Assessment of 3D Consolidation Settlement of Soil by Considering the Effect of Surcharge Pressure

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Abstract. The aim of the study is to assess 3D consolidation settlement of soil by considering the effect of surcharge pressure on surrounding soil. In this study a 3D consolidation apparatus is developed and performed a series of 3D consolidation test under different surcharge pressures. Silty-clay soil and silty-sand with clay soil are used in this study. Consolidation tests are performed under different surcharge pressures like 0.0, 10.0, 15.0 and 20.0 kN/m^2. From this study, it is observed that with the increase of surcharge pressure, the compression indices and coefficient of consolidation values decreases for both the soils. The surcharge pressures have a significant effect on consolidation characteristics. With the increase of surcharge pressure on the surrounding soil, the void ratio of surrounding soil reduces and it become denser, and as a result, the lateral strain of soil particles under consolidation as well as lateral extractions of pore water reduces, and corresponding compression index and the rate of consolidation also reduces. During the consolidation test as this apparatus allows vertical and lateral strain with vertical and lateral pore water dissipation under different surcharge pressures, it can be simulate to the in-situ field consolidation settlement.

Keywords: Surcharge Pressure, 3D Consolidation, Compression Index, Lateral Strain, Pore Water

1 Introduction

Deformation analysis of the soil is one of the most uncertain and indecisive tasks in geotechnical engineering. The work presented in this part of study is concerned with the deformation analysis of the soil under surcharge pressure. In the present days, the settlement of supporting soil has been calculated using one-dimensional consolidation of soil. Three-dimensional consolidation cases of soil have been considered as a modification to the one-dimensional consolidation. A natural porous medium like, soil may have been created by sedimentation process, and this sedimentation makes horizontal stratification layers and hence, the permeability of soil different in horizontal and vertical directions. Due to the anisotropic nature of the soil in horizontal and vertical directions, and different seepage characteristic through the different direction of soil, the coefficient of consolidation and coefficient of permeability in the horizontal direction are typically different from the coefficient of consolidation and coefficient of permeability in the vertical direction. There is also a large effect of surcharge pressure on the consolidation of soil. The effect of surcharge pressure is under-estimated in the process of consolidation. Hence, in this study, it is proposed to use the three-dimensional consolidation cases as the basic problem rather than a further extension of one-dimensional consolidation theory, where the effect of surcharge pressure on the three-dimensional consolidation process is also taken under consideration. In three-dimensional consolidation cases with the application of load and surcharge pressure, there is vertical as well as the lateral strain of soil along with vertical and radial drainage of water.

Significant efforts have been made in the development of concepts, theories and formulations for evaluating consolidation characteristics of saturated soils during the last three decades. However, experimental confirmation has not kept pace with theoretical advance. The general theory of three-dimensional consolidation was first introduced by Biot (1941) [1], in which coupling between solid and fluid was considered. In the past few decades, many investigators had been developed different analytical solution based on Biot's consolidation theory. Skempton and Bjerrum (1957) [2] proposed a correction factor (μ) to modify one-dimensional consolidation settlements to bring out two and three-dimensional effects. Ai and Cheng (2013) [3] reported numerical analysis for three-dimensional consolidation with the anisotropic permeability of a layered soil system, and the effect of anisotropy of permeability on the consolidation behaviour had been discussed. Ai et al. (2010) [4], and Ai and Cheng (2009) [5] presented alternative approaches to solving the Biot's consolidation problem, and obtained an organised solution to the consolidation problems. Several attempts by different researchers are also had been taken to evolve an analytical procedure to solve the Biot's consolidation equations using directly Laplace transform [6] and [7]. The effects of soil particles on consolidation characteristics had been evaluated, and it was found that the fine fraction had a more significant influence on the consolidation characteristics [8]. In all the past investigations, evaluation technique of three-dimensional consolidation was analytical or numerical based, and assumptions were not as replicating to the field condition. The previous investigators do not considered the effects of surcharge pressure on the consolidation of soil. Hence, it is important to develop an experimental solution for three-dimensional consolidation problems by considering the effects of surcharge pressure.

