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Research Article

Consolidation Attributes and Deformation Response of Soft Clay Reinforced with Vertical Scoria Drains under Road Embankment

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Application of vertical drains in soft clay soils is a common practice widely known to facilitate the consolidation rate. To overcome the adverse impact of a long-lasting consolidation process, highly permeable materials such as sand and crushed aggregates are used as drains. However, limited information exists regarding the applicability of scoria gravel as a vertical drain that no concisely documented information is observed in the literature. This study hence aimed at investigating suitability of scoria as a vertical drain in perpetuating the consolidation process of soft clay under highway embankment. Finite element-based numerical simulation was used to model the drain. The model was carried out by using 3D version of Plaxis software. In order to incorporate the effect of gradual load increment on the consolidation rate, the staged construction approach was employed. Both the square and triangular installation patterns were considered in the model in order to explore the critical effects of the drain installation pattern on the rate of consolidation. The numerical analysis also included varying dimensions of the vertical drain so as to investigate the effects of the dimension parameters of the vertically installed scoria drains. The conducted numerical analysis revealed that the rate of consolidation was considerably accelerated with provision of a group of scoria drains. With increase in the diameter of the drain, the consolidation rate increases, whereas the consolidation rate is inversely related to increase in drain spacing. For the drain installed at a spacing of 2 m, a diameter of 0.4 m, and a length of 8 m any arbitrary settlement magnitude is achieved 25 days earlier than the case without drains. Besides, incorporation of scoria drains lessens the pore pressure developed. The comparative analysis conducted on the effect of drain arrangement revealed that no considerable difference was witnessed in the performance of the square and triangular installation patterns even though the consolidation rate remains slightly faster in the case of the triangular installation pattern.

1. Introduction

Clayey ground underlying road embankments commonly experiences a long-lasting deformation that takes considerable duration of time for the consolidation process to be fully accomplished [1]. Upon placement of external loading, the excess pore pressure begins to rise which is a typical characteristic of clayey foundations [2]. Clay soil is typically known for its poor workability, in which embankment loads result in bearing failure and excessive deformation after construction [3]. In many practical cases, the removal of massive clay deposits down to larger depths is technically and economically not feasible. In the effort to overcome this challenge, the employment of vertical drains to purposely speed up the consolidation rate is one of the widely applied remedial measures [4]. The principle of vertical drains is primarily employed to provide additional vertically installed drainage faces in the form of cylindrical or square holes filled with highly permeable materials [5]. Vertical drains made of crushed aggregates, sand, and prefabricated vertical drains are commonly provided without removing the massive volume of unsuitable clayey soil [6–8]. A vertical drain improves the permeability of low-permeable soils by reducing the drainage path [9]. The author in [4] stated that vertical drains are fundamentally installed in groups to accelerate the soil consolidation process by shortening the drainage path and activating radial drainage, thereby increasing the shear strength of the soil while reducing its postconstruction settlement [10–12].

In addition to its drainage role, the vertical drain also plays a reinforcing role that is pertinent in improving the overall load bearing capacity of soft grounds [13]. With the rapid consolidation process, soft soils gain shear strength rapidly which allows for a faster pace of construction works. This significantly increases the long-term stability of the structures built on clayey ground as the potential consolidation settlements are accomplished mostly before or during the construction phase [14–24].

Scoria is a highly porous pyroclastic material made of solidification of volcanic lava [25, 26]. The Ethiopian rift valley is known for its large coverage of volcanic materials such as pumice, scoria, and cinder [27]. Melese and Hamisi Chengula and Kilango Mnkeni [28, 29] reported that scoria is abundantly found in volcano-prone areas of the Ethiopian rift. From an application point of view, scoria gravel is widely used for the improvement of weak subgrade materials and as a replacement material for the production of light weight concrete. The use of scoria as an additive when blended with other materials is recently becoming a common practice, especially in improving highway subgrade. Conventionally, it does not meet requirements of pavement materials without blending with other materials [30]. Gomes and October [31] in the study on blended properties of cinder-blended subgrades for construction of roads concluded that volcanic scoria considerably performs well in reducing plasticity and improving gradation and density of weak subgrades. Because of its light weight, scoria is also used in the production of construction blocks as well [25]. It is also similarly used as a cement additive in the construction of reinforced concrete structures to improve the engineering properties of concrete [32–34]. Hossain and Hearn et al. [32, 35] reported that the blending of scoria as an additive material in concrete works proved effective in improving the strength, durability, and heat insulation properties of the concrete. Saltan and Ozen [36] in the experimental study on the usability of scoria as a subbase material reported the appropriateness of scoria as a partial replacement. Findings of the study revealed that scoria is effective in improving the Californian bearing ratio and lessening the plastic index of the pavement subbase.

