Evaluation of vertical drain with different materials

Ali Akhtarpour\(^1\), Mohammed Sh Mahmood\(^2\), and Ameer Alali\(^3\)

\(^1\) Ph.D., Asst. Prof., Civil Eng. Dept., Ferdowsi University of Mashhad, I.R. Iran. Email: akhtarpour@um.ac.ir
\(^2\) Ph.D., Asst. Prof., Civil Eng. Dept., University of Kufa, Iraq. Email: mohammedsh.alshakarchi@uokufa.edu.iq
\(^3\) Formerly M.Sc. Student, Civil Eng. Dept., Ferdowsi University of Mashhad, I.R. Iran. Email: ameeraljabery1987@gmail.com

Abstract. Accelerate the drainage process and consolidate saturated clay soils is important to achieve stability of the construction. Vertical drains, with a suitable grid and depth, the result of shortening the path of water flow inside the soil and soil consolidation rate increases from several years to several months. Sombar earth dam, a case study, in Gholaman village in North Khorasan province, Iran, is used to provide agricultural and drinking water in the area. The recent paper shows a comparison between the results of Sombar dam stability with vertical drains of two different materials using the Mohr-Coulomb model with the aid of GeoStudio 2012 computer software. The drains materials are sand and geotextile and the investigated parameters are permeability ratio (\(k_y/k_x\)), drains geometry and time of the dam construction. The results are presented as ratios, settlement ratio (\(SS_{\text{SAND}}/SS_{\text{GEO}}\)) and safety factor ratio (\(FSS_{\text{SAND}}/FSS_{\text{GEO}}\)). The results revealed that there are clear increases in the consolidation settlement ratio, but, slightly increase in safety factors ratio using sand drains comparing to the geotextile. The \(k_y/k_x\) has a clear effect on settlement and factor of safety in sand drains.

1. Introduction

Soft clay has a low bearing capacity and high compressibility features. Thus, it is necessary to apply improvement techniques prior to construction to avoid unacceptable differential settlement [1]. To increase the soft soil shear strength, using vertical drains for preloading of soft clay is one of the common methods, in addition, to control its post-construction settlement. Various types of vertical drains were adopted and have been studied, including gravel piles, geosynthetic vertical drains and sand drains [2, 3]. Consolidation time can be reduced from about 1 to 5 years without a vertical drain to about 50 days with prefabricated vertical drains (PVDs) [4]. The efficiency of the vertical drainage method is a function of their distances, depth and diameter of the boreholes and more efficiency in alloys with horizontal permeability exceeding vertical permeability [5]. Depending on scaled model tests, the using of PVDs is successful for the improvement of ultra-soft with increasing in the undrained shear strength and a substantial amount of pore pressure dissipation [6].

The Mohr-Coulomb models (MC) are simple and easily determinable model parameters in numerous engineering applications and the stress-strain response depends on the liquid limit value [7]. The linear elastic-perfectly plastic model (or MC) is one of the most commonly used pressure-sensitive constitutive models [8]. It is necessary for a two-dimensional (2D) finite-element analysis with the plane-strain model to convert the system of vertical drains into an equivalent drain wall [9].
The variation of a factor of safety (increase) with time is primarily influenced by the rate of dissipation of excess pore pressure within the depth of soil up to which the critical slip surface passes. Installation of vertical drains also decreases the post-construction settlement of the embankment and helps to settle the embankment more uniformly [10]. In the recent paper, the authors investigate the effect of vertical drains (geotextile and sand) in the foundation soil on the stability of the Sombar dam, using Mohr-Coulomb model with aid of GeoStudio 2012 [11] computer software. The authors develop a reliability analysis of the stability due to the vertical drains for the different studied parameters.

