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Research Article

Effect of Vertical Pressure on Horizontal and Vertical Permeability of Soil and Effect of Surcharge Pressure on 3D Consolidation of Soil

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Permeability and consolidation of soil are known as the most variable soil properties. The values of permeability and consolidation of soil may vary with depth even in case of homogeneous soil layers, and because of that, the determination of appropriate values of permeability and consolidation is a complex and complicated engineering task. In this study, horizontal and vertical permeability apparatus and a 3D (three-dimensional) consolidation apparatus are developed to determine the effects of vertical pressure on horizontal and vertical permeability and the effects of vertical surcharge pressures on three-dimensional consolidation of soil. A series of horizontal and vertical permeability tests of soil under different vertical pressures and a series of 3D consolidation tests under different surcharge pressures are performed. From the study, it is observed that the horizontal and vertical permeability of soil changes with the changes in vertical pressures, and 3D consolidation of soil also changes with the changes in surcharge pressures. The horizontal and vertical permeability values obtained from the newly developed horizontal and vertical permeability apparatus are used in Terzaghi's one-dimensional consolidation theory to find out the consolidation characteristics of the soil, and it is compared with the results obtained from the newly developed 3D consolidation apparatus.

1. Introduction

The coefficient of permeability also known as hydraulic conductivity is a most uncertain soil property, and the uncertainty of soil properties can be as high as 240% [1, 2]. There are several factors that are affecting the permeability of soil, and these are grain size, properties of pore water pressure, temperature, void ratio, mean pressure, stratification of soil, entrapped air and organic impurities, adsorbed water, the degree of saturation, the shape of particles, the structure of soil mass, etc. Amongst all above factors, there are mainly two factors that mostly affect the coefficient of permeability, that is, grain size and interstices between soil particles. Except from these two factors, vertical pressure is also another factor that largely affects the permeability of any soil. The soil with relatively homogeneous layers shows different coefficients of permeability with the changes in depth. Because the self-load of soil increases corresponding to the increases in depth, the soil becomes denser with the increases in the depth of the soil. Different researchers proposed many equations to predict the hydraulic conductivity (k) of saturated porous materials. Amongst the different proposed equations, a frequently usable equation was proposed by Kozeny [3], and later, it was modified by Carman [4, 5]. Though both the authors never published together, the resulting equation is largely known as the Kozeny–Carman equation. The Kozeny–Carman equation has several limitations like the equation is only valid for nonplastic soils and the equation is inadequate for clay soil as the interactions between solid and fluid are not considered. In addition to that, the permeability predicted by the Kozeny–Carman equation is isotropic, whereas the permeability is often anisotropic [6]. Kezdi preferred laboratory permeability tests for determining the coefficient of permeability over analytical processes [7]. Rozsa discussed the laboratory method and recommended an in situ test, that is, pumping from a well to determine the coefficient of permeability values [8]. In numbers of practical cases, it was preferred to use the pumping test method on site but fails to do the same in the soil layers above the groundwater table. Kovacs proposed a different view and used the grain-size distribution curve to determine the permeability of soil [9].

Based on the above studies and analysis, the formula-based calculation should be recommended for determining the coefficient of permeability, not only because this is simple but also it is reliable in most of the cases. In the entire previous studies of laboratory cases of horizontal and vertical permeability tests, the effects of vertical pressures on the coefficient of permeability were overlooked. In this study, a series of horizontal and vertical permeability tests are conducted by using the newly developed horizontal and vertical permeability apparatus under different vertical pressures.

The design of shallow foundations has to be based on the analysis of bearing capacity failure and deformation analysis of the supporting soil. Deformation analysis of the soil is one of the most uncertain and indecisive tasks in geotechnical engineering. The work presented in this article is concerned with the deformation analysis of the soil under different vertical surcharge pressures. In present days, the settlements of supporting soil are analyzed by using one-dimensional consolidometer, and three-dimensional consolidation cases of soil are considered as a modification to the one-dimensional analysis. The concept of one-dimensional consolidation may represent a clay layer, which is overlain and confined by a desiccated crust to minimize horizontal movement of soil and water. The one-dimensional theory may not be feasible for the case in which vertical and horizontal movement of soil and vertical and the horizontal expulsion of water happen. Therefore, it may not be logical to apply a one-dimensional consolidation theory for evaluation of three-dimensional settlements. A natural porous medium like soil may have been created by the sedimentation process, and this sedimentation makes horizontal stratification layers of soil, and accordingly, the permeability of soil is different in horizontal and vertical directions. Due to the anisotropic nature of the soil in horizontal and vertical directions, 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. Usually, the coefficient of consolidation is determined by using the one-dimensional oedometer test, and the measurement of settlement rates is limited to the vertical direction only. There is also a large effect of surcharge pressures on the consolidation of soil. The effect of surcharge pressures is underestimated in the process of consolidation. Hence, in this article, the three-dimensional consolidation cases have been proposed as the basic problem, rather than a further extension of the one-dimensional consolidation theory, where the effect of surcharge pressures on the consolidation process is also taken into consideration. In three-dimensional consolidation cases, there will be vertical as well as the horizontal strain of soil along with vertical and radial drainage of water corresponding to the application of vertical loads and surcharge pressures.

Great efforts have been made in the development of concepts, theories, and formulations for evaluating consolidation characteristics of saturated soil during the past three decades. However, experimental confirmation has not kept pace with theoretical advance. The general theory of three-dimensional consolidation was first introduced by Biot [10], in which the researcher considers coupling between solid and fluid. In the past few decades, many investigators have developed a different analytical solution based on Biot's consolidation theory. Skempton and Bjerrum proposed a correction factor (μ) to modify one-dimensional consolidation settlements to bring out two- and three-dimensional effects [11]. Ai and Cheng presented numerical analysis for 3D consolidation with the anisotropic permeability of a layered soil system, and the effect of anisotropic permeability on the consolidation behavior has been discussed [12]. Ai et al. [13] and Ai and Cheng [14] presented alternative approaches to solving Biot's consolidation problem and obtained an organized solution to the consolidation problems. Ai and Wang [15] and Ai et al. [16] also developed an analytical procedure to solve Biot's consolidation equations by directly using the Laplace transform method. In all of the past investigations, the evaluation technique of three-dimensional consolidation was analytical or numerical based, and assumptions are not as replicating to the field conditions. Laskar and Pal developed an experimental solution for three-dimensional consolidation problems, which can replicate the in situ settlement of shallow footing, but the effects of surcharge pressures on three-dimensional consolidation of soil have not been discussed [17]. Hence, it is important to evaluate the effects of surcharge pressures on three-dimensional consolidation of soil. In this study, it is tried to evaluate the effects of vertical pressures on the horizontal and vertical permeability of soil and effects of surcharge pressures on 3D consolidation of soil.