2 Aim and Scope of the Study

The study aims to predict consolidation characteristics of soil based on three-dimensional consolidation of soil under different surcharge pressures. In this study, a three-dimensional consolidation apparatus is developed and performed a series of three-dimensional consolidation test under different surcharge pressures. During the three-dimensional consolidation test, vertical and lateral strains of the soil, and vertical and lateral movements of pore water are allowed. In this study, two different types of soil are used to perform the three-dimensional consolidation tests under different surcharge pressures. It is observed that the three-dimensional consolidation settlement of the same soil changed with the changes of surcharge pressure. With the increase of surcharge pressure, the lateral strain of soil reduces during the consolidation process; and due to this, compression index and coefficient of consolidation also reduced. Using developed apparatus, three-dimensional consolidation characteristics of soil can be evaluated under different surcharge pressures. As this apparatus allows vertical and lateral strain with vertical and lateral pore water movement under different surcharge pressures, it is possible to correlate with in-situ field conditions during the consolidation process.

3 Development of Apparatus to Apply Surcharge Pressure During Three-Dimensional Consolidation Test

Fig. 1 shows the developed three-dimensional consolidation apparatus, where three-dimensional consolidation can perform under different consolidative pressures. In the mentioned three-dimensional consolidation apparatus surcharge pressure is introduced as shown in Fig. 2 to measure the effect of surcharge pressure on three-dimensional consolidation of soil. In this test, soil sample is bounded by the porous cast iron consolidation cell which is open at top and bottom sides. The internal and external dimension of this porous cast iron consolidation cell is 300 mm × 300 mm × 450 mm (height) and 310 mm × 310 mm × 450 mm (height) respectively. This porous box is surrounded by porous stone plates of 12 mm thick. A concrete tank of internal dimension 334 mm × 334 mm × 450 mm (height) is fabricated to hold that porous consolidation cell along with porous stone plates. Surcharge pressures are applied on top of the soil sample using cast iron plates of cross-sectional area 299 mm × 299 mm, with 61 mm diameter centre hole and under this surcharge loading plate, a porous stone plate is placed of the same cross-sectional area and centre hole as surcharge loading plate. A filter paper, a porous stone and a perforated loading plate of 60 mm diameter are consecutively inserted through 61 mm diameter hole of surcharge loading plate. Below the porous stone plate of 60 mm diameter, a filter paper is used having the same diameter. To apply the load on that loading plate, a lever loading frame is fabricated as shown in Fig. 1. A dial gauge (0.0−25 mm) of sensitivity 0.01 mm is installed in the loading frame to measure the vertical settlement of loading plate.

4 Theoretical Considerations for Consolidation

Assumptions of present three-dimensional consolidation test are as follows:

1. The soil layers are homogeneous, and the soil properties are isotropic;
2. The soil layers are two-faced saturated;
3. Vertical and horizontal movements of soil particles are allowed during the process of consolidation;
4. The compression of the soil layer is due to the change in volume only, which in turn is due to the squeezing out of water from the void space in vertical as well as in horizontal directions;

5. Darcy’s law is valid;
6. In case of plastic settlement, if all the soil particles are inter-connected, then vertical movement of soil particles occurs due to horizontal movements of underneath soil particles; and
7. The lower boundary of stress remains constant throughout the consolidation process.

