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Analysis of 3D Consolidation Settlement of C-ϕ Soil using PLAXIS 3D under Different Drainage Conditions

Arpan Laskar[1][0000-0002-9446-7968] and Sujit Kumar Pal[2]

[1] Asst. Prof., C.E. Dept., Techno College of Engineering Agartala, Tripura, INDIA
[2] Professor, C.E. Dept., National Institute of Technology Agartala, Tripura, INDIA
`arpan2k8@yahoo.co.in`

Abstract. This paper presents the three-dimensional (3D) consolidation behavior of C-ϕ soil under different drainage conditions using finite element method (FEM) based "PLAXIS 3D Foundation" program. An axial-symmetry condition has been used in this analysis to imitate the in-situ field conditions. Maintaining proper drainage conditions during the analysis of the consolidation settlement of soil is crucial. Drainage condition has an immense effect on the consolidation settlement of soil as consolidation is directly related to the permeability of the soil. The consolidation mechanisms and behaviour of soil under different lateral drainage conditions have not been studied well, and that is why in the majority of cases, a considerable difference is observed between predicted and in-situ consolidation characteristics. In this study, five different lateral drainage conditions are considered, and corresponding numerical analysis with "PLAXIS 3D foundation" have been conducted. One-quarter of the physical consolidation cell is used as its symmetry for the FEM analysis, and the soils under consolidation are modelled as elasto-plastic material. The results of numerical analysis are co-related with the results obtained from 3D consolidation physical model testing. It is observed that the drainage conditions have a considerable effect on the rate of settlement of soil but does not have any effect on the surface settlement. Three-dimensional consolidation analysis becomes more representative to the in-situ condition if it is possible to take care the boundary drainage conditions suitably.

Keywords*:* Consolidation, FEM, PLAXIS, Drainage; In-situ.

1 Introduction

As the process of consolidation governs by the different behaviors of soil, significant effort has been made to understand better how soils consolidate and what factors influence the process of consolidation. Karl von Terzaghi was the first to develop the analytical theory to explain and predict the process of one-dimensional consolidation in 1923[1]. In his theory, he made use of several assumptions which may be applicable for many applications in geotechnical engineering; but in three-dimensional cases, it may not apply to the actual field conditions. In the consolidation theory of Karl von Terzaghi, there is an assumption that the ratio of the compressibility and hydraulic conductivity remains comparatively constant throughout the process of consolidation. This theoretical assumption is applicable for the soils which are relatively dense at the beginning of the consolidation process, such that their total volumetric strain is relatively small. Consolidation of soil having high void ratio may not follow the constant material properties throughout the consolidation process.

During the progress of consolidation of soil, the void ratio changed with the change of depth, and so that the horizontal and vertical permeability of that soil get change. In the field, the soil under consolidation may have different soil characteristics corresponding to the variation of soil depth. As horizontal permeability and lateral movements of soil particles also have a significant effect on consolidation characteristics of the soil, considering horizontal permeability and lateral movements of soil particles, with vertical permeability and settlement of soil is very important to precisely predict the consolidation characteristics of the soil. So in this part of the study, a commercially available three-dimensional finite element software package called PLAXIS 3D FOUNDATION is selected to determine the three-dimensional consolidation settlement characteristics of the soil. The linear elastic behavior of soil can be efficiently solved by the conventional method. However, most of the field oriented problems shows non-linear elasto-plastic behavior rather than the elastic behavior of soil. A numerical computer program based on FEM is reasonable when the conventional method based on analytical solutions is incapable to solve the elasto-plastic behavior of soil.

Over the years' by simulating field conditions many investigators have presented their studies on development of concepts for assessing consolidation characteristics. Biot (1941) [2] first introduced the general theory of 3D consolidation by considering coupling between solid and fluid. Different researchers had developed different analytical solution based on Biot's 3D consolidation theory. Edelman (1953) [3] studied an analytical solution of consolidation taking the nonlinear characteristics of soil into account by assuming Young's modulus of soil, which varies linearly with depth but permeability of the soil was assumed constant with depth. Skempton and Bjerrum (1957) [4] proposed a correction factor (μ) to bring three-dimensional consolidation effects in one-dimensional consolidation settlement. Hwang and Witczak (1984) [5] developed a numerical procedure for probabilistic solution of consolidation of soils with multidimensional soil variability and water flow. Ai and Cheng (2013) [6] performed a numerical 3D consolidation analysis with an anisotropic permeability (*k*) of a layered soil system and shown the effects of anisotropy of permeability on the consolidation behaviour of soil. Ai et al. (2013) [7] presented an analytical solution for 3D consolidation of a multi layered porous medium with anisotropic permeability by using the transfer matrix method and they presented that the anisotropy of permeability had great effect on the surface settlement. The wide use of computers and the parallel advances of numerical techniques has made possible more precise analyses. The variation of permeability with strain and the non-linear behavior of the soil skeleton can now be simply taken into account.

