Stability analysis of geosynthetically piled foundation earth dam; a case study: Sombar dam

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Abstract. The use of drains in a regular grid and required depth in the soil are reduced the time of drainage process and soil consolidation considerably. Sombar dam is a project to use optimum seawater flow and flood control to provide agricultural water as well as to develop the area under cultivation of the existing dam in Gholaman village as well as the city of Raz in north Khorasan province, Iran. The purpose of this research is assessing the influence of vertical geotextile drainage (length and spacing), for different permeability ratios (ky/kx), on the dam stability during the construction using GeoStudio2012 software. The analysis is performed using models of Mohr-Coulomb and modified cam clay. The results show that there is a significant effect of the drains for the studied parameters. After 24 months with maximum drain depth (24m) and minimum drain spacing (2m) the values of the studied parameters are closer to each other.

1. Introduction
The effectiveness of the drainage technique is related to drain’s diameter, depth and spacing and these drains cause the pore pressure, generated during the construction, to be more rapidly decayed and structural sinks at the time of construction [1]. Corresponding to the tests using scaled model, the use of prefabricated vertical drains (PVDs) is successful for the enhancement of ultra-soft with increasing in the shear strength and dissipation of pore pressure [2]. A method of installing PVDs in two stages had helped in dissipating the pore water pressure [1]. From field monitoring, the pre-consolidation time significantly reduced by the installation of the vertical drains, i.e., from one to five years without a vertical drain to fifty days with PVDs [3]. The drain discharge capacity of PVDs is an influencing factor on the vertical drain behavior where this capacity should be conducted using a laboratory test by confining the drain in clay [4]. The concept of a unique $e \sim \log \sigma'_v$ relationship eliminates the need for the evaluation of the clay compressibility with respect to time, $(\partial e / \partial t)_{\sigma'_v}$ [5]. Asha and Mandal (2015) investigated the natural PVD (NPVD) and polymer-based PVD (PPVD) used for marine clay laboratory theoretically and numerically [6]. Krishnamurthy and Kamal (2016) concluded, from the FEM study, that the vertical drains enhance the factor of safety of embankment after construction until the end of consolidation [7]. All mentioned researchers showed that the proposed technique in the finite element method is reliable and easy in the analysis of an embankment. For vertical drains, using the theory of consolidation, the drains are assumed in the transverse section of the circle, therefore, the diameter dw transformed into a wall drain of “a” in width and “b” in thickness, while d is the average equivalent diameter of the drain and a and b are PVD dimensions, as in Eq. 1 [8].

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Detailed laboratory tests are useful to determine the geotechnical properties for the analysis of consolidation with PVD [3]. The simplest method to reflect the influence of vertical and radial consolidation was stated by Carillo (1942) as in Eq. 2 [9].

\[
(1 - U) = (1 - U_v)(1 - U_h)
\]  

(2)

Where U is the total average degree of consolidation, \(U_v\) is the average vertical degree of consolidation, and \(U_h\) is the average horizontal degree of consolidation.

A conservative prediction in the strains are achieved by the Mohr-Coulomb [10,11]. The authors examined the influence of sand drains under the Sombar dam and they concluded that the consolidation rate of the foundation increases related to no drain condition [12]. There is a significant effect of \(ky/kx\) ratio on the dam stability concerning the use of sand drains under the Sombar dam [13]. The recent paper investigates, using GeoStudio 2012, the efficiency of geosynthetically vertical drains system for different arrangements and drain lengths, the effect of the vertical to the horizontal ratio of permeability in the foundation of an existing earth dam (Sombar). The investigation is used the Mohr-Coulomb and modified cam clay models for comparison purposes.

2. Materials and Methodology

2.1. Selected Site and Data Collection

The study area is located in the province of northern Khorasan in the northeast of Iran adjacent to the Turkmenistan. The needed data are dependent on the final report on geotechnical work of the Sombar dam. The dam core has a symmetrical gradient of 1:0.4 (V: H). The barrier has been positioned along the length of the contact with the supports. Fig. 1 presents the geometric of the Sombar dam after the final report, geotechnical studies of the Sombar dam [14, 15].