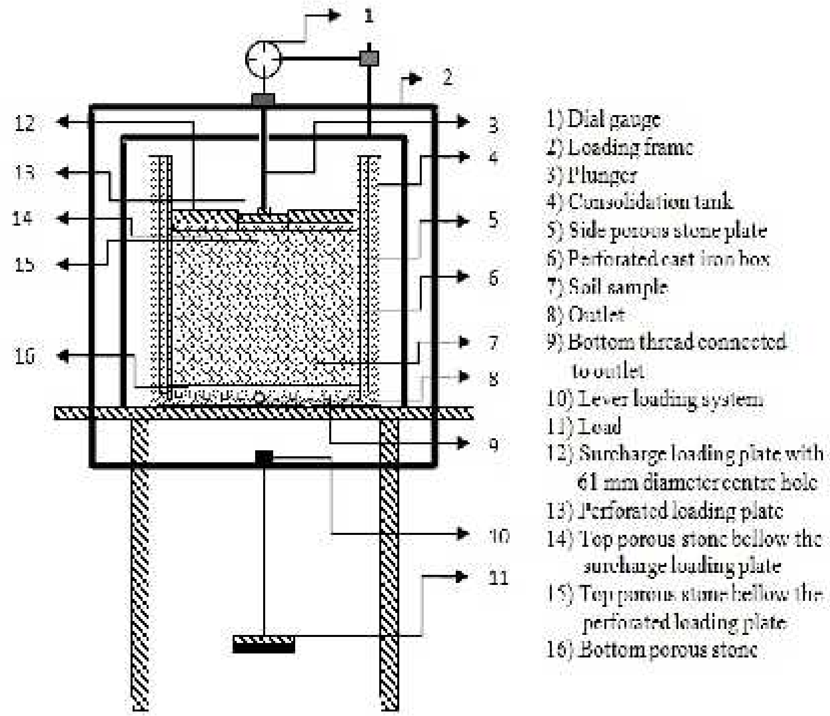

Fig. 1. Schematic diagram of developed three-dimensional consolidation apparatus to apply surcharge pressure during three-dimensional consolidation test

5 Testing Materials and Program

Silty-clay soil and silty-sand with clay soil are used in this investigation. A series of standard classification tests are carried out to categories these test materials. The physical properties along with maximum dry density (MDD) and optimum moisture content (OMC) using standard Proctor compaction energy of two types of soils are listed in Table 1.

Using silty-clay soil and silty-sand with clay soil, eight numbers of three-dimensional consolidation tests are performed under different surcharge pressures.

6 Specimen Preparation and Experimental Procedures

Soil samples are remolded at a maximum dry density (MDD) obtained from standard Proctor compaction in porous cast iron box in three consecutive layers, and these soil samples are considered as an ideal two-faced soil-system during the test. The inner sides of the cast iron consolidation cell are covered by filter paper before molding the soil sample. After molding the sample, four consecutive sides of the cast iron consolidation cell are covered by porous stone plates (side porous stone plate) as shown in Fig. 1. Over the soil sample filter paper, porous stone and cast iron plate of the cross-sectional area of 299 mm × 299 mm with the centre hole of 61 mm diameter are placed one above the other. The cast iron plates of size 299 mm × 299 mm with the centre hole of 61 mm diameter are placed over the soil specimen to apply initial seating pressure of 5.0 kN/m^2, and surcharge pressures of 10.0, 15.0 and 20.0 kN/m^2. A filter paper, a porous stone and a perforated loading plate of 60 mm diameter have been placed consecutively through the 61 mm diameter centre hole. The load is applied by lever loading frame system to the top perforated loading plate of 60 mm diameter through a plunger connecting the loading frame and perforated loading plate. Initially, 5.0 kN/m^2 stress is applied as a seating pressure and kept it for 48 hours to saturate the soil sample. After 48 hours, 100, 200, 400 and 800 kN/m^2 stresses are consecutively applied to the soil sample, and each stress is applied for 24 hours. With the application of stresses on soil, vertical settlements corresponding to different time interval are measured by a strain gauge.

7 Test Results and Analysis

In this study, three-dimensional consolidation tests are performed under different surcharge pressure using developed three-dimensional consolidation apparatus shown in Fig. 1. Consolidation tests are performed under different surcharge pressures like 0.0, 10.0, 15.0 and 20.0 kN/m^2. Fig. 2 shows the schematic diagram of the soil under consolidation and surcharge pressure on surrounding soil. Figs. 3 and 4 show the compression indices of silty-clay soil and silty-sand with clay soil, and Figs. 5 and 6 show the coefficient of consolidation values of silty-clay soil and silty-sand with clay soil under different consolidative vertical stresses and surcharge pressures. From the Figs. 3 to 6, it is observed that with the increases of surcharge pressure, for the same soil and under the same consolidation pressure, the consolidation settlement of soil reduces.

