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Flow through Double Layered Porous Media Perpendicular to Bedding Plane: An Experimental & Simulation Work

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Abstract: ***Permeability (k) is an essential property of soil and has its importance in various fields of soil mechanics and geotechnical engineering. It is the ease with which water can percolate through the interconnected voids in a soil mass. To determine the permeability of soil samples, experimentation work needs to be carried out. The permeability analysis of layered soil samples, i.e., double-layered or triple-layered soil samples, much more time is consumed to achieve accurate results. So, to bypass this time consumption and laborious physical work, Computational Fluid Dynamics (CFD) analysis proves to be beneficial. ANSYS Fluent 14 software is a powerful tool which works on CFD technique seems to provide accurate results for permeability analysis as compared to laboratory results. In the present study, CFD analysis of double-layered soil samples is carried out using ANSYS Fluent 14 software, and the results obtained by this technique are compared with the laboratory results. Experimental as well as a numerical study was carried out to determine permeability and pressure drop variation for double layer combinations developed using the five soil types namely gravel (G), coarse sand (CS), fine sand (FS), fly ash (FA) and silt (S), and a formulation was proposed to calculate viscous resistance factor experimentally which was validated through simulation results. The permeable soil layer was modeled as porous media obeying Forchheimer's law.***

Keywords : Permeability, Porosity, Darcy's law, Forchheimer's equation, ANSYS Fluent.

I. INTRODUCTION

Flow through porous media is an important phenomenon having its importance for Civil Engineers, Geotechnical Engineers, Geologists and also in the field of earth sciences. Permeability is the governing phenomenon in flow through porous media. Knowledge of permeability is useful in several civil engineering applications such as seepage through the body of earth dams, groundwater recharge, riverbank filtration, sand filters, etc. In natural conditions, flow can be normal, parallel, or inclined to the bedding plane. In general, the flow is normal to the bedding plane.The governing equation for flow through porous media is given by Henry Darcy in the form of Darcy's law. As per Darcy's law, the equivalent coefficient of permeability value for stratified soil deposit in case of flow normal to the bedding plane is given by equation 1.

$$k_{calc} = \sum_1^n W_i \Big/ \sum_1^n \frac{W_i}{k_i} \qquad (1)$$

Where,

k_{calc}= calculated permeability of stratified soil based on Darcy's law; W_i= thickness of i^{th} layer; k_i= permeability of i^{th} layer; n = number of layers.

Experimental analysis on single and multiple layers of porous media is studied by several researchers, but the verification of these experimental studies by using a computational/simulation technique is very limited in the literature.

Gupta et al. (2016) studied the influence of position and thickness of individual soil layer on the permeability of layered soil mass and concluded that the experimentally measured permeability of stratified soil mass is dependent on the nature of exit soil layer [1]. Alam et al. (2015) carried out their experimental investigations on double-layered stratified soil mass and concluded that the exit layer in a layered soil system plays an important role in governing the permeability of layered soil mass. Effect of the interface was also studied by them [2]. Sobieski et al. (2014) have validated Darcy's and Forchheimer's law experimentally and numerically using ANSYS Fluent and carried out their work on water flow through a porous granular bed. Eight different methods were suggested to derive flow model parameters from a set of measurement data. They concluded that Forchheimers's law gives better results as compared to Darcy's law [3,4]. Prakash et al. (2013) conducted their experimental work on triple-layered soil mass using three different soil materials and concluded that the bottom layer governs the equivalent permeability coefficient in layered soil analysis. Another finding by them is that the equivalent permeability coefficient is not just dependent on the individual permeability values of soil layers comprising the soil mass but also depend on their relative positioning [5]. Chakraborty et al. (2006) found that the direct measurement of permeability is time taking and costly. So, they proposed indirect methods to calculate the permeability by incorporating the available soil properties, mainly, particle size distribution [6]. Phani Kumar et al. (2004) studied the effect of the fly ash content on the free swell potential, swell index, swelling pressure, compaction, plasticity and hydraulic conductivity characteristics of expansive soil experimentally. As the content of

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fly ash increases, the dry unit weight and strength increased and plasticity, hydraulic conductivity, as well as the swelling properties of the blend, decreased.