2. Theoretical Background
Baron [12] provided a method for analyzing a cylindrical element of soil with a vertical drain in its center. The theory was based on the simplification of the hypothesis of single-dimensional consolidation of the hypocrisy. The governing differential equation as in Eq. 1:

\[
\frac{\partial u}{\partial t} = C_h \left( \frac{1}{r \partial r} + \frac{\partial^2}{\partial z^2} \right) \]

(1)

Where \( u \): excess water pressure in the hole due to the increase of tension, \( t \): time, \( C_h \): the horizontal coefficient of consolidation and \( r \): the radial distance of the drain. The solution of the above equation is presented in Eq. 2 and Eq. 3 [12]:

\[
U_h = 1 - \exp\left(\frac{-8Th}{\mu}\right) \]

(2)

\[
T_h = \frac{C_h t}{D_e} \]

(3)

Where \( U_h \): the average degree of radial consolidation, \( T_h \): dimensionless factor, \( D_e \): the diameter of soil equivalent and \( \mu \) is the component that is included in the drain spacing, the drain equivalent diameter, and drain discharge capacity; it is represented as in Eq. 4 and Eq. 5 [12]:

\[
\mu = \frac{n^2}{n^2 - 1} \ln(n) - \frac{3n^2 - 1}{4n^2} \]

(4)

\[
n = \frac{D_e}{d_w} \]

(5)

Where \( n \): the drain spacing, \( d_w \): the equivalent diameter of the drain.

An approximate solution for vertical drain is shown based on the hypothesis equal strain for the area affected (disturbed and undisturbed) by the drain. The theory is based on simplifying the assumptions of Darcy law. The governing equations are Eq. 6 to Eq. 9 [13]:

\[
U_r = 1 - \exp\left(\frac{-8fr}{F}\right) \]

(6)

\[
F = F(n) + F_s + F_r \]

(7)

\[
F = \ln\left(\frac{n}{s}\right) + \left(\frac{s}{r_w}\right) \ln(z) - 0.75 + \frac{\pi z(2l - z^2)}{a_w} \]

(8)

\[
s = \frac{r}{r_w} \]

(9)

Where \( F_s \): the drain area, \( F_r \): resistance, \( k_h \): permeability of the undisturbed soil area, \( k_w \): permeability in the drain area, \( k_s \): permeability of the disturbed soil area \( l \): drainage length and \( q_w \): drainage.

The equivalent diameter for tape strips: By using the conventional consolidation theory for vertical drains, we assume that the vertical drainage is in the transverse section of the circle. Most over-drained
drains have a trapezoidal shape and this trapezoidal surface can be close to the surface of the circle of the equivalent diameter. Therefore, the diameter $d_w$ deformed into a wall drain with a width of “a” and thickness of “b” as in Eq. 10 [14].

$$d_w = \left(\frac{a+b}{2}\right)$$  \hspace{1cm} (10)

Various methods have been proposed to consider the coherent effect of vertical and radial consolidation. The simplest version was given by Carroll [15] as in Eq. 11.

$$(1 - U) = (1 - U_v)(1 - U_h)$$ \hspace{1cm} (11)

Where $U$: the total average degree of consolidation, $U_v$: the average vertical degree of consolidation, and $U_h$: the average horizontal degree of consolidation.

If the drain capacity is low, a resistance to water movement is created (collection of water near the drain). According to Xie [16], Eq. 12 should be considered to maintain a low level of the wall resistance.

$$\frac{\pi}{2} \times \frac{k_h}{q_{w}} \times l_m^2 < 0.1$$ \hspace{1cm} (12)

Where $k_h$: the hydraulic conductivity of the soil in the horizontal direction (m/sec), $l_m$: the length of the drain (m).

The relationship between strain and stresses in Mohr-Coulomb model is completely linear to a point and after this point the stress-strain curve becomes a horizontal line. The potential for failure can be expressed as in Eq. 13 [11].

$$F = \sqrt{\frac{2}{3}} \sin \left(\theta + \frac{\pi}{3}\right) - \frac{\sqrt{2}}{3} \cos(\theta + \frac{\pi}{3}) \sin \phi - \frac{2}{3} \sin \phi - c \cos \phi$$ \hspace{1cm} (13)

When the angle of internal friction is zero, the criterion for collapse in Mohr-Coulomb model becomes as in Eq. 14 [11].

$$F = \sqrt{\frac{2}{3}} \sin \left(\theta + \frac{\pi}{3}\right) - c$$ \hspace{1cm} (14)