2 Aim of the Study

In engineering practice, Terzaghi's 1923 [1] one-dimensional consolidation theory is used in most of the cases to calculate settlement of soil. To determine the settlement of soil, most recently Biot's 1941, the three-dimensional theory has been used, based on a linear stress-strain constitutive relationship and also a linear form of Darcy's flow rule. The wide use of computers and the parallel advances of numerical techniques has made possible more precise analyses. The variation of permeability with strain and the non-linear behavior of the soil skeleton can now be simply taken into account. The aim of this study is to evaluate the three-dimensional settlement of soil using a 3D consolidation apparatus and a commercially available three-dimensional finite element software package called PLAXIS 3D FOUNDATION and develop the ability for making a predictive simulation. The comparison of the numerical result to the result obtained from the presently developed three-dimensional consolidation apparatus is also bringing out in this study.

3 Soil Properties

a C-ϕ soil is used in this study. Seeral tests are carried out to analyse this test material. Different properties of these soil are listed in Table 1.

Table 1. Basic properties of soil

Soil properties	
Specific gravity (G)	2.60
Liquid limit, LL (%)	53.35
Plastic limit, PL (%)	29.32
Plasticity index, PI (%)	24.03
Sand (4.75 mm > 0.075 mm), (%)	4.86
Silt (0.075 mm > 0.002 mm), (%)	41.46
Clay (< 0.002 mm), (%)	53.68
Classification of soil as per IS	CH
Optimum moisture content, OMC (%)	25.75
Maximum dry density, MDD (kg/m^3)	1560
Coefficient of permeability at MDD (m/s)	3.39E-10

4 Instrumentation

Fig. 1 shows the design of newly developed three-dimensional consolidation apparatus. In the following sections, the different parts of this present consolidation apparatus are discussed. In this study this apparatus has been used to analyze 3D consolidation settlement of soil. This apparatus has been developed by author Laskar and Pal (2017) itself [8].

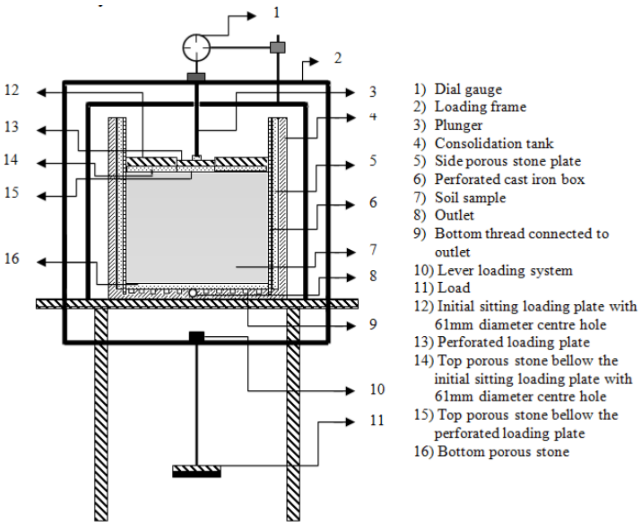


Fig. 1. Schematic diagram of newly developed three-dimensional consolidation apparatus [8]

5 Experimental Results and Analysis

Three-dimensional consolidation tests are conducted on the above mentioned soil, which are compacted at MDD and OMC. Fig. 2 shows anisotropic flow directions of pore water through soil under three-dimensional consolidation test. Under these different five anisotropic flow condition 3D consolidation tests are conducted. The sample preparation and procedure of test is same as explained in Laskar and Pal (2017) [8].

5.1 Calculation of Rate of Consolidation using Three-Dimensional Consolidation Apparatus under Different Drainage Conditions

The coefficient of consolidation (c_v) has calculated by three-dimensional consolidation apparatus under different boundary conditions. The evaluation method of the coefficient of consolidation (c_v) is same as Laskar and Pal 2017 [8]. The coefficient of consolidation (c_v) has been calculated under following different drainage conditions as follows.

