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Impact of Overburden on Hydraulic Conductivity and Numerical Analyses of Seepage and Stability of Cement Stabilized Embankments

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Abstract The study introduces new approaches for determining hydraulic conductivity of natural and cemented soils under varying overburden and consolidation loads, followed by numerical evaluations of seepage and canal stability when cemented soils are utilised. This was done mostly due to the fact that Pakistan has several canal breaches and embankment failures annually. Therefore, it is crucial to examine the stability of existing canals in terms of seepage and stability and to recommend ways for their reinforcement. This study attempts to examine constant seepage conditions and the stability of existing canals. Results reveal that overburden loads can impair hydraulic conductivity considerably. At higher stresses of 200 kPa of overburden stress, the hydraulic conductivity of natural soils was reduced by 189%, and by 306% and 133% for the mix of 5% cement and silty clay and 10% cement, respectively. In addition, it was noted that the canal embankments were only marginally safe due to the constant seepage. Varying ratios of 5% and 10% cement with silty clay having 1 m thick layers with different dimensions were used to analyse and reinforce the weak canal embankments. It was also discovered that 5% cemented soil layers provided greater stability. This research suggests techniques for fortifying both the present and future canal embankments.

Keywords Overburden Stress, Consolidation Stress, Hydraulic Conductivity, Cemented Soils, Triaxial Test

1. Introduction

Canals deliver drinking and agricultural water. These canals have homogeneous clayey silt embankments. Embankments can collapse, destroying property, lives, and crops. Erosion, seepage, overtopping, and piping cause most breach failures. Multiple embankment failures and related failure mechanisms are observed, mainly in Pakistan [1]. The potential for the collapse of such canal embankments necessitates the discovery of ways for reinforcing and stabilizing existing embankments, as well as the development of strategies for the future construction of embankments.

The use of cement in soils to increase their shear strength and stiffness is a well-researched topic in geotechnical engineering. The literature suggests that cement stabilization can significantly improve the mechanical properties of soils, with the optimal cement content and curing time varying depending on the soil type and conditions, see, e.g., references [2]-[4].

The benefits of cement in soils for preventing the collapse of canal embankments are discussed by [1]. The authors [5] showed that cemented soils can increase strength up to 30%, however, cemented soils have showed higher compressibility which can cause more seepage if used in canal embankments. This creates need to study the seepage and stability characteristics in detail for utilization of cemented soils in canal embankments. To do this, advanced soil properties including reliable values of hydraulic conductivity are required. Based on observations of frequent incidents of embankment failure and field conditions, it can be inferred that a significant portion of canal embankments in Pakistan exhibit inadequate stability [6].

The objective was to reinforce the stability of canal embankments through the implementation of cemented soil layers. In order to determine the optimal placement locations within the cross section of the embankment to effectively reduce the potential failure zone and enhance overall stability, detailed numerical analyses were required. To the best of our knowledge, there are no published works of similar analyses within the existing literature. The computation of optimal positioning for layers of cemented soils to reinforce existing canal embankments, as well as the subsequent evaluation of the impact of these layers on seepage response, represents a complex engineering problem. Finite Element Method (FEM), which has been successfully applied in numerous geotechnical applications, is required to analyze this problem effectively.

The conventional laboratory method for determining the hydraulic conductivity (HC) of soil samples, as depicted in Figure 1, involves allowing water to flow through a sample from one side, while it is connected to the other side for a set duration [7]. However, there are certain limitations to this type of determination of hydraulic conductivity. For example, head of water can be fixed up to limited depth, and the absence of consolidating stresses may lead to unrealistic hydraulic conductivity as comparison to its relevant in-situ condition.

Traditionally a single value of hydraulic conductivity is used in stability analysis of various geotechnical structures. Most often this value of hydraulic conductivity is estimated without considering the effect of overburden pressure. This may overestimate/underestimate the computed values of the stability. In canal embankments, it is possible that there may be the effect of overburden/lateral loads pressure on the hydraulic conductivity of soils at different depths as shown in Figure 2.

Figure 1. Traditional permeability testing

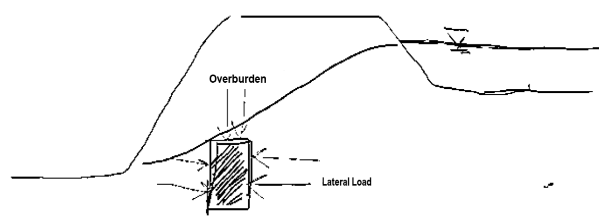


Figure 2. Effect of overburden pressure/lateral loads on hydraulic conductivity at different depths of canal embankments

Since there is the effect of overburden pressure on hydraulic conductivity of soils at different depths as shown in Figure 3. In Figure 3, two types of loads acting on points 1 and 2, i.e., the load of structure and the load of soil, from point 1 to point 2, the soil load will have increased (overburden pressure), which may have an influence the hydraulic conductivity of soils. Previously, several studies have been conducted to determine hydraulic conductivity of cemented soils; see, for example, [8]–[13]. Marine clay stabilized with cement has been tested for the hydraulic conductivity [14]. It was seen that hydraulic conductivity is reduced up to 100 times while using metakaolin up to 5% [14]. The studies conducted by [8] showed that hydraulic conductivity shows a reduction while adding cement for sandstone residual soils. Contrary to this, [11] defines that addition of cement along with addition of pulverized fly ash could improve the permeability of soil. Lastly, authors [15] proved that using cement mixed with soil could reduce the pore size but at the same time increases the hydraulic conductivity.

The above-mentioned references do not discuss the influence of overburden stress on the hydraulic conductivity values of cemented soils.

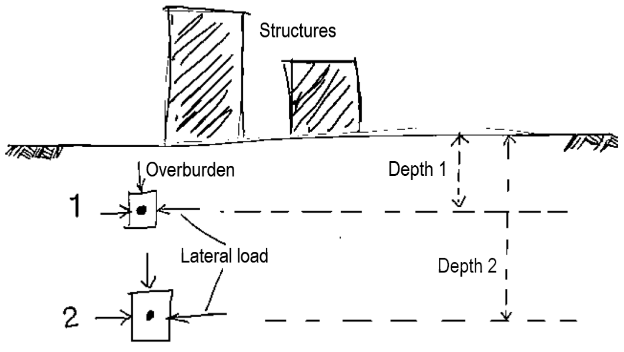


Figure 3. Illustration of two points at various depths, may possess different permeability.

This shows that there are still uncertainties as to how the addition of cement to soil can have an influence on the hydraulic conductivity, ultimately this demands further detailed investigation. Moreover, cemented soils could have more uncertain hydraulic conductivity values when it is under overburden stress. As per authors' knowledge, no study was detected on hydraulic conductivity of cemented soils under various overburden stresses. This implies that this issue needs to be addressed right away.

