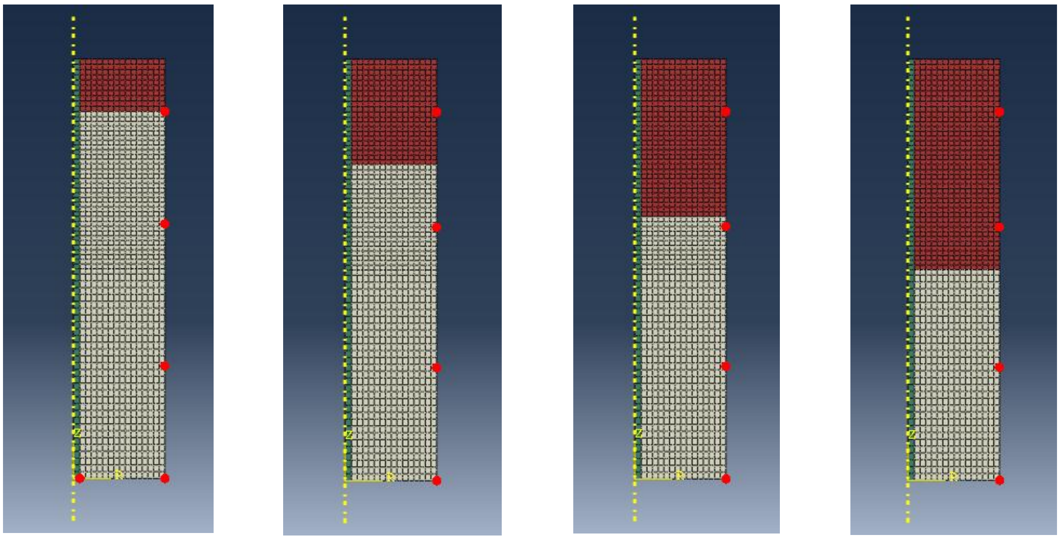
LIST OF SYMBOLS

c_c = compression index, dimensionless
c_k = permeability index, dimensionless
e = void ratio, dimensionless
e_o = average void ratio at the initial in-situ effective stress, dimensionless
k_{hi} = initial coefficient of horizontal permeability of undisturbed soil, m/sec,
R_u = average excess pore water pressure ratio, dimensionless
U_p = average degree of consolidation based upon pore-water pressure, dimensionless
ρ = settlement at any time, m
ρ_∞ = settlement at effective stress equal to initial effective stress plus the additional load, m
σ' = vertical effective stress, kPa, and
σ_i' = initial effective vertical stress, kPa.



Geometry of the fully-saturated soil and nodal number



1/8 L unsaturated soil

1/4 L unsaturated soil

3/8 L unsaturated soil

1/2 L unsaturated soil

Figure 1. Geometry of half unit, mesh, and nodal positions and numbers.

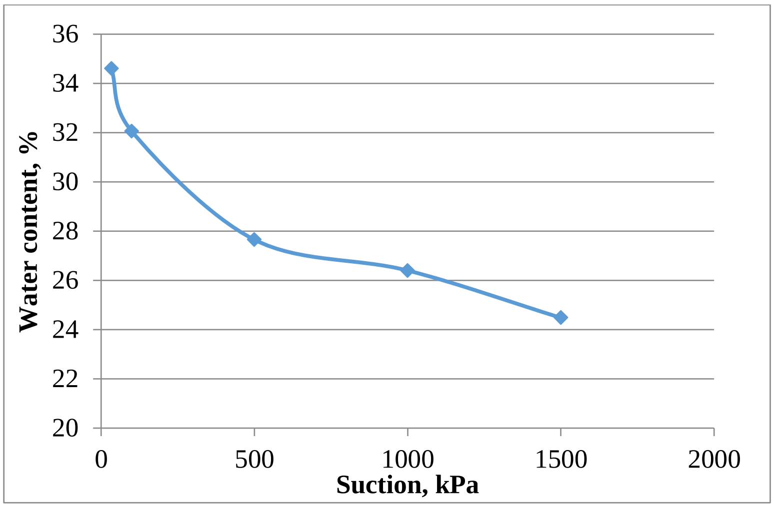
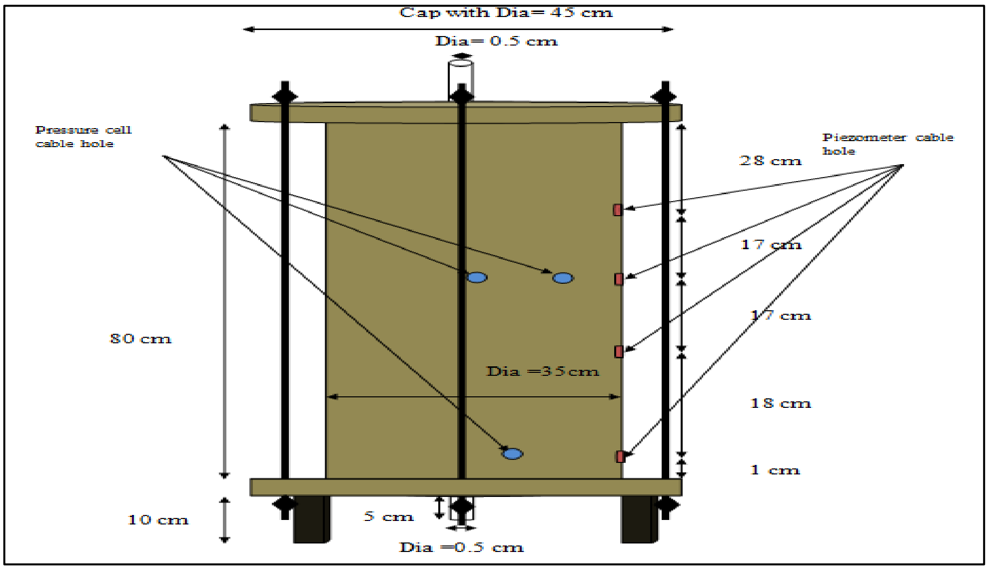