2. Aim and Scope of the Study

In this study, new horizontal and vertical permeability apparatus are developed and shown in Figures 1 and 2, respectively. A three-dimensional consolidation apparatus (Figure 3) is also presented in this study to determine the effect of surcharge pressures on three-dimensional consolidation of soil. The study aims to find out the horizontal and vertical permeability of soil under different vertical pressures and 3D consolidation of soil under different surcharge pressures. In this study, the permeability values of soil obtained from the developed laboratory apparatus are used in Terzaghi's one-dimensional consolidation theory to find out the consolidation characteristics of soil, and it is compared with the 3D consolidation results obtained from the developed 3D consolidation apparatus.

3. New Permeability and Consolidation Apparatus

Horizontal and vertical permeability apparatus are fabricated to measure the horizontal and vertical permeability of

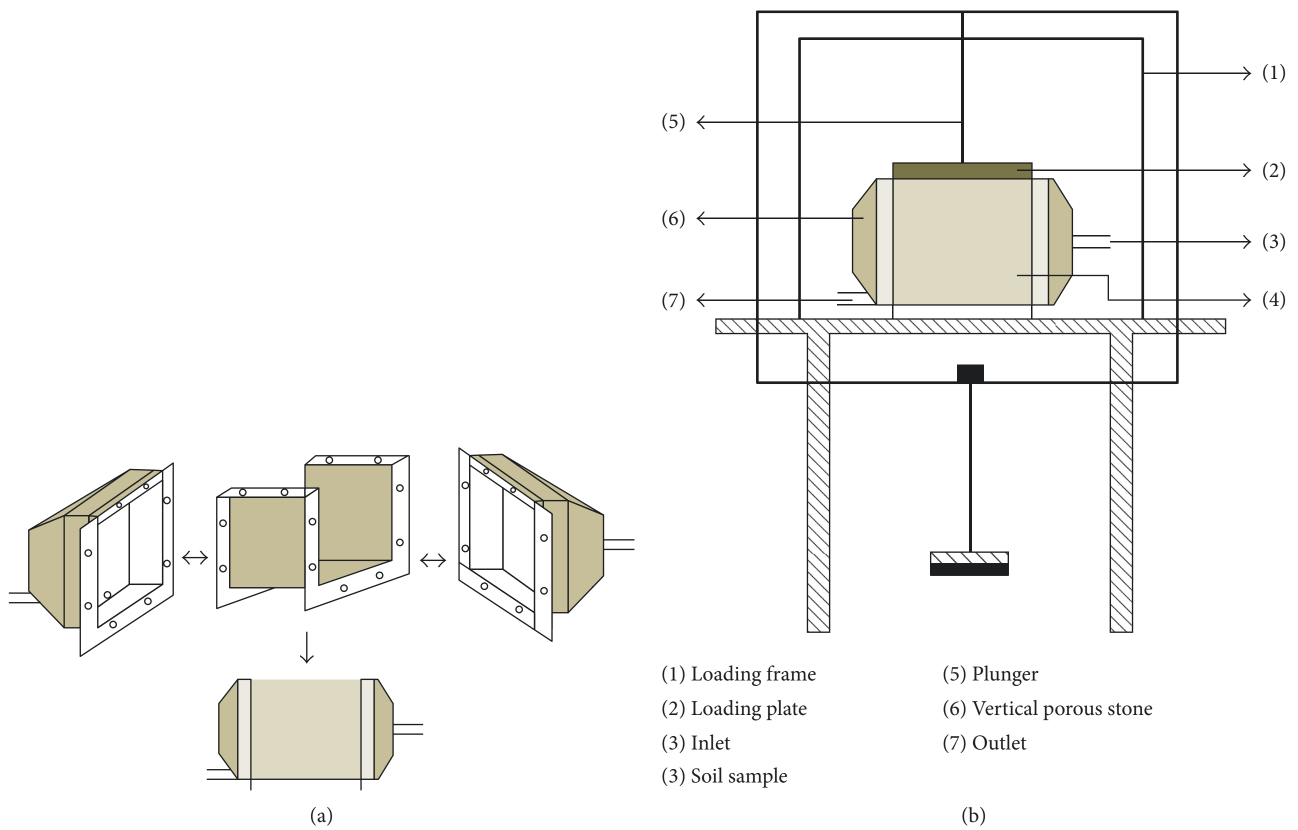


Figure 1: Horizontal permeability apparatus. (a) Mould assembly for determination of horizontal permeability. (b) Horizontal permeability cell under constant vertical pressure.

soil under constant confined vertical stress. A 3D consolidation setup is also fabricated to perform 3D consolidation tests under different surcharge pressures where vertical and horizontal expulsion of pore water is allowed.

3.1. Horizontal and Vertical Permeability Apparatus. Figures 1 and 2 show the newly developed horizontal and vertical permeability apparatus along with different parts.

3.1.1. Permeability Cell. The permeability cell is made of noncorrosive cast iron. The inner volume of the permeability cell is 1000 cc. The internal size of the permeability cell is 100 mm × 100 mm × 100 mm. Figures 1(a) and 2(a) show the assembly of horizontal and vertical permeability cells. These permeability cells are used to test the soil samples under confined vertical pressures.