This article presents the research related to seepage and stability analyses for stability of canal embankments with addition of cement. The article presents new approaches to determination of hydraulic conductivity of cemented soil considering various overburden and consolidating stresses. Furthermore, the seepage analyses are conducted based upon evaluated hydraulic conductivity followed by stability analysis by using numerical analysis. The results showed that overburden stresses have a significant influence on the hydraulic conductivity of natural as well as cemented soils. The stability analyses showed that existing canal embankments have a marginal factor of safety which can be improved by using cemented soils.

2. Materials and Method

An experimental and numerical modelling programme was planned to address the challenges indicated in the introduction. The flow chart depicts many processes in the methodology (Figure 4). Each stage is then discussed in greater detail below.

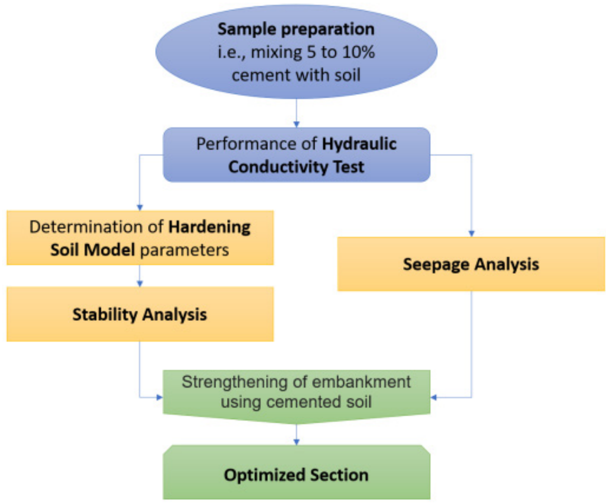


Figure 4. Illustration of methodology using flow chart.

2.1. Materials

In this study, both natural soil and ordinary Portland cement (OPC) were utilized. The soil samples were obtained from embnakmnet of the canal, and its characteristics were analyzed through sieve analysis (Figure 5). The soil collected was clayey silt and had a specific gravity range of 2.68-2.70 with bulk density in the range from 1.7 to 1.8 g/cm^3. The optimal water content of the collected samples was determined to be 14.5%, at maximum dry density of 1.83 g/cm^3. Additional characteristics, including the liquid limit (32%), plastic limit (26%), and plasticity index (6.3%), were also evaluated.

To prepare the samples for testing, a mixture of cement, soil and water was utilized. For the oedometer tests, cement content was varied at 5% and 10% by dry weight of the soil. The samples were prepared at the optimal moisture content of 14.5%. Following the mixing of the soil, cement, and water, the samples were allowed to harden for 1, 3, and 24 hours before testing. Results indicated that the addition of cement led to a reduction in the bulk density of the cemented soil samples.

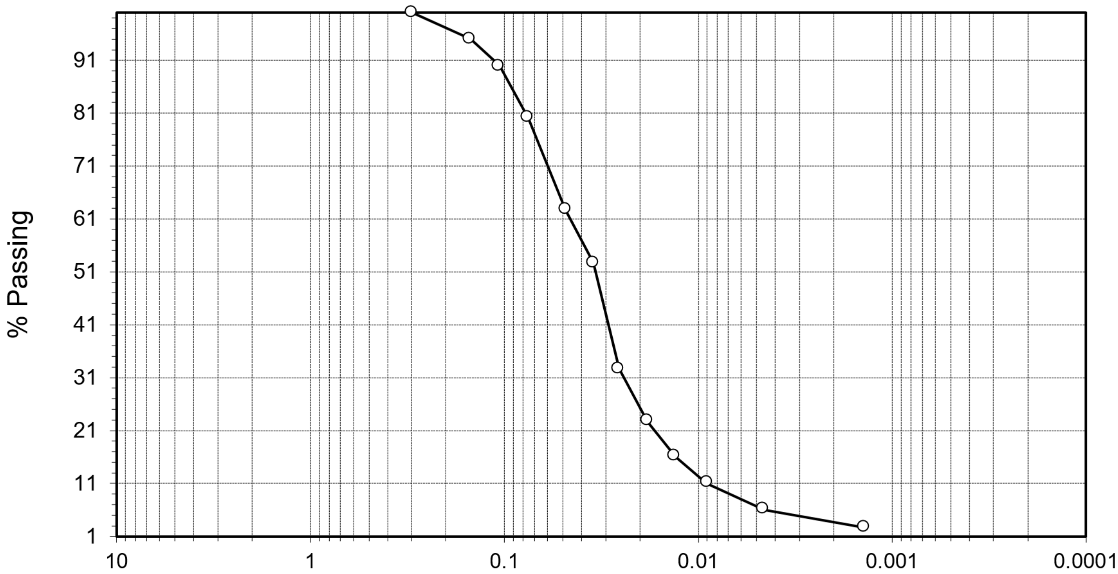


Figure 5. Particle size analysis of soil

In this study, specimens were prepared using a process whereby the material was poured above the water level repeatedly until the mold reached the desired height of 20mm, following the sample preparation method [16]. Proper sample preparation ensures that the soil sample is representative of the in-situ conditions, which is essential for accurately characterizing soil properties such as shear strength, and stiffness. A porous stone was used to cover the bottom and top of the mold. All of the samples were prepared in conditions that were fully saturated. A series of incremental loads of 5, 10, 20, 40, 80, 160, 320, and 640 kPa were applied. After each load was put on the samples, they were left to settle for at least 24 hours or until there was no noticeable change in height. In the triaxial apparatus, cement percentages of 0%, 5%, 10%, and 15% by dry weight of soil were used for the hydraulic conductivity tests. Moisture content was kept at 15% and 20% for all samples. After mixing the soil, cement, and water together, the samples were left to dry for 0, 7, and 15 days so that the cement and soil could bond properly.

2.2. Methods

The triaxial apparatus was modified for determination of hydraulic conductivity at various overburden and consolidating stresses. The choice of triaxial was made since testing HC in-situ of cemented soils at, e.g., 10 m below ground or head may not be practically possible.

The sample was placed in triaxial cell in such a way that, water was allowed from bottom of sample and collected from top of sample while maintaining consolidating stresses from sides, as shown in Figure 6. The triaxial was set in a way that the inflow and outflow from sample were controlled by pressure-volume controllers. This was done by installing an additional controller to a traditional triaxial testing apparatus. The detailed setup of triaxial apparatus modified for this study is shown in Figure 7.

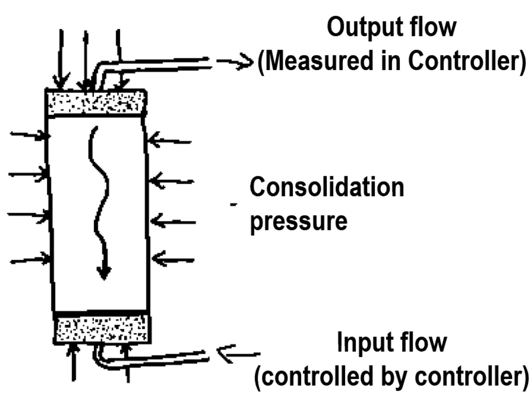


Figure 6. Mechanism for determination of hydraulic conductivity in Triaxial setup.