Table 1. Basic properties of soils

Soil properties	Silty-clay soil	Silty-sand with clay soil
Specific gravity (G)	2.60	2.58
Liquid limit, LL (%)	53.35	25.30
Plastic limit, PL (%)	29.32	19.03
Plasticity index, PI (%)	24.03	4.27
Sand (<4.75 mm & > 0.075 mm), (%) Silt (<0.075 mm & > 0.002 mm), (%) Clay (< 0.002 mm), (%)	4.86 41.46 53.68	61.60 21.68 16.72
Soil classification as per USCS	CH	SM
Optimum moisture content, OMC (%)	25.75	13.10
Maximum dry density, MDD (kN/m^3)	15.60	18.80

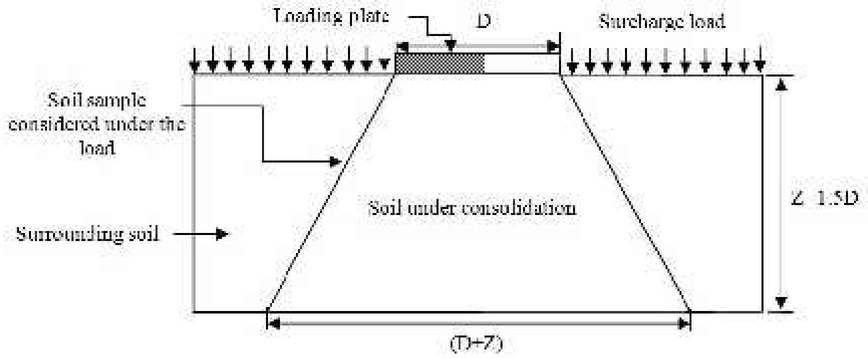

Fig. 2. Schematic diagram of soil under consolidation and surcharge pressure on surrounding soil

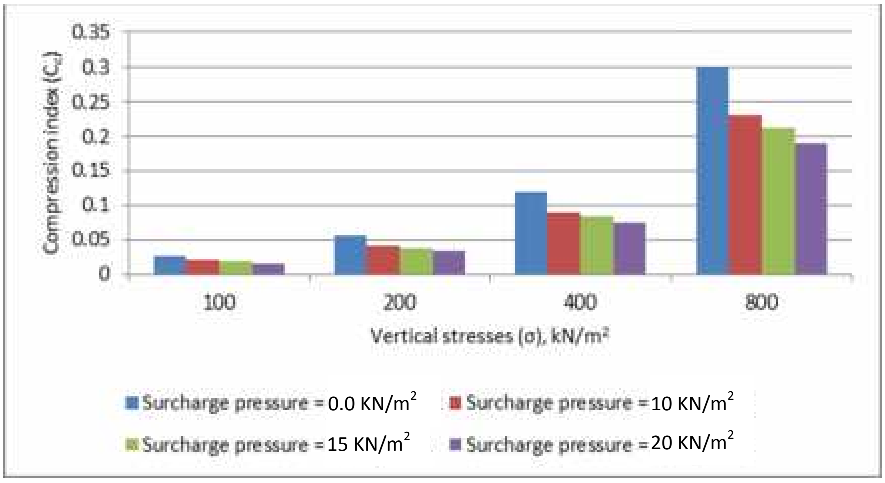

Fig. 3. Compression indices of silty-clay soil under different vertical stresses and surcharge pressures