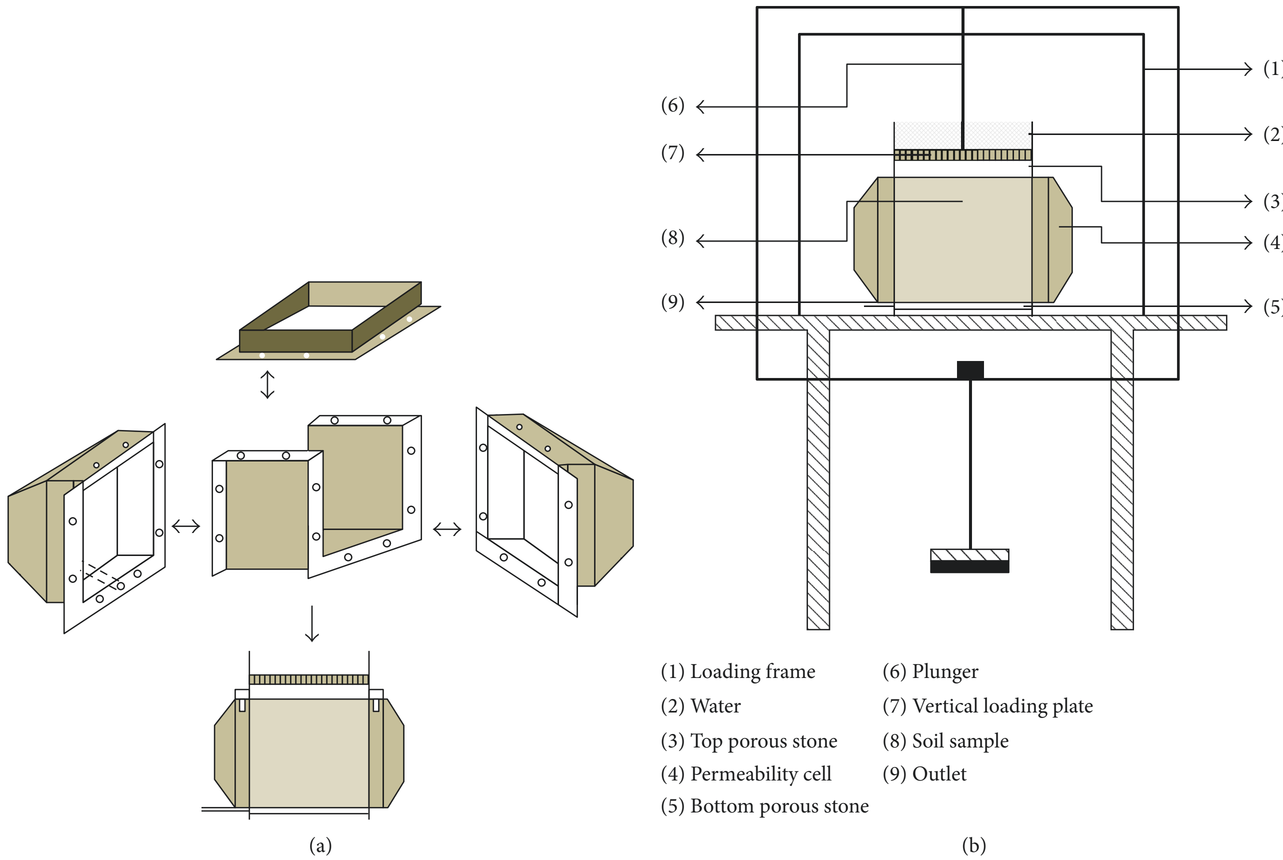
3.1.2. Porous Stone. Porous stones are placed on the two opposite sides of the permeability cells. In the horizontal permeability cell, porous stones are placed on the two opposite vertical sides, and in the case of the vertical permeability cell, porous stones are placed on the top and bottom of the sample as shown in Figures 1(b) and 2(b), respectively. The size of the porous stones is 100 mm × 100 mm × 12 mm (thickness). A sheet of Whatman filter paper of the similar cross-sectional size of the porous stones is placed between the stone and the soil surface to prevent movement of soil particles.

3.1.3. Vertical Loading Plate. A 100 mm × 100 mm square plate of 12 mm thickness is used to apply the load on the surface of the soil sample. For horizontal permeability and vertical permeability, a solid vertical loading plate and a perforated vertical loading plate are used, respectively. The loading plate is connected to the loading frame using a plunger.

3.1.4. Loading Device. A lever loading system as shown in Figures 1(b) and 2(b) is fabricated, which is enabled to apply vertical force axially in suitable increments to the test specimen through a plunger. This device is capable of maintaining specified loads for long periods of time while the specimen is deforming.

3.1.5. Set of Standpipes. A glass standpipe of 10 mm diameter is used for variable head test arrangement in a horizontal permeability test setup.

3.1.6. Constant Head Tank. An appropriate water reservoir is used for constant head test arrangement, which is capable of supplying water to the vertical permeability setup to maintain the constant head.



(1) Loading frame
(2) Water
(3) Top porous stone
(4) Permeability cell
(5) Bottom porous stone
(6) Plunger
(7) Vertical loading plate
(8) Soil sample
(9) Outlet

Figure 2: Vertical permeability apparatus. (a) Mould assembly for determination of vertical permeability. (b) Vertical permeability cell under constant vertical pressure.

3.2. Three-Dimensional Consolidation Setup. Figure 3 shows the three-dimensional consolidation apparatus along with different parts of it. This apparatus is the extension of the apparatus developed by Laskar and Pal [17].

3.2.1. Consolidation Cell. The consolidation cell is made of noncorrosive cast iron. The inner and outer dimensions of the consolidation cell are 300 mm × 300 mm × 450 mm (height) and 310 mm × 310 mm × 450 mm (height), respectively. The consolidation cell is fabricated with porous cast iron plates, which is open at the top and bottom sides as shown in Figure 3.

3.2.2. Porous Stone. Porous stones are placed at the top, bottom, and four consecutive sides of the soil specimen. The porous stones are made of silicon carbide. The size of the bottom porous stone is 299 mm × 299 mm × 12 mm (thickness). The size of the top porous stone is the same as the bottom porous stone, but there is a hole of 61 mm diameter at the center through which a 60 mm diameter of another porous stone can be inserted. A sheet of Whatman filter paper of the similar cross-sectional size of the porous stones is placed between the stone and the soil surface to prevent movement of soil particles.