Figure 2. Soil-water characteristic curve, SWCC, based upon results obtained from the plate-pressure method.



(a)

Figure 3. Schematic diagram of the designed consolidometer cell.

(b)

Figure. 3 Cont.

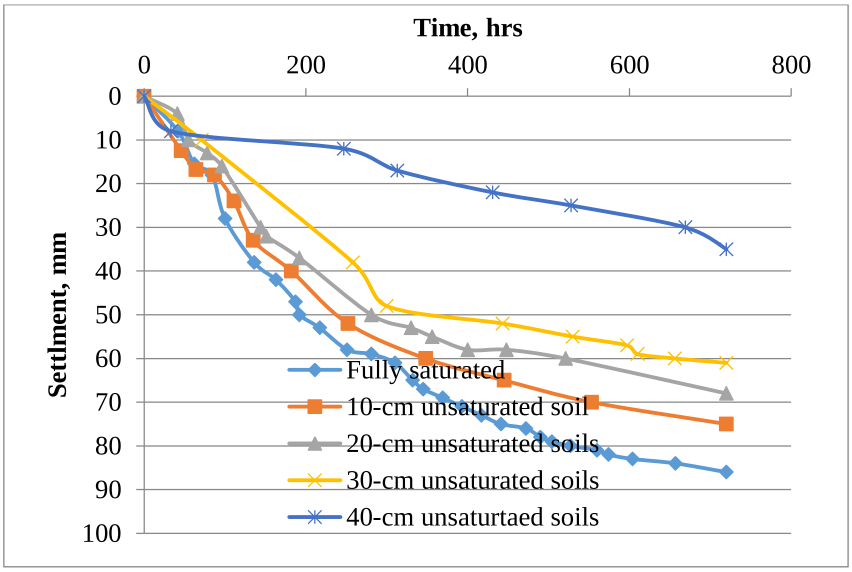
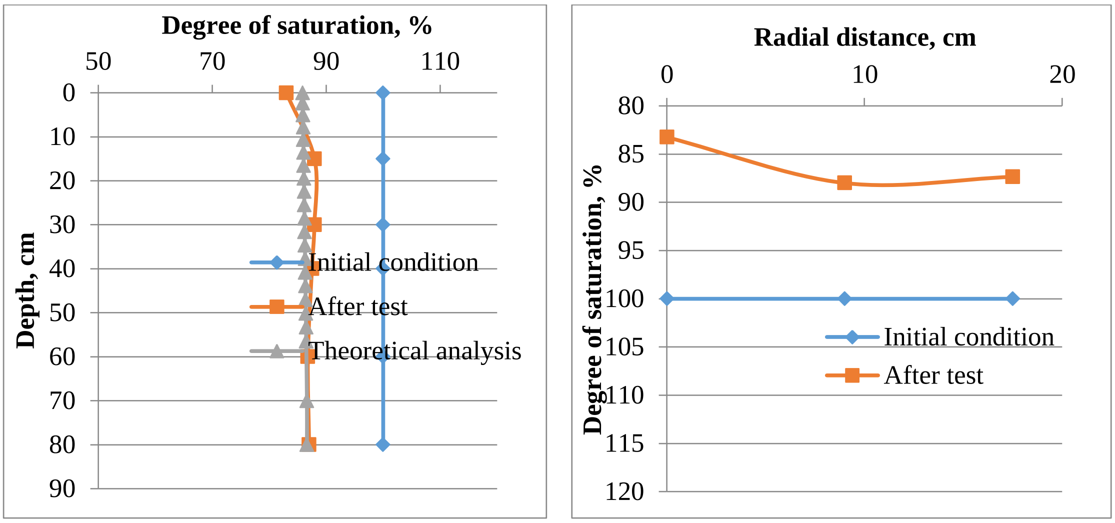
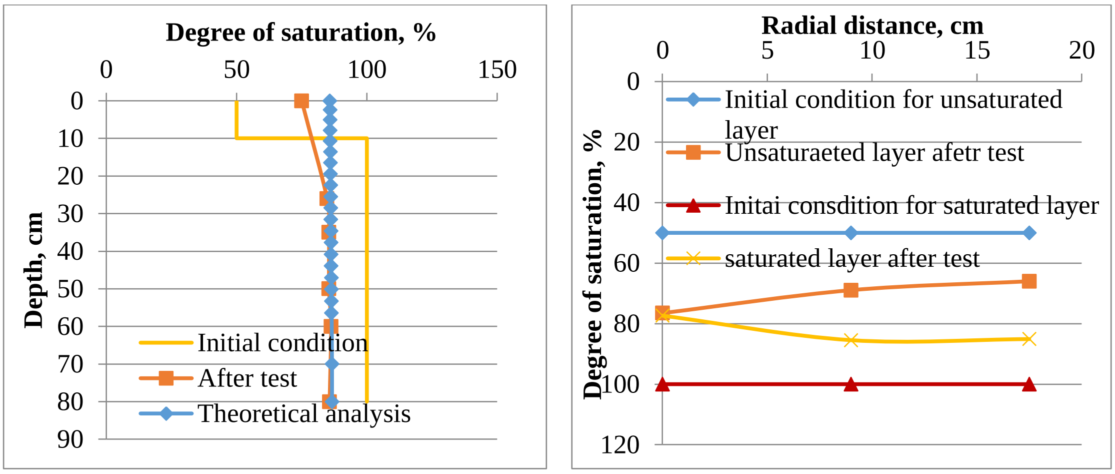