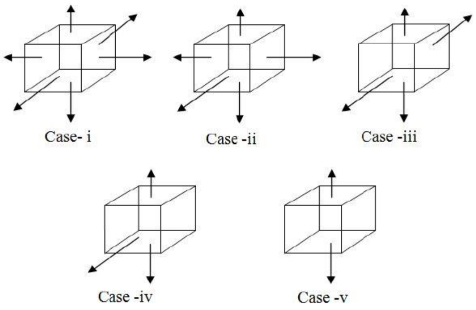


Fig. 2. Anisotropic flow direction of pore water through soil under three-dimensional consolidation [8]

The coefficient of consolidation of silty-clay soil is measured under different flow conditions as shown in Fig. 2. Different anisotropic flow conditions are created using different consolidation cells. The effects of different flow conditions on the rate of consolidation of silty-clay soil are assessed and presented in Fig. 3.

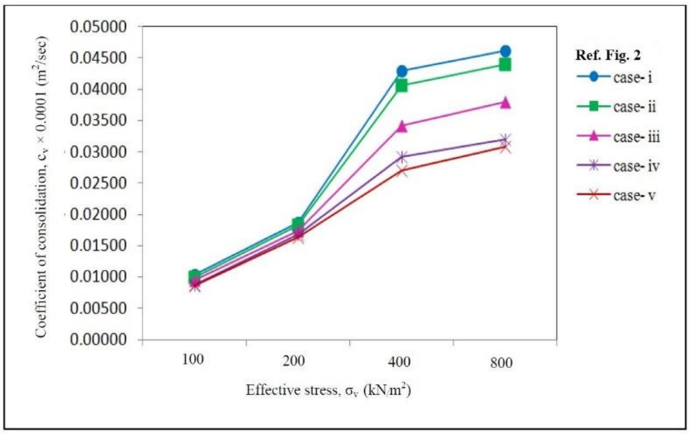


Fig. 3. Coefficient of consolidation of silty-clay soil under different radial flow conditions

5.2 Effect of Anisotropic Flow of Water on Three-Dimensional Consolidation Characteristics of Soil

In actual field conditions, in-situ soils are not isotropic in all the directions. These anisotropic characteristics of the soil, affect the direction of pore water flow. In some of the practical cases, it may have impermeable soil layers or stones on one or several sides of the foundation soil, and it affects the direction of extraction of pore water at the time of the consolidation process. Consideration of the effects of anisotropy radial pore water flow on consolidation of soil is essential regarding the accurate prediction of consolidation properties. In this study, silty-clay soil compacted at a maximum dry density (MDD) is used as a consolidative soil, and five numbers of 3D consolidation tests are conducted at different flow conditions as shown in Fig. 2. These 3D consolidation tests under different anisotropic flow conditions are conducted by the three-dimensional consolidation apparatus shown in Fig. 1. Five (05) different consolidation cells are used to generate different flow conditions at the time of consolidation test. Fig. 4 shows the surface settlements of the soil with different time intervals at different radial flow conditions and from this figure, it is observed that the settlements are considerably different during the process of consolidation of soil, but it is same at the initial and final stages of settlement. As final settlements of the soil in all the 3D consolidation tests under different radial flow conditions are same, the compression index values are identical for all the pore water flow boundary conditions. The anisotropic flow of water does not have any effect on initial and final surface settlements but has a significant influence on the surface settlement during the process of consolidation, and similar observation also noticed by Ai and Cheng (2013) [6].

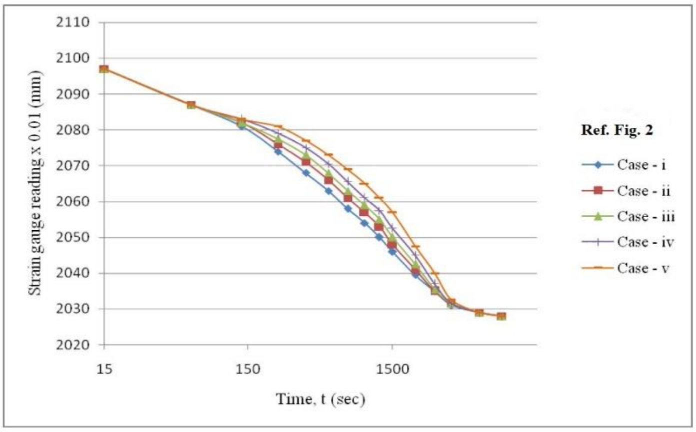


Fig. 4. Comparison of surface settlements at anisotropic radial flow conditions

The anisotropic flow of water has a significant effect on the rate of consolidation of soil as shown in the Fig.3. From Fig.3, it is observed that the coefficient of consolidation value is maximum at free flow in radial and vertical directions (Case-i of Fig. 2), but decreases with the increase of restraint in flow at radial directions. The coefficient of consolidation of any soil is purely based on the rate of expaltion of pore water from that soil sample. As Case-i of Fig. 2 allow flow of pore water through all the directions during the consolidation process, it shows a high rate of extraction of pore water compared to other Cases shown in Fig. 2; and that is why, the Case-i showing the maximum coefficient of consolidation value and the Case-v showing the lowest coefficient of consolidation value, although the consolidative soil is identical for all the Cases.

