EFFECT OF CHANGE IN THE COEFFICIENT OF PERMEABILITY ON CONSOLIDATION CHARACTERISTICS OF CLAYS

Mohammed Y. Fattah(1) **Maysam Th. Al-Hadidi(2)**
Ahmed S. al-Shammary(2)

1) **Building and Construction Engineering Dept., University of Technoilogy, Baghdad, Iraq.**
2) **Civil Engineering Dept., College of Engineering, University of Baghdad, Iraq.**

ABSTRACT:

The settlement rate and pore water pressure dissipation rate are mainly controlled by the permeability of soil. Both laboratory and field tests show that the permeability is varied during the loading and consolidation process. It is known that consolidation process is accompanied by decrease in void ratio which leads to decrease in the coefficient of permeability. The importance of the decrease of the coefficient of permeability on the time rate of settlement and pore water pressure needs to be investigated.

This paper takes into account the change in coefficient of permeability during consolidation and studies its effect on consolidation characteristics of a clay layer. The finite element method is used in the analysis and the package Geo-Slope is adopted through coupling the programs SIGMA/W and SEEP/W. The relationship between the applied pressure and permeability was determined experimentally for three samples.

It was concluded that the effect of permeability is clear at later times of consolidation due to decrease in void ratio and hence slower dissipation of pore water pressure. Taking into account variable permeability leads to longer times of consolidation. At later times (after 400 days), the excess pore water pressure predicted for the case of variable permeability is greater than conventional case by about (10 – 12) %.

الخلاصة

ان معدل نسبةُ الهطول ومعدل تبدد ضغط الماء المسامي يمكن ان يسَيْطَر عليه بشكل رئيسي من خلال نفاذيةِ التربةِ. وقد اظهرت كلتا إلاختبارات الحقلية والمختبرية أنّ النفاذية متغيرة أثناء عمليةِ التحميل والانضمام، ومن المعروف ايضاً بأنّ عمليةِ الانضمام تكون مصحوبة بنقصانِ في نسبةِ الفراغات و التي تُؤدّي إلى تغيير في معاملِ النفاذيةِ، لذا وجد مَنْ الضَّرُوري أنْ يُتم التحري عن تاثير نقصانِ معاملِ النفاذيةِ على المعدل الزمني للهبوط وضغطِ الماءِ المسامي.

لذلك في هذا البحثِ تم دراسة تاثير التغييرَ في معاملِ النفاذيةِ أثناء عملية الانضمام على معاملات الانضمام في التربة الطينية، حيث تم استعمال طريقة العناصرِ المحددةِ في التحليلِ والبرنامجين المسميين SIGMA/W و SEEP/W و التي يمكن من خلالهما حساب ذلك التاثير من خلال اعتماد العلاقة بين الضغطِ والنفاذيةِ الموجودة ضمنيا في هذين البرنامجين ولثلاث عينات .

إستنتجَ بأنّ تأثيرَ النفاذيةِ يمكن ملاحظته بشكل اكثر وضوحاً خلال الفترة التي تلت 400 يوم من تسليط الاحمال بسبب النقصان في نسبةِ الفراغات والتبدد البطيئ في ضغطِ الماءِ المسامي. اخذين في الحسبان ان النفاذيةِ المتغيّرة تقود الى زيادة في وقت الانضمام .كما وجد ان ضغط الماءِ المسامِي الفائضِ في حالة النفاذيةِ المتغيّرةِ اكبر مِنْ الحالةِ التقليديةِ بحوالي (10 – 12) %.

Keywords: Consolidation, coefficient of permeability, settlement, pore water pressure.

INTRODUCTION

Consolidation is generally related to fine-grained soils such as silts and clays. Since water can flow out of a saturated soil in any direction, the process of consolidation is essentially three-dimensional. However, in most field situations, water will not be able to flow out of the soil by flowing horizontally because of the vast expanse of the soil in horizontal direction. Therefore, the direction of flow of water is primarily vertical or one-dimensional. As a result, the soil layer undergoes one-dimensional (1-D) consolidation settlement in the vertical direction.

Consolidation theory is required for the prediction of both the magnitude and the rate of consolidation settlements to ensure the serviceability of structures founded on a compressible soil layer. Terzaghi's theory of 1-D consolidation makes the following assumptions including that the soil is homogeneous and fully saturated, the solid particles and the pore water are incompressible, the flow of water and compression of soil are one-dimensional (vertical), strains are small, Darcy's law is valid at all hydraulic gradients, but the most important assumption is that the coefficient of permeability and the coefficient of volume compressibility remain constant throughout the consolidation process. Terzaghi gave a theory of soil consolidation based on the effective stress principle, which was derived on several ideal assumptions to get a simplified theory. To avoid the limitations involved in Terzaghi's theory, many efforts are being made by scholars to solve the problems in practical engineering situations.

It is known that consolidation process is accompanied by decrease in void ratio which leads to decrease in the coefficient of permeability. Effect of the decrease of the coefficient of permeability on the time rate of settlement and pore water pressure needs to be investigated. Cavalcante and Assis (2002) showed the influence of the permeability gradient during the construction of tailings dams, built by the upstream method, using the hydraulic fill technique. During the hydraulic disposition, two mechanisms affect the tailings permeability: the hydraulic segregation and the consolidation due to the staged construction procedure. These mechanisms influence considerably the permeability distribution along the fill and, consequently, the behaviour of the dam. Results show that the pore pressure immediately after deposition may reach quite high values (532 kPa), but dissipates in a short period of time (1 to 10 days). Then, this effect should be taken into account in a short-term stability analysis of tailings dams. On the other hand, after pore pressure dissipation, there is a gain in the shear strength (13 %), which should also be considered, but in a long-term stability analysis of tailings dams.

The settlement rate and pore water pressure dissipation rate are mainly controlled by the permeability of soil. Both laboratory and field tests show that the permeability is varied during the loading and consolidation process. The formula proposed by Taylor (1948) and verified by Tavenas et al. (1983) can be used to represent variation of the permeability of soft clay during the consolidation:

$$\boldsymbol{k = k_o \cdot 10^{\left[-\frac{(e_o - e)}{c_k}\right]}} \qquad (1)$$

where: e_o : the initial void ratio,
e : the void ratio at the condition under consideration,
k : the permeability,
k_o : the initial permeability, and
c_k : constant which is equal to 0.5 e_o (Tavenas et al., 1983).

A semi-analytical solution was presented by Ying et al. (2005) for the case of void ratio *e*-log effective stress *p* and *e*-log permeability conductivity *k*v, especially. The semi-analytical results were compared with those obtained from experimental investigations with a set of advanced consolidation system. Furthermore, the behavior of nonlinear consolidation of soils is analyzed and the differences between the semi-analytical results and Davis's nonlinear theory were discussed. It was concluded that the semi-analytical solution is a very effective method for solving the difficult consolidation problems taking varied compressibility and permeability into account. The degree of consolidation defined by effective stress and by settlement is different in this method. The advanced consolidation system with back pressure is an effective method for analyzing the consolidation behavior of clay. Fairly good agreement exists between theoretical results and the consolidation test results.

This paper takes into account the change in coefficient of permeability during consolidation and study its effect on consolidation characteristics of a clay layer.

DESCRIPTION OF THE PROBLEM:

The problem consists of tracing the settlement and pore water pressure changes in a clay layer under the effect of uniformly distributed load 80 kN/m^2. The finite element method is used in the analysis and the package Geo-Slope is adopted through coupling the programs SIGMA/W and SEEP/W.

LABORATORY WORK:

In order to define the coefficient of permeability as a function of the applied pressure, a testing program was planned on samples taken from three sites located in Baghdad city. These soil samples are named by S_1, S_2 and S_3.

The identification and classification tests included grain size distribution, Atterberg limits and specific gravity. Table 1 shows the index properties of the soils from the three sites.

Consolidation test was carried out on undisturbed soil samples according to the specification of ASTM D-2435-02. For each load increment, the coefficient of consolidation, c_v, was calculated using Casagrande's procedure in addition to the coefficient of volume change, m_v. Then the coefficient of permeability, k, was calculated according to the following relation:

$$k = m_v \, . c_v \, . \gamma_w \qquad (2)$$

where γ_w is the unit weight of waater.

The relationship between the applied pressure and permeability is plotted for each sample as shown in Figure 1.

FINITE ELEMENT ANALYSIS:

SIGMA/W is a finite element software product that can be used to perform stress and deformation analyses of earth structures. Its comprehensive formulation makes it possible to analyze both simple and highly complex problems. For example, one can perform a simple linear elastic deformation analysis or a highly sophisticated nonlinear elastic-plastic effective stress analysis. When coupled with SEEP/W (another GEO-SLOPE software product), it can also model the pore-water pressure generation and dissipation in a soil structure in response to external loads. SIGMA/W has application in the analysis and design for geotechnical, civil, and mining engineering projects.