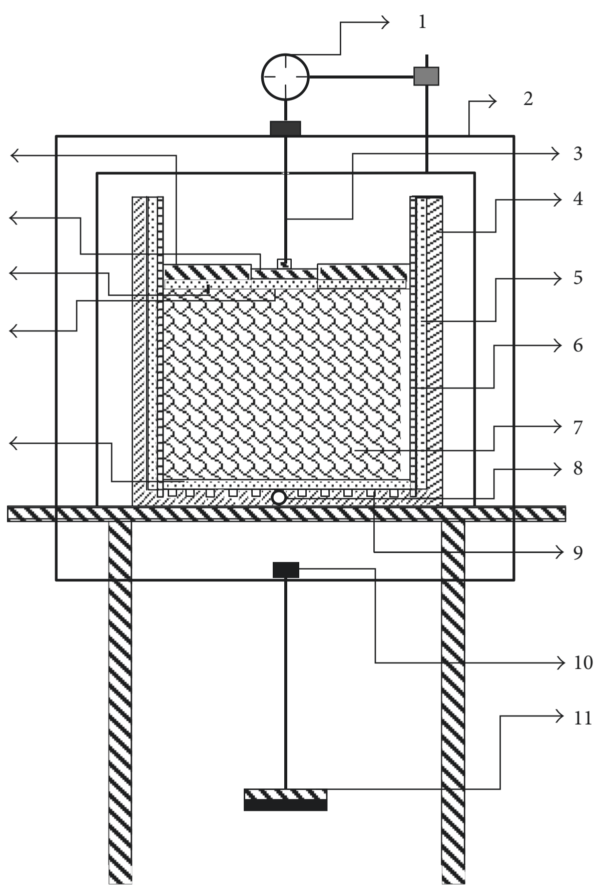
3.2.3. Loading Plate. A 60 mm diameter cast iron loading plate is used to apply the load on the soil specimen. This loading plate is connected to the loading frame by a plunger.

3.2.4. Plate to Apply Surcharge Load. Cast iron plates are fabricated, having a cross-sectional area of 299 mm × 299 mm with a 61 mm diameter center hole like a top porous stone. These plates are fabricated in such a way that these plates can apply 10, 15, 20, and 25 kN/m^2 (kPa) seating loads on top of the specimen except the 61 mm diameter center portion.

3.2.5. Consolidation Tank. A plain cement concrete consolidation tank is fabricated within which the consolidation cell is placed. The consolidation tank contains the soil specimen between the top and bottom porous stones. The tank is capable of being filled with water to a level higher than the top of the upper porous stone.

3.2.6. Dial Gauge. A dial gauge is used, which can read the values to an accuracy of 0.01 mm.

3.2.7. Loading Device. A lever loading system as shown in Figure 3 is fabricated, which is enabled to apply vertical force axially in suitable increments to the test specimen through



(1) Dial gauge
(2) Loading frame
(3) Plunger
(4) Consolidation tank
(5) Side porous stone plate
(6) Perforated cast iron box
(7) Soil sample
(8) Outlet
(9) Bottom thread connected to outlet
(10) Lever loading system
(11) Load
(12) Initial sitting loading plate with 61mm diameter centre hole
(13) Perforated loading plate
(14) Top porous stone below the initial sitting loading plate with 61mm diameter centre hole
(15) Top porous stone below the perforated loading plate
(16) Bottom porous stone

Figure 3: Schematic diagram of the developed 3D consolidation apparatus.

a plunger. This device is capable of maintaining specified loads for long periods of time while the specimen is deforming.

4. Theoretical Considerations for Consolidation

Assumptions of the developed three-dimensional consolidation test are as follows:

(1) The soil is homogeneous and isotropic.
(2) The soil is fully saturated.
(3) Darcy's law is valid.
(4) Vertical as well as lateral movements of soil particles are considered during the consolidation process.
(5) Load is applied in the vertical direction only.
(6) Excess pore water drains out from a void space in vertical and lateral directions.
(7) All the soil particles are interconnected.
(8) During the consolidation process, the lower boundary of stress remains constant.
(9) Under the plastic settlement of soil, the vertical movement of soil particles occurs due to horizontal movements of underneath soil particles.

5. Testing Materials and Program

Two different types of soils are used in this investigation. A series of tests are carried out to categorise these test materials. The physical properties along with maximum dry density (MDD) and optimum moisture content (OMC) obtained from the standard Proctor compaction test are listed in Table 1.

Horizontal and vertical permeability tests are performed on silty sand with clay soil and silty-clay soil under the four different vertical stresses. 3D consolidation tests are also performed with the same soils and same ranges of vertical stresses. Validation of 3D consolidation test results is also tried to bring out by using horizontal and vertical permeability values.

6. Specimen Preparation and Experimental Procedures

The soils used for the experiments are silty sand with clay and silty-clay soil of Agartala, Tripura, India. The properties of these two types of soil are presented in Table 1.

6.1. Horizontal Permeability under Confined Vertical Pressure. Soil samples are remolded at their maximum dry densities (MDDs) in the permeability cell in three consecutive layers. After compaction of soil in the cell, the sample is removed from the cell, and the cubical sample is covered by a rubber membrane tube that is open at the two horizontal opposite ends of the sample. The specimen is then again placed in the permeability cell. The two caps along with the porous stone plate are attached to the cell on the two vertical sides as shown in Figure 1(a), and the extra edges of the rubber membrane are stressed to the joining face of the cell and cap. The joint is made water resistant by using rubber sill. After assembling the permeability mold with the soil sample, it is placed on the loading frame. A loading plate is placed over the sample that is connected to the loading frame using a plunger as shown in Figure 1(b). The soil specimen is connected to the standpipe through the inlet. The standpipe is filled with water, and a falling head permeability test is performed under the vertical loads 100, 200, 400, and 800 kN/m^2 (kPa). The vertical loads are applied to the soil specimen by using the loading frame.