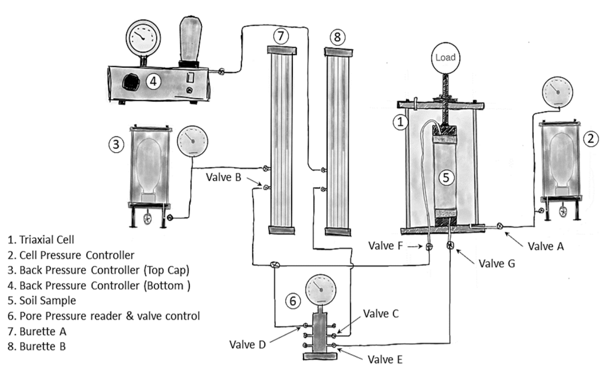


Figure 7. Triaxial Apparatus with double burette system

2.3. Testing Procedure

The prepared sample was installed in triaxial cell (1) as shown in Figure 6. Sample was placed between porous stones from both sides and was wrapped in latex rubber membrane. O-Rings were placed on top and bottom of caps to ensure no leakage from sample. Once the sample was mounted on triaxial cell, immediately confining stresses (σ) of 10kPa and back pressure (from top cap) of 5kPa were introduced to avoid any disturbance of expansion of sample. Hence effective stresses (σ') as 5kPa were maintained. After the initial application of σ' = 5kPa, the saturation was applied. To do this, the backpressure and cell pressure were both raised while keeping σ' at 5kPa. The backpressure was set as 200 kPa. This value was set on trial and error basis, by performing b-check to ensure the degree of saturation as minimum 90% as defined by [17]. Once the saturation of sample was ensured to the minimum requirements, the required consolidating stresses were applied. For example, when sample had backpressure as 200kPa and cell pressure (σ) was 205 kPa, an additional 45 kPa was introduced in cell pressure to get σ' = 50kPa. The entire procedure was followed as described by [18].

The samples were tested at confining loads corresponding to equivalent overburden stresses of 50, 100, 150, and 200 kPa. The cell pressure was applied via controller 2 and valve A as shown in Figure 6. Whereas backpressure was applied via controller 3 and value B and F while valve D was closed. After the consolidation of sample at required confining stresses and back pressure of 200kPa, the top and bottom of sample achieved 200kPa. With the help of additional pressure-volume controller, the additional stresses, corresponding to required depth (each 10kPa ≈ 1 meter), were applied at bottom cap via pressure controller 4 and valve G as shown in Figure 6.

2.4. Numerical Modeling of Seepage and Stability of Canal Embankments

The seepage response of the cemented canal embankments was analyzed using SEEP/W which was based on finite element approach [19]. The stability analysis of canal embankments strengthened using layers of cemented soils was performed with PLAXIS 2D which also used the finite element approach.

3. Results and Discussions

3.1. Hydraulic Conductivity due to Different Water Heads

The hydraulic conductivity was tested for soil with no cement, 5% cement and 10% cement. All samples were prepared at 10% of moisture content. A comparison is also made between these soils. It was observed that the hydraulic conductivity of soils with no cement was in the range of $7.19\text{x}10^{-6}$ to $1.62\text{x}10^{-5}$ m/day at various stresses and heads. It was observed that that the increase in head also caused a slight increase in hydraulic conductivity at all the confining stresses i.e., 50, 100, 150 and 200 kPa (Figure 8).

The average increase in hydraulic conductivity was about 10% to 12% in cemented as well as non-cemented soils. The hydraulic conductivity for the soils with 5% cement was $8.89\text{x}10^{-6}$ to $3.5\text{x}10^{-5}$ m/day. It was observed that 5% cemented soils showed slightly higher hydraulic conductivity at lower confining stresses, and this may be due to an increase in voids due to the addition of cement. Similarly, the hydraulic conductivity of soils with 10% cement was in the range of $1.81\text{x}10^{-5}$ to $2.83\text{x}10^{-5}$m/day for various confinements.

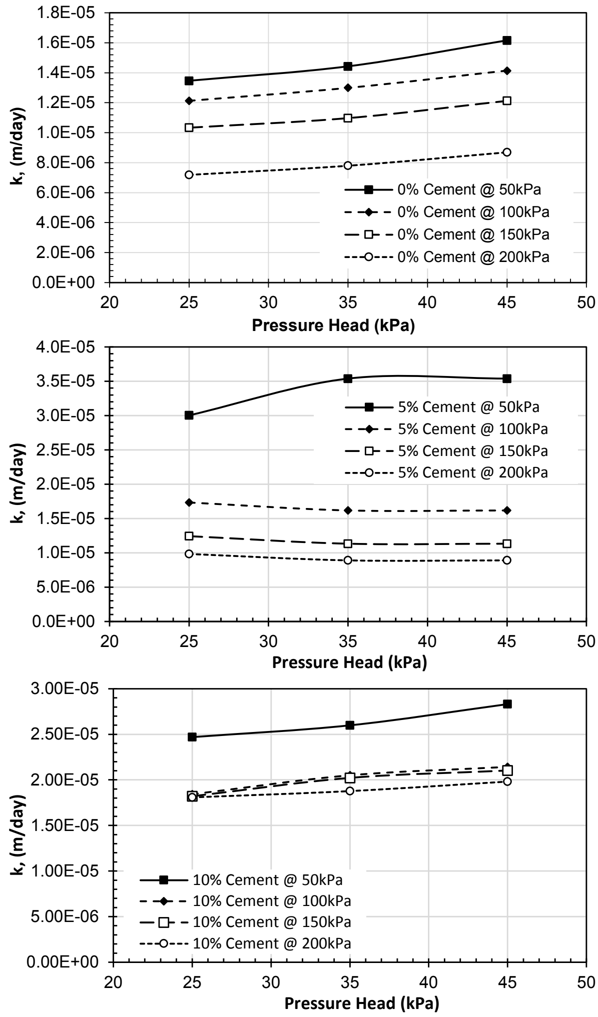


Figure 8. Hydraulic conductivity of soil with 10% cement at various heads for different confinement

3.2. Hydraulic Conductivity under Various Consolidating Stresses

It was observed that the hydraulic conductivity was reduced significantly by applying confining stresses in all the soils tested, i.e., 0%, 5% and 10%. It was reduced to 47% at 25 kPa head, 46% at 35 kPa head and 46% at 45 kPa head in soils with zero percent cement at confining stress of 50 kPa (Figure 9).

However, cemented soils i.e., 5%, 10% showed abrupt changes from confining stresses of 50 kPa to 100kPa. Moreover, 5% Cemented Soils showed 42% till 100 kPa stresses followed by similar behavior as that of soils with 0% cement. Whereas 10% cemented soils showed 26% till 100 kPa of confining stresses followed by similar behavior as that of soils with 0% cement.

