EFFECT OF PVD AND VACUUM PRESSURE ON SATURATED-UNSATURATED SOFT SOILS

Dr. Ala Nasir Aljorany
Professor
Engineering College-Baghdad University
E-mail:alaAljorany@gmail.com

Fatema Safaa Noori
Graduated student
Engineering College-Baghdad University
E-mail:fatemasafaa@yahoo.com

ABSTRACT

Soft clays are generally sediments deposited by rivers, seas, or lakes. These soils are fine-grained plastic soils with appreciable clay content and are characterized by high compressibility and low shear strength. To deal with soft soil problems there is more than one method that can be used such as soil replacement, preloading, stone column, sand drains, lime stabilization and Prefabricated Vertical Drains, PVDs. A numerical modeling of PVD with vacuum pressure was analyzed to investigate the effect of this technique on the consolidation behavior of fully and different depths of partially saturated soft soils. Laboratory experiments were also conducted by using a specially-designed large consolidmeter cell. Five tests were conducted with a vacuum pressure of about 40 kPa applied for a period of 30 days where the degree of consolidation reached 75% based on pore-water pressure distribution. The results showed that using vacuum pressure with vertical drains reduces the consolidation time by about 68%. Existence of an unsaturated soil layer decreases settlement of soil by about 22%, 32%, 425, 54% as the unsaturated depth increases by 1/8, 1/4, 3/8, and 1/2L respectively and causes a rapid increase in soil pore-water pressure.

KEY WORDS: soft soils, PVD, vacuum pressure, unsaturated soil, and degree of consolidation.

تأثير أعمدة التصريف الطولية وضغط التفريغ على الترب الرخوة المشبعة وغير المشبعة

فاطمة صفاء نوري
طالبة دكتوراه
كلية الهندسه-جامعة بغداد

د. علاء ناصر حريب
أستاذ
كلية الهندسه-جامعة بغداد

الخلاصة

تتكون الترب الرخوة في مناطق ترسيب الأنهار، أو البحار، أو البحيرات. و تكون هذه الترب على شكل طبقات تتداخل مع طبقات الرمل والغرين التي تعرضت الى حالات الجفاف والترطيب بصورة دورية قرب السطح. و لغرض دراسة سلوك التربة الرخوة بأستخدام أعمدة التصريف الطولية والمفرغ تم تصميم وإنشاء خلية إنضمام خصيصا لهذه الدراسة. حيث تم إجراء خمسة فحوص بتسليط ضغط سالب (40 kPa-) لمده لاتقل عن ثلاثين يوما حيث تصل درجة أنضمام التربة الى 75% بالأعتماد على توزيع ضغط الماء. بألأضافه الى الدراسة العملية أجريت دراسة نظرية بالإعتماد على طريقة العناصر المحددة بإستخدام برنامج ABAQUS بإصداره ال 6.13. حيث أظهرت النتائج كفاءة هذه الطريقة في تحسين التربة وتقليل الزمن اللازم للوصول الى إنضمام عالي داخل التربة. إن وجود الطبقة غير المشبعة يعمل على تقليل هطول التربة بنسبه 22%و 32%و 42و 54% عندما تزداد عمق التربة بنسبة 1/8و 1/4و 3/8و 1/2 ولا تؤثر على توزيع ضغط الماء على طول عمود التصريف.

الكلمات الرئيسية: الترب الرخوة، أعمدة التفرغ الطولية ،ضغط التفريغ، الترب غير المشبعة، و درجة الأنضمام.

1. INTRODUCTION

Large areas covered with thick soft clay layers deposits are not suitable for construction of many infra structures. The growth of 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 used for construction. Prefabricated Vertical drains (PVDs) together with vacuum preloading 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 PVDs increases the hydraulic gradient and creates as an additional surcharge load.