For a given water content, an increase in fly ash content significantly increases the resistance to penetration of the blends [7]. Sridharan et al. (2002) carried out their study on an equal thickness of soil layers in a double-layered stratified porous media subjected to a flow normal to the bedding plane. They conclude that due to mutual interference between the soil layers comprising the stratified soil mass, Darcy's law has some limitations [8]. Boadu (2000) developed regression-based models to find hydraulic conductivity of compacted soils from grain size distribution in a saturated state. The grain size distribution was adequately represented in the model. Models developed by them surpasses the existing models for finding the hydraulic conductivity [9]. Arya et al. (1999) presented a model to develop a relationship between the particle size distribution and hydraulic conductivity and computing permeability as a function of water content [10]. Wolf et al. (1992) developed a multiport permeameter for finding the hydraulic conductivity and proposed that hydraulic conductivities obtained from standard laboratory procedures were slightly lesser as compared to those values that were obtained from grain size analysis [11].In the present study, the permeability of single soil layers perpendicular to the bedding plane is determined experimentally, and the same has been verified by simulation using Ansys Fluent 14 software. To achieve the aim of the present study, a new permeameter was fabricated having a length of 50 cm and diameter 15 cm.

II. EXPERIMENTAL PROCEDURE

The basis for the selection of different types of materials was to cover a wide range of variation in the permeability. The combinations of double-layered soil sample used in the present study are shown in figure 1.

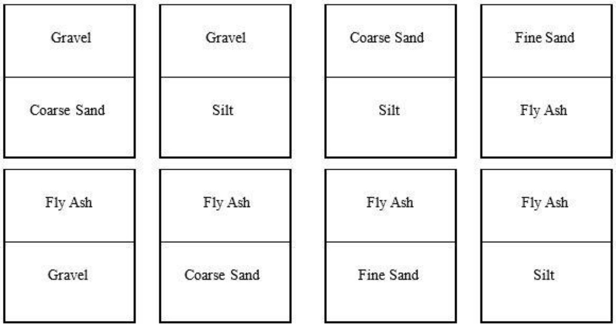


Fig. 1. Double layered soil combinations used in present study.

The various experiments carried out to achieve the objectives of the present study have been briefly summarised below-

A. Particle Size Distribution

To determine the percentage of varying size of soil particles in a soil sample, particle size distribution analysis is carried out. For the soil particles with particle size greater than 75 microns, dry sieve analysis is carried out. For the soil particles finer than 75 microns, sedimentation analysis is carried out. The standard procedure to carry out this analysis is adopted as per IS 2720: Part IV-1985 [12]. The particle size distribution for various soil types used in the present study is shown in figure 2,3,4,5 and 6.

B. Specific Gravity

The specific gravity of soil is an important parameter and is required for computing various quantities such as unit weight of soil, voids ratio, degree of saturation, etc. It is determined in the laboratory using pycnometer for coarse-grained soils and density bottle for fine-grained soils (IS 2720: Part- III 1980) [13].

C. Permeability

Permeability is the property of soil which permits the fluid to percolate through it. In the laboratory, the following methods are adopted to calculate the permeability of soil mass depending upon the property of soil mass [14].

a. Constant Head Test

To determine the permeability of coarse-grained soil mass, the constant head test is taken into account. In this test, water is allowed to pass through a soil sample of known length and cross-sectional area in a given time (IS 2720: Part 17-1986) [15]. The permeability is calculated at a known porosity of 40%. By knowing the specific gravity of the material and volume of the mould, the mass required at 40% porosity to fill the mould was determined (IS 1498-1970) [16]. A known mass of each soil is filled in three equal layers with a required compactive effort and thus giving 40% porosity to the testbed. Using the above-mentioned parameters, the formula given as equation 2 is used to calculate the permeability of the coarse-grained soil mass. Equation 3 is used to convert the coefficient of permeability obtained at recorded temperatures to find the value of permeability at 27^0C.