Hydraulic Conductivity Functions

Analyzing saturated seepage processes requires establishing the hydraulic conductivity versus pore-water pressure relationship. In the case of a transient analysis, the volumetric water content function must also be defined. Both of these functions can be either measured directly in the laboratory or predicted using a variety of methods. The volumetric water content function can be predicted from the grain-size distribution curve and the hydraulic conductivity function can be predicted using the volumetric water content function and the measured saturated hydraulic conductivity.

The capacity of soil to conduct water can be viewed in terms of hydraulic conductivity (or the coefficient of permeability). The hydraulic conductivity is dependent on the water content. Since the water content is a function of pore-water pressure and the hydraulic conductivity is a function of water content, it follows that hydraulic conductivity is also a function of pore-water pressure. Figure 2 presents the form of the relationship between hydraulic conductivity and pore-water pressure. This relationship is known as a conductivity function.

The variation of hydraulic conductivity with pore-water pressure makes the finite element equations nonlinear, and an iterative process is consequently required to solve the equations. Hydraulic head (pore-water pressure plus elevation) is the primary unknown computed. Since the hydraulic conductivity is related to hydraulic head, the appropriate hydraulic conductivity is dependent on the computed results. During transient processes, the amount of water entering an elemental volume of soil may be larger than the amount of water exiting the volume, or vice versa. This results in a certain amount of water either being retained or released during a particular time increment.

Elastic-Plastic Model

The eastic-plastic model describes an elastic, perfectly-plastic relationship. Stresses are directly proportional to strains until the yield point is reached. Beyond the yield point, the stress-strain curve is perfectly horizontal.

Plastic Matrix, Elastic-Plastic Model

In SIGMA/W, soil plasticity is formulated using the theory of incremental plasticity (Hill, 1950). Once an elastic-plastic material begins to yield, an incremental strain can be divided into elastic and a plastic component.

Only elastic strain increments, $d\varepsilon^e$, will cause stress changes. As a result, stress increments can be written as follows.

$$\{d\sigma\} = [C_e]\ \{d\,\varepsilon^e\} \tag{3}$$

Consequently, the yield function can be written as follows in equation form.

$$F = F(\sigma_x, \sigma_y, \sigma_z, \tau_{xy}) \tag{4}$$

An incremental change in the yield function is given by:

$$dF = \frac{\partial F}{\partial \sigma_x} d\sigma_x + \frac{\partial F}{\partial \sigma_y} d\sigma_y + \frac{\partial F}{\partial \sigma_z} d\sigma_z + \frac{\partial F}{\partial \tau_{xy}} d\tau_{xy} \tag{5}$$

Alternatively, this equation can be written in the following matrix form.

$$dF = \left\langle \frac{\partial F}{\partial \sigma} \right\rangle \{d\sigma\} \tag{6}$$

The theory of incremental plasticity dictates that the yield function, $F < 0$, and, when the stress state is on the yield surface, dF is zero. This latter condition is termed the neutral loading condition, and, can be written mathematically as:

$$dF = \left\langle \frac{\partial F}{\partial \sigma} \right\rangle \{d\sigma\} = 0 \tag{7}$$

The plastic strain is postulated to be:

$$\{d\,\varepsilon_p\} = \lambda \left\{ \frac{\partial G}{\partial \sigma} \right\} \tag{8}$$

Where:

G = plastic potential function, and

λ = plastic scaling factor.

Substituting the plastic strain from equation (8) into the incremental stress equation (equation 3) gives

$$\{d\sigma\} = [C_e]\{d\varepsilon\} - [C_e]\lambda\left\{\frac{\partial G}{\partial \sigma}\right\} \tag{9}$$

Substituting the stress vector, {ds}, into the neutral loading condition (equation 6), the following expression for the plastic scaling factor, λ, can be derived.

$$dF = \left\langle\frac{\partial F}{\partial \sigma}\right\rangle[C_e]\{d\varepsilon\} - \left\langle\frac{\partial F}{\partial \sigma}\right\rangle[C_e]\,\lambda\left\{\frac{\partial G}{\partial \sigma}\right\} = 0 \tag{10}$$

$$\lambda = \frac{\left\langle\frac{\partial F}{\partial \sigma}\right\rangle[C_e]}{\left\langle\frac{\partial F}{\partial \sigma}\right\rangle[C_e]\left\{\frac{\partial G}{\partial \sigma}\right\}}\{d\varepsilon\}$$

From equations (8) and (10), a relationship between stress increments and strain increments can be obtained.

$$\{d\sigma\} = \left([C_e] - [C_p] \right)\{d\varepsilon\} \tag{11}$$

Where:

$$[C_p] = \frac{[C_e]\left\{\frac{\partial G}{\partial \sigma}\right\}\left\langle\frac{\partial F}{\partial \sigma}\right\rangle[C_e]}{\left\langle\frac{\partial F}{\partial \sigma}\right\rangle[C_e]\left\{\frac{\partial G}{\partial \sigma}\right\}} \tag{12}$$

To evaluate the plastic matrix, [Cp], the yield function, F , and the plastic potential function, G , need to be specified.

The following equation provides a common form of the Mohr-Coulomb criterion expressed in terms of principal stresses (Chen and Zhang, 1991).

$$F = \sqrt{J_2}\sin\left(\theta + \frac{\pi}{3}\right) - \sqrt{\frac{J_2}{3}}\cos\left(\theta + \frac{\pi}{3}\right)\sin\phi - \frac{I_1}{3}\sin\phi - c\cos\phi \tag{13}$$

Figure 3 shows the finite element mesh used in this case. A layer of clay 25 m thick is modeled. The water table is assumed to be at the ground level. Eight node isoparametric elements are used. Due to symmetry, only half of the axi-symmetric problem is considered. The right and left boundaries are allowed to move vertically, while the bottom boundary is restrained both horizontally and vertically.

Analysis Results:

Finite element analysis was carried out for two cases; in the first case, the coefficient of permeability is considered constant during the consolidation process while in the second case, the coefficient of permeability is changed with the applied pressure (effective stress) during consolidation. Figure 4 shows a comparison of the total surface settlement calculated after 1000 days for the two cases. It can be noticed that the maximum effect of permeability occurs below the center of the problem. A decrease in the maximum surface settlement of the order of (12 - 15) % can be predicted when the permeability change is considered. Another comparison is made in Figure 5 at time 450 days. The figures show that during consolidation, the effect of permeability is clear, then the difference decreases at the end of consolidation (after 1000 days).

The same results are also noticed in Figure 6 which displays the percent of settlement at the end of load application to the final (total) consolidation settlement.

Figure 7 shows the distribution of the final consolidation settlement with depth along the centerline. It can be noticed that the effect of change of the permeability increases with depth. The maximum difference between the settlements predicted in these cases is in the percentage of (16 - 22) %. Similar relations are shown in Figure 8 after 450 days of consolidation, but also the difference between the two cases is greater at middle periods of consolidation, and then decreases at the end.

Figure 9 presents the variation of horizontal displacement along sec. (a-a), (shown in Figure 3), 5 meters away from the problem centerline. It can be noticed that the effect of changing the coefficient of permeability is pronounced at the ground surface and a difference of about (12 - 14) can be noticed. Similar results are presented in Figure 10 which shows that the effect of permeability is greater at time 450 days.

The effect of permeability on the time rate of settlement is explained in terms of consolidation ratio (degree of consolidation) as shown in Figure 11. The degree of consolidation of the clay layer at any time is calculated as the ratio between the excess pore water pressures dissipated at that time to the initial excess pore water pressure. It is evident that the effect of permeability is clear at later times of consolidation due to decrease in void ratio and hence slower dissipation of pore water pressure. Taking into account variable permeability leads to longer times of consolidation.

Figure 12 traces the dissipation of pore water pressure at point (a) 12 m deep with time. It is noticed that the pore water pressure predicted in the case of variable permeability is greater than in conventional constant permeability case due to smaller rate of dissipation.

Figure 13 shows the isochrones of excess pore water pressure at different times. At early stages, the effect of permeability is not clear, while at later times (after 400 days), the excess pore water pressure predicted for the case of variable permeability is greater than conventional case by about (10 – 12) %.

CONCLUSIONS:

1. The maximum effect of permeability occurs below the center of the problem. A decrease in the maximum surface settlement of the percentage of (12 - 15) % can be predicted when the permeability change during consolidation is considered.
2. The effect of permeability is clear at later times of consolidation due to decrease in void ratio and hence slower dissipation of pore water pressure. Taking into account variable permeability leads to longer times of consolidation. At later times (after 400 days), the excess pore water pressure predicted for the case of variable permeability is greater than conventional case by about (10 – 12) %.