2. THEORETICAL BACKGROUND

Loading of unsaturated soils generates excess pore-water and pore-air pressures; dissipation of pressure with time reduces the volume of soil, i.e., soil consolidation. There are many differential equations to describe the consolidation of unsaturated soils. **Terzaghi, in 1943**, presented a linear differential equation to express the consolidation of saturated soils and **Fredlund and Hasan, in 1979**, derived a non-linear differential equation to describe the consolidation of unsaturated soils. In their derivation they adopted the assumption of Terzaghi together with the following assumptions: air phase is continuous, coefficient of permeability with respect to water and air and moduli of volume change remain constant during the consolidation process, and the diffusion of air and water through the consolidation process is ignored **Fredlund, and Hasan, 1979, Fredlund and Rahardjo 1986, and Shan et al., 2013**. They proposed differential equations to express the variation of air and water with time and degree of consolidation of air and water in addition to time factors as follows:

$$U_w = 1 - \frac{\int_0^{2H} u_w dy}{\int_0^{2H} u_{wi} dy} \quad (1)$$

$$U_a = 1 - \frac{\int_0^{2H} u_a \, dy}{\int_0^{2H} u_{ai} \, dy} \quad (2)$$

$$U_r = 1 - e^{-\frac{8}{fn}T_r} \quad (3)$$

$$T_w = \frac{c_v^w t}{H^2} \quad (4)$$

and

$$T_a = \frac{c_v^a t}{H^2} \quad (5)$$

where U_w *and* U_a are degrees of consolidation for water and air, respectively; U_r radial consolidation, H thickness of drainage path; u_{wi} *and* u_w initial pore-water and water pressures at any time, respectively; u_{ai} *and* u_a initial pore-air and air pressures at any time, respectively; fn coefficient, T_w *and* T_a time factors for water and air, respectively; T_r time factor for radial consolidation, t time; and c_v^w *and* c_v^a coefficients of consolidation with respect to water and air, respectively.

They expressed the variation of pore-pressure as follows:

$$\frac{\partial u_w}{\partial t} = -C_w \frac{\partial u_a}{\partial t} + c_{v1}^w \left[k_w \frac{\partial^2 u_w}{\partial y^2} + \frac{\partial u_w}{\partial y} \frac{\partial k_w}{\partial y} \right] \quad (6)$$

and

$$\frac{\partial u_a}{\partial t} = -C_a \frac{\partial u_w}{\partial t} + c_{v1}^a \left[(u_a + u_{atm}) \{ k_a \frac{\partial^2 u_a}{\partial y^2} + \frac{\partial u_a}{\partial y} \frac{\partial k_a}{\partial y} \} + k_a \frac{\partial^2 u_a}{\partial y^2} \right] \quad (7)$$

where k_w *and* k_a coefficients of permeability with respect to water and air, respectively; C_w *and* C_a interactive constants with respect to water and air, respectively; c_{v1}^w and c_{v1}^a coefficients; and u_{atm} atmospheric pressure. Equations 6 and 7 should be solved simultaneously to get the pore pressure.

The average excess pore water pressure under vacuum pressure can be found from equation 8 and 9 based on the drainage condition:

For two-way drainage:

$$u = -pvac\,[\left(1-\frac{z}{H}\right) - 2/\pi \sum_{n=1}^{\infty} \frac{1}{n} \sin(\lambda_n z) e^{\lambda_n{}^2 .cv.t}] \quad (8)$$

While for one-way drainage:

$$u = -pvac\,[1 - 4/\pi \sum_{n=1}^{\infty} \frac{1}{2n-1} \sin(a_n z) e^{a_n{}^2 .cv.t}] \quad (9)$$

where n is ratio of radius of the axisymmetric influence zone around a single drain to radius of equivalent drain λ_n coefficient equal to $2n/\pi$, and $a_n$coefficient equals to $(2n-1)\pi/2H$ **Chai, and Carter, 2011.** In the nineties of the last century an emphasis was started to be imposed on the implementation of unsaturated soil mechanics into routine geotechnical engineering practices **Fredlund, 2000**. Thereafter the effect of using PVD and vacuum pressure on the consolidation of saturated-unsaturated soils has been investigated by using ABAQUS software.