$$k_{obs} = \frac{QL}{Aht} \tag{2}$$

$$\frac{k_{27}}{k_T} = \frac{\mu_T}{\mu_{27}} \tag{3}$$

Where,

Q = discharge collected(cm^3) in time t(s); A = cross sectional area of the sample(cm^2); h = difference in manometer levels(cm); L = distance between manometer tapping points(cm); k_{27}= permeability at 27°C (cm/s) ; k_T= permeability at test temperature (cm/s); μ_T= dynamic viscosity of water at test temperature; μ_{27}= dynamic viscosity of water at 27°C temperature.

b. Falling Head Permeability Test

This test is applicable to estimate the permeability value of fine sands, silty, and clayey soils (IS 2720: Part 17-1986) [15]. Since the passage of fluid is very less through such types of soil materials, so constant head test is not applicable in this case. In this test, water is filled in the standpipe and is allowed to flow through the soil mass. During the test, the water level will drop continuously and height of fall from h_1 to h_2 and time of fall is recorded using these values in the formula mentioned below as equation 4 will provide a value of permeability of the soil mass.

$$k_{obs} = 2.3\frac{aL}{At}\log_{10}\frac{h_1}{h_2} \tag{4}$$

Where,

a= area of stand pipe (cm^2); L= length of sample (cm); A= cross-sectional area of sample (cm^2); t= time (sec); h_1=

initial head (cm); h_2= final head (cm).
In the present study, the required sediment samples were collected in an appropriate amount. After proper cleaning and sieving of sediments to remove unwanted impurities, a considerable amount of sample was taken for each type and kept in the oven to dry for about one day at 105^0C temperature as per IS 2720: Part-I 1983 [17].

III. SIMULATION WORK

Computational Fluid Dynamics (CFD) techniques were used to simulate the fluid flow behaviour through porous media models using ANSYS Fluent 14 software. ANSYS Fluent 14 is a commercial software based on CFD technique using a finite volume approach [19]. The computational model was modelled having the same geometry as of experimental setup (50 cm in length and 15 cm in diameter). This model was meshed using GAMBIT software.
Permeable materials were modelled as porous medium obeying Forchheimer's equation. The pressure drop, Δp (N/m^2), across a porous media of thickness Δx (m) is represented by equation 5.

$$\frac{\Delta p}{\Delta x} = \frac{\mu}{\alpha} V + \frac{1}{2} C_2 \rho V^2 \qquad (5)$$

Since the flow is laminar in the present study, C_2 has been considered to be zero, as the pressure drop is directly proportional to the velocity [20].
For different head values, velocity is recorded, and the value of the viscous resistance coefficient is calculated as per equation 6. Since pressure drop is obtained by simulation, simulated permeability(k_{simu}) can be determined.

$$\frac{1}{\alpha} = \frac{\rho g}{\mu L} \sum_{i=1}^{n} (\frac{\Delta h_i}{V_i})/n \qquad (6)$$

Where,
V = Fluid velocity (m/s); μ = Dynamic viscosity ($kgm^{-1}s^{-1}$); ρ = Density of fluid (kg/m^3); 1/α = viscous resistance coefficient (1/m^2); C_2 = inertial resistance coefficient (1/m); g = acceleration due to gravity(m/s^2); L = Length of specimen(cm); Δh_i = head difference for i^{th} number of observations(cm); V_i = Outlet velocity observed for different values of head difference(cm/s).

IV. RESULTS AND DISCUSSION

Specific gravity for gravels, coarse sand, fine sand, fly ash and silt were found to be 2.64, 2.63, 2.60, 1.98, 2.57. The specific gravity of fly ash was less than other sediment types due to a high proportion of cenospheres or hollow particles [18].
Particle size distribution analysis was carried out for the materials used in the study. Gradation curves for each material were prepared and presented in figure 2,3,4,5 and 6.