Many studies have documented the wide application of scoria material as road subgrade and subbase and as an additive material in concrete work. Almost all of the works concentrated on its applicability in improving weak pavement courses and concrete properties. None of the previously conducted works reported on the suitability and applicability of scoria as a vertical drain. In this study, hence, the potential use of volcanic scoria as a vertical drain is explored. The study specifically focuses on the consolidation and deformation attributes of soft clay subgrade under the impact of highway embankments and vertically installed scoria drains. Besides, the performance and suitability of scoria material as a vertical drain is emphasized. Its effectiveness in shortening the consolidation duration of soft clay is also evaluated for both square and triangular vertical drain installation patterns. Lastly, the influence of drain dimension parameters is explored via finite element-based numerical modeling.

2. Methods and Materials

2.1. Characterization of Materials Used. The numerical analysis conducted in this study considered four different materials, which include soft clay, volcanic scoria, and natural gravel fill. The soft clay is considered as foundation of the road reinforced with vertical drains installed at various spacing. The massive clay soil is reinforced with a group of scoria drains without removing total or some part of it via conventional excavation. The clay soil is of massive thickness underlain by relatively hard strata situated at large depth. Samples of clay soil for the determination of physical properties were collected from Jimma town, Ethiopia. As observed from the conducted laboratory tests, the permeability of the clay soil is considerably insignificant, which is a typical characteristic of problematic expansive soil. The materials considered in the study have the properties summarized in Table 1 and Figure 1.

Scoria gravel was used as a cylindrical vertical drain for the prior intention of shortening the radial drainage path in a clay soil. The considered scoria material was sampled from the outskirt of Adama City, Ethiopia, which is one of the areas well known for its predominant coverage of volcanic slag. Scoria by its nature is highly permeable sinusoidal material [33, 37, 38]. Granular vertical drains apparently play dual (drainage and reinforcement) role. In addition to perpetuating consolidation rate, vertical drains are also known for their reinforcing role as stabilizing material. Therefore, through the provision of vertical drains load bearing capacity, permeability, and deformation characteristics of soft clay are improved [30, 36]. Accordingly, scoria drains having various diameters and lengths are vertically installed at different spacings. The permeability of scoria in the horizontal direction is usually several times larger than that in the vertical direction. Hence, the rate of consolidation becomes considerably faster compared to the conventional soil system [25, 31].

A sand blanket is placed on top of the clay mass right after the installation of the vertical drains to allow the dissipation of water in the lateral direction. With gradual increment in magnitude of embankment load, the developed excess pore pressure gets relief through the vertical drains. The horizontal sand drain receives the upward dissipating water via the scoria drain so that the water can possibly flow to roadside ditch. The sand layer hence facilitates the lateral dissipation of water without infiltration of water into the fill material. The sand drain lets excess water to flow to roadside ditch without disturbing the moisture content of the fill material [4]. Coarse sand is commonly preferred over fine sand to be used as a horizontal drain because of development of relatively large voids between solid grains [8]. The voids are hence suitable room for the fast flow of excess water, which significantly contributes to the rapid consolidation of the clay soil. Even though the primary purpose of having sand drain for its drainage role, it is also beneficial in making the loading area level and uniform [6].

A natural granular selected material was used as an embankment material. For the purpose of material characterization, a sample for embankment fill was collected

Table 1: Physical properties of the materials required.