Figure 4. Variation of soil settlement with time.



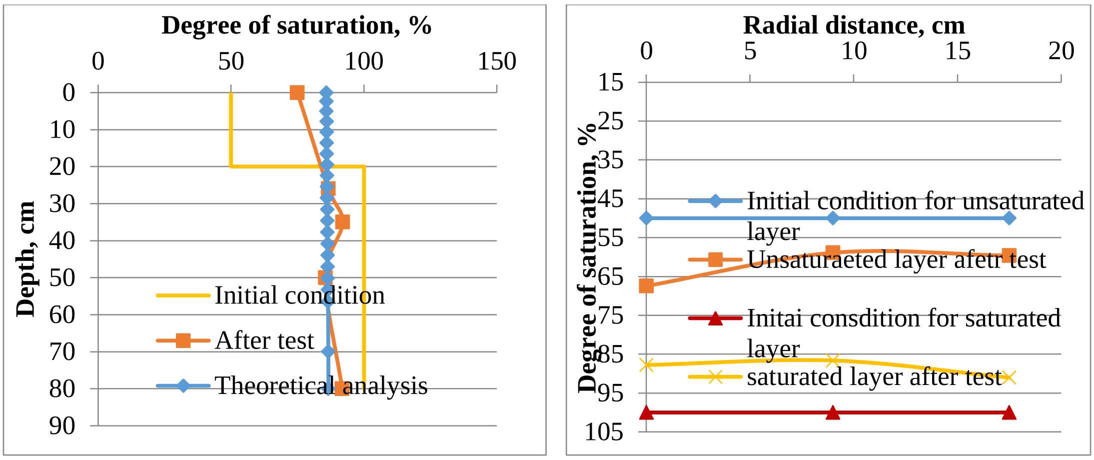
(a) Variation of water content with depth (b) Radial variation of water content

Figure 5. Variation of water content after 30 days of applying vacuum pressure on a fully saturated soft soil.