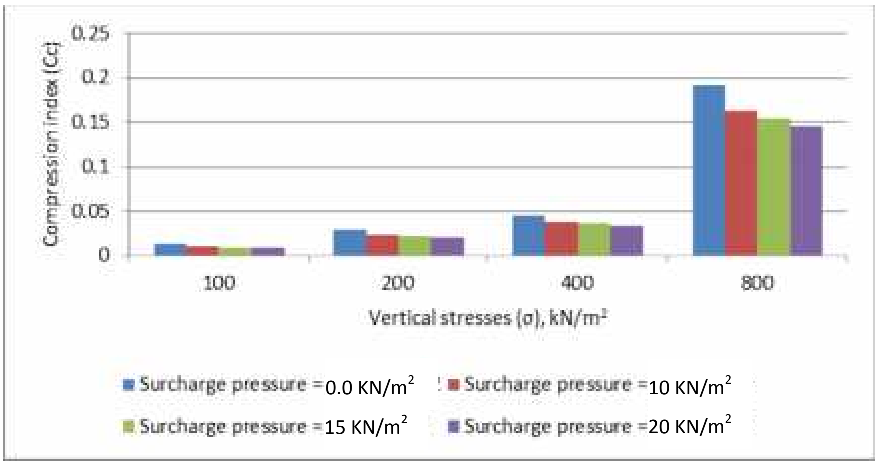

Fig. 4. Compression indices of silty-sand with clay soil under different vertical stresses and surcharge pressures

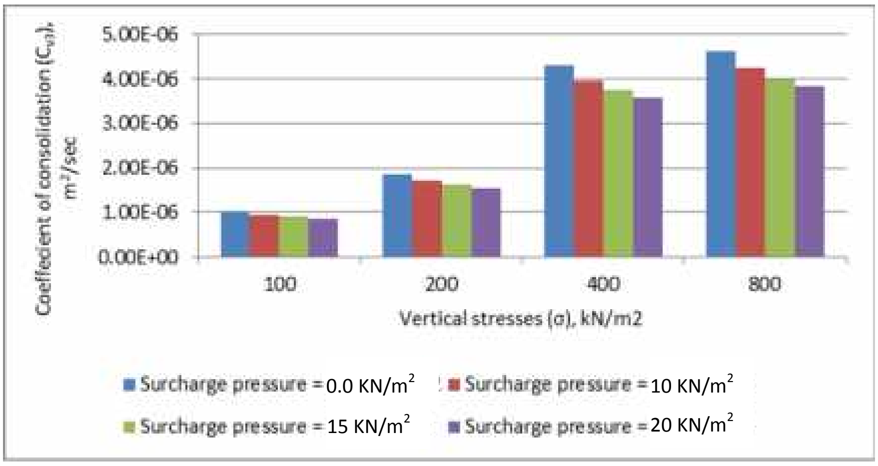

Fig. 5. Coefficient of consolidation values of silty-clay soil under different vertical stresses and surcharge pressures

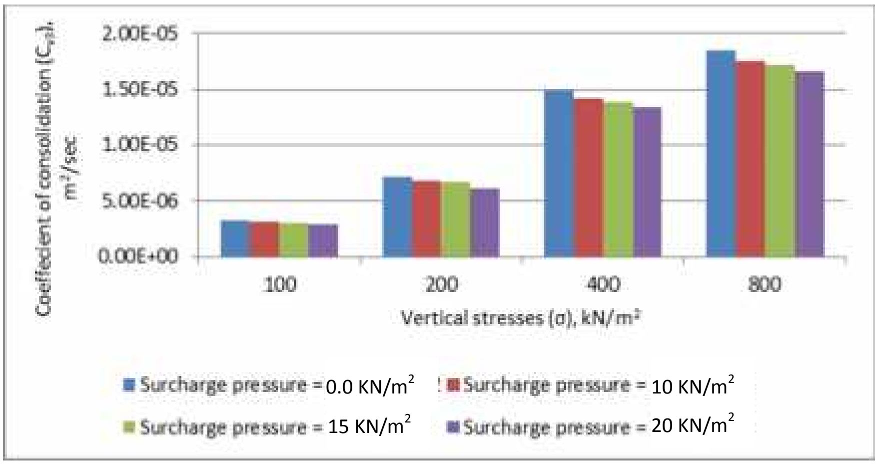

Fig. 6. Coefficient of consolidation values of silty-sand with clay soil under different vertical stresses and surcharge pressures