REFERENCES

- ASTM D2435, (2002), “Standard Test Methods for One-Dimensional Consolidation Properties of Soils,” Annual Book of ASTM Standards, Vol. 04.08, ASTM International, West Conshohocken, PA, pp. 1–10.
- Cavalcante, L. B., Assis, A. P., (2002), “Effects of Nonhomogenity of Permeability on Tailings Dams “, International Journal of Mining, Reclamation and Environment, Volume 16, Issue 4 , pp. 314 – 330.
- Chen, W.F., Zhang, H., (1991), “Structural Plasticity: Theory, Problems, and CAE Software”, Springer-Verlag.
- Hill, R., (1950), “The Mathematical Theory of Plasticity”, Oxford University Press.
- Tavenas, F., Jean, P., Leblond, P., and Leroueil, S. (1983), “The Permeability of Natural Soft Clays, Part II: Permeability Characteristics”, Canadian Geotechnical Journal, Vol. 20, pp. 645-660.
- Taylor, D. W., (1948), “Fundamentals of Soil Mechanics”, John Wiley and sons.

- User's Guide Manual of SIGMA/W, (2002), GEO-SLOPE International Ltd, Calgary, Alberta, Canada.
- Ying, Z., Kang, X., Xi, L., (2005), “Nonlinear Analysis of Consolidation with Variable Compressibility and Permeability”, Journal of Zhejiang University SCIENCE, Vol. 6A, No. 3, pp.181-187, http://www.zju.edu.cn/jzus.

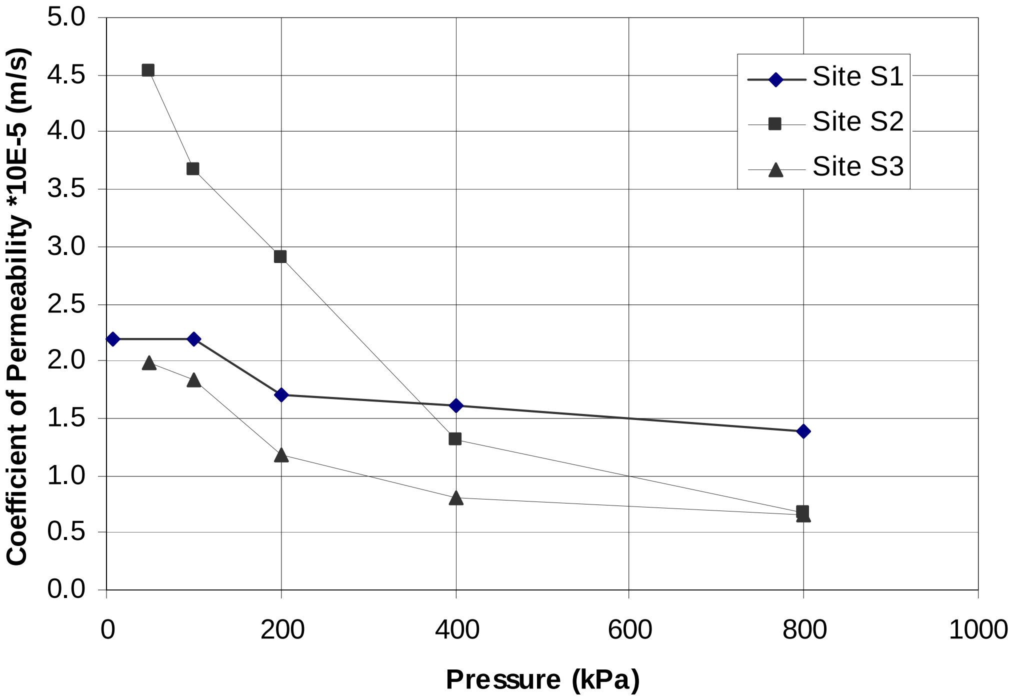


Fig.(1) Variation of the coefficient of permeability with pressure for the three soils.

Table 1: Index properties of the three soils.

Property	Soil 1	Soil 2	Soil 3
Initial water content %	23.90	25.12	25.64
Liquid limit	56	56	50
Plastic limit	25	23	24
Plasticity index	31	33	26
Specific gravity	2.79	2.80	2.79
% fines (Silt + clay)	98	97	81
Cohesion (kN/m^2)	118.0	177.0	93.23
Angle of friction (degrees)	0	0	0
Soil Description	Gray to brown silty clay stiff to very stiff	Brown to gray stiff clay	Brown silty clay ,stiff

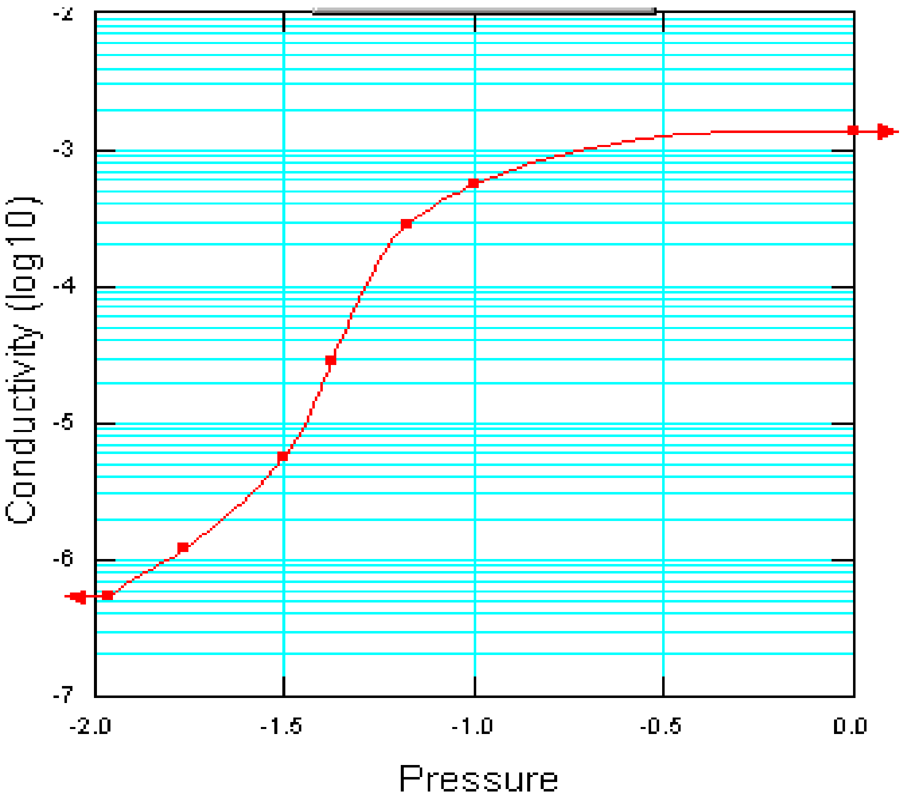


Fig. 2: A typical hydraulic conductivity function (SIGMA/W Manual, 2002).