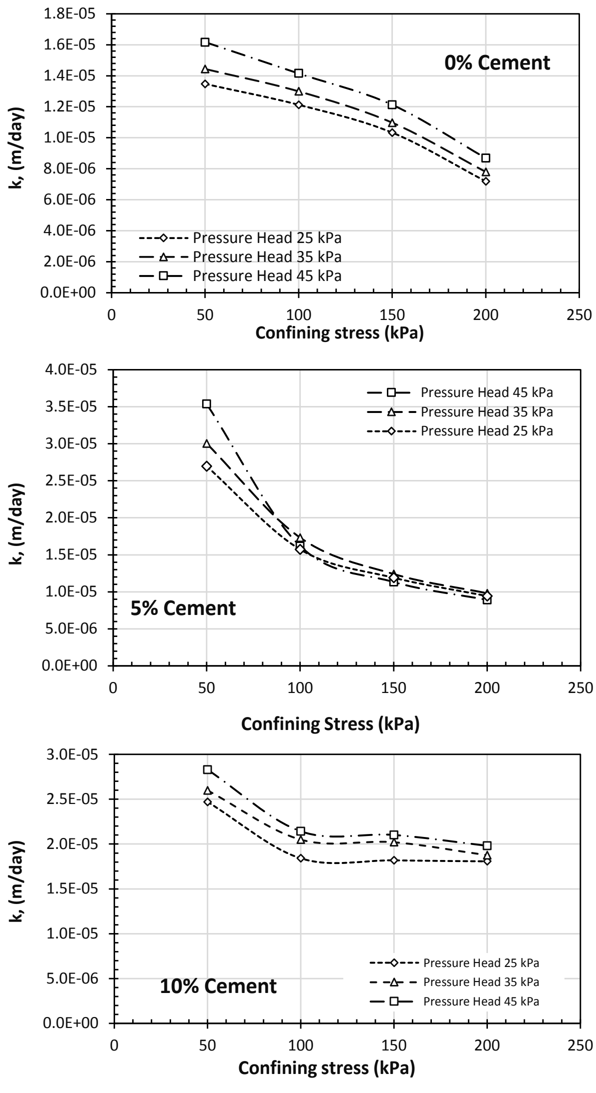


Figure 9. Hydraulic Conductivity of soil with 10% cement at various confining stresses

From the results (Figure 10), it was shown that the hydraulic conductivity decreases with the increase in confining stresses. It is obvious that voids in soil skeleton are reduced as the confining stresses are increased which in turn cause the hydraulic conductivity to decrease. However, the cemented soils showed an abrupt decrease in hydraulic conductivity till 100kPa stresses. This might be due to the reason that some of bonding might have broken at higher confining stresses i.e., 100 kPa therefore rearrangement occurs and the voids in skeleton are probably reduced which cause less water flow/hydraulic conductivity.

Generally, it was observed that the addition of cement caused hydraulic conductivity to increase; this might be due to the fact that addition of cement causes more voids in skeleton. It was observed that initially 5% cemented soils showed higher hydraulic conductivity, which later showed similar behavior as of no cement soil beyond 100 kPa stresses. This might be due to the breakage of bonds created due to cement. (Probably the effect of 5% cement vanishes after the confinement of 100 kPa).

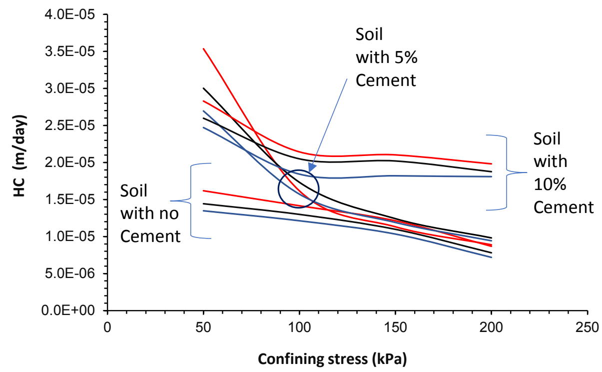


Figure 10. Hydraulic conductivity of soil with no cement, 5% cement and 10% cement.

Moreover, soils with 10% cement showed more hydraulic conductivity. Beyond these stresses, there is no abrupt change/reduction in hydraulic conductivity, and it shows similar behavior to typical soils. However, the amount of hydraulic conductivity was slightly higher at 10% cement, which may imply that there is some permanent bonding that causes an increase in voids; that bonding is probably not broken up to 200 kPa stresses. However, the sample with 5% cement shows similar values as of natural soil beyond 100 kPa, which implies that bonding is broken beyond 100 kPa and shows similar behavior to soil with 0% cement.

3.3. Seepage Analysis

The embankment comprises of foundation of 10 m depth and embankment of height 5 meters; these dimensions are taken from an actual canal (Figure 11). The inside slope was 2.5:1 and outside was 2:1 (Horizontal: Vertical). The top width of canal is 13 meters, it is pertinent to mention that initially canal was of 6-meter width and in a rehabilitation another 6 meters were added with inward slope of 1:1 thus making total width of 13 meters. The foundation of embankment is assumed as fixed foundation. The water level was assumed as worst-case scenario i.e., 0.3 meters below the embankment surface.

The global mesh coarseness was set after increasing the density until the change in results (total discharge along a cross section at the drainage trench) changed less than 2 percent. This criterion was here considered as accurate enough. The final coarseness was set to “very fine” with additional reduction of element size (0.3) for the lines at between till core and till support (downstream) and till support and bottom filter. A calculation with the same global coarseness but 0.2 element size of the above-mentioned lines gave 2 percent change in the results. Figure 12 shows the meshes generated using analysis in PLAXIS and SEEP/W. The mesh was optimized and at contact points of core and adjacent soil support, it was set very fine. This was done to increase the number of node and calculation points in those regions hence leading towards more accuracy and less tolerated errors.