8 Discussions

In this study, three-dimensional consolidation tests are performed on silty-clay soil and silty-sand with clay soil under different surcharge pressures using developed three-dimensional consolidation apparatus as shown in Fig.1. In the three-dimensional consolidation of soil, lateral and vertical movements of soil particles, and lateral and vertical movements of pore water are taken into consideration. The soil under consolidation may have surrounding soil as shown in Fig. 2, which affects the lateral movements of soil particles under consolidation and it also affects the lateral movement of pore water. If surcharge pressure increases on the surrounding soil particles, these surrounding soils become denser, and as a result, lateral movements of soil under consolidation get resisted, and at the same time horizontal pore water movements will also reduce. The compression indices and coefficient of consolidation values of silty-clay soil and silty-sand with clay soil under different vertical stresses and surcharge pressures are shown in Figs.3 to 6 and Table 2. From these figures and table, it is observed that with the increase of surcharge pressure, the compression indices and coefficient of consolidation values decrease for both the soils. The surcharge pressures have a significant effect on consolidation characteristics. The rate of consolidation of soil is proportional to the rate of extraction of pore water from the soil. With the extraction of pore water from soil mass, the arrangement of the skeleton of soil changes and due to which settlement occurs. At the time of rearrangement of soil particles with the extraction of water, it may move in horizontal as well as in vertical directions. With the increase of surcharge pressure on the surrounding soil, the void ratio of the surrounding soil reduces and it becomes denser, and as a result, the lateral movement of soil particles under consolidation as well as lateral extractions of pore water reduces. Due to this reason corresponding compression index and the rate of consolidation also reduces.

Table 2. Three-dimensional consolidation of soils under different surcharge pressures

Types of soil	Surcharge pressure	Consolidative vertical stress	Compression index	Coefficient of consolidation
	(kN/m^2)	σ (kN/m^2)	C_c	c_{v3} (m^2/sec)
Silty-sand with clay soil	0.0	100	0.013	3.26E-06
		200	0.029	7.13E-06
		400	0.0461	1.49E-05
		800	0.192	1.85E-05
	10.0	100	0.0106	3.08E-06
		200	0.0243	6.78E-06
		400	0.0387	1.42E-05
		800	0.1632	1.76E-05
	15.0	100	0.0099	3.04E-06
		200	0.0228	6.65E-06
		400	0.0365	1.39E-05
		800	0.1542	1.72E-05
	20.0	100	0.0093	2.94E-06
		200	0.0215	6.15E-06
		400	0.0345	1.34E-05
		800	0.1458	1.66E-05
Silty-clay soil	0.0	100	0.0261	1.03E-06
		200	0.056	1.87E-06
		400	0.119	4.30E-06
		800	0.2993	4.61E-06
	10.0	100	0.0202	9.40E-07
		200	0.042	1.72E-06
		400	0.0904	3.95E-06
		800	0.2304	4.24E-06
	15.0	100	0.0181	9.00E-07
		200	0.0382	1.62E-06
		400	0.0831	3.77E-06
		800	0.2119	4.00E-06
	20.0	100	0.0157	8.60E-07
		200	0.0334	1.53E-06
		400	0.0739	3.60E-06
		800	0.1907	3.85E-06

9 Conclusion

This study concentrates on the development of a three-dimensional consolidation apparatus through which three-dimensional consolidation tests are performed under different surcharge pressures. The entire tests are performed on silty-clay soil and silty-sand with clay soil of Agartala, Tripura, India. From this study it is observed that the consolidation characteristics are largely affected by the surcharge pressures during the three-dimensional consolidation of soil. With the increase of surcharge pressure on the surrounding soil, the surrounding soils become denser, and it reduces the lateral movements of consolidating soil particles, and at the same time it also reduces the lateral pore water movement. From this study, it is also observed that the compressibility and the rate of consolidation of the soil under three-dimensional consolidation reduced due to an increase of surcharge pressure on the surrounding soil.

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