Properties/parameters	Units	Clay soils	Scoria	Sand	Embankment
Moisture content (w_c)	%	48.75	—	—	21
Liquid limit (LL)	%	88	—	—	44
Plasticity index (PI)	%	53	—	—	16
Activity (A)		0.64	—	—	—
Specific gravity (G_s)		2.72	2.50	2.63	2.61
Bulk unit weight (γ)	kN/m^3	16.11	13.78	18.60	19.76
Permeability (K)	m/s	2.78^*10^{-9}	1.02^*10^{-4444}	8.25^*10^{-5}	4.05^*10^{-5}
Unconfined compressive strength (UCS)	kPa	39.52	—	—	—
Secant Young's modulus (E_{50})	MPa	—	41.5	38	35.5
Compression index (C_c)		0.42	—	—	—
Cohesion (c)	kPa	24.27	0.00	1	3
Friction angle (Ø)	°	6.95	40.71	37	33

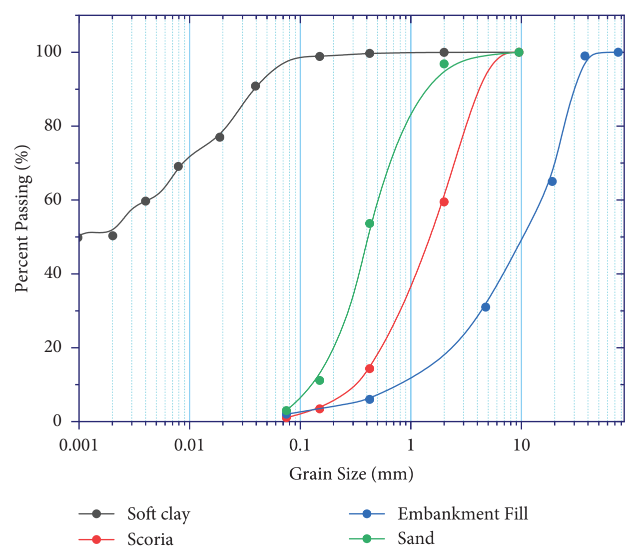


Figure 1: Particle size distribution of the soft clay, scoria, embankment fill, and sand envelope.

from the quarry site situated in the vicinity of Jimma City, namely, Bada Buna. The embankment material is directly placed on top of the sand envelope. The material is therefore the top layer used in the numerical simulation. In this specific study, the fill material will serve as both preloading and an integral part of the pavement structure. Even though it plays a preloading role, the material is not removed at the commencement of the actual construction work. Hence, it is a permanent part of the road embankment structure. The test standards used to investigate the physical properties of the considered materials are summarized in Table 2.

The mineral composition of the scoria material was determined using the analytical method of elemental analysis. Accordingly, the X-ray diffraction (XRD) method was used to chemically characterize the scoria gravel material and the chemical composition of the material is illustrated in Figure 2. X-ray diffraction is basically employed to measure the average spacing and orientation between layers and crystals [39]. Besides, the size, shape, crystal structure, and internal stress of small crystalline regions are investigated [40]. The conducted experimental result revealed that chemical composition of the scoria material is dominated by SiO_2 accounting 53.35% and followed by Al_2O_3 which is 16.34% by weight. Contrarily, MnO, K_2O, and TiO_2 are some of the scarce chemicals from which scoria was composed.

2.2. Numerical Modeling

2.2.1. Definition of the Problem. In the current study, soft clay mass reinforced with a group of vertically installed granular scoria drains was numerically modeled via the principle of finite element method. As scoria is a highly permeable material, it was primarily used to speed up the consolidation process of the clay mass under the embankment load. A group of scoria drains were installed up to a certain depth in the clay mass. The horizontal sand blanket is placed immediately on top of the clay mass to allow effective lateral dissipation of pore water. Consolidation analysis was carried out using the three-dimensional version of Plaxis software. Under the imposed embankment load, the performance of vertical drains in perpetuating the consolidation rate was investigated. The numerical model is also intended to simulate the deformation response and consolidation attributes of the soft clay.

Table 2: The standards used to experimentally characterize the materials.