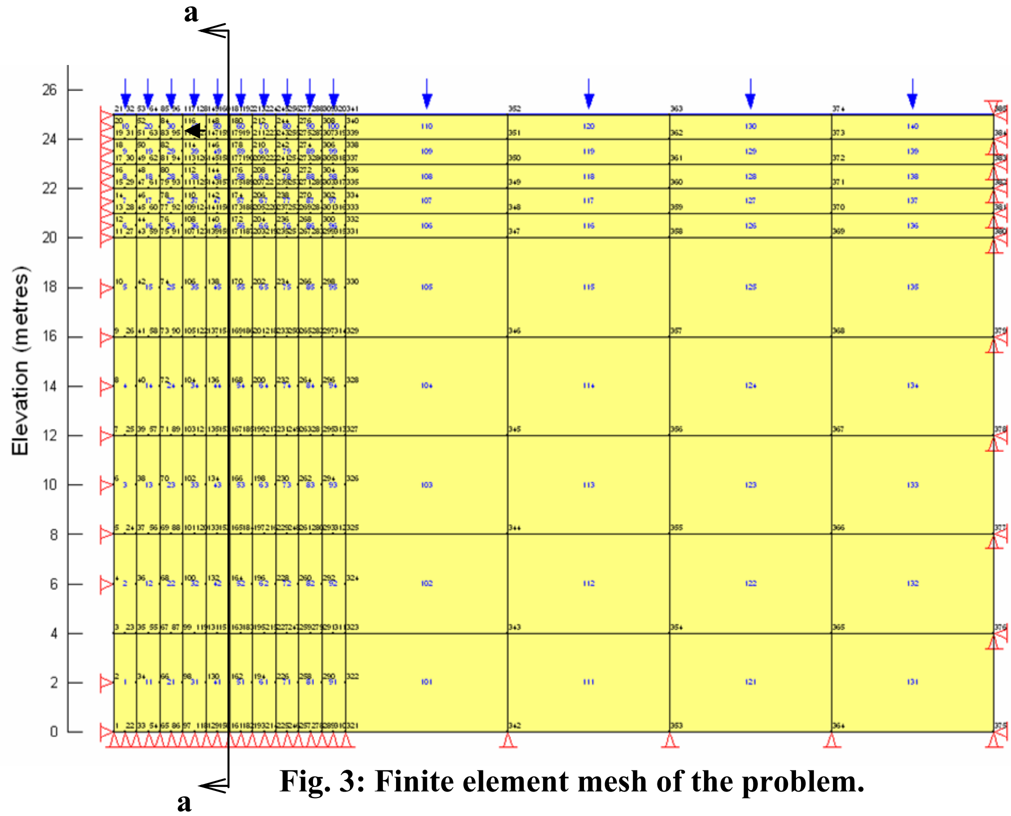
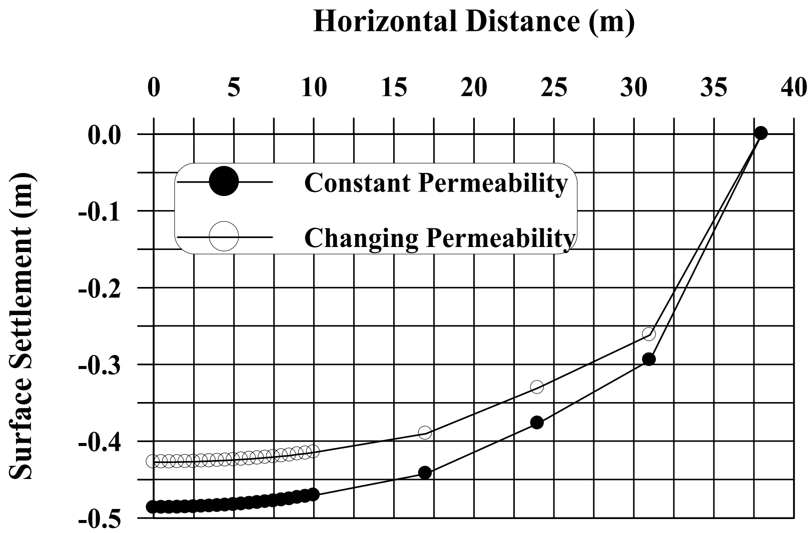
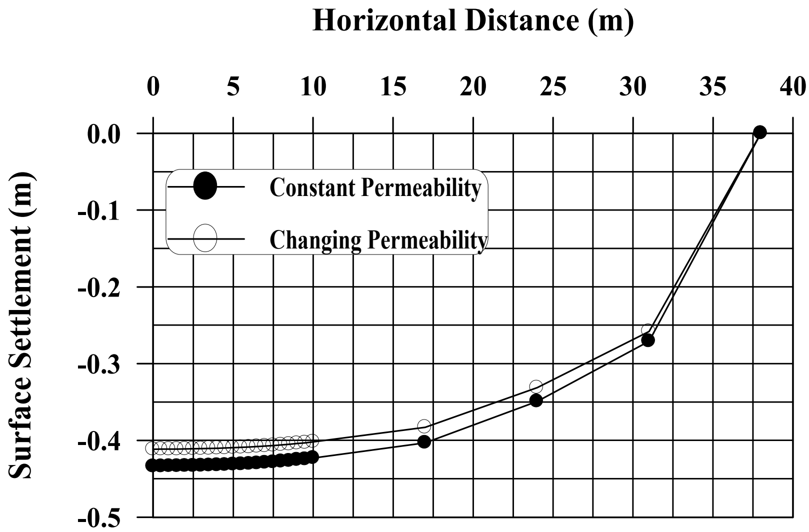


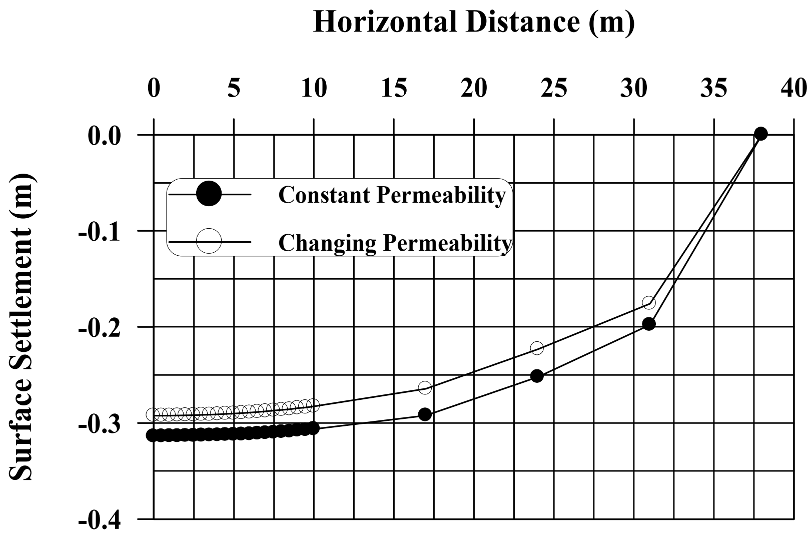
Fig. 3: Finite element mesh of the problem.



a. Site S1

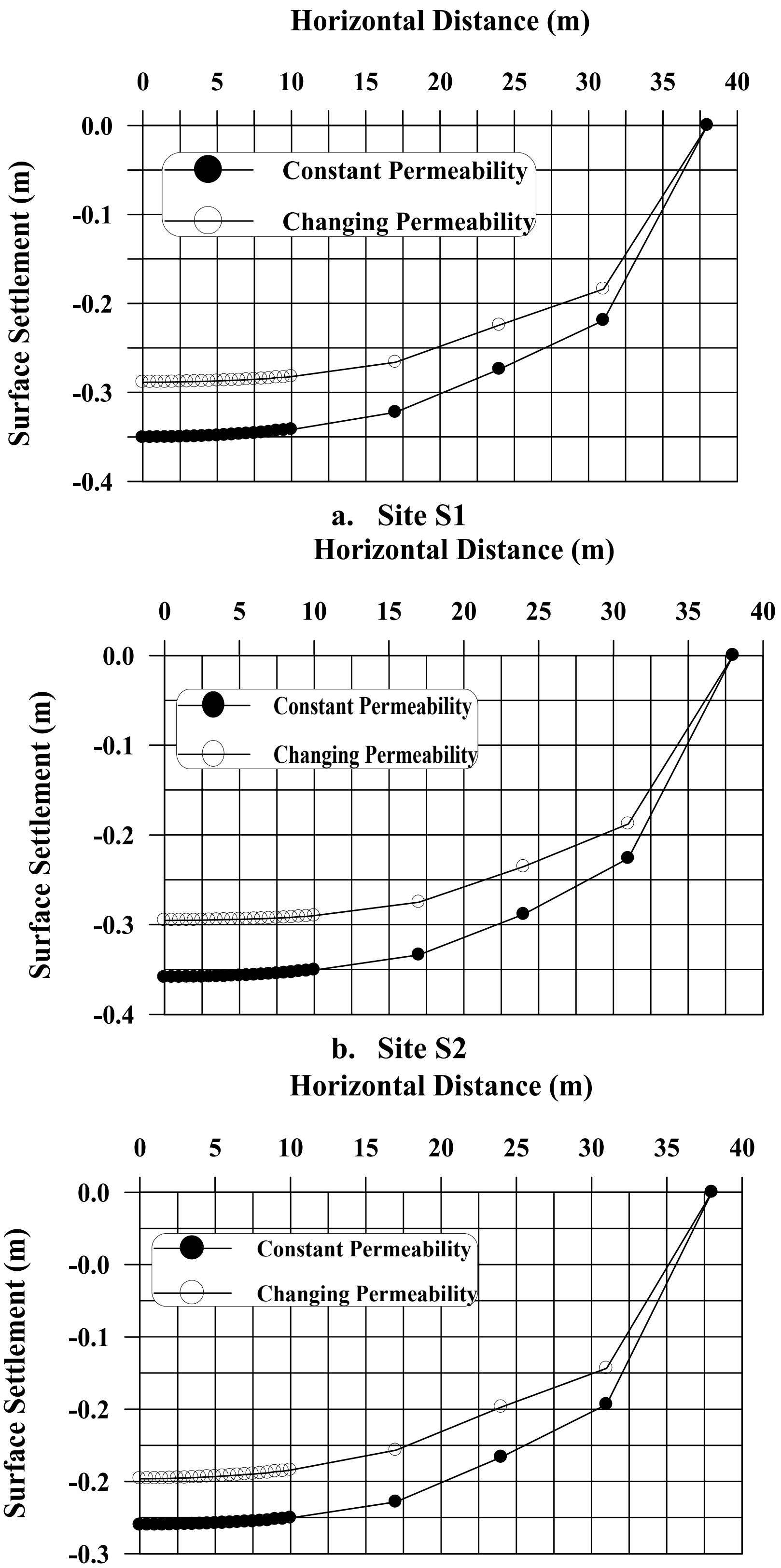


b. Site S2



c. Site S3

Fig. 4: Effect of different conditions of permeability on the surface settlement at the end of consolidation (1000 days).