6.2. Vertical Permeability under Confined Vertical Pressure. The permeability mold is assembled as shown in

Table 1: Physical properties and compaction characteristics of soils [18].

Soil properties	Silty sand with clay soil	Silty-clay soil
Specific gravity	02.58	02.50
Liquid limit (%)	25.30	53.35
Plastic limit (%)	19.03	29.32
Plasticity index (%)	04.27	24.03
Grain size		
Sand (%)	61.60	4.86
Silt (%)	21.68	41.46
Clay (%)	16.72	53.68
Optimum moisture content (OMC) (%)	13.10	25.75
Maximum dry density (MDD) (kN/m^3)	18.80	15.60
Coefficient of permeability at MDD (m/s)	$8.87E-09$	$3.39E-10$

Figure 2(a). After assembling the mold, the soil sample is remolded at their maximum dry density (MDD) in the permeability cell in three consecutive layers. A collar is attached to the top of the mold so that a constant water head can maintain on top of the soil surface. Through the collar, a filter paper, a porous stone, and a perforated loading plate of 99 mm × 99 mm cross-section are inserted. The loading plate is connected to the loading frame using a plunger as shown in Figure 2(b). The quantity of flow for a convenient time interval is collected and measured when the steady state of flow has been established under the vertical loads 100, 200, 400, and 800 kN/m^2 (kPa). The vertical loads are applied to the soil specimen by using the loading frame.

6.3. 3D Consolidation. The inner sides of the cast iron consolidation cell are covered by a filter paper before placing the soil sample. Soil samples are placed in the consolidation cell at their maximum dry density (MDD). Side porous stone plates (as shown in Figure 3) are placed at the four consecutive sides of the consolidation cell. A filter paper, a porous stone plate, and a cast iron plate of a cross-sectional size of 299 mm × 299 mm having a center hole of 61 mm diameter are placed on the soil sample, one above the other. The cast iron plate is placed on the soil sample to apply an initial seating pressure of 5 kN/m^2 (kPa) and surcharge pressures of 10, 15, 20, and 25 kN/m^2 (kPa). Through the 61 mm diameter center hole, a filter paper, a porous stone, and a perforated loading plate of 60 mm diameter have inserted consecutively. The vertical load is applied to the top perforated loading plate through a plunger by the lever loading frame system as shown in Figure 3. A stress of 5 kN/m^2 (kPa) is applied to the soil sample by the loading plate as a seating load, and it was kept for 48 hours to saturate the soil sample. A strain gauge is attached to the loading frame system to measure the settlement of soil under different loads. After 48 hours, different vertical stresses like 100, 200, 400, and 800 kN/m^2 (kPa) are consecutively applied to the soil sample. The vertical stresses are applied for 24 hours, and a strain gauge measures the corresponding settlement with time.

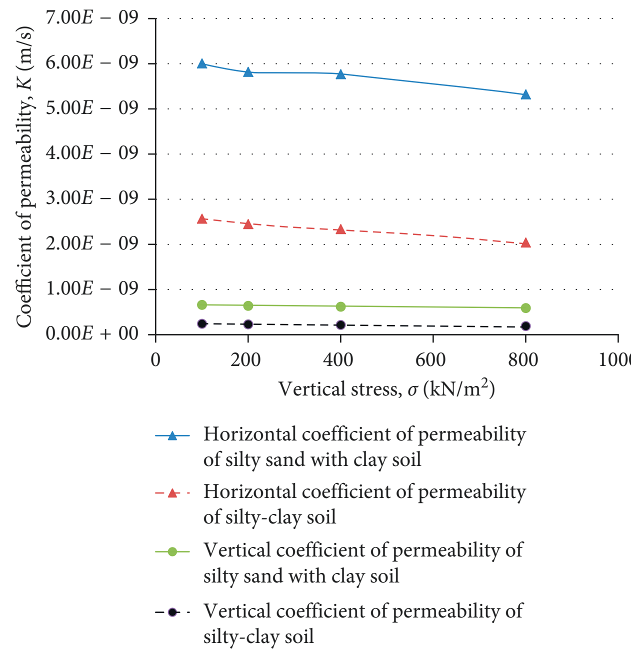


Figure 4: Horizontal and vertical coefficients of permeability under vertical confined stresses.

7. Test Results and Analysis

Experiments are conducted on two-faced soil samples. The physical properties along with maximum dry density (MDD) and optimum moisture content (OMC) obtained from the standard Proctor compaction test of the soils are presented in Table 1. Horizontal and vertical permeability tests, conventional one-dimensional consolidation tests, and three-dimensional consolidation tests are conducted on these soil samples, which are remolded at their MDD and OMC. By using the developed apparatus as shown in Figures 1 and 2, horizontal and vertical permeability tests are conducted under different vertical confined pressures. Three-dimensional consolidation tests with and without surcharge pressures are conducted by using the developed 3D consolidation apparatus as shown in Figure 3.

7.1. Horizontal Permeability under Vertical Confined Stress. Horizontal permeability tests on silty sand with clay soil and silty-clay soils are performed under different vertical stresses. The horizontal permeability tests are performed by using the developed horizontal permeability apparatus as shown in Figure 1. The falling head method is used in these tests to measure the horizontal coefficient of permeability. Horizontal permeability tests are conducted under 100, 200, 400, and 800 kN/m^2 (kPa) vertical stresses. Figure 4 shows the horizontal coefficient of permeability of silty sand with clay soil and silty-clay soil under different vertical stresses. From this figure, it is observed that, with the increase of vertical stresses, the horizontal coefficient of permeability decreases. The horizontal coefficients of permeability without vertical stress are $9.91E-09$ and $4.60E-10$ m/sec for silty sand with clay soil and silty-clay soil, respectively, and at 800 kN/m^2 (kPa) vertical stresses, the horizontal coefficients of permeability are $5.30E-09$ and $2.00E-09$ m/s for silty sand with clay soil and silty-clay soil, respectively.