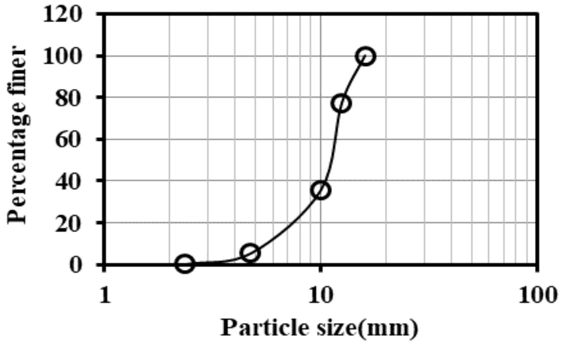


Fig. 2. Particle size distribution for gravel.

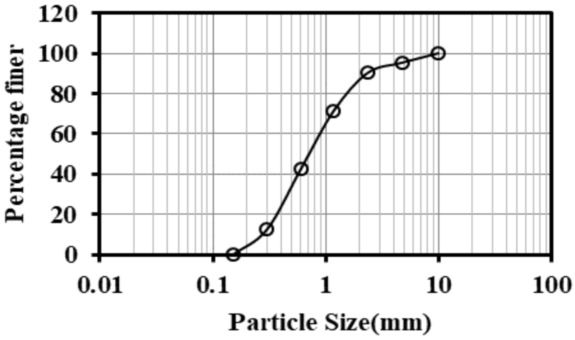


Fig. 3. Particle size distribution for coarse sand.

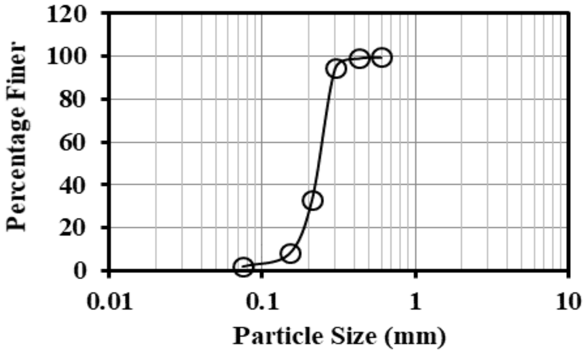


Fig. 4. Particle size distribution for fine sand.

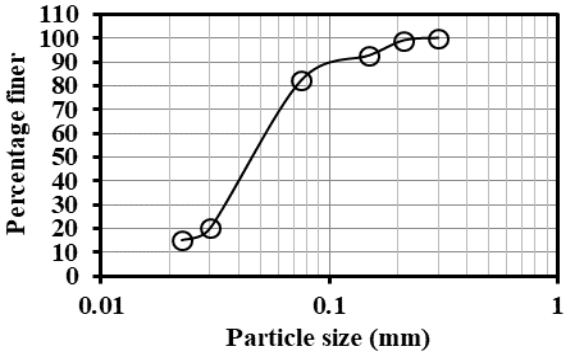


Fig. 5. Particle size distribution for fly ash.

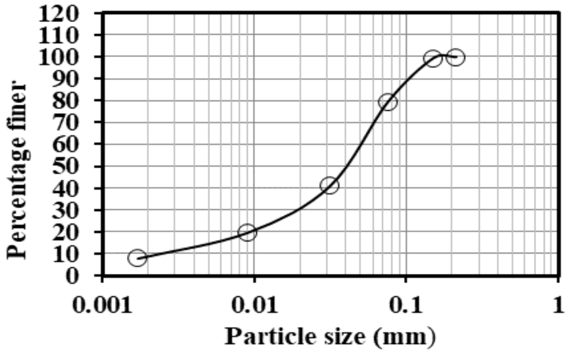


Fig. 6. Particle size distribution for silt.

Table 1 shows the values of viscous resistance for simulation in ANSYS Fluent 14 for the different types of soil materials used in the present study. Table 2 is a perusal of all the permeability values obtained during the present work. Observed permeability, which is obtained from experimental analysis, calculated permeability obtained by using Darcy's law and simulated permeability, which is obtained from the pressure drop results, which is an outcome of simulation work. In this study, simulated permeability and calculated permeability are obtained close to each other. Since some experimental values such as velocity and viscous resistance coefficient are achieved via laboratory studies, and they are used as input values in ANSYS Fluent 14 for simulation. Also, it is observed that during layered analysis, at the junction where two soil layers meet, a mixed soil layer is formed in between the two soil layers during the passage of water through the soil sample due to which the experimental results and calculated results are found not to be the same. Sometimes entrapped air also varies these permeability values.