6 Analysis of Settlement of Soil using PLAXIS 3D Foundation

6.1 Three-Dimensional Consolidation Modelling Results

Consolidation settlements are calculated for silty-clay soil under the constant load 200 kN/m^2. After completion of the calculation process, the result can be evaluated in the *output* program. In the output program, the displacement and stresses corresponding to the individual work plans and calculation phases can be viewed. Before applying the 200 kN/m^2 load, an initial seating pressure 5.0 kN/m^2 is applied. Fig. 5 showing shadings of total displacements at the seating pressure stage under the load 5.0 kN/m^2 and Fig.6 showing shadings of total displacements under the load 200 kN/m^2. After the completion of calculation stage the consolidation settlement under the load 200 kN/m^2 is 5.24 mm.

Elasto-Plastic Consolidation. When a non-linear material model is used, iterations are needed to arrive at the correct solution. Due to plasticity or stress-dependent stiffness behavior, the simple equilibrium equations are not necessarily satisfied. Therefore, the equilibrium equation is inspected here. Here equilibrium equation is written in the sub-incremental form

$$\underline{K}\delta\underline{v} + \underline{L}\delta\underline{p}_n = \underline{r}_n \tag{1}$$

Where,

$\underline{\underline{K}}$ = stiffness matrix;
$\underline{v}$ = nodal displacement vector;
$\underline{\underline{L}}$ = coupling matrix;
$\underline{P}_n$ = excess pore pressure vector;
$\underline{r}_n$ = global residual force vector.

The total displacement increment $\Delta\underline{v}$ is the summation of sub-increments $\delta\underline{v}$ from all iterations in the current step

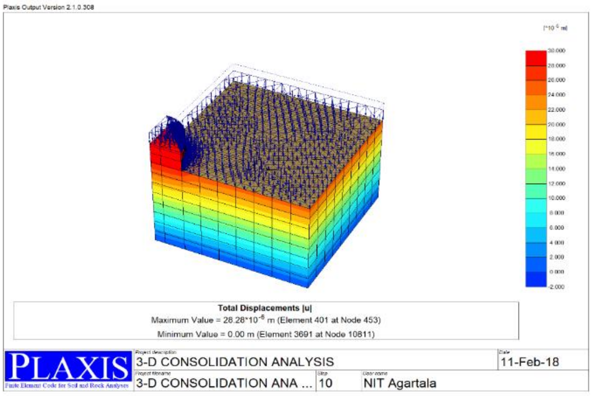
$$\underline{r}_n = \int \underline{\underline{N}}^T \underline{b}\, dV + \int \underline{\underline{N}}^T \underline{t}\, dS - \int \underline{\underline{B}}^T \underline{\sigma}\, dV \tag{2}$$

With,

$\underline{b} = \underline{b}_0 + \Delta\underline{b}$; and (3)
$\underline{t} = \underline{t}_0 + \Delta\underline{t}$ (4)

Where,
$\underline{u}$ = continuous displacement vector within an element;
$\underline{\underline{N}}$ = matrix contains the interpolation functions;
$\underline{\underline{B}}$ = strain interpolation matrix;
$\underline{b}$ = body force due to self-weight; and
$\underline{t}$ = surface tensions.

In the first iteration, we consider $\underline{\sigma} = \underline{\sigma}_0$, i.e., the stress at the beginning of the step. Successive iterations are used on the current stresses that are computed from the appropriate constitutive model.