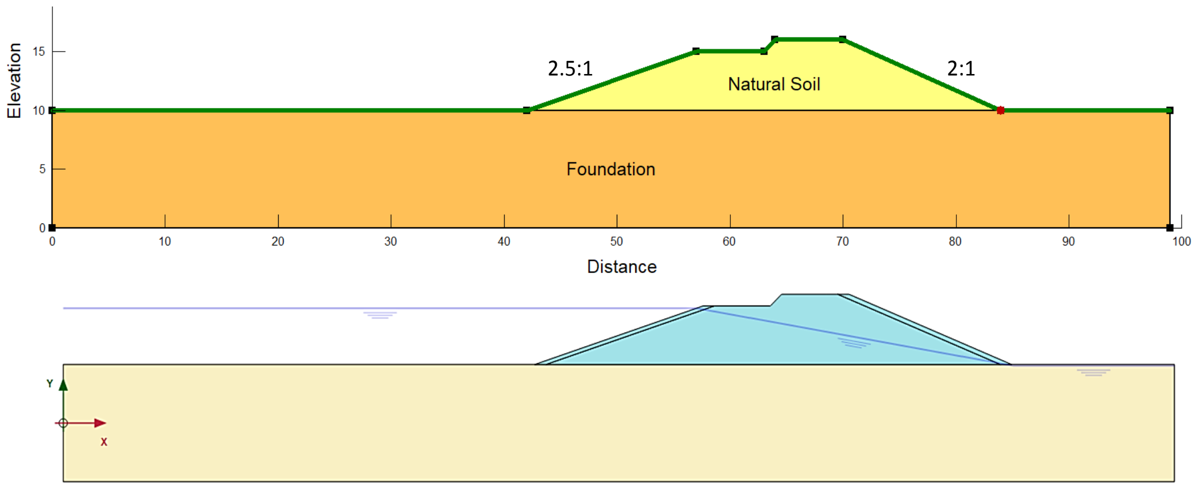


Figure 11. Geometric model of the embankment dam showing boundary conditions

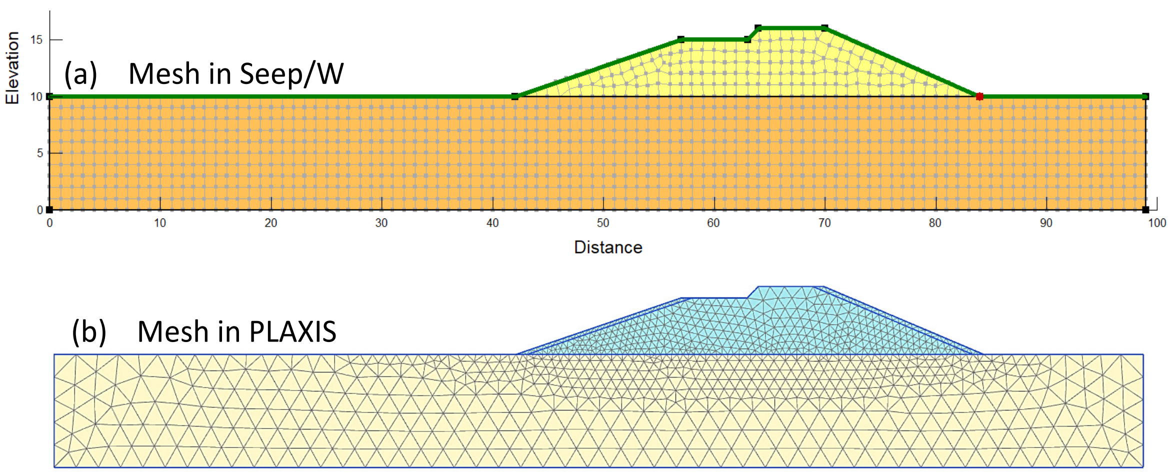


Figure 12. The mesh generated for (a) SEEP/W and (b) PLAXIS

3.4. Background to Seepage through Embankments

Seepage studies based upon numerical analyses depend extensively on the available data of hydrological and geological investigations in sites. In case of the unviability of field data, the small-scale physical models can be constructed in laboratory (e.g. [20]–[22]) mimicking the field conditions for fetching the data. Physical models can also be beneficial to understand the seepage behavior prior to construction of actual embankment dams which can help to investigate potential problems pertaining to various problems and coming up with the optimized confidant dam design. However, there are several restrictions and constraints associated with physical models, thus creating a demand for alternative options as numerical modelling [23]–[25] which can help solve complex engineering problems. However, numerical modelling can take less time efforts, which is economical based upon mathematical solutions unlike physical or field modelling [26]. Historical failures of dams in 1700s and 1800s drew attention of researchers, thus, motivating them for scientific solutions towards the optimized design and construction. In response to earlier research of fluid flow though porous media by Henri Darcy was published in 1856 [20]. That study, currently known as Darcy's Law, was based on flow of water through vertical filters in laboratory [27] and came up with a simple equation of discharge velocity and hydraulic gradient as shown in equations 1 and 2 below:

$$v_d = k.i = Q/A \tag{1}$$

$$Q = k.i.A \tag{2}$$

Where q (m^3/s) is the seepage rate, v_d (m/s) is discharge velocity, i (m/s) is hydraulic gradient, k (m/s) is coefficient of permeability, and A (m^2) is cross sectional area. Later in the 1880s it was described by [21] that, velocity and pore pressure within porous medium can be governed by Laplace differential equation. This method became popular once the research by [28] was published. It is since then, seepage analysis by Laplace equation has become standard procedure whether it is a graphical procedure or electrical analog models [29]. However, it depends upon the personal skills and time for plotting the graphs [29]. The solution for seepage by Casagrande [30] is shown in Figure 13 and Equation 3, given as:

$$q = k.a.\sin^2 \beta \tag{3}$$

Where q (m^3/s) is the seepage rate, a is seepage length surface, k (m/s) is hydraulic conductivity, and β is angle of the downstream slope. The seepage surface length a, is calculated [20] using upstream head h as shown in Equation 4.

$$a = S - \sqrt{S^2 - \frac{h^2}{\sin^2 \beta}} \tag{4}$$

Where S is the length of curve ĀBC (m), and h (m) is upstream head. However, having error of 4 to 5% the equivalent straight length ĀC, the S can be written as Equations 5 and 6.

$$S = \sqrt{d^2 - h^2} \tag{5}$$

$$d = L + 0.3\Delta \tag{6}$$

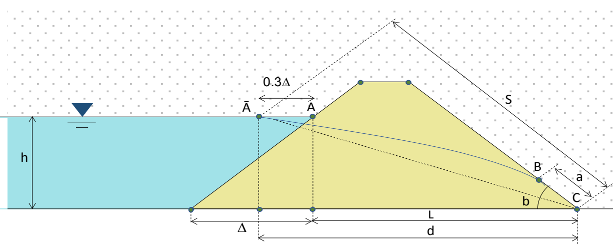


Figure 13. Flow through embankment dam, Casagrande's solution

The phenomenon of seepage through an embankment can be mathematically simulated through SEEP/W software, which performs analyses based upon finite element method. The software is based on fundamental laws of flow in numerical form for steady and transient flow types. The equation [19] governing seepage in SEEP/W can be written as Equation 7, shown below:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \tag{7}$$

where, Q is applied boundary flux, k_x and k_y are hydraulic conductivity in x and y directions respectively, t is time, H is the total head and θ volumetric water content.

Whereas, the specific discharge in PLAXIS is governed by Equation 8 using continuity equation [30] through porous media is written as:

$$\frac{\partial(\rho_w \theta)}{\partial t} + \nabla \times (\rho_w q) = 0 \tag{8}$$

Assuming the constant ρ_w, the equation for water content $\theta = n \times S$, and Darcy's law $q = -k\nabla H$, the Equation 8 leads to Equation 9:

$$\frac{\partial(nS)}{\partial t} = \nabla \times k\nabla H \tag{9}$$

where, k is hydraulic conductivity and H is the total head.

Hydraulic conductivity depends upon material properties for example, saturation and porosity etc. For this seepage analysis in this study, the finite element program GeoStudio SEEP/W [19] was used. Whereas, for the stability analysis PLAXIS 2D [31] was used.