![Figure 1. The Geometric of the Sombar Dam [14, 15].](image)

2.2. Materials

Depending on the geotechnical investigations of the Sombar dam, the type of the dam is a limestone with a clay core and sandy crust. The dam’s site is typically fine-grained alluvium with coarse-thick layers up to 30 meters wide across the valley. The fine-grained alluvium is classified as CL-ML, CL, and ML. The coarse aggregates are classified as SC, SC-SM, SM according to the unified soil classification system (USCS). Accordingly, the body of the dam is composed of two fine-grained and coarse aggregate units. The dominant texture of the dam is composed of fine aggregates with low permeability and moderate permeability. The thickness of the bottom of the river varies and reaches up to 30 meters. The right-sided trenches with a thickness of up to 3 meters covered the bedrock. The groundwater level is about 4 meters from the ground and extends to the two supports with a very gentle gradient. Table 1 illustrates the soil properties in the dam.
and foundation. The total final consolidation settlement of the dam is 0.9m (reference value). The consolidation coefficient ($C_v$) is $2.25 \times 10^{-3}$ cm$^2$/sec, $1.1 \times 10^{-3}$ cm$^2$/sec and $1 \times 10^{-3}$ cm$^2$/sec under vertical stress of 2kg/cm$^2$, 4kg/cm$^2$ and 8kg/cm$^2$ respectively.

| Type of Soil | Test method | Unit weight, kN/m$^3$ | $E$, kPa | $C$, kPa | $\phi$, degree | $k$, m/sec |
|--------------|-------------|------------------------|----------|----------|----------------|------------|
| Clay core    | UU          | 22900                  | 80       | 0        |                |            |
|              | CU          | 22900                  | 45       | 15       | $10^{-9}$      |            |
|              | CD          | 19100                  | 32       | 27       |                |            |
| Sandstone    |             | 40000                  | 42       | 42       | $10^{-9}$      |            |
| Fine-grained | CU          | 19                     | 1416     | 14       | 14             | $10^{-9}$ |

2.3. Methods

As a back analysis of the Sombar Dam, GeoStudio 2012 software [16] was used in the analysis to solve the consolidation equations. Mohr-Coulomb model (MC) is used for the modelling of dam and geosynthetically piled (vertical drains) foundation under effective stress. A comparison of the results is made using another modelling method named "Modified Cam-Clay (MCC)". The pre-defined characteristics of the geotextile is a major advantage. The study uses qualitative analysis to gain insights into the behavior of the dam. The effect of geotextile vertical drains on the dam settlement, safety factor of upstream and downstream were investigated. The drains parameters were depth (8, 15, 18 and 24m), spacing (2, 3 and 4m) in addition to the coefficient of permeability ratio ($k_y/k_x$) of 1 and 0.1 for construction stages of 4, 8, 15 and 24 months using the two mentioned modelling methods. The worst combination is considered to create pore pressure. A correlation analysis is made to correlate the different studied parameters. All correlation analyses and figures are produced using the M.S. Excel ver.10 program. Figure 2 shows the schematic of the drains distribution in the foundation of the dam.

![Figure 2. Schematic of the Geotextile Vertical Drains.](image)

The finite element technique is used to solve simultaneous equilibrium and equations based on elasticity theory and Biot's proposed equations [16]. The equilibrium equations of the Hook relationship, Darcy law and contiguity equations are the basic relations for the expression of system equations. Consolidation analysis is based on the mathematical model that has been done with a time-staged construction of the dam. Corresponding to the long dam crown, the calculations are based on the 2-D (plane) strain state.

3. Results

3.1. For $k_y/k_x=1.0$

3.1.1. Analysis of the settlement

The total settlement of the dam, without drains state, is estimated to be 0.9m (reference value). Figure 3 shows a schematic of the earth dam settlement after 24 months. Figure 4 demonstrates the settlement during the dam construction for different depths and spacing of the geotextile vertical drain. There is a significant increase in the dam settlement with increasing the depth of
drain and decreasing in drains spacing in progress of the time and all these changes are in a linear trend. For 24m depth, the drains caused approximately constant changes in the consolidation settlement within the time and for all drains spacing with a correlation factor (R) of 0.95. This situation may be related to the assumption of \( ky/kx=1.0 \). The mean settlement value is 0.833m and a standard deviation of 0.028 (for 24m depth). This value of settlement achieves 92.5% of the total final settlement of the dam (reference value) and this is higher than the maximum settlement ratio (49% at 24months) for no drain condition.

**Figure 3.** Settlement Schematic Using MC for \( ky/kx=1 \) after 24 Months.

**Figure 4.** Dam Settlement versus Construction Time for Different Drains Depth and Spacing.

3.1.2. Analysis of the Upstream Safety Factor

Figure 5 illustrates the schematic of the failure slip in upstream. Figure 6 shows the factor of safety in upstream of the dam for the different studied parameters (construction time and drains depth and spacing). As expected, there is a major increase in the safety factor, similar to the settlement situation, but the changes are not in linear trend, while the change is linear for the no drains condition.
For all drains spacing and the depth of ≥15m, there are convergent values of safety factors especially with the progress of time, then, there is a unique value at the time of 24 months with correlation factor (R) of 0.9. The mean value of the upstream safety factor is 1.99 (for 24m depth) and standard deviation of 0.045, likewise, within the time and all drain spacings. This value of factor safety (1.99) is 41% greater than the no drain condition.

Figure 5. Schematic of the Slope Failure in the Dam Upstream with MC for ky/kx=1 after 24months.