3. EXPERIMENTAL WORK APPARATUS

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 of the piezometers. **Fig. 1** 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 gage; and a circular glass window for inspection as shown **in fig 2**. The base of the model contained a drainage hole of 5 mm in diameter and was provided with a valve. Linear differential variable transducer, *LVDT*, was used to measure the settlement of soil surface. However, since the space above the soil in the consolidometer is very humid the performance of the *LVDT* was highly affected. Accordingly, it was found that a point gauge can successfully be used to measure the settlement of the soil surface since the measurement is done through a mechanical vernear placed on the top flange of the consolidometer as shown in **fig. 3**.

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 four series involved applying a vacuum pressure of 40 kPa at the top of an unsaturated soil layer, 1/8 L, 1/4L , 3/8L, 1/2L, 50% degree of saturation, laid on the top of 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**, 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 apparatus; 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, 1/2 from the total depth of the soil sample. Then a 25 mm × 3 mm band drain with discharge capacity equal to 100 m^3/ year 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. For both tests a vacuum pressure of 40 kPa was applied 720 hours 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.

5. THEORETICAL ANALYSIS

Numerical modeling by using the software ABAQUS 6.13 was done to investigate the effect of PVD and vacuum pressure on the behavior of saturated-unsaturated soft soils where it was assumed that both layers exhibit an elasto-plastic behavior according to modified cam-clay model. 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. **Fig. 4** shows the mesh used in the numerical model and nodes where data were extracted. 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, 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 passions 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 modulus, *E*, equal to 1800 kPa and Poisson's ratio equal to 0.4. A note should be taken that the smear effect has been neglected through the numerical analysis, since the soil is remolded the horizontal and the vertical coefficient of permeability and coefficient of vertical consolidation assumed to be the same. Application of a vacuum pressure on the top of a saturated soft soil results in a suction pressure on the water existing between soil particles and the surface will be under a negative pore pressure. In this research vacuum pressure was modeled as a boundary condition on the soil surface and/or on the top of the *PVD* only.

6. RESULTS AND DISCUSSION

A comparison between the settlement of a fully saturated soft soil with and without PVD under -40 kPa is shown in **fig. 5.** The results show that PVD presentation increases soil settlement 200% for the same time period.

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 of the total soil depth is shown in **fig. 6a** Settlement of soil was measured by using a point gauge and also was theoretically predicted by using the software ABAQUS and a comparison between the two results is shown in **fig. 6b** It can be noticed that a good agreement was obtained between measured and predicted values of soil settlement which indicates that the software can be used with an accepted accuracy to predict settlement of soil with the presence of a vertical drain. It is obvious that the presence of an unsaturated layer decreases soil settlement. The variation of pore-water pressure with time and depth for saturated-unsaturated soil profile is presented in **Fig. 7.** It can be seen that as the thickness of the unsaturated soil layer increases pore-water pressure developed and reaching the final value of applied vacuum gets faster. **Fig. 8a through c** shows the variation of pore-water pressure with time for 24 hours of application of vacuum pressure from which it is clear that rapid variation pore-water pressure occurs through the unsaturated layer but a less appreciable variation is depicted through the fully saturated soil. Based upon the distribution of pore-water pressure, the average degree of consolidation after 30 days was found to be 75% based on the method of **Chu, and Yan, 2005**. Loading soils of stable structures increases pore-water pressure and volume of soil and vice versa; since soft soils possess structures where the volume decreases when applying vacuum loads. This reduction in the volume of soil continues until equilibrium is achieved **Chai, and Carter, 2011, and Huang F., and Wang G., 2012**. Since the degree of saturation through the unsaturated layer was 50 %, the air phase would be continuous and allows the vacuum pressure to propagate faster causing a rapid increase in pore-water pressure through unsaturated soil, **Fredlund and Rahardjo, 1993**.