3.5. Calculations of Case Studies for Seepage and Stability Analyses

3.5.1. Seepage Behaviour of Cemented Canal Embankments

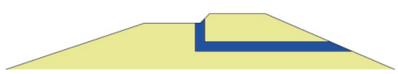
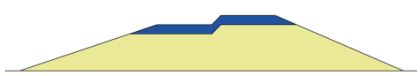
The seepage calculations were conducted in “flow only mode” where the calculation type was set to “steady State Groundwater flow”. The left, lower and right boundaries were set to be closed in foundation (no flow through these boundaries). In order to see the effect of hydraulic on the total discharge at center, outer edge, and toe were evaluated. The phreatic level was defined in water mode of initial phase, after which calculation was carried out in accordance with SEEP/W [19]. After initial calculations, the global error was manually set to 0.001 (instead of default value 0.005).

Table 1 shows the description of different case studies for seepage analyses. The hydraulic conductivity of foundation of embankment was fixed as $1.6x10^{-6}$ m/day for all the cases. The hydraulic conductivity of natural soil was $1.3x10^{-5}$ m/day whereas, same for 5% and 10% cemented soil were $3.5x10^{-5}$ and $2.47x10^{-5}$ m/day respectively. Six analyses were performed in case A with varying hydraulic conductivity values. The impact of consolidating stresses and water head was analyzed. Moreover, in all other cases from case B to G, two analyses were conducted for each, i.e., using with 5% and 10% cemented soil while keeping the k values same for natural soil and embankment material.

Calculation on all these cases was also performed using PLAXIS 2D in order to evaluate factor of safety for each case. The same geometry and flow parameters were used in PLAXIS 2D. The mesh was set to be similar to that in SEEP/W. The parameters used in PLAXIS 2D for determination of factor of safety are shown in Table 3. These parameters were evaluated by performing additional tests followed by model validation.

From seepage analysis results, it was observed that, natural soils (Case A) at various confining stresses i.e., σ_3 =50, 100, 150, and 200 kPa did not show much influence on seepage flux at toe of embankment. The average seepage flux at toe of embankment was 8.19 to $8.32x10^{-7}$ m^3/day. The typical seepage flux behavior is shown in Figure 15 for Case A with k determined at 50 kPa. Negative pore pressures were observed above the phreatic line and pore pressures at bottom of canal were observed between 40 to 60 kPa.

Table 1. Details of placement of cemented layers in cross section of canal embankment

Condition		Description
Case A		“Normal case”, no cement
Case B		Case A, cemented layer around all sides
Case C		Case A, cemented layer on outer side
Case D		Case A, cemented layer on inner side
Case E		Case A, cemented layer within the embankment
Case F		Case A, three cemented layers within embankment
Case G		Case A, cemented layer on top

The Hardening Soil model was further optimized in accordance with the test results from laboratory and is shown in Figure 17. The input parameters of the HS model are given in Table 3 for natural soil, 5%, and 10% cemented soils respectively. The Figures 17(a-c), show the strain-stress behavior of natural soil, 5%, and 10% cemented soil at 100 kPa.

It was further observed that in all cases from B to F, the overall seepage flux did not show much influence due to cement utilization in embankment apart from Case F where a slight reduction in seepage was observed. Moreover, the pore pressure behavior also did not show much influence due to utilization of cemented soils. The detailed evaluated parameters for all cases from A to B are shown in Table 2. It was observed that using cemented soils did not influence much on the seepage flow from canal embankment.

3.6. Stability Analysis

The stability analysis was performed by using the HS model in finite element analysis program PLAXIS 2D. These parameters were evaluated from the natural clayey silt collected from canal. The Figure 14 shows the loading-unloading and reloading behavior of 10% cemented soil in triaxial test at confining reference stresses of 100 kPa for evaluation of E_{ur} and E_{50} [5].

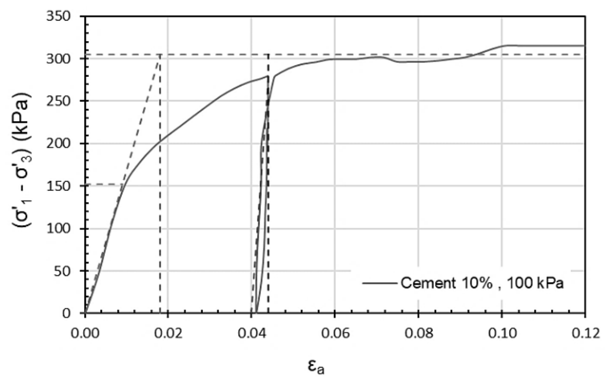


Figure 14. Example of determination of Modulus of Elasticity, 10% Cemented Soils [2]

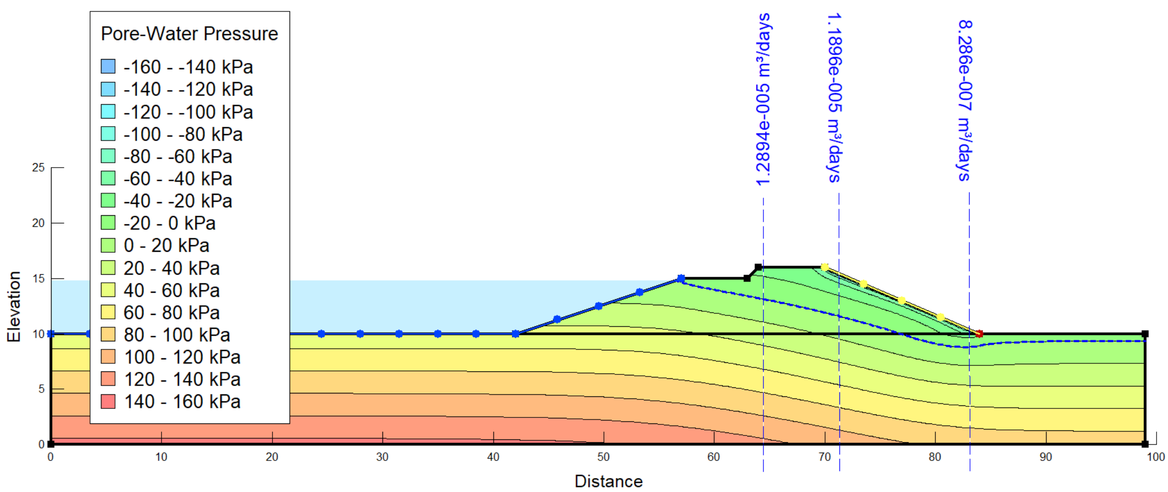


Figure 15. Typical behavior of flow through embankment at center, outer edge, and toe, Case A at σ_3=50 (cf. Table 1).

Table 2. Details of evaluated parameters of seepage flux (m^3/day) for cases from A to B.