Sn	Soil tests	Standard codes of ASTM and AASHTO
1	Moisture content	ASTM D-2216
2	Sieve analysis	ASTM D-421
3	Hydrometer analysis	ASTM D-422
4	Liquid limit	ASTM D-4318
5	Plastic limit	
6	Linear shrinkage	BS 1377 (AASHTO)
7	Modified proctor compaction	T-180 (AASHTO)
8	Specific gravity	ASTM D-854
9	Triaxial compression test	ASTM D-4767
10	UCS test	ASTM D-2166
11	Odometer	ASTM D-2435
12	Permeability	ASTM D-5084-03
13	Free swell	IS 2720 part 40 (AASHTO)
14	Soil classification	ASTM D-2487 ASTM D-3282, M-145 (AASHTO)

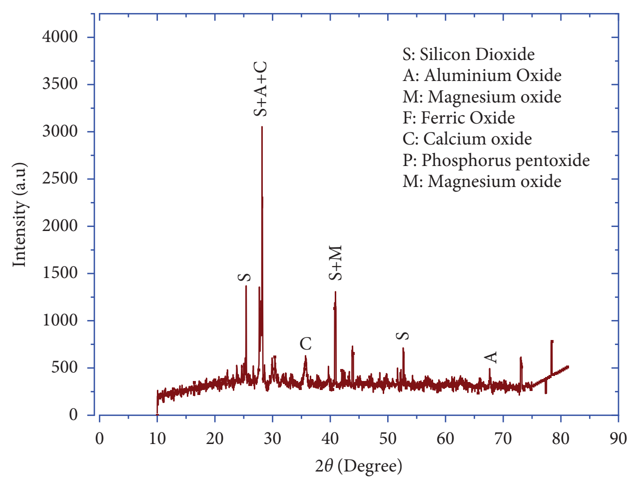
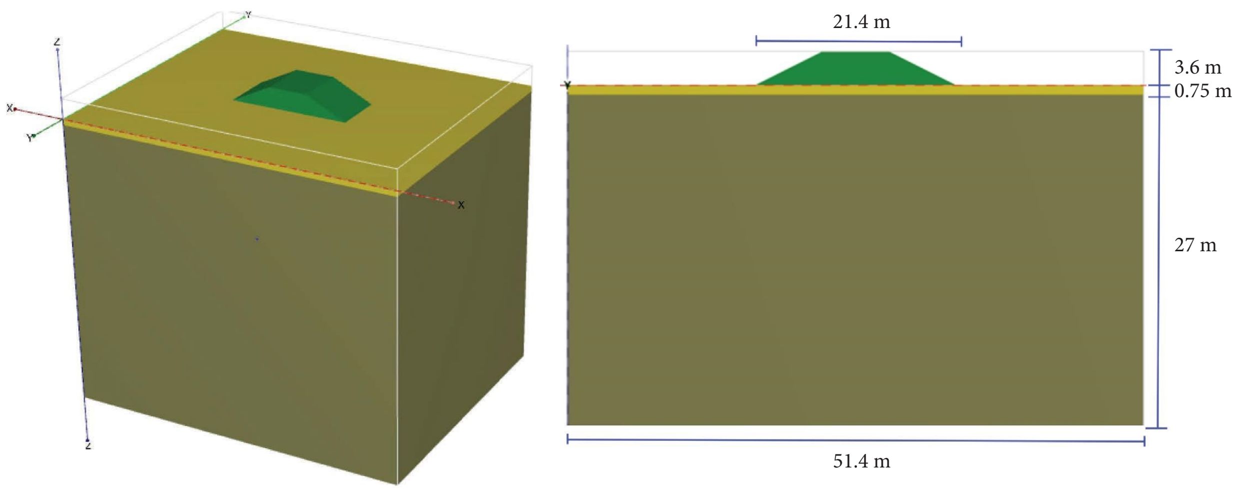


Figure 2: Chemical composition of volcanic scoria via XRD.