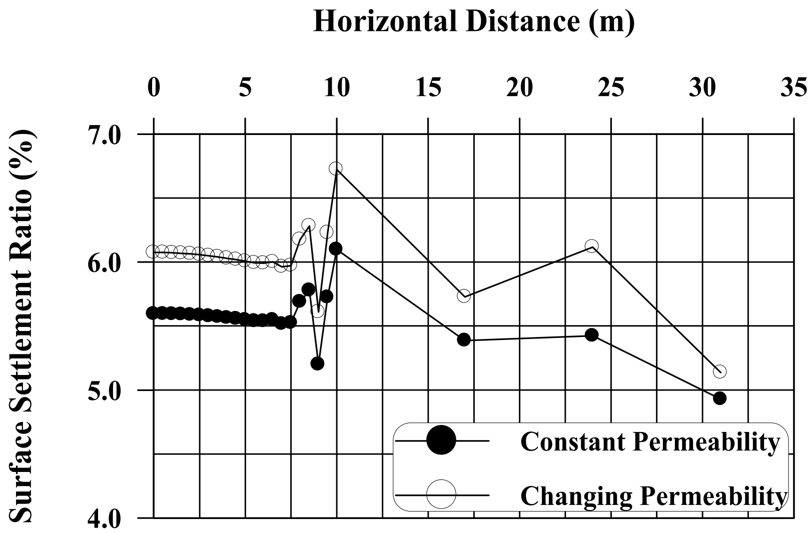


a. Site S1

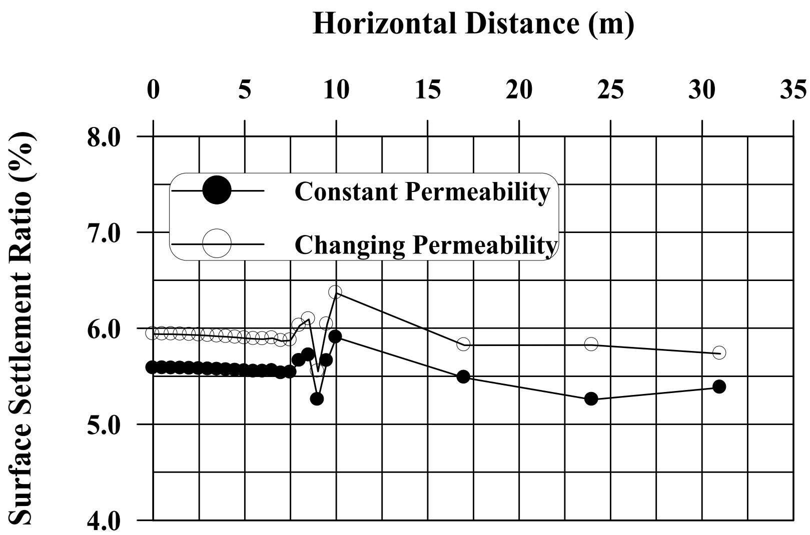
b. Site S2

c. Site S3

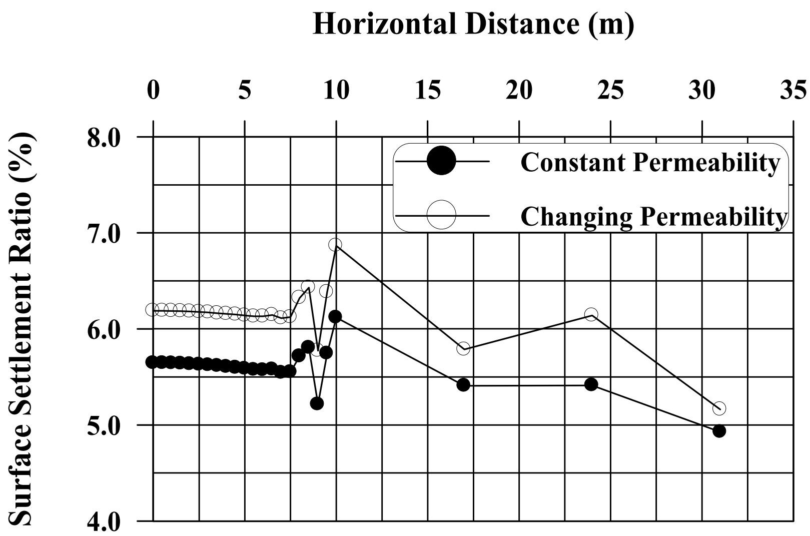
Fig.5: Effect of different conditions of permeability on the surface settlement at (450 days).



a. Site S1

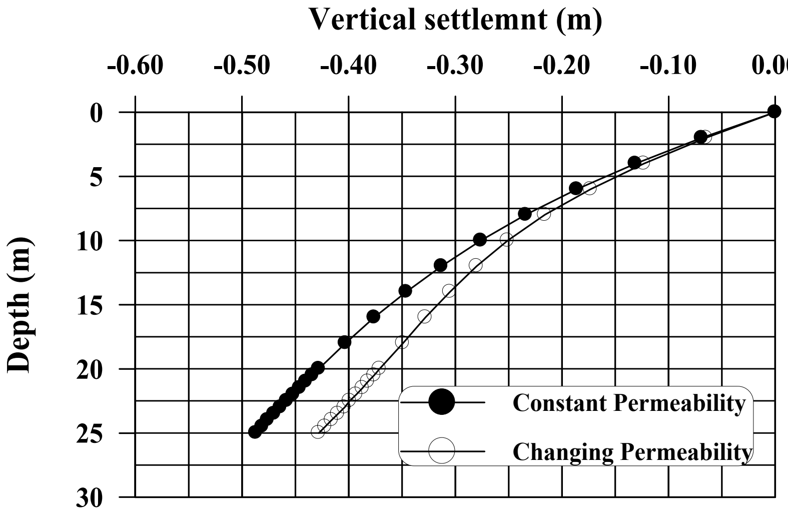


b. Site S2

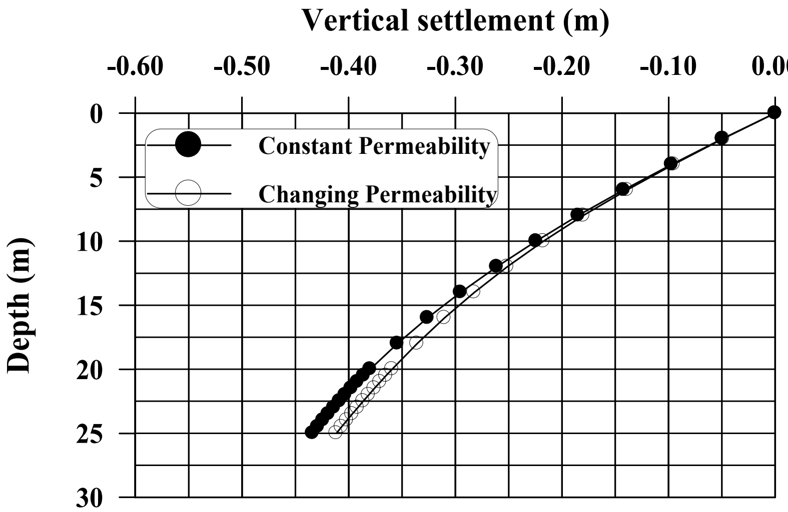


c. Site S3

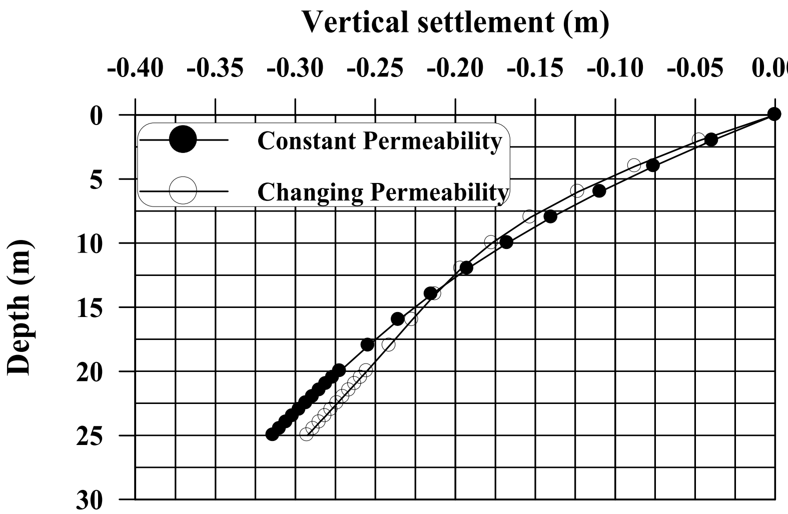
Fig. 6: Effect of different conditions of permeability on the surface settlement.