(a) Variation of water content with depth (b) Radial variation of water content

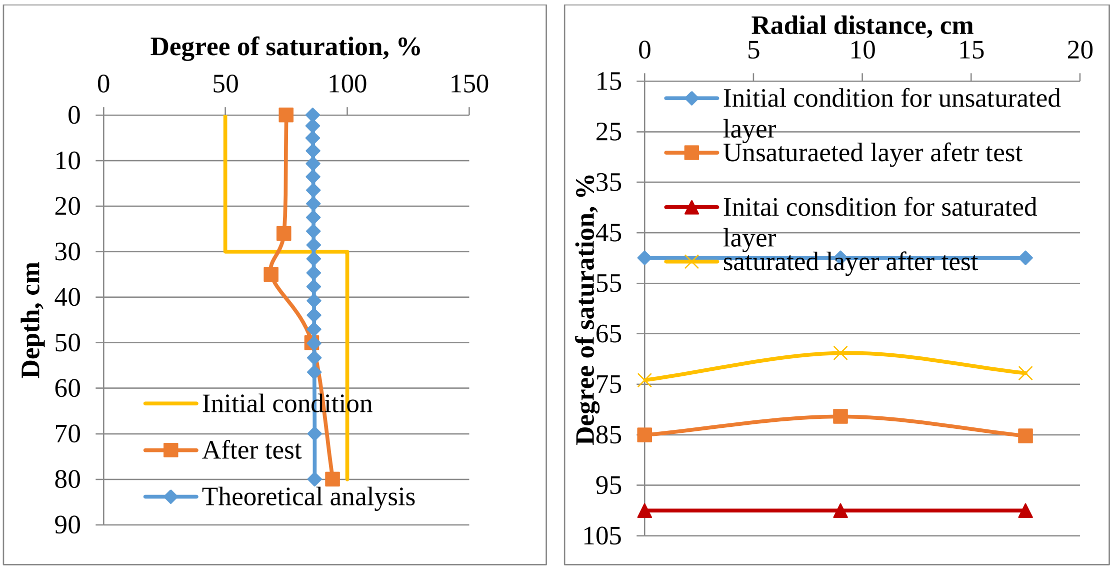
Figure 6. Variation of water content after 30 days of applying vacuum pressure on 1/8 L unsaturated soils.



(a) Variation of water content variation with depth

(b) Radial variation of water content

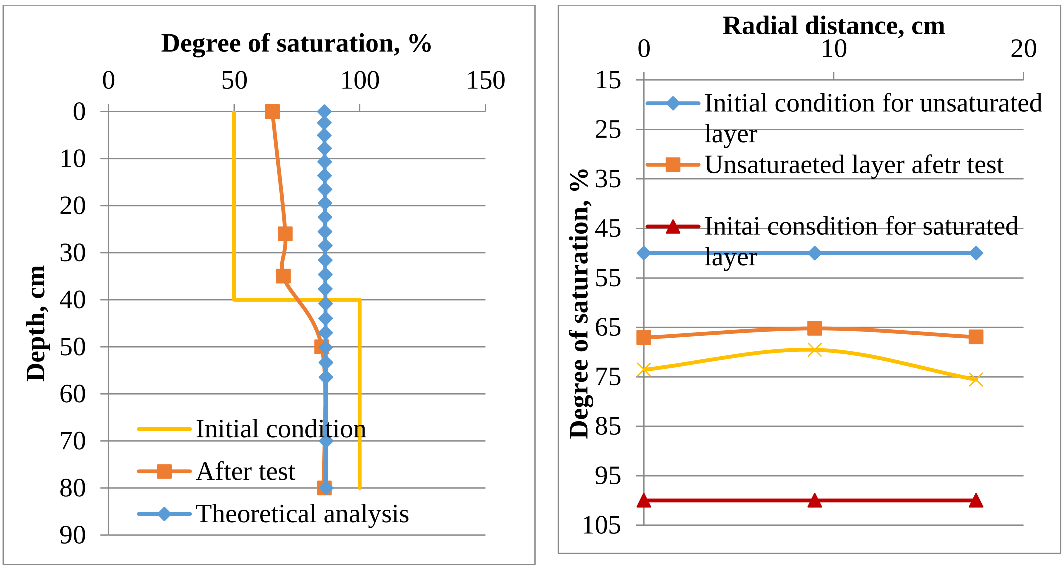
Figure 7. Variation of water content variation after 30 days of applying vacuum pressure on a 1/4 L unsaturated soils.



(a) Variation of water content variation with depth

(b) Radial variation of water content variation

Figure 8. Variation of water content after 30days of applying vacuum pressure on a 3/8 L unsaturated soils.



(a) Variation of water content with depth

(b) Radial variation of water content

Figure 9. Variation of water content after 30 days of applying vacuum pressure on a 1/2 L unsaturated soils.

Table 1. Physical and chemical properties of the natural soil used in the experiments.

Property	**Value**
Liquid limit, LL	36%
Plastic limit, PL	18%
Liquidity index, LI	0.61
Specific gravity, Gs	2.73
Clay content < 0.005 mm	45.3 %
Silt content 0.005 to 0.074 mm	49.21 %
Sand content > 0.074 mm	5.49 %
Maximum dry unit weight, kN/m^3	17.06
Optimum moisture content,	19%
Soil symbol according to USCS	CL
Organic material	2.1 %
SO_3	3.20 %
Total soluble salts	10 %
pH	8.1
Gypsum content	7.224 %
Radiation	Negative
Initial void ratio, e_o	1.092
Compression index, c_c	0.4
Coefficient of vertical consolidation, $c_{v,}$ m^2/day	$1.46*10^{-3}$
Swelling index, c_r	0.03