2.2.2. The Model Geometry. Various geometrical shapes are employed to numerically model geotechnical problems. These commonly used geometries include unit cell, axis symmetric, plane strain, equivalent homogeneous soil, and three-dimensional models. The selection of the proper and suitable geometry for the simulation of vertical drains depends on and is affected by the specific purpose for which the geometry is modeled. However, many literatures reported that the 3D model is the most effective geometry for simulating the deformation and stress characteristics of soil material [13]. The 3D model can assume two forms, namely, full three-dimensional and three-dimensional rows or slices of columns. Due to the vast extent of the road embankment, modeling of the entire area of the embankment was found to be impossible without significant technical gain. Thus, only a portion of the road embankment was modeled. In the current study, hence the three-dimensional slice of rows was used to simulate a group of scoria drains made of six rows and fifteen columns. The problem to be modeled is made of a number of material layers having their own dimension. The clay mass treated with scoria drains is 27 m thick and the considered model has an overall area of 51.4 m × 39 m. The drains were introduced to a certain depth of the massive clay deposit (ranges from 8 m to 15 m). In practical scenes, vertical drains can be installed either in square or triangular pattern. The group performance of granular drains is usually influenced by the spacing and arrangement of the drains [9]. In this specific model, three drain spacing (1.5 m, 2 m, and 2.5 m) were considered for parametric study. Of the 51.4 m by 39 m area of the model, drains were introduced to 9 m by 21.4 m area (9.6% of the total area of the model). Similarly, the considered drain diameter ranges from 0.4 m to 0.8 m. A 0.75 m thick sand blanket is provided on top of the soft clay as a horizontal drainage media. In addition to its drainage role, the sand layer allows an even and leveled loading surface to develop. Figure 3(b) shows the cross-section of the road embankment and material layers considered for the numerical model. The embankment is 7 m wide which is anonymous to the typically practiced width of unpaved road in Ethiopian context. The slope of the 3.6 m thick test embankment (made up of granular fill) has an inclination of 1 : 2 (vertical : horizontal). The 3D view of the model geometry is depicted in Figure 3(a).



(a)

(b)

Figure 3: (a) 3D view of geometry of the model and (b) cross-section of the embankment and material layers.

2.2.3. Numerical Analysis Process. The numerical model conducted is analogous to a 7 m wide typical unpaved road cross-section whose foundation material is completely clay soil. The performance of the foundation material is therefore a function of different factors, as its response to external loading does not remain consistent over time. Especially, deformation characteristics of the clay mass are time dependent feature. In order to simulate the deformation and consolidation-related attributes of the foundation material under embankment load, consolidation analysis was carried out. The consolidation process of clayey soils is influenced by many factors, such as loading duration, drainage condition, and rate of loading [13, 41]. The overall processes of the numerical simulation pass through two major analyses. The first one is by which the initial in-situ properties of the weak soil are simulated. During this phase of simulation, only the massive clay is modeled in a complete absence of any external loading and drains. Second, the clay mass is modeled after being treated with a group of vertically installed scoria drains. After installation of the drains, the sand blanket and the granular embankment material are permanently placed in a sequential manner for certain time duration. In this stage, the sole massively compressible soil is directly subjected to embankment load.

The hardening soil (HS) constitutive model, which considers shear and compression hardening of soft soil, was employed to simulate the properties and deformation characteristics of the soft clay, scoria drains, sand and embankment fill. The material parameters used in the numerical model are summarized in Table 3. Mohr–Coulomb is one of the oldest widely used soil model to numerically simulate soil behaviors exhibiting linear interfaces and nonsophisticated boundary conditions [42]. Hardening Soil is an advanced and versatile material model that takes into account the key drawbacks existing within the Mohr–Coulomb model [43, 44]. HS is a powerful soil model that overcomes some limitations associated with the soft soil (SS) model, especially with regard to overconsolidated soils [43, 45].

2.2.4. Boundary Conditions, Mesh Density, and Material Interfaces. Numerical boundary conditions such as load, displacement, stress, and hydraulic boundaries are applied to numerical models so that the numerical problems are solvable. These boundary conditions are believed to numerically represent the actual boundary conditions in real physical problems. In some sophisticated domains, however, it is not easy to suitably simulate the physical boundary conditions via finite element-based numerical models [46]. In the current study, displacement and drainage boundary conditions were considered. The displacement boundary condition was applied to both the vertical and bottom sides of the geometry. Accordingly, the model was fixed both laterally and vertically from the bottom, whereas all the vertical sides were subjected to lateral fixity. With regard to drainage, a flow boundary was specified to take into account the presence of the ground water table at a depth of 1 m from the surface. A summary of the flow boundary is presented in Table 4. Any stress boundary condition has not been considered in the numerical analysis. There is no quantified magnitude of external stress that the soft clay supports except for the self-weight of the sand and embankment layers. The pressure imposed by the fill material and sand drain is not specified as a stress boundary since both materials are integral parts of the model geometry.