Fig. 9 shows the numerical analysis results of fully saturated soils for radial variation of pore-water pressure with time from which it is obvious that the variation of pore-water pressure near the drain occurs in a very short time but it takes a longer time near the outer boundary of the model due to soil resistance.

7. CONCLUSIONS

The results of this research showed that a system of prefabricated vertical drains accompanied by the application of vacuum pressure is an effective method to accelerate the consolidation of soft soils. The pore-water pressure decreases significantly when a vacuum pressure is applied. Soil settlement was observed to decreases when an unsaturated soil layer is presence. It can be noticed that the time settlement of half depth of unsaturated soil is about 35% of that of fully saturated full depth soil profile. Pore-water pressure propagated faster in the unsaturated soil layer than in a fully saturated soil. A good agreement was found between the experimental results and the numerical analysis.

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LIST OF SYMBOLS

a_n	coefficient, 1/m
c_v^a	coefficient of consolidation with air, dimensionless
c_v^w	coefficient of consolidation with respect to water, dimensionless
c_{v1}^a	coefficient, dimensionless
c_{v1}^w	coefficient, dimensionless
C_a	interactive constants with respect air, dimensionless
C_w	interactive constants with respect to water, dimensionless
fn	coefficient, dimensionless
H	thickness of drainage path, m

k_a	coefficients of permeability with respect to air, m/sec
k_w	coefficients of permeability with respect to water, m/sec
n	ratio of radius of the axisymmetric influence zone around a single drain to radius of equivalent drain, dimensionless
u_a	pore-air pressures at any time, kPa
u_{ai}	initial pore-air, kPa
u_{atm}	atmospheric pressure, kPa
u_w	pore-water pressures at any time, kPa
u_{wi}	initial pore-water, kPa
U_a	degrees of consolidation for air, %
U_r	degree of radial consolidation, %
U_w	degrees of consolidation for water, dimensionless%
t	time, sec
T_a	time factors for air, dimensionless
T_r	time factor for radial consolidation
T_w	time factors for water, dimensionless
z	Depth below surface, m and
λ_n	Coefficient, 1/m

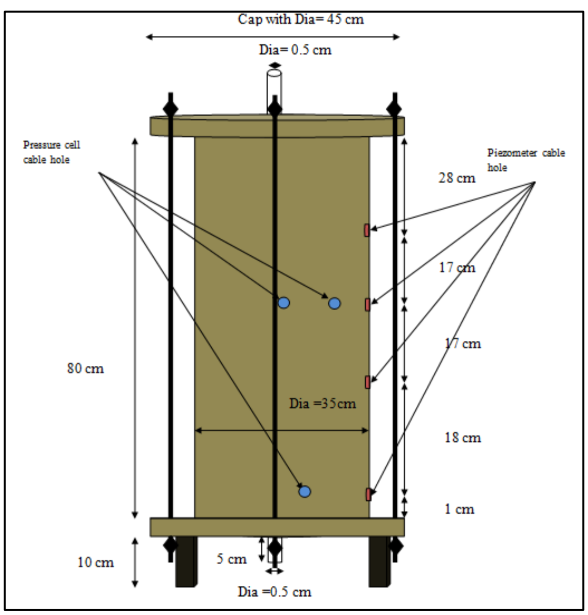


Figure 1. Schematic diagram of the designed consolidmeter cell.

Figure 2. Cap detalies of the consolidometer

(a) The vernear of the point gage (b) The point gauge placed on the top flange

Figure 3. The point gauge used in this research to measure the settlement of the soil surface.