a. Site S1

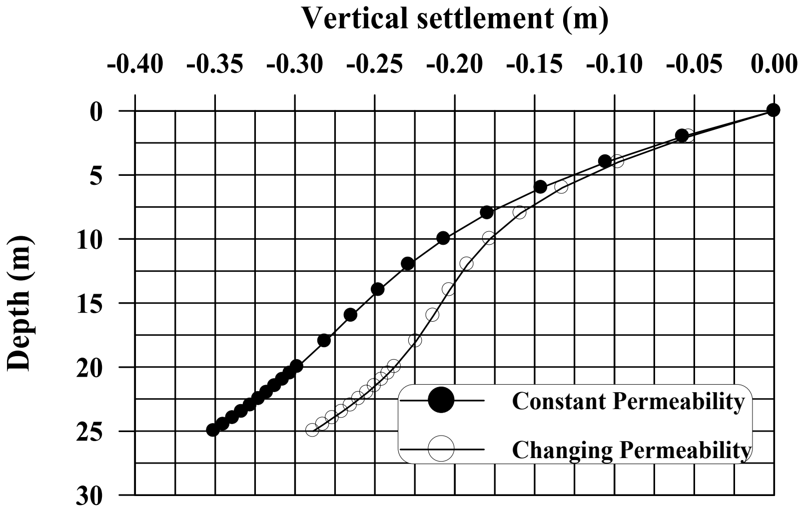


b. Site S2

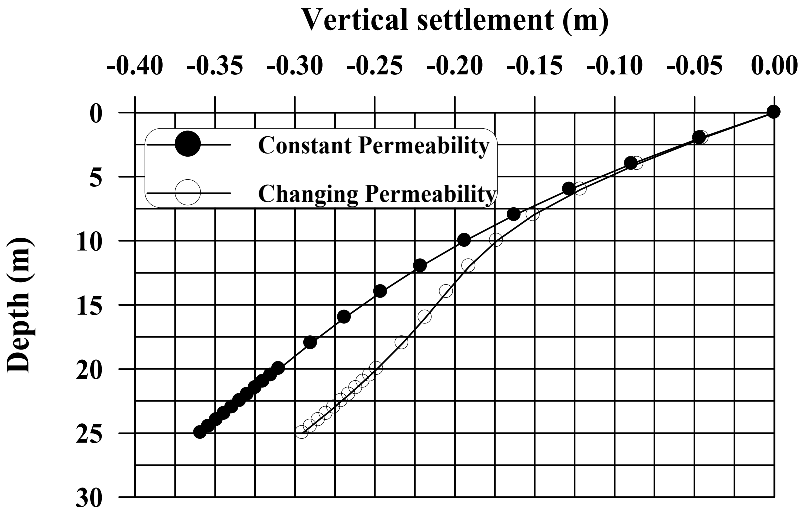


c. Site S3

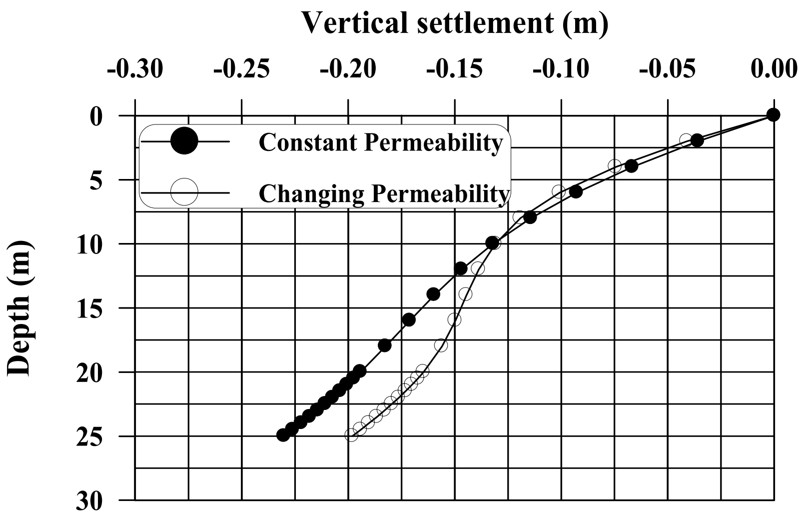
Fig. 7: Variation of vertical displacement along the foundation centerline at the end of consolidation (1000 days).



a. Site S1



b. Site S2



c. Site S3

Fig. 8: Variation of vertical displacement along the foundation centerline at (450 days).