Figure 7 shows a graph between observed permeability and simulated permeability. All the observations in this graph lies close to the line of perfect agreement, which indicated the accuracy achieved in the present study. Similarly, in figure 8, which is plotted between observed permeability and calculated permeability, good accuracy is seen.

Table 3 indicates the percentage error between k_{obs} and k_{simu}, $k_{obs,}$ and k_{calc}. The maximum percentage error i.e. -29.07% is obtained in the case where FA is in top layer, and G is in bottom layer. The reason for this error is due to the fact that fly ash particles are very fine and when the flow of water passes through this layer, the fines of fly ash gets penetrated into the gravel layer and thereby reducing the permeability of the stratified soil mass.

Figure 9 shows the pressure contours for all the soil combinations used in the present study. The pressure contours are the results of simulation work. These contours clearly show the pressure at each and every point inside the study domain.

Figure 10 represents the graphs of length of sample v/s pressure drop for the soil combinations in the present study. Since the total length of soil sample is 50 cm and the double layers are of equal thickness i.e. 25 cm each so the pressure drop graph shows a sudden variation after 25 cm length of sample. The pressure drop variation also depends upon the k_1/k_2 ratio (where k_1 is the permeability of the more permeable layer and k_2 is the permeability of less permeable layer).

Table- I: Values of Viscous resistance coefficients for different soil types.

S.No.	Soil Type	$1/\alpha (1/m^2)$
1.	Gravel	1.41×10^{10}
2.	Coarse Sand	2.47×10^{10}
3.	Fine Sand	1.55×10^{11}
4.	Fly Ash	1.83×10^{12}
5.	Silt	2.75×10^{13}

Table- II: Observed Permeability, Simulated Permeability and Calculated Permeability for various soil combinations.

S. N.	Combinations	k_{obs} (cm/s)	k_{simu} (cm/s)	K_{calc} (cm/s)
1.	G (top) - CS (bottom)	4.65×10^{-2}	5.68×10^{-2}	5.70×10^{-2}
2.	G (top) - S (bottom)	6.35×10^{-5}	8.00×10^{-5}	7.98×10^{-5}
3.	CS (top) - S (bottom)	6.20×10^{-5}	8.00×10^{-5}	7.97×10^{-5}
4.	FS (top) - FA (bottom)	8.86×10^{-4}	1.11×10^{-3}	1.07×10^{-3}
5.	FA (top) - G (bottom)	9.22×10^{-4}	1.19×10^{-3}	1.15×10^{-3}
6.	FA (top) - CS (bottom)	1.03×10^{-3}	1.19×10^{-3}	1.14×10^{-3}
7.	FA (top) - FS (bottom)	9.05×10^{-4}	1.11×10^{-3}	1.07×10^{-3}
8.	FA (top) - S (bottom)	5.97×10^{-5}	7.52×10^{-5}	7.46×10^{-5}