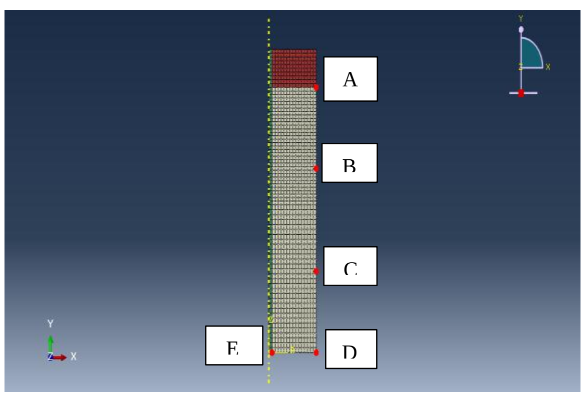


Figure 4. Saturated and unsaturated layers of soil, the mesh, and numbers of nodes used in the numerical modeling.

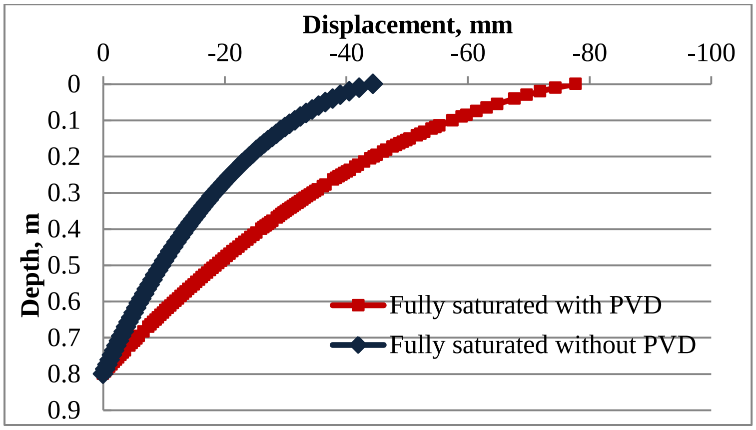
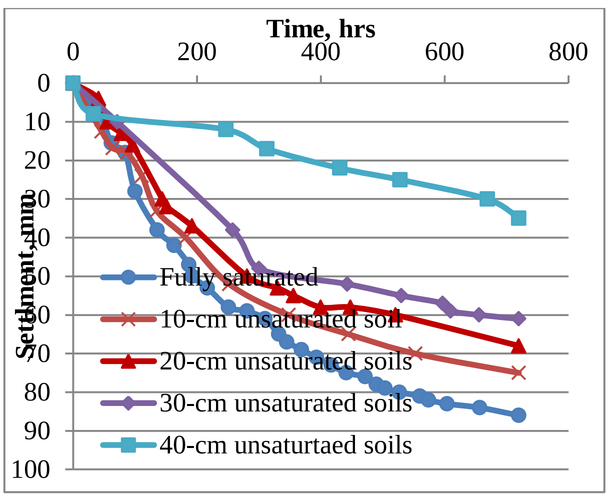
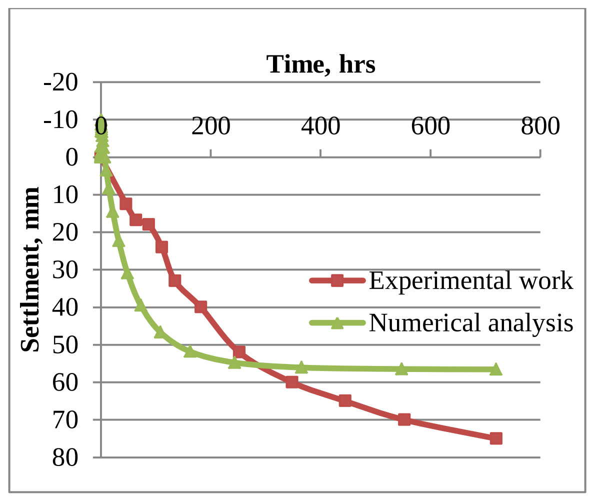


Figure 5. Comparison of soil settlement for fully saturated soils with and without PVD under -40 kPa.