3. Materials and Method

The earth dam of Sombar has located 2 km from the asphalt road between Gholaman city and the Castle village in northern Khorasan province, Iran. Due to the length of the crown of the dam, the calculations are based on the plane strain state for the maximum barrier section. The dam is a type of earth limestone with a clay core and sandy crust. The site of the dam is mostly fine-grained alluvium with coarse-thick layers up to 30 meters wide across the valley. Figure 1 shows the section in the soil foundation and the dam. The fine-grained alluvium was classified as CL-ML, CL, and sometimes ML, and the coarse aggregates are classified as SC, SC-SM, SM according to the unified soil classification system (USCS). The groundwater level is around 4m from the ground level. The coefficient of consolidation is 2.25*10-3 cm2/sec under vertical stress of 2kg/cm2, 1.1*10-3 cm2/sec under 4kg/cm2 and 1*10-3 cm2/sec under 8kg/cm2 [17, 18]. Table 1 summarizes the soil properties of the foundation and dam.
Table 1. Summary of Soil Properties the Foundation and Dam.

| Soil type             | Test method | Unit weight, kN/m$^3$ | k, m/sec | $\Phi$, degree | C, kPa | E, kPa | v   |
|-----------------------|-------------|-----------------------|----------|----------------|--------|--------|-----|
| Clay core             | UU          | 20                    | 10-9     | 0              | 80     | 22900  | 0.48|
|                       | CU          | 19                    | 10-9     | 14             | 14     | 1416   | 0.48|
|                       | CD          | 27                    | 32       | 42             | 42     | 19100  | 0.25|
| Sandstone             | -           | 22                    | 10-5     | 42             | 42     | 40000  | 0.2 |
| Foundation Fine-grained | CU          | 19                    | 10-9     | 14             | 14     | 1416   | 0.48|

Software named "GeoStudio 2012" are used to solve the consolidation equations. Using SIGMA/W and SLOPE/W (from GeoStudio) in sequence facilitates the modelling of staged construction with Multiple analyses method. SIGMA/W together with SEEP/W are performed for A fully-coupled consolidation analysis. Mohr-Coulomb Model (MC) is adopted for the analysis of the dam and the underlined foundation under effective stress. The basic equations of equilibrium of the Hook relationship, Darcy law and equations of contiguity are applied. The investigation program includes the effect of sand and geotextile vertical drains in foundation soil on the dam settlement and safety factor. The drains depth (8, 15, 18 and 24m), the drains spacing (2, 3 and 4m) for each drains depth. These parameters are investigated corresponding to two coefficient of permeability ratios ($ky/kx$) of 1 and 0.1 and construction stages of 4, 8, 15 and 24 months. Figure 2 shows the distribution of the drains in the foundation of the dam. The presentation of the results in terms of the ratios for comparison purposes, the settlement ratio is $S_{SAND}/S_{GEOTEX}$ and the factor of safety ratio is $FS_{SAND}/FS_{GEOTEX}$. The lowest values of safety factor are adopted in the comparison.
4. Results
Generally, with vertical drains (sand or geotextile) in the foundation soil of the Sombar dam, the rate of consolidation settlement is increased with respect to the no drain condition as probable due to water escape from the soil through the drains. For comparison purposes, this paper investigates the change percentages in settlement and factor of safety using sand or geotextile drains. The settlement ratio \( \frac{S_{SAND}}{S_{GEOTEXT}} \) and safety ratio \( \frac{FS_{SAND}}{FS_{GEOTEXT}} \) are discussed.

Figure 3 illustrates the general schematic of dam settlement using vertical drains. The settlement ratios \( \frac{S_{SAND}}{S_{GEOTEXT}} \) show that the settlement rate exhibits increasing with using of sand drains regardless of the drain diameter comparing to the geotextile drains, as shown in Figure 4, but these differences in settlement ratios are not reach +6%. The settlement ratio for the 0.5m sand drain, as be expected, is larger and approximately in constant trend. This condition may be attributed by the high permeability of sand in both directions corresponding to the geotextile material.