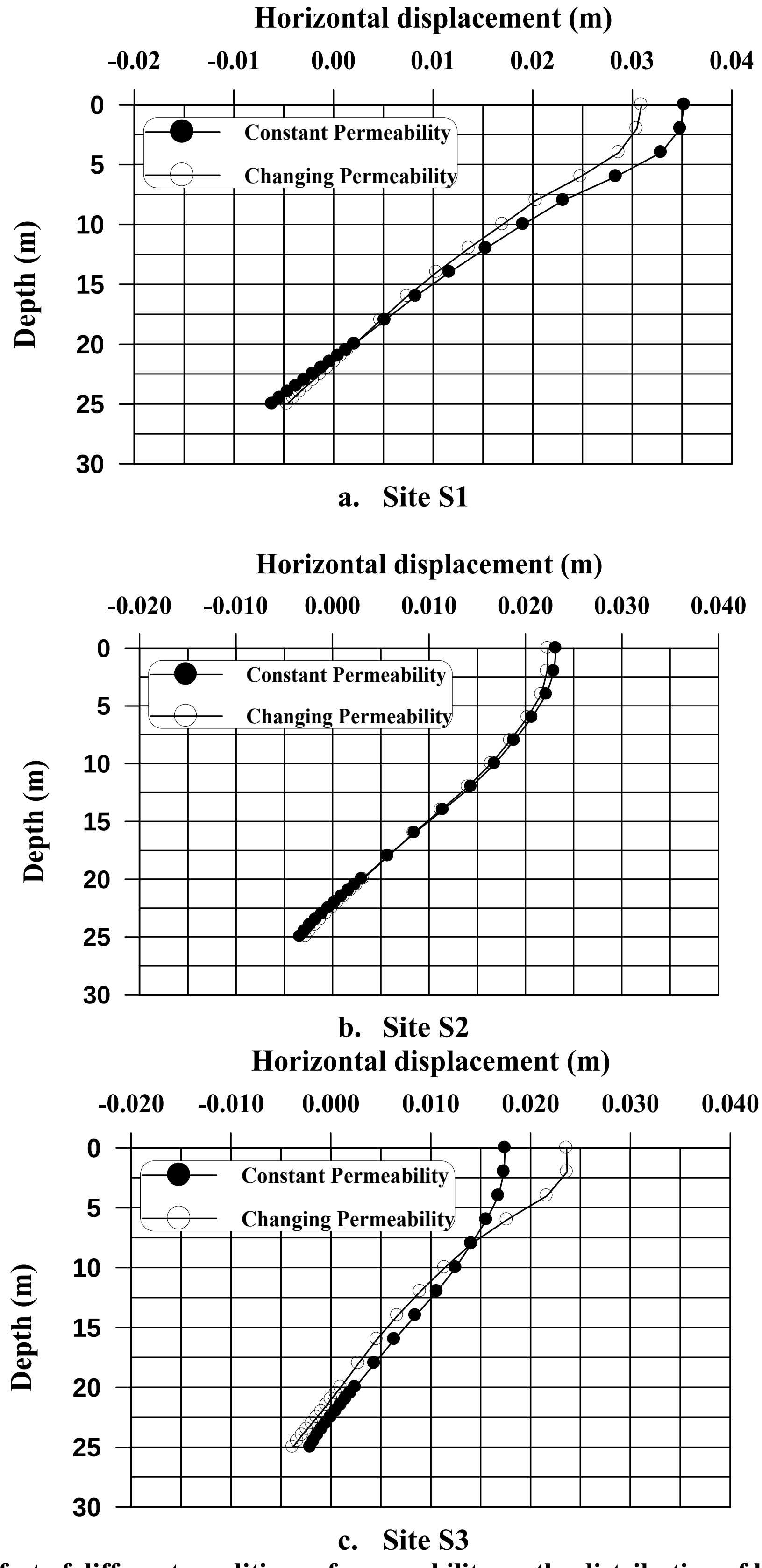
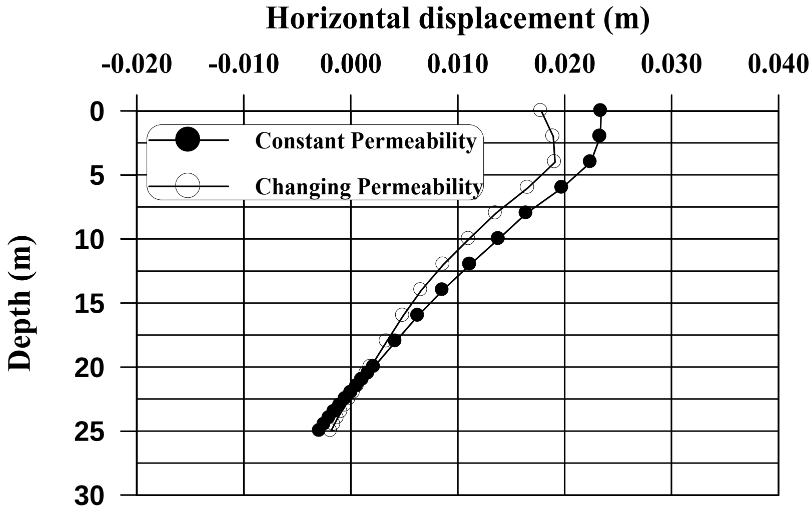
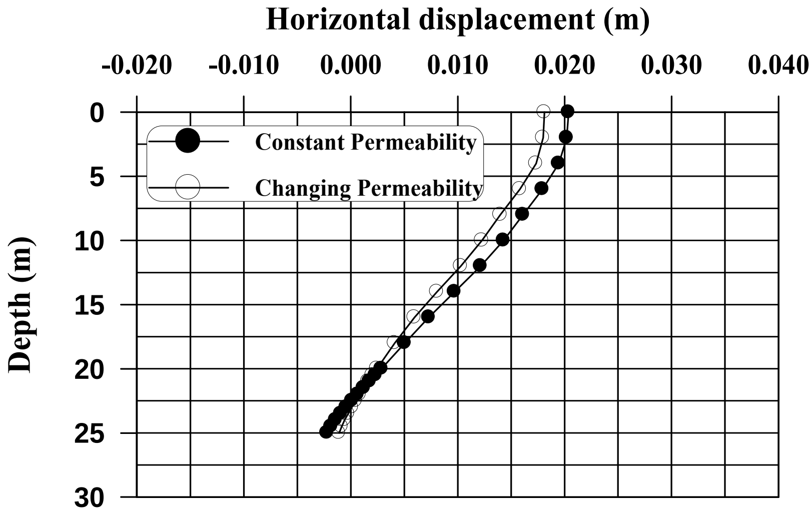


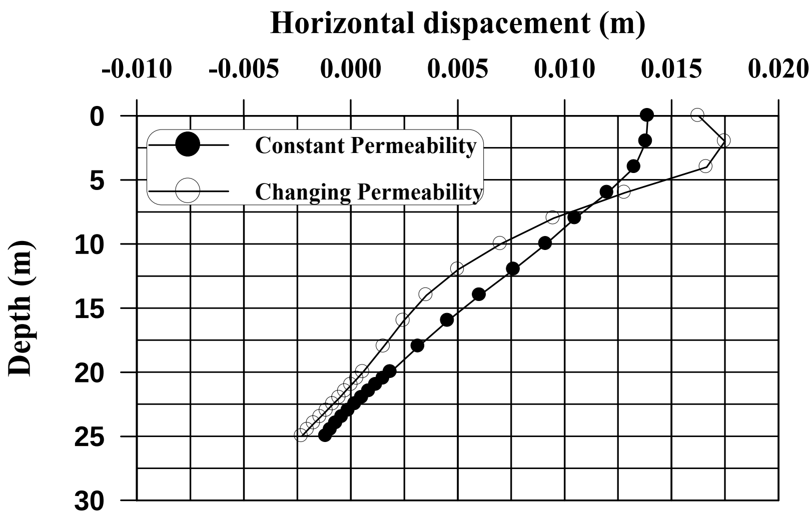
Fig. 9: Effect of different conditions of permeability on the distribution of horizontal displacement with depth along the foundation centerline at the end of consolidation (1000 days).



a. Site S1

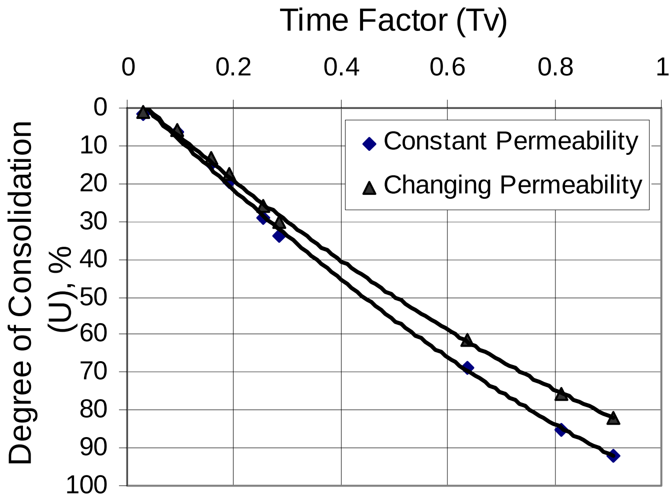


b. Site S2

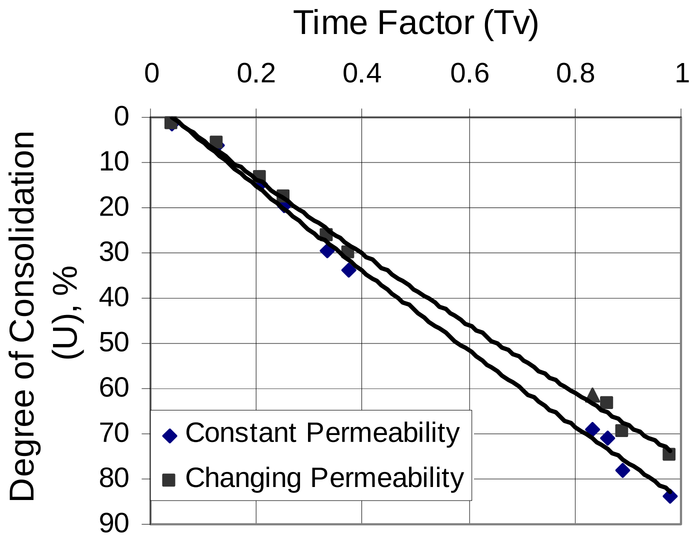


c. Site S3

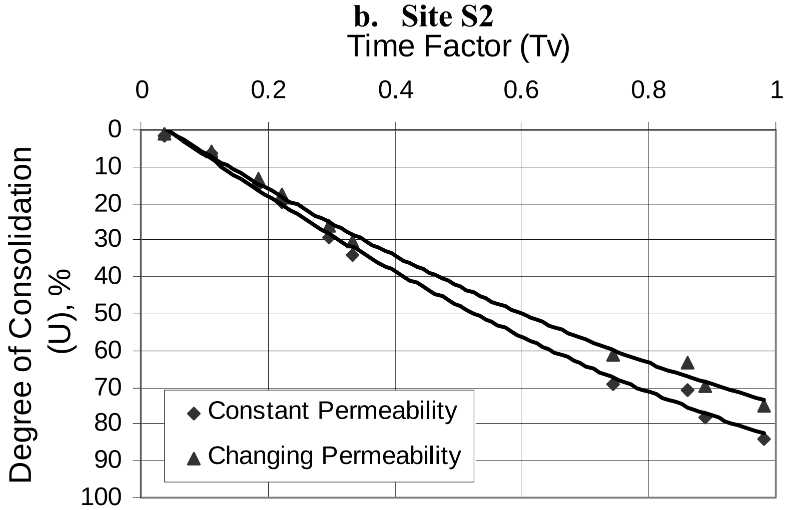
Fig. 10: Effect of different conditions of permeability on the distribution of horizontal displacement with depth along the foundation centerline at (450 days).