(a) Settlement of soil surface after 30 days.



(b) Experimental results and numerical analysis results for 1/8 L unsaturated soil layer.

Figure 6. Comparison of settlement of soil for fully saturated soil with different depth of unsaturated layer.

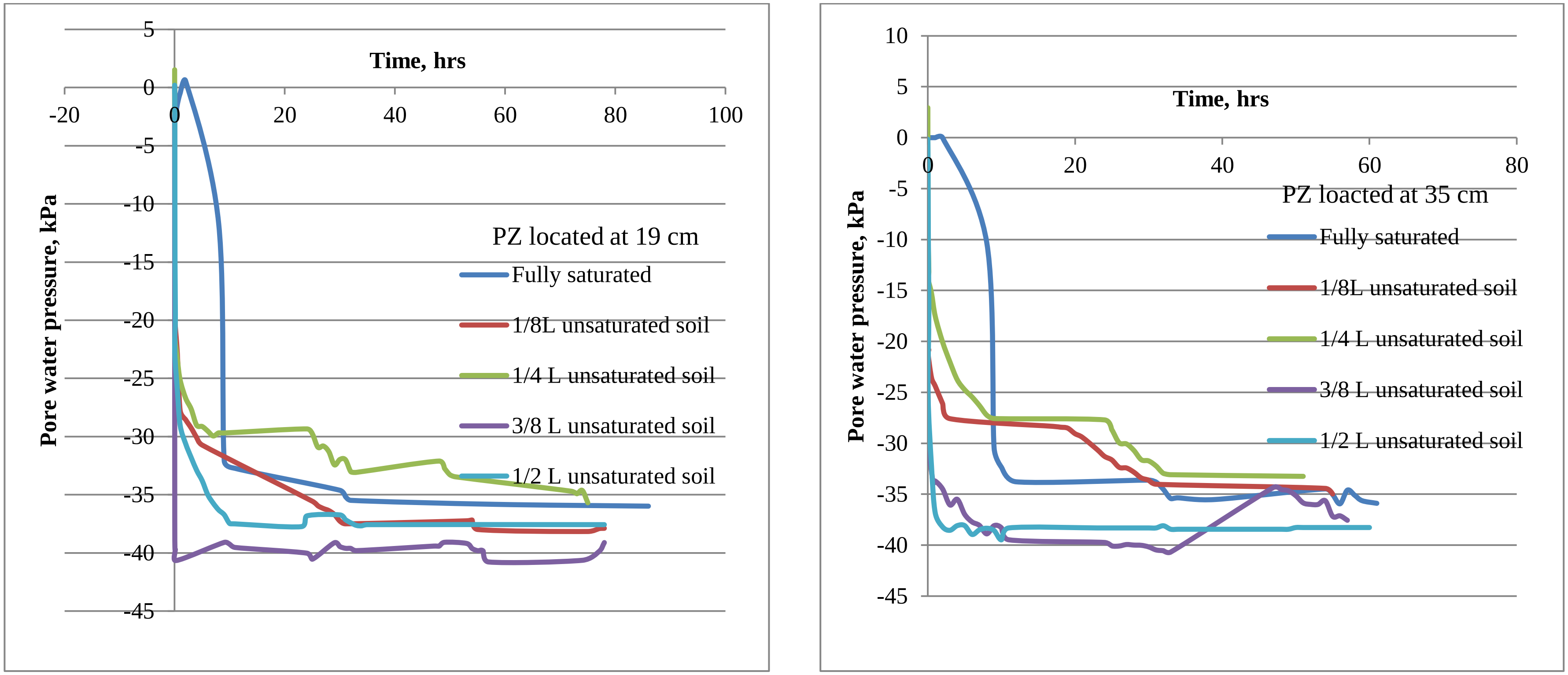
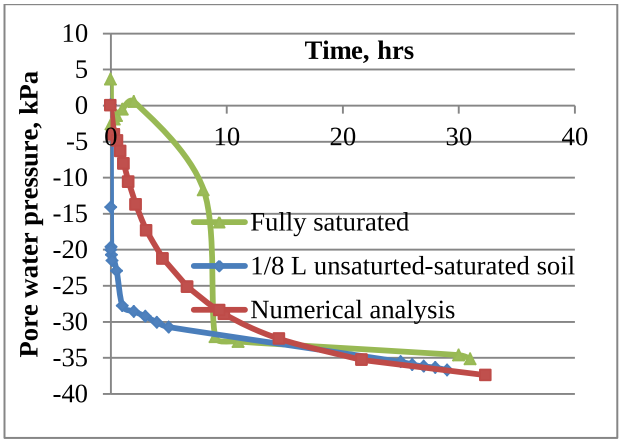
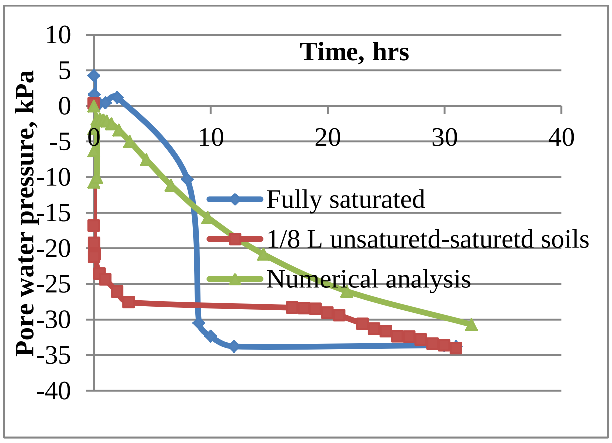