7.2. Vertical Permeability under Confined Vertical Stress. Vertical permeability tests on silty sand with clay soil and silty-clay soil are also performed under different vertical stresses. The vertical permeability tests are performed by using the developed vertical permeability apparatus as shown in Figure 2. The constant head method is used for the vertical permeability test to measure the vertical coefficient of permeability. Like horizontal permeability tests, vertical permeability tests are also conducted under 100, 200, 400, and 800 kN/m^2 (kPa) vertical stresses. Figure 4 also shows the vertical coefficient of permeability of silty sand with clay soil and silty-clay soil under different vertical stresses. From this figure, it is observed that, with the increase of vertical stresses, the vertical coefficient of permeability decreases. The vertical coefficients of permeability without vertical stresses are $8.87E-09$ and $3.39E-10$ m/s for silty sand with clay soil and silty-clay soil, respectively, and at 800 kN/m^2 (kPa) vertical stresses, the vertical coefficients of permeability are $5.42E-10$ and $1.40E-10$ m/s for silty sand with clay soil and silty-clay soil, respectively.

7.3. Rate of Consolidation from Coefficient of Permeability. The coefficient of consolidation is evaluated by using permeability values in Terzaghi's consolidation theory. In Terzaghi's consolidation theory, the combined effects of compressibility and permeability are used to assess the coefficient of consolidation values. Table 2 presents the coefficient of volume change values under different vertical pressures for silty sand with clay soil and silty-clay soil tested by 1D oedometer. Horizontal and vertical permeability values under different vertical pressures are evaluated using the developed horizontal and vertical permeability apparatus and are shown in Figure 4.

According to Terzaghi's consolidation theory,

$c_{vx} = k_x/m_v\gamma_w$ = coefficient of consolidation in the x direction

$c_{vy} = k_y/m_v\gamma_w$ = coefficient of consolidation in the y direction

$c_{vz} = k_z/m_v\gamma_w$ = coefficient of consolidation in the z direction

For the case of axisymmetry, $c_{vx} = c_{vy} = c_{vh}$ (say).

$c_{vh} = k_h/m_v\gamma_w$ = coefficient of consolidation in the horizontal direction.

Now,

$c_{v3} = c_{vx} + c_{vy} + c_{vz} = c_{vz} + 2c_{vh} = (k_z/m_v\gamma_w) + 2k_h/m_v\gamma_w$.

So,

Table 2: Coefficient of volume change under different vertical pressures for silty sand with clay soil and silty-clay soil tested by 1D oedometer.

Types of soil	Vertical stress σ (kN/m^2)	Coefficient of volume change $m_v \times 10^{-4}$ (m^2/kN)
Silty sand with clay soil	100	02.90
	200	01.50
	400	00.75
	800	00.56
Silty-clay soil	100	03.80
	200	02.40
	400	01.10
	800	00.86

Table 3: 3D coefficient of consolidation of soils using horizontal and vertical permeability values under different vertical pressures.

Types of soil	Vertical stress σ (kN/m^2)	Coefficient of consolidation $c_{v3} \times 10^{-6}$ (m^2/s)
Silty sand with clay soil	100	4.341
	200	8.126
	400	16.093
	800	19.896
Silty-clay soil	100	1.380
	200	2.082
	400	4.538
	800	4.814

$$c_{v3} = \frac{k_v}{m_v\gamma_w} + 2\frac{k_h}{m_v\gamma_w}, \qquad (1)$$

where c_{v3} = three-dimensional coefficient of consolidation, k_v = vertical coefficient of permeability, k_h = horizontal coefficient of permeability, m_v = coefficient of volume change, and γ_w = unit weight of water.

By using (1), three-dimensional coefficients of consolidation are assessed with the help of k_v and k_h values and are presented in Table 3. Three-dimensional consolidation values are also evaluated by using the 3D consolidation apparatus, and the resultant values of the 3D coefficient of consolidation are shown in Table 4.

7.4. Rate of Consolidation of Soil by Using the 3D Consolidation Apparatus. The coefficient of consolidation (c_v) is determined by comparing the relationship between elapsed time (t) and dial gauge reading of the soil sample in the laboratory to the theoretical relationship between T_v and U. "Taylor's square root of time fitting method" is used to find out the c_v values for the three-dimensional cases [17]. In case of the three-dimensional consolidation, the coefficient of consolidation is calculated by using the equation $c_v = (T_v)_{90}R^2/t_{90}$ for silty sand with clay soil and silty-clay soil of Agartala, Tripura, India. The coefficients of consolidation values obtained by using the developed 3D consolidation apparatus are presented in Table 4.

Table 4: Values of 3D coefficient of consolidation of soils by using the developed 3D consolidation apparatus under different vertical pressures.

Types of soil	Vertical stresses σ (kN/m^2)	Coefficient of consolidation $c_{v3} \times 10^{-6}$ (m^2/s)
Silty sand with clay soil	100	3.267
	200	7.131
	400	14.927
	800	18.471
Silty-clay soil	100	1.037
	200	1.870
	400	4.301
	800	4.618

A comparison is developed between the coefficient of consolidation values, assessed by the developed 3D consolidation apparatus, and horizontal and vertical permeability apparatus. The comparison is presented in Figures 5 and 6.

7.5. Compression Indices of Soil Using the 3D Consolidation Apparatus under Different Surcharge Pressures. In this study, three-dimensional consolidation tests are performed by using the three-dimensional consolidation apparatus as shown in Figure 3, which is the extension of the 3D consolidation apparatus presented by Laskar and Pal [17]. Silty sand with clay soil and silty-clay soil are used in the test. Consolidation tests are performed under different surcharge pressures like 0.00, 10.00, 15.00, 20.00, and 25.00 kN/m^2 (kPa). Table 5 shows the compression index values under different surcharge pressures and consolidative vertical stresses.