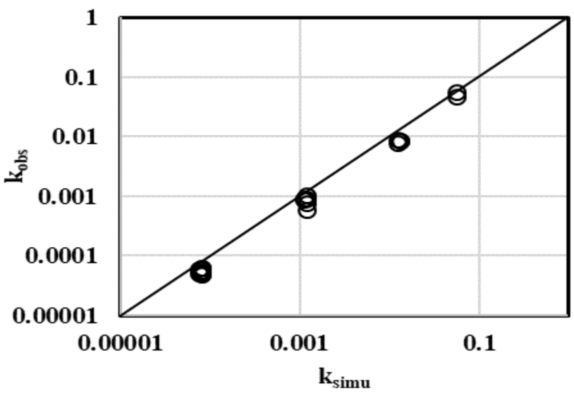


Fig. 7. Observed Permeability v/s Simulated Permeability

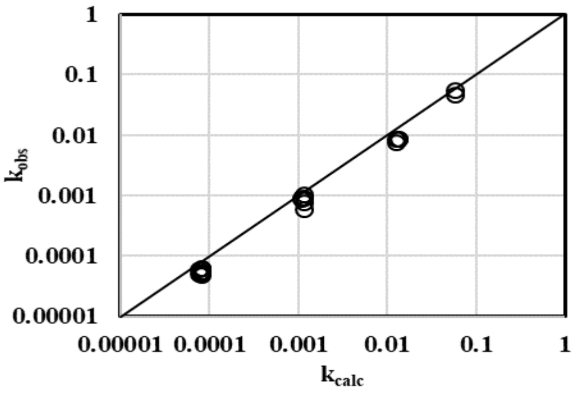
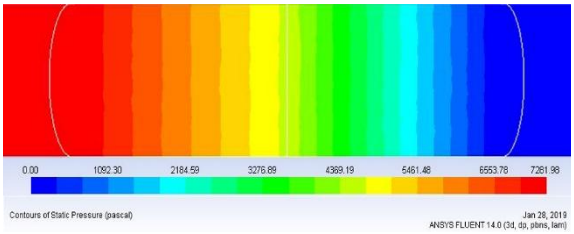


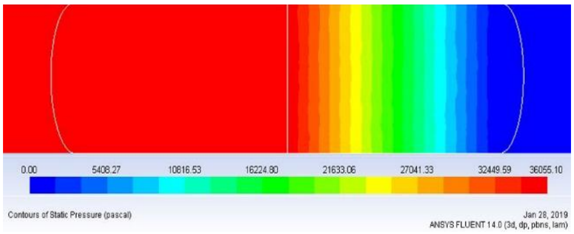
Fig. 8. Observed Permeability v/s Calculated Permeability

Table -III: Percentage error between k_{obs} and k_{simu}, k_{obs} and k_{calc}

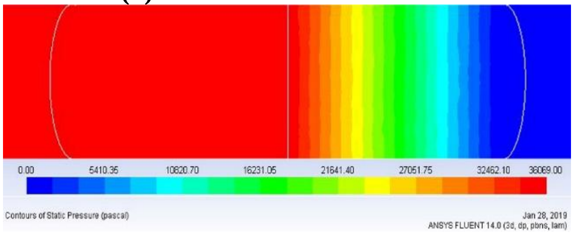
S.N.	Material	Percentage error b/w k_{obs} and k_{simu}	Percentage error b/w k_{obs} and k_{calc}
1.	G (top) - CS (bottom)	-22.15	-22.58
2.	G (top) - S (bottom)	-25.98	-25.67
3.	CS (top) - S (bottom)	-29.03	-28.55
4.	FS (top) - FA (bottom)	-25.28	-20.77
5.	FA (top) - G (bottom)	-29.07	-24.73
6.	FA (top) - CS (bottom)	-15.53	-10.68
7.	FA (top) - FS (bottom)	-22.65	-18.23
8.	FA (top) - S (bottom)	-25.96	-24.96