3.1.3. Analysis of the Downstream Safety Factor

Similar to upstream safety behavior, the safety factors of the downstream show that there is a weighty increase with increasing the depth of drains and construction time while the changing is vice versa for the spacing of the drain, as shown in Fig. 7.

As in upstream, the dominant drain depth is 15m where the values of safety factor are convergent to each other. Also, the depth of 24m still gives an approximately constant value of safety factor.
depending on correlation analysis (beyond 0.9) with a mean value of 2.04 and a standard deviation of 0.056 and similarly within the time and all drains spacing. This value of factor safety, moreover, is +40% corresponding to the no drain condition. Figure 8 represents the schematic of the failure in the dam downstream.

![Safety Factor of Dam Downstream versus Construction Time for Different Drains Depth and Spacing.](image)

**Figure 7.** Safety Factor of Dam Downstream versus Construction Time for Different Drains Depth and Spacing.

![Schematic of the Slope Failure in the Dam Downstream with MC for ky/kx=1 after 24months.](image)

**Figure 8.** Schematic of the Slope Failure in the Dam Downstream with MC for ky/kx=1 after 24months.

### 3.2. For ky/kx=0.1

For no drains state with ky/kx=0.1, the settlement has been estimated to be 0.35m after the end of 24 months or 38% of the final settlement (reference value, 0.9m). As expected, the settlement percentage (38%) is less than the condition of ky/kx=1 (49%) and it is related to the low permeability ratio.
Figure 9 illustrates the settlement values for different drain spacing and time for drain depth of 24m. There is increasing in the settlement with respect to the no drain condition, for example, the settlement ratios \((\text{sett}_{time}/\text{sett}_{final})\) are 83%, 77% and 72% for drains spacing of 2m, 3m and 4m respectively at 24 months and 24m drain depth.

As shown in Fig. 10, the behavior of the settlement for \(ky/kx=0.1\) was different. There is a significant gradient from the initial time (4 months) to the end of the period corresponding to the condition of lower \(ky/kx\) (0.1). These results are closer to the real state of water dissipation from the soil.

Similar to the results of settlement, the safety factor of the dam upstream shows a gradual increase in values with time for all spacings of the drain with a depth of 24m, as in Fig. 11. There is a significant increase in the factor of safety concerning the no drain condition. For example, after 24 months, the factor of safety is 2.017 with a drain depth of 2m while this factor is 1.15 in case of no drains.

Figure 12 shows clearly the differences between the two studied cases of \(ky/kx\) ratios \((0.1 \text{ lower than } 1)\) and the difference is higher at the start of the time. This result is revealed the effect of the permeability in both directions on the expected values.

For emphasis purposes, Fig. 13 presents the safety factor in the dam downstream. For the ratio of \(ky/kx=0.1\). The results are as in the upstream. For example, after 24 months and with drains of 2m spacing and 24m depth, the downstream safety factor is 2.044 or 77% increase with respect to the no drain condition (1.154).
3.3. Effect of Modelling Method
To investigate the effect of modelling method on the studied parameters, an analysis is made using the Modified Cam-Clay model. Fig. 14 indicates the comparison between both modellings (MC and MCC) on the results of the settlement. The settlement values from the Mohr-Coulomb model (MC) are lower than their values from the Modified Cam-Clay model (MCC) with an approximately constant difference of about 92%.

**Figure 14.** Consolidation Settlement versus Time for Different Modelling Methods for Specific Drain Depth and Spacing.

Fig. 15 shows the comparison of both modelling methods for upstream and downstream safety factors. As in settlement results, the MC model showed lower values whereas the downstream has more proximate results with average percentage difference (MCFS/MCCFS) of 98.5% while this percentage in upstream is about 96.5%.
Figure 15. Safety Factor versus Time in both Upstream and Downstream of the Dam for both Modelling Methods and Specific Drain Depth and Spacing.

4. Conclusions
This investigation highlighted the importance of earth dam stability and performance using the geotextile vertical drains and the following statements can be concluded:
1. The investigation of geotextile drain has shown that the settlement and safety of the dam are increased and their values were calculated for different drain depths and spacing.
2. The changes in the settlement and safety factors were affected by the ky/kx ratios.
3. Taken together, these findings suggest a role for ky/kx ratios in promoting the dam stability. For a lower ky/kx ratio, lower values of dam settlement and safety were achieved.
4. This study has identified that the Mohr-Coulomb model (MC) is the easier method, but, affords lower values than the Modified Cam-Clay model (MCC) for all studied parameters of the dam and foundation, as stated by the literature.
5. There is a definite need for using a vertical drain in the foundation of the earth dam and the geotextile materials are easy to use with pre-defined and design properties.
6. A further study could assess different drain materials for application and performance. An experimental investigation is needed to verify the results of the recent study.

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