Figure 5 illustrates the results of safety factors ratio \( \frac{FS_{SAND}}{FS_{GEOTEXT}} \) in upstream (lowest) for the of 9m depth and 4m spaced drains. One can notice that there is clear difference behavior between FS ratios with respect to 0.3m and 0.5m sand drains. The 0.5m diameter reveals more 100% increase related to the geotextile drain while, unexpectedly, the 0.3m sows less 100% and this may be as a reason of low stiffness of sand drain comparing to geotextile drain.
With decreasing the drain spacing, the settlement ratio shows more straight lines with converging trends at the end of the construction time, as shown in Figure 6. There is a high difference between the sand and geotextile drains, sustainably, the sand drains revealed more settlement. One can conclude that the sand drain is more effective for settlement, regardless of the diameter, comparing to the geotextile one. But with decreasing of drain spacing, the factor of safety ratio exhibits a constant trend for the different sand geometry with respect to the geotextile, as shown in Figure 7. The values of safety factor ratios are around the unity especially with advancing in time of the dam construction. This situation, due to a decrease in drain spacings, the stiffness of the drains, with different materials, is more comparable.
5. Discussion

The recent paper compares the effect of vertical drains in foundation soil with two different materials on the behavior of Sombar earth dam, settlement and factor of safety. This comparison is prepared to make the reliability of the results from the settlement ratio (S\textsubscript{SAND}/S\textsubscript{GEOTEXT}) and safety ratio (FS\textsubscript{SAND}/FS\textsubscript{GEOTEXT}). The study covered different parameters including drain geometry, drain materials and soil permeability ratio (k\textsubscript{y}/k\textsubscript{x}).

There is a clear increasing trend of settlement ratio (S\textsubscript{SAND}/S\textsubscript{GEOTEXT}) from different studied drain parameters, i.e., unrelatedly of drain geometry, sand drain contributes a larger settlement rate, as stated by Mahmood et al. [19]. While for safety factor ratio (FS\textsubscript{SAND}/FS\textsubscript{GEOTEXT}) from the geotextile is little more than from sand drain, but with decreasing of the drain spacing, the values of FS from both drain types are identical and this may be due to the comparable stiffness in the lowest spacing.
To investigate the effect of ky/kx, Figs. 8 and 9 present a probability density function (pdf) for settlement and factor of safety ratios respectively for different values of ky/kx. The pdf shows the distribution of data (SSAND/SGEOTEXT and FSSAND/FSGEOTEX) around the mean value of the data. These analyses are made using the continuous random variable method with the aid of computer software named “Risk Tools (RT)” after Mahsuli, 2014 [20].

With decreasing in the ky/kx of the soil, the peak “pdf” (mean value) less and the curve is more splayed, as in Figure 8, but, with anisotropic soil condition (kx more than ky), there is a clear increase in the settlement rate from sand drains. An interesting result is in safety factor ratios, with decreasing in ky/kx, the resulted ratios of FS are slightly increased, as shown in Figure 9, however, dissimilarity to settlement ratios, the distribution of the pdf of FS ratios is close to the peak value (mean) in the anisotropic condition. These results indicate that there is a significant effect of permeability ratio (ky/kx) on the stability of the dam with respect to use the sand drains.

![Figure 8. Pdf Curves of Settlement Ratios for Different ky/kx.](image1)

![Figure 9. Pdf Curves of Safety Factor Ratios for Different ky/kx.](image2)
6. Conclusions
Comparisons are made to investigate the effect of vertical drains in the dam foundation with different materials (sand and geotextile) on the settlement and safety factor as a ratio of the different materials. There are clear increases in the rate of consolidation settlement, but, little in safety factors with using sand drains corresponding to the results of geotextile for different studied parameters. There is a significant effect of ky/kx ratio on the stability of the dam with respect to use the sand drains. With decreasing of the ratio of vertical to horizontal permeability (ky/kx), as in anisotropic soils, the settlement ratios (SSAND/SGEOTEX) remain larger and safety factor ratios (FSAND/FSGEOTEX) are slightly above 1 with respect to time and depth change.