8. Discussions

The following discussions are made in this section:

(i) Assessment of horizontal and vertical permeability of soil under vertical stress and comparison between them

(ii) Evaluation of coefficient of consolidation using horizontal and vertical permeability values and comparison of it with the coefficient of consolidation obtained from the 3D consolidation test

(iii) Effects of surcharge pressures on 3D consolidation of soil

8.1. Assessment of Horizontal and Vertical Permeability of Soil under Vertical Stress and Comparison between Them. In most of the cases, the permeability of soil is different in horizontal and vertical directions. The coefficient of permeability is one of the most uncertain soil properties, and its value may vary based on different magnitudes. Vertical stress on soil is one of the most important factors among the several factors, which are having a large impact on the permeability of soil. A relatively homogeneous soil layer will

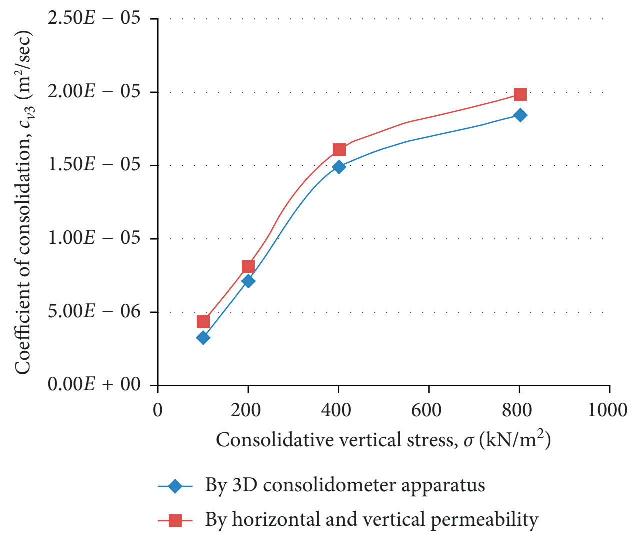


Figure 5: Comparison of coefficient of consolidation of silty sand with clay soil evaluated by the 3D consolidation apparatus and horizontal and vertical permeability values.

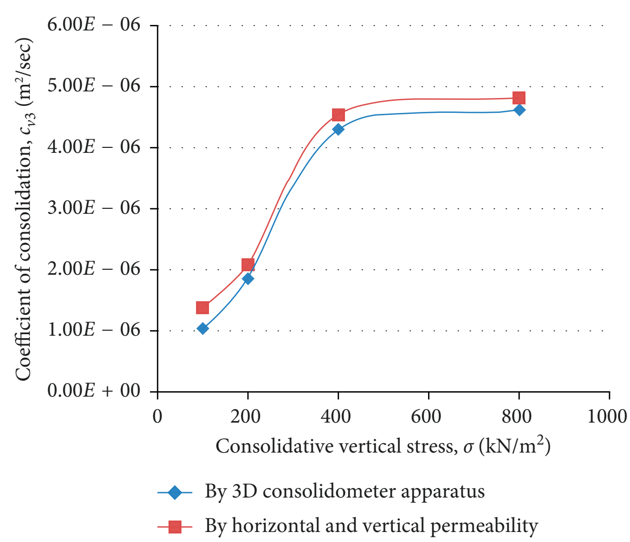


Figure 6: Comparison of coefficient of consolidation of silty-clay soil evaluated by the 3D consolidation apparatus and horizontal and vertical permeability values.

show different permeabilities under different vertical stresses. In this study, horizontal and vertical permeability tests are performed under different vertical stresses using the developed horizontal and vertical permeability apparatus as shown in Figures 1 and 2. These permeability tests are performed on silty sand with clay soil and silty-clay soils, which are compacted at MDD and OMC. The horizontal and vertical coefficients of permeability results under different vertical stresses on silty sand with clay soil and silty-clay soil are presented in Figure 4. From this figure, it is observed that horizontal permeability of the soil is higher than the vertical permeability of the soil, and with the increase of vertical stresses, the horizontal and vertical permeability of soil decreases. With the increase of vertical stresses on soil, consolidation of soil occurs and thereby the

Table 5: Compression indices and coefficient of consolidation of soils using the 3D consolidation apparatus under surcharge pressures.

Types of soil	Surcharge pressures (kN/m^2)	Consolidative vertical stresses σ (kN/m^2)	Compression indices C_c	Coefficient of consolidation $c_{v3} \times 10^{-6}$ (m^2/s)
Silty sand with clay soil	00	100	0.0130	03.26
		200	0.0290	07.13
		400	0.0461	14.92
		800	0.1920	18.47
	10	100	0.0106	03.08
		200	0.0243	06.78
		400	0.0387	14.16
		800	0.1632	17.55
	15	100	0.0099	03.04
		200	0.0228	06.65
		400	0.0365	13.87
		800	0.1542	17.16
	20	100	0.0093	02.94
		200	0.0215	06.15
		400	0.0345	13.44
		800	0.1458	16.63
	25	100	0.0088	02.70
		200	0.0203	05.86
		400	0.0326	12.88
		800	0.1370	15.86
Silty-clay soil	00	100	0.0261	01.03
		200	0.0560	01.87
		400	0.1190	04.30
		800	0.2993	04.61
	10	100	0.0202	00.94
		200	0.0420	01.72
		400	0.0904	03.95
		800	0.2304	04.24
	15	100	0.0181	00.90
		200	0.0382	01.62
		400	0.0831	03.77
		800	0.2119	04.00
	20	100	0.0157	00.86
		200	0.0334	01.53
		400	0.0739	03.60
		800	0.1907	03.85
	25	100	0.0133	00.84
		200	0.0257	01.51
		400	0.0642	33.10
		800	0.1668	03.71

void ratio of soil decreases [19–21]. Due to a decrease in the void ratio with the increase of vertical stresses, the permeability of this soil reduces.

8.2. Evaluation of the Coefficient of Consolidation Using Horizontal and Vertical Permeability Values and Comparing It with the Coefficient of Consolidation Obtained from the 3D Consolidation Test. In this study, the coefficient of consolidation of silty sand with clay soil and silty-clay soil is evaluated by using horizontal and vertical permeability values and compared it with the coefficient of consolidation values obtained from the 3D consolidation apparatus. The coefficient of consolidation is evaluated by using horizontal and vertical permeability values in Terzaghi's consolidation theory. In Terzaghi's consolidation theory, the combined effects of compressibility and permeability are used to assess the coefficient of consolidation values. Table 3 presents the coefficient of consolidation values that are evaluated by using horizontal and vertical permeability values. Coefficients of consolidation of silty sand with clay soil and silty-clay soils are also evaluated using the developed 3D consolidation apparatus, and the values are shown in Table 4. A comparison of these two different methods by which the coefficient of consolidation values is evaluated (i.e., by using permeability values and 3D consolidation apparatus) is drawn and presented in Figures 5 and 6. From these figures, it is observed that the coefficients of consolidation values evaluated from the permeability values are closer to the coefficient of consolidation values evaluated from the developed 3D consolidation apparatus. Errors between these two evaluation methods are assessed and presented in Table 6. The errors are observed within the range of −4.00 to −25.00% depending on the vertical stresses.