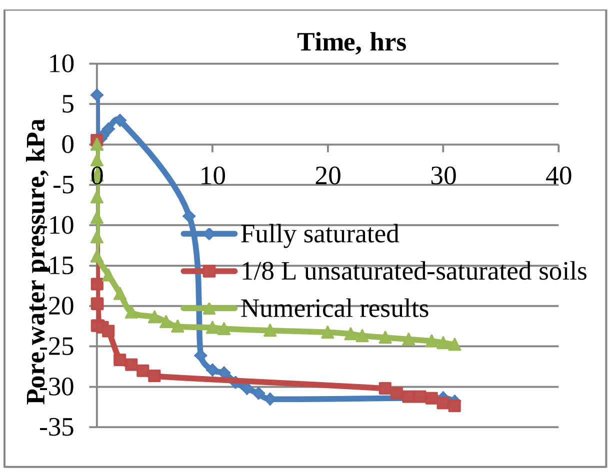
Figure 7. Variation of pore-water pressure with time for 30 hours.



(a) At point A



(b) At point B



(c) At point C

Figure 8. Comparison of variation of pore-water pressure with time for 1/8 L unsaturated soil.

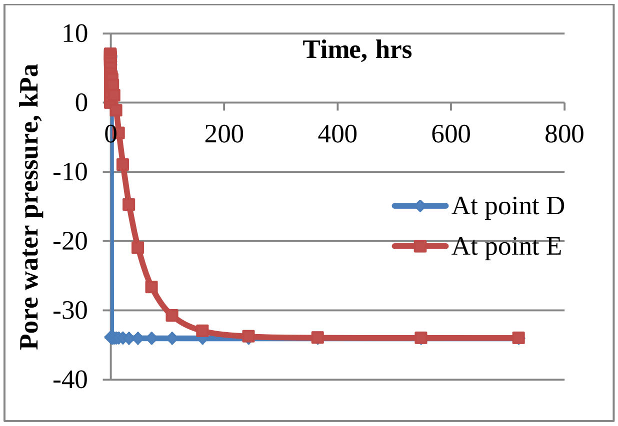


Figure 9. Numerical analysis of radial variation of pore-water pressure with time.

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

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