Total Displacements |u|
Maximum Value = $28.28*10^{-6}$ m (Element 401 at Node 453)
Minimum Value = 0.00 m (Element 3691 at Node 10811)

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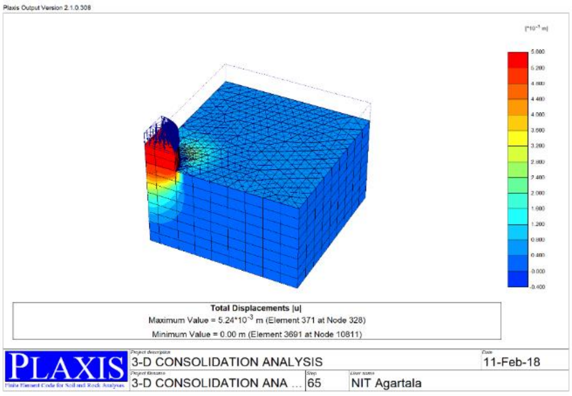
Fig.5. Shadings of total displacements of silty-clay soil layer under the load 5.0 kN/m^2



Total Displacements |u|
Maximum Value = $5.24*10^{-3}$ m (Element 371 at Node 328)
Minimum Value = 0.00 m (Element 3691 at Node 10811)

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Fig.6. Shadings of total displacements of silty-clay soil layer under the load 200 kN/m^2

6.2 Comparison of Test Results

In this chapter three-dimensional consolidation settlement of two different types of soils are analysed by using FEM. After analysing the three-dimensional consolidation settlement using PLAXIS 3D FOUNDATION software a comparison study is performed between consolidation settlement results of different soils, evaluated by presently developed three-dimensional consolidation apparatus and numerical analysis by PLAXIS 3D FOUNDATION.

Fig. 7 presenting consolidation settlement values of silty-clay soil corresponding to 200 kN/m^2 load. From this figure, it is observed that the consolidation settlement value obtain from FEM analysis is deflected by 4.73 % from the settlement value obtained from presently developed three-dimensional consolidation apparatus.

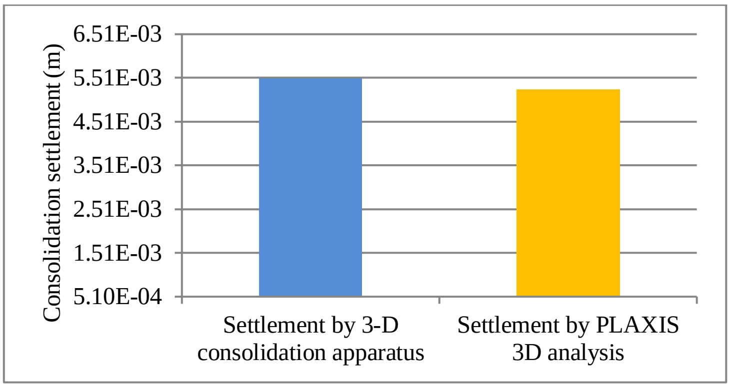

Fig. 7. Consolidation settlement values of silty-clay soil corresponding to 200 kN/m^2 load

7 Practical Implications

The success of a study depends on the practical implication of the solution of that study. Following is the different implication of this study:

The conventional method of evaluation of settlement from the result of oedometer tests assumes that the soil only has vertical strain and there will be no lateral strain, and it also assumes that the pore water dissipation only occurs in the vertical direction and there will be no radial drainage of water. The lateral confinement of soil sample in case of one-dimensional oedometer test is taken to be representative of the actual soil conditions. Presently developed three-dimensional consolidation apparatus allows the vertical as well as horizontal movement of soil particles and it also allows the vertical as well as the radial flow of pore water during the consolidation process. In many practical cases it was seen that the time taken for actual field soil settlement is much smaller than the predicted time of settlement by traditional oedometer test (Duncan (1993) [9], Leroueil (1988) [10]). In this regard, newly developed three-dimensional consolidation apparatus is much efficient to predict actual field consolidation settlement.

8 Conclusion

The effects of the anisotropic flow of pore water on three-dimensional consolidation characteristics of the soil are obtained using a three-dimensional consolidation apparatus. Using the three-dimensional consolidation apparatus, the effects of five different anisotropic flow conditions of pore water on three-dimensional consolidation of soil is evaluated. The coefficient of consolidation (c_v) has been determined by comparing the relationship between elapsed time (t) in logarithmic scale and dial gauge readings of the soil sample in the laboratory to the hypothetical relationship (Taylor's method) between T_v and U.

The proposed solution permits to be solved the three-dimensional consolidation problem, with different boundary conditions. Experimental results indicate that the anisotropic permeability does not have any influence on initial and final surface settlements, but it has a great influence on the surface settlement during the process of consolidation. The rate of consolidation of soil has been immensely effected by the anisotropic flow of water.

In this study, FEM based numerical analysis of three-dimensional consolidation settlement is also performed. A comparative study is also performed between the resultant consolidation settlement of different soils, obtained by presently developed three-dimensional consolidation apparatus and FEM based numerical analysis. From the comparison of the consolidation settlement results it is observed that the deflections of numerical analysis results from experimental results is 4.73 %.

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