a. Site S1

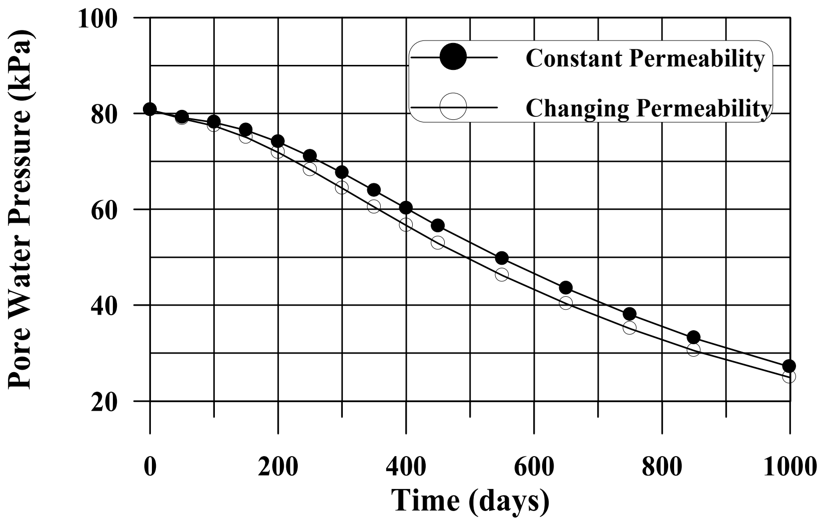


b. Site S2

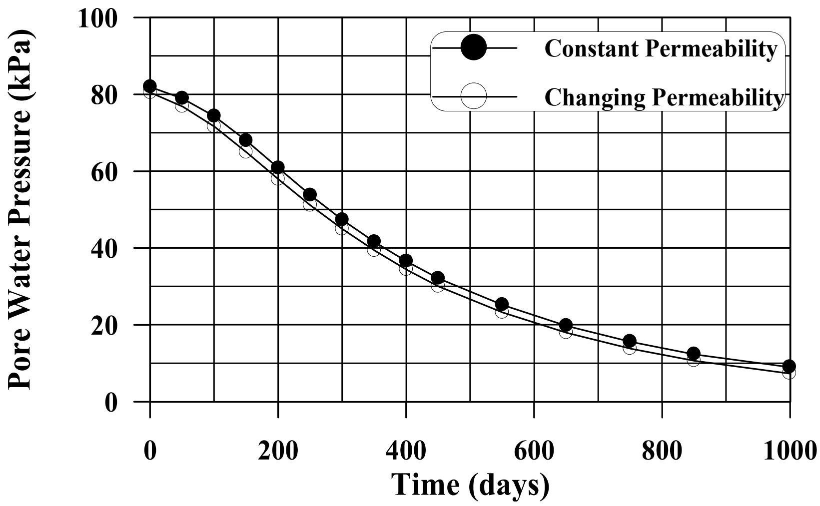


c. Site S3

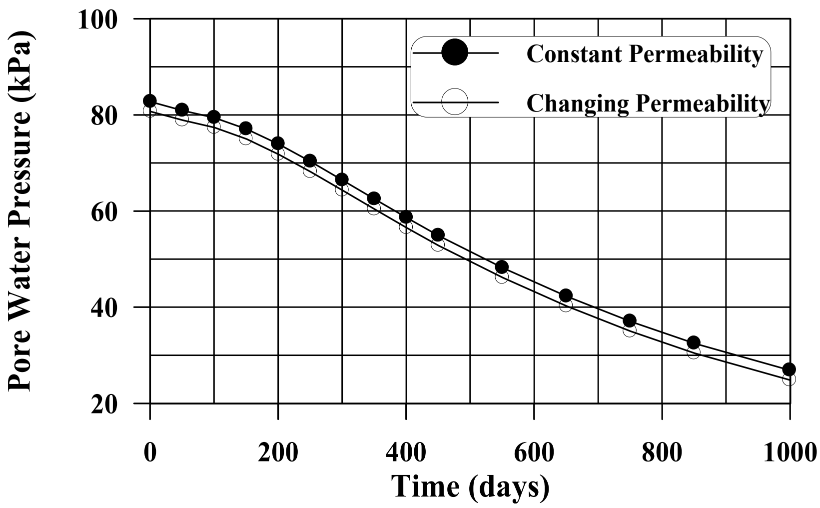
Fig. 11: Effect of different conditions of permeability on the degree of consolidation with time at node (a) 12 m deep.



a. Site S1



b. Site S2



c. Site S3

Fig. 12: Effect of different conditions of permeability on the change in pore water pressure with time at node (a).

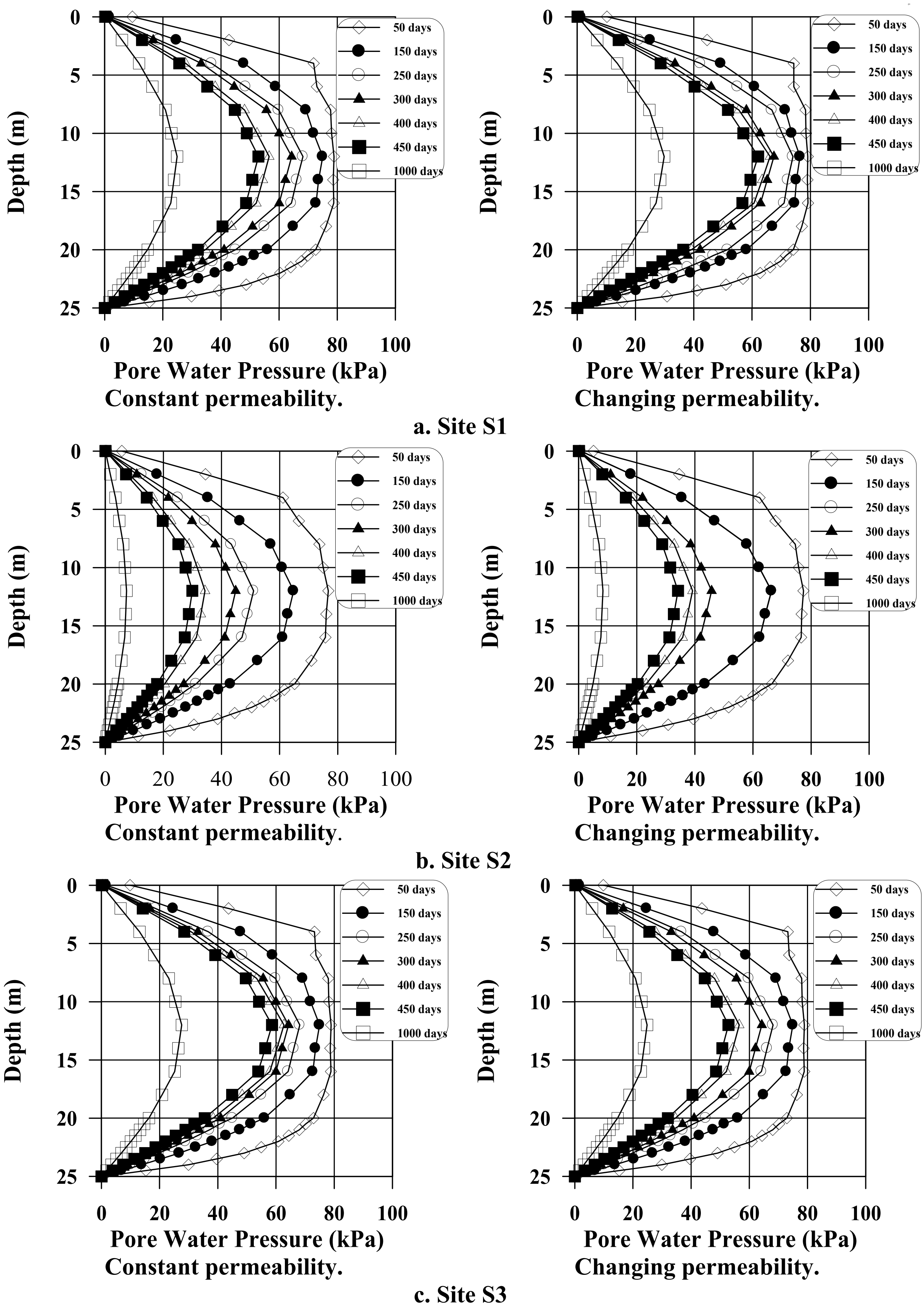


Fig. 13: Effect of different conditions of permeability on the change in pore water pressure along the centerline at time of load application.