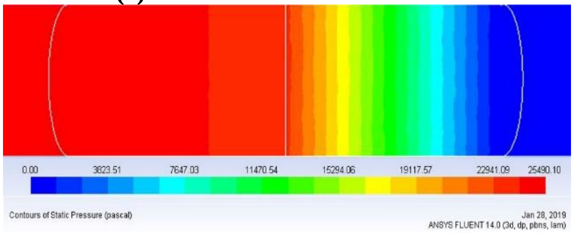
(a) Pressure Contour for G-CS



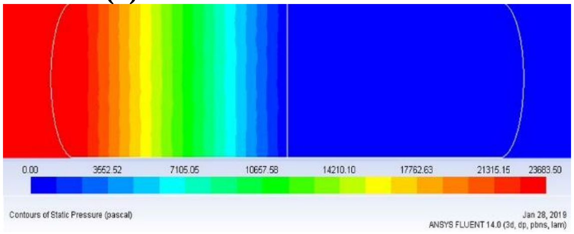
(b) Pressure Contour for G-S



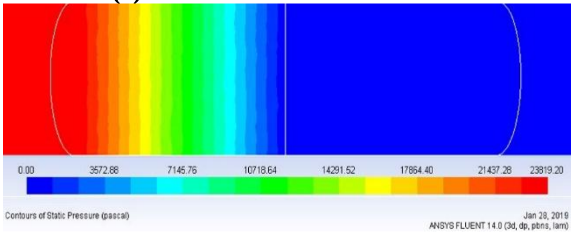
(c) Pressure Contour for CS-S



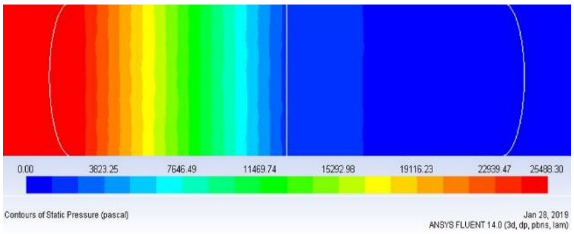
(d) Pressure Contour for FS-FA



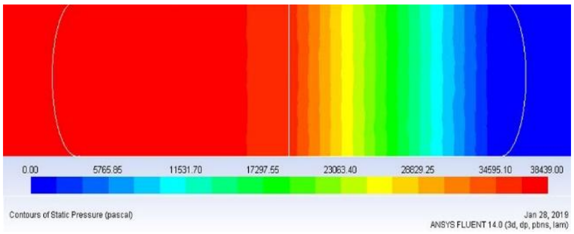
(e) Pressure Contour for FA-G



(f) Pressure Contour for FA-CS

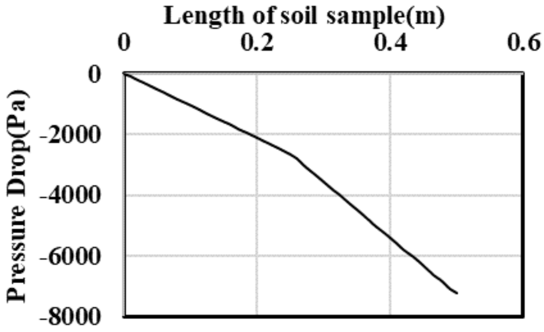


(g) Pressure Contour for FA-FS

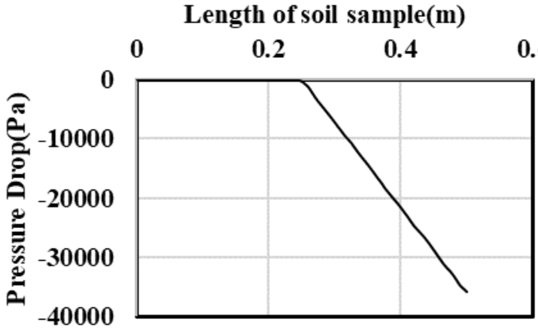


(h) Pressure Contour for FA-S

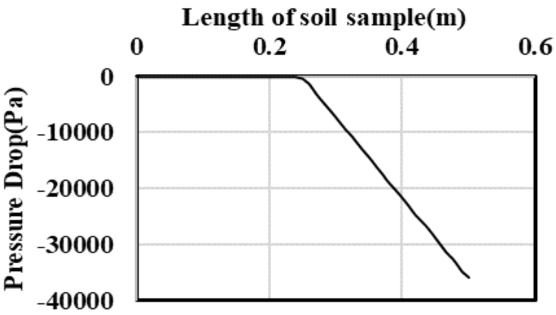
Fig. 9. Pressure contours for various double layered soil combinations



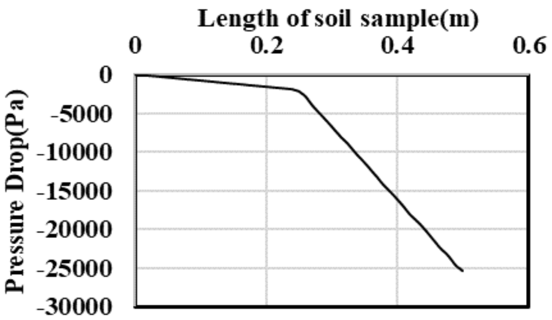
(a) Length of sample v/s Pressure drop for G-CS sample