Description	Seepage Flux from Embankment		
	At Center (m^3/day)	Outer Edge (m^3/day)	At Toe (m^3/day)
Case A σ_3=50 kPa	$1.28\text{x}10^{-5}$	$1.18\text{x}10^{-5}$	$8.28\text{x}10^{-7}$
Case A σ_3=100 kPa	$1.18\text{x}10^{-5}$	$1.09\text{x}10^{-5}$	$8.29\text{x}10^{-7}$
Case A σ_3=150 kPa	$1.04\text{x}10^{-5}$	$9.71\text{x}10^{-6}$	$8.29\text{x}10^{-7}$
Case A σ_3=200 kPa	$7.94\text{x}10^{-6}$	$7.44\text{x}10^{-6}$	$8.32\text{x}10^{-7}$
Case A Head 3.5 m	$1.35\text{x}10^{-5}$	$1.25\text{x}10^{-5}$	$8.28\text{x}10^{-7}$
Case A Head 4.5 m	$1.49\text{x}10^{-5}$	$1.37\text{x}10^{-5}$	$8.30\text{x}10^{-7}$
Case B (5% cement)	$1.36\text{x}10^{-5}$	$1.23\text{x}10^{-5}$	$8.19\text{x}10^{-7}$
Case B (10% cement)	$1.34\text{x}10^{-5}$	$1.22\text{x}10^{-5}$	$8.22\text{x}10^{-7}$

Table 2 continued.

Case C (5% cement)	$1.31x10^{-5}$	$1.19x10^{-5}$	$7.96x10^{-7}$
Case C (10% cement)	$1.31x10^{-5}$	$1.19x10^{-5}$	$8.04x10^{-7}$
Case D (5% cement)	$1.30x10^{-5}$	$1.20x10^{-5}$	$8.44x10^{-7}$
Case D (10% cement)	$1.30x10^{-5}$	$1.20x10^{-5}$	$8.42x10^{-7}$
Case E (5% cement)	$1.38x10^{-5}$	$1.29x10^{-5}$	$8.14x10^{-7}$
Case E (10% cement)	$1.35x10^{-5}$	$1.25x10^{-5}$	$8.22x10^{-7}$
Case F (5% cement)	$1.44x10^{-5}$	$1.33x10^{-5}$	$6.72x10^{-7}$
Case F (10% cement)	$1.39x10^{-5}$	$1.28x10^{-5}$	$7.06x10^{-7}$
Case G (5% cement)	$1.39x10^{-5}$	$1.28x10^{-5}$	$7.06x10^{-7}$
Case G (10% cement)	$1.34x10^{-5}$	$1.18x10^{-5}$	$8.49x10^{-7}$

The details of evaluated parameters of seepage flux are presented in Table 2. It observed that 5% cemented soil hardened at lower strains as seen in Figure 17(b) as compared to 10% cemented soil Figure 17(c) followed by a reduction in deviatoric stresses. Furthermore, it was noted that the natural soil exhibited a contractant behavior (as depicted in Figure 17(d)), whereas the soils with 5% and 10% cement content exhibited a behavior of dilatancy (as shown in Figure 17(e) and 17(f) respectively).

Table 3. Material Parameters for Hardening Soil Model.

Description		Natural Soil	5% Cemented Soil	10% Cemented Soil
Material Model		Hardening Soil	Hardening Soil	Hardening Soil
E_{50}^{ref}	kN/m²	3500	$22.0x10^3$	$22.0x10^3$
E_{oed}^{ref}	kN/m²	4000	$18.0x10^3$	$19.2x10^3$
E_{ur}^{ref}	kN/m²	$18.50x10^3$	$71.1x10^3$	$70.2x10^3$
power (m)	-	0.5	0.5	1.0
v'_{ur}	-	0.2	0.2	0.2
K_0^{nc}	-	0.412	0.4122	0.3982
P_{ref}	kN/m²	100	100	100
c'_{ref}	kN/m²	6.0	10.0	8.0
φ′(phi)	°	36.0	36.5	37.0
ψ (psi)	°	0.0	7.0	8.0
R_f	-	0.9	0.9	0.9
γ_{unsat}	kN/m³	16.1	13.1	13.8
γ_{sat}	kN/m³	17.65	14.6	15.80
Kx	m/day	$1.3x10^{-5}$	$2.47x10^{-5}$	$3.0x10^{-5}$

Furthermore, at consolidating stresses of 200 kPa, all soils showed strain hardening behavior as shown in Figure 17(g-i) for natural, 5%, and 10% cemented soils respectively. All the performed tests were matched with hardening soil model after optimization except natural soils volumetric behavior, where it can be seen in Figure 17(d) that hardening soil model was slightly underestimated the deformations while axial stresses were applied.

The evaluated factor of safety was obtained as 1.35 for natural soils, i.e., Case A (cf. Table 1). The slip surface of the canal embankment is shown in Figure 16.

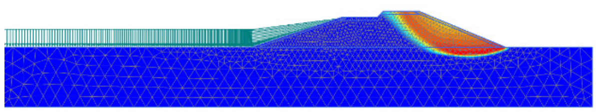


Figure 16. Slip surface of failure zone during stability analysis of Case A (cf. Table 1).

According to [32], permissible safety factor for canal embankment is 1.5. This implies that existing stability of the canal embankments is marginal. This is consistent with field conditions related to failure of such embankments which have occurred during past. The compaction in such canal embankments is less than 90-95% of the relative compaction.

Therefore, frequent failures have occurred in such type of canal embankments [1]. Stability analysis calculations suggest that there is need for stabilization of the embankments. It has been observed by [2] that cemented soils can significantly improve the strength of soils. The stability analyses were performed for difference cases of stabilized canal embankments i.e., Case B to F. with 5 and 10% cemented soils. Table 4 shows the results of various cases of stability analysis.