Table 6: Comparison of the coefficient of consolidation evaluated by horizontal and vertical permeability values and the 3D consolidation apparatus.

Soil types	Vertical stresses σ (kN/m^2)	Coefficient of consolidation by permeability values $c_{v3} \times 10^{-6}$ (m^2/s)	Coefficient of consolidation by 3D consolidation apparatus $c_{v3} \times 10^{-6}$ (m^2/s)	Errors (%)
Silty sand with clay soil	100	04.341	03.267	−24.75
	200	08.126	07.131	−12.24
	400	16.093	14.927	−07.24
	800	19.896	18.471	−07.16
Silty-clay soil	100	1.380	1.037	−24.95
	200	2.082	1.870	−10.18
	400	4.538	4.301	−05.21
	800	4.814	4.618	−04.05

8.3. Effects of Surcharge Pressures on 3D Consolidation of Soil. In this part of the study, 3D consolidation tests are performed on silty sand with clay soil and silty-clay soil under different surcharge pressures by using the developed 3D consolidation apparatus as shown in Figure 3. In a three-dimensional consolidation of soil, lateral and vertical movements of soil particles, as well as lateral and vertical movements of pore water, are taken into consideration. The soil under consolidation may have isotropic or anisotropic surrounding soil layers that affect the lateral movement of soil particles under consolidation and also affect the lateral movement of pore water. If the surcharge pressure on surrounding soil increases, then the soil gets denser, and hence, the horizontal movement of consolidating soil and horizontal pore water reduces. The results of 3D consolidation of silty sand with clay soil and silty-clay soil under different surcharge pressures are presented in Table 5. From this table, it is observed that with the increase in surcharge pressures, the compression index and coefficient of consolidation values decrease for both the soils. The surcharge pressures have a great influence on consolidation characteristics. The rate of consolidation of soil is proportional to the rate of extraction of pore water from the soil sample. With the extraction of pore water from soil mass, the arrangement of the skeleton of soil changed and due to which settlement occurs. At the time of rearrangement of soil particles with the extraction of water, it may move in horizontal and in vertical directions. Due to the increase in surcharge pressures, the void ratio of soil reduces, and it becomes denser, and because of that, the horizontal movement of soil particles and lateral extraction of pore water reduce, and the corresponding compression index and the rate of consolidation also reduce.

9. Practical Field Applications

Correct prediction of permeability and consolidation characteristics of soil are the most important and critical task in the geotechnical engineering field. A soil layer in in situ condition may show different permeability values in horizontal and vertical directions. Again, the vertical depth of the soil layer is also a key factor that affects the permeability of the soil. With the change in depth of a soil layer from the ground surface, the vertical stress on that soil layer will change and so that the permeability of the same soil layer will change with the changes of depth and corresponding vertical stresses. In this study, horizontal and vertical permeability apparatus are fabricated to assess the horizontal and vertical permeability of soil under different consolidative vertical stresses. By using these permeability apparatus, it is possible to precisely predict the permeability of soil by considering the in situ vertical stresses on that soil.

The conventional method of evaluation of settlement from the result of oedometer tests assumes that the soil only has a vertical strain and there will be no lateral strain. It also assumes that the pore water dissipation only occurs in the vertical direction, and there will be no radial flow of water. The lateral confinement of the soil sample in the case of the one-dimensional oedometer test is to be taken as representative of the actual soil conditions. The newly developed three-dimensional consolidation apparatus allows the vertical and horizontal movement of soil particles, and it also allows the vertical and the radial flow of water during the consolidation process under different consolidative vertical pressures and surcharge pressures. In this study, it is observed that there is a large effect of surcharge pressures on consolidation characteristics of the soil. In in situ conditions, any consolidating soil layer may have different surcharge pressures, which affect the consolidation behavior of that soil. As the developed 3D consolidation apparatus may perform the 3D consolidation tests under different surcharge pressures, it may appropriately imitate the in situ soil conditions and may predict more precise consolidation results.

10. Concluding Remarks

This study concentrates on the development of the horizontal and vertical permeability apparatus, where it is possible to perform the test under different vertical stresses. A 3D consolidation apparatus is also presented in this study by which 3D consolidation tests are performed under different surcharge pressures. The entire tests are performed with silty sand with clay soil and silty-clay soil of Agartala, Tripura, India. Based on the results and discussions made above, the following conclusions may be outlined:

(1) The horizontal permeability of the soil is higher than the vertical permeability of the soil, and the

permeability of soil decreases with the increase in vertical stresses.

(2) In case of the 3D consolidation of soil, the consolidation characteristics are largely affected by the surcharge pressures. With the increase in surcharge pressures, the surrounding soil of consolidating soil becomes denser, and due to this, it reduces the lateral movements of consolidating soil particles. It also reduces the lateral movement of pore water. The compressibility and the rate of consolidation of soil under 3D consolidation reduce due to the increase in vertical surcharge pressures.

(3) Coefficients of consolidation of silty sand with clay soil and silty-clay soil are evaluated using horizontal and vertical permeability values and compared it with coefficients of consolidation values obtained from the developed 3D consolidation apparatus. The coefficient of consolidation is evaluated using horizontal and vertical permeability values in Terzaghi's consolidation theory, where combined effects of compressibility and permeability are used to assess the coefficient of consolidation values. After comparing the coefficient of consolidation results obtained from these different two methods (i.e., by using permeability values and 3D consolidation apparatus), the errors between them are observed within the range of −4.00 to −25.00%.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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