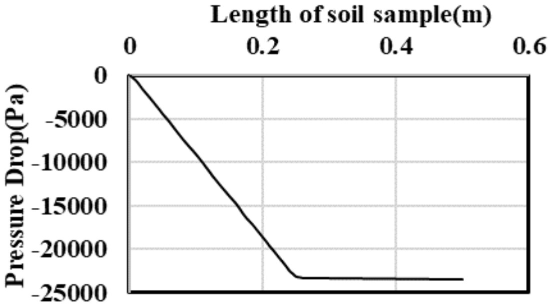
(b) Length of sample v/s Pressure drop for G-S sample



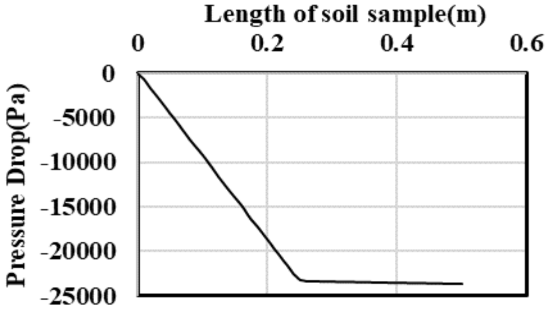
(c) Length of sample v/s Pressure drop for CS-S sample



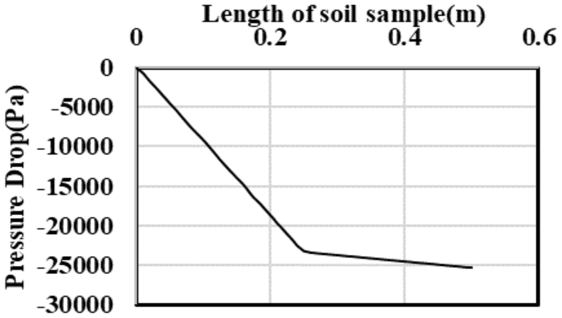
(d) Length of sample v/s Pressure drop for FS-FA sample



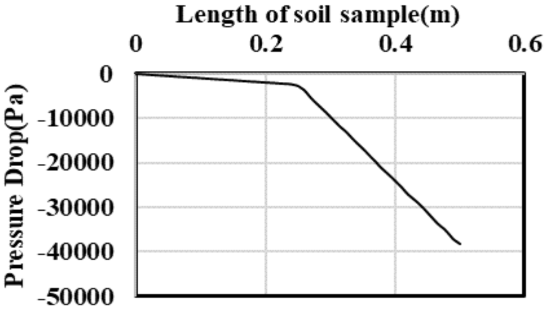
(e) Length of sample v/s Pressure drop for FA-G sample



(f) Length of sample v/s Pressure drop for FA-CS sample



(g) Length of sample v/s Pressure drop for FA-FS sample



(h) Length of sample v/s Pressure drop for FA-S sample

Fig. 10. Length of sample v/s Pressure drop for all the possible soil combinations in the present study.

V. CONCLUSION

i) It has been found that CFD can provide a good alternative to the standard experimental procedure for finding the coefficient of permeability.

ii) The CFD analysis is less time consuming as compared to the experimental analysis.

iii) The accuracy of CFD permeability analysis as compared to the experimental analysis also seemed to be pretty good.

iv) The ratio of individual permeability of soil materials in a stratified soil sample have a tendency to vary the equivalent permeability result.

v) Formation of mixed soil layer at the interface of two soil layers varies the actual equivalent permeability, which should be obtained during the experimental analysis.

vi) For more a number of soil layers, simulation analysis will prove to be a better alternative than the standard experimental study.

vii) For further study, a correction factor needs to be implemented in simulation results so that the simulation and experimental permeability results should lie close to each other with a minimum percentage of error.

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