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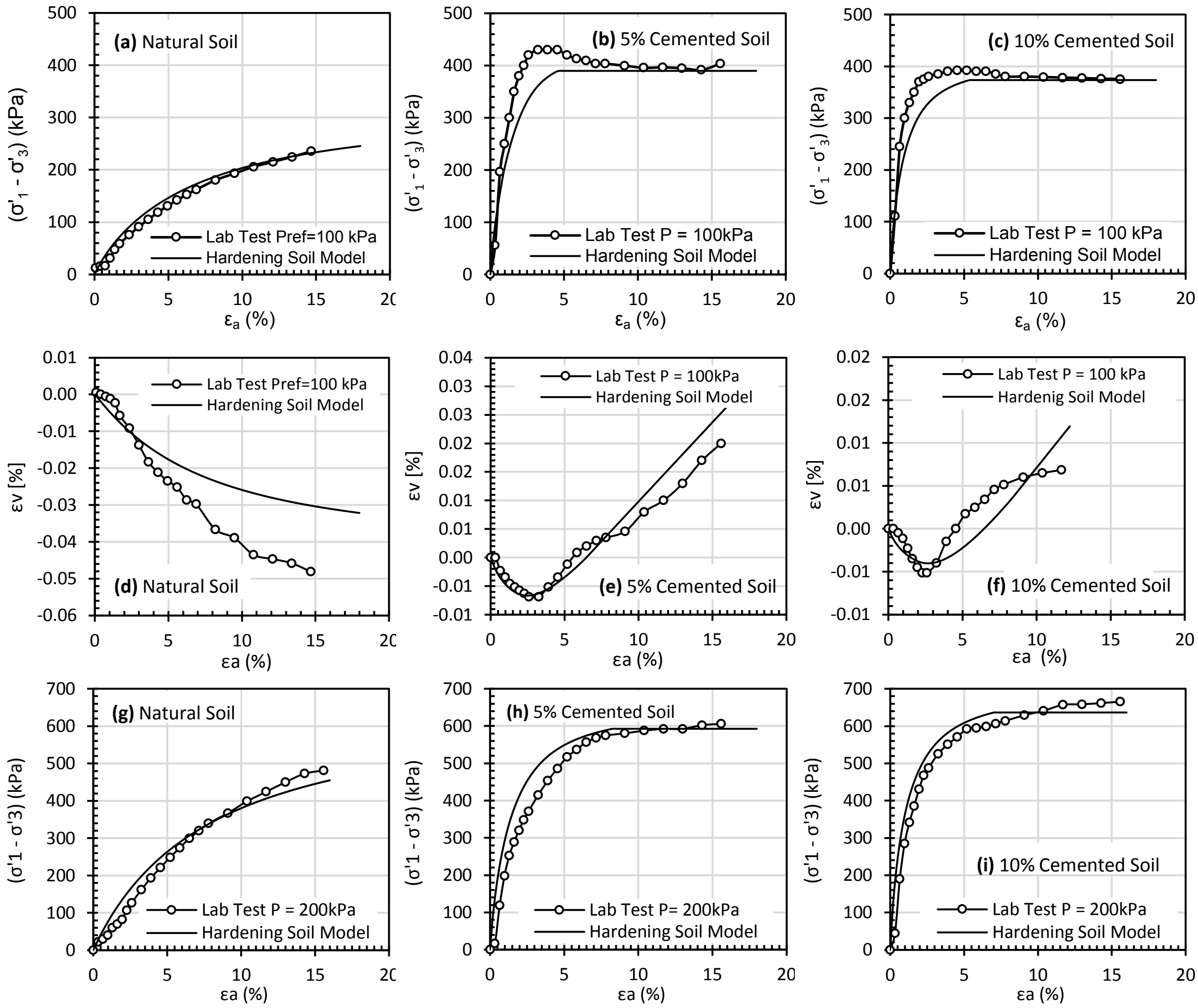

Figure 17. Model validation of hardening soil model in PLAXIS with laboratory tests. (a, b, and c show stress-strain behavior at σ = 100kPa. Similarly, d, e, and f show volumetric behavior and g, h, and i show stress-strain behavior at σ = 200kPa of natural soil, 5% cemented soil, and 10% cemented soil respectively).

Table 4. Evaluated Stability Analysis of Case A to F

Description	**Factor of safety**	
Case A	1.354	
	5% cemented soil	**10% cemented soil**
Case B	1.678	1.625
Case C	1.367	1.370
Case D	1.362	1.355
Case E	1.733	1.708
Case F	1.530	1.521
Case G	1.467	1.463

The value of safety factor for case E is about 1.5. Stabilization as mentioned in case D is better than case E. The reason is that case D requires less volume of cemented soils than that of case E. In addition, more stability is obtained in case D as compacted to case E. For existing canal embankments, stabilization procedure as mentioned in case A is preferred. The value of safety factor obtained for case A is about 1.6. In all the cases, the value of safety factor for 5% cemented soil is more as compared to 10% cemented soil. This is because, the co-efficient of permeability is slightly higher in case of 5% cement soil. This finding shows a positive impact in the sense that less volume of cement is required in case of 5% cemented soils. In this study, it is tired to evaluate the impact of change of permeability on the compared results of slope stability. In the experimental program, permeability was calculated at different consolidation pressures (50, 100, 150 and 200 kPa) and various heads (2.5, 3.5 and 4.5). As mentioned earlier, the value of permeability of soil evaluated at a consolidation stress of 200kPa is 10 times lower than that of at 50 kPa. It is also generally observed that there is a variation in permeability values obtained in horizontal and vertical directions. Stability analysis was performed to evaluate the impact of change in permeability on stability of canal embankment. For this purpose, the value of permeability of canal embankment is horizontal plane, taken as $1.7\text{x}10^{-6}$ m/day. The value of vertical permeability was taken as 10 times lower than that of horizontal direction both in embankment and foundation soil. The value of safety factor was 1.25 which was lower than the case when both the horizontal and vertical permeability were taken as same. This supports the hypothesis, that decrease in permeability w.r.t depth due to overburden pressure may have a significant effect on stability of canal embankments.

4. Conclusions

In this study, an experimental program was performed to investigate the effect of overburden pressure on hydraulic conductivity of the soils. In addition, numerical analyses were carried out to evaluate seepage and stability of the canal embankment. It was observed that the hydraulic conductivity was reduced significantly by applying confining stresses in all the soils tested. The hydraulic conductivity decreased 47% at 25 kPa head, 46% at 35 kPa head and 46% at 45 kPa head in soils with zero percent cement at confining stress of 50 kPa. It was observed that the hydraulic conductivity of soils with no cement was in the range of $7.19\text{x}10^{-6}$ to $1.62\text{x}10^{-5}$ m/day at various stresses and heads. The same for 5% soil was $8.89\text{x}10^{-6}$ to $3.5\text{x}10^{-5}$ m/day and for 10% cemented soil was in the range of $1.81\text{x}10^{-5}$ to $2.83\text{x}10^{-5}$ m/day The cemented soils i.e., 5%, 10% showed abrupt changes from confining stresses of 50 kPa to 100kPa, which showed 42% and 26% reduction for 5% and 10% commented soils respectively followed by similar behavior as that of soils with 0% cement.

Overburden stresses of 200 kPa induced a loss of 189% in the hydraulic conductivity of natural soils, as well as reductions of 306% and 133%, respectively, in the case of a c/s ratio of 0.05/0.95 and 0.1/0.9. In addition, it was discovered that the canal embankments had a precarious level of safety because of the consistent seepage. From seepage analysis results, it was observed that, natural soils at various confining stresses i.e., 50, 100, 150, and 200 kPa did not show much influence on seepage flux at toe of embankment. The average seepage flux at toe of embankment was about $8.32x10^{-7}$ m^3/s. The results of slope stability analysis indicated that existing stability of the canal embankments is marginal. Different geometrical layers of cemented soils ranging from 5 to 10% cemented soils were suggested to strengthen both the existing and new canal embankments. By adding layers of cemented soil, the potential failure zones of the canal embankments were reinforced, resulting in increased stability. Despite using a low cement content and a smaller volume of cemented soil layers than the natural clayey silt, the seepage response of the canal embankments strengthened with cemented soil layers was comparable to those constructed with natural soil. These findings indicate that the approach of strengthening canal embankments using cemented soil layers was successful. The strengthening techniques presented in this study would be beneficial for practicing engineers in ensuring stability of canal embankments.

5. Future Research

Based on the conclusions that adding layers of cemented soil increased stability and the seepage response was comparable to natural soil, future research could focus on the following:

- Further investigation of the optimal amount of cement content and volume of cemented soil layers required for strengthening canal embankments.
- Studying the long-term effectiveness of the cemented soil layer approach in improving the stability of canal embankments.
- Assessment of the impact of environmental factors such as temperature, rainfall, and soil composition on the effectiveness of cemented soil layers in improving the stability of canal embankments.

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