References
[1] Indraratna B, Perera D, Rujikiatkamjorn C and Kelly R 2012 Soil Disturbance Analysis Due to Vertical Drain Installation Proc. of the Institution of Civil Engineers: Geotechnical Engineering 168 (3) 236-246. http://dx.doi.org/10.1680/geng.14.00052.
[2] Indraratna B, Rujikiatkamjorn C, Wijeyakulasuriya V, McIntosh G and Kelly R 2010 Soft soils improved by prefabricated vertical drains: performance and prediction, In Almeida M (ed), Symposium on New Techniques for Design and Construction in Soft Clays 227-246, Brazil: Officina de Textos.
[3] Indraratna B, Rujikiatkamjorn C, Balasubramaniam A S, McIntosh G 2012 Soft Ground Improvement Via Vertical Drains and Vacuum Assisted Preloading 30(4) 16-23. DOI: 10.1016/j.geotexmem.2011.01.004.
[4] Dhar A S, Siddique A and Ameen S F 2011 Ground Improvement using Pre-loading with prefabricated Vertical Drains International Journal of Geoengineering Case Histories, geoengineer.org 2(2) 86-104.
[5] Bergado, D T, Anderson L R, Miura N and Balasubramaniam A S 1996 Soft Ground Improvement: In Lowland and Other Environments American Society of Civil Engineers, New York, USA.
[6] Chu J, Bob M W and Choa V 2006 Improvement of ultra-soft soil using prefabricated vertical drain, Geotextiles and Geomembranes 24(6) 339–348.
[7] Sandhya Rani R, Nagendra Prasad K and Sai Krishna T 2014 Applicability of Mohr Coulomb & Drucker Prager Models for Assessment of Undrained Shear Behaviour of Clayey Soils International Journal of Civil Engineering and Technology (IJCIET) 5(10) 104-123.
[8] Coombs W M, Crouch R S and Heaney C E 2013 Observations on Mohr-Coulomb Plasticity under Plane Strain J. Eng. Mech. ASCE 139 1218-1228.
[9] Indraratna B 1997 Plane-Strain Modelling of Smear Effects Associated with Vertical Drains Journal 0f Geotechnical and Geoenvironmental Engineering 123 474-478.
[10] Krishnamoorthy A and Kamal S 2016 Stability of an Embankment on Soft Consolidation Soil with Vertical Drains Journal of Geotechnical and Geological Engineering. DOI: 10.1007/s10706-015-9975-4.
[11] GeoStudio User's Manual (Sigma/w Modelling) 2012 3rd Edition.
[12] Barron R A 1948 Consolidation of Fine-Grained Soils by Drain Wells Trans. ASCE 113 718-742.
[13] Hansbo S 1981Consolidation of Fine - Grained Soils by Prefabricated Drains Proceedings of the 10th International Conference on Soil Mechanics Foundation Engineering Stockholm Balkema Rotterdam The Netherlands 3(4) 677–682.
[14] Indraratna B, Bamunawita C, Redana I W and McIntosh G 2003 Modelling of prefabricated vertical drains in soft clay and evaluation of their effectiveness in practice Journal of Ground Improvement 7(3) 127-138.
[15] Carillo N 1942 Simple Two-and Three Dimensional Cases in the Theory of Consolidation of Soils Journal of Mathematics and Physics 21(1) 1-5.
[16] Xie K H 1987 Consolidation Theories and Optimization Design for Vertical Drains PhD Thesis Hewing University Chin.
[17] Final Dam Report: Geotechnical studies of the Sombar Dam 2007 (in Persian).
[18] Alali Ameer 2017 The Effect of Vertical Drains On Stability and Settlements During Construction of an Embankment Dam On Saturated Soft Soil (Case Study: Sombar Dam) M.Sc. Thesis Faculty of Engineering, Ferdowsi University of Mashhad, Iran (in Persian)
[19] Mahmood Mohammed Sh, Akhtapour Ali and Alali Ameer A A unpublished Mechanical Behavior of Dam-Vertically Sand Drained Foundation, Case study: Sombar Dam J. Eng. Technol. Sci. Indonesia.
[20] Mahsuli M, Haukaas T 2014 Rt-Risk Tools (software) www.inrisk.ubc.ca.