One of the commonly faced challenges in determining the dimensions of numerical models is the proximity of the fixed boundaries to the main area of interest in the model. The proximity of the fixed boundaries to the main area of interest (loaded area) influences the accuracy of the calculation. The iteration and mesh density to be generated are also impacted, which in turn affects the overall calculation result. In order to overcome the boundary effect, therefore,

Table 3: Input parameters used for the numerical model.

Properties/parameters	Units	Clay soils	Scoria	Sand	Embankment
Initial void ratio (e_o)		1.321	0.5	0.5	0.5
Unit weight	kN/m^3	16.11	13.78	19.84	18.513
Overconsolidation ratio (OCR)		1	—	—	—
Lateral Earth pressure coefficient at rest (K_o)		1	0.211	0.168	0.156
Natural moisture content (w_c)	%	48.75	—	—	21
Stiffness modulus for unloading/reloading (E_{ur})	MPa	—	124.4	114	106.5
Stiffness modulus for primary loading (E_{50})	MPa	—	41.5	38	35.5
Oedometric modulus (E_{oed})	MPa	—	41.5	114	106.5
Permeability in X direction (K_x)	m/day	2^*10^{-4}	8.812	7.128	3.499
Permeability in Y direction (K_y)	m/day	2^*10^{-4}	8.812	7.128	3.499
Vertical permeability (K_v)	m/day	2^*10^{-4}	8.812	7.128	3.499
Compression index (C_c)		0.42	—	—	—
Modified compression index (λ^*)		0.184	—	—	—
Modified swelling index (κ^*)		0.037	—	—	—
Stress level dependency of stiffness (M)		0.5	0.5	0.5	0.5
Strength reduction factor (R_{int})		1	1	1	1
Cohesion (c)	kPa	24.27	0	1	3
Friction angle (Ø)	°	6.95	40.71	37	33
Dilation angle (Ψ)	°	0.00	6.785	6.16	0.00

Table 4: Summary of boundary conditions for groundwater flow.

Material layers	Boundary limits	X_{min}	X_{max}	Y_{min}	Y_{max}	Z_{min}	Z_{max}
Sand	$X = 0$ to 61.4 m $Y = 0$ to 9 m $Z = -1$ m to 0 m	Open	Open	Closed	Closed	Open	Open
Soft clay	$X = 0$ to 61.4 m $Y = 0$ to 9 m $Z = -52$ m to -1 m	Open	Open	Closed	Closed	Open	Open
Embankment (1st fill)	$X = 20$ to 41.4 m $Y = 0$ to 9 m $Z = 0$ to 1.2 m	Open	Open	Closed	Closed	Open	Open
Embankment (2nd fill)	$X = 22.4$ to 39 m $Y = 0$ to 9 m $Z = 1.2$ m to 2.4 m	Open	Open	Closed	Closed	Open	Open
Embankment (3rd fill)	$X = 24.8$ to 36.6 m $Y = 0$ to 9 m $Z = 2.4$ m to 3.6 m	Open	Open	Closed	Closed	Open	Open

considerable clearance should be left between the exterior boundaries of the model and area of interest [1, 47]. As stated by Grizi et al. [48], the distance from center of the loaded area to the exterior boundaries, ranging from four to ten times the length (width) of the loaded area is preferably used. In the current study hence the model dimension was selected taking into account the influence of proximity. Accordingly, for the 7 m road width, the exterior edges of the model in the bottom and transversal directions were conservatively positioned at distances of 31.35 m and 25.7 m from the top finished level of the embankment and center of the road section, respectively. The influence of boundary position can be estimated through comparing the mean effective stresses and normalized vertical displacements at various depths and lateral distances from center point of the loaded area. The dimension of the domain along the longitudinal direction is extremely large as the road section is of kilometers long. Therefore, the dimension of the model along this direction was considered to be 39 m. Since the total width of the model in the longitudinal direction is subjected to embankment loading, estimating the reasonable dimension by using effective stresses and normalized vertical displacements is not suitably possible. However, the possible distance of the bottom and lateral (in the transversal direction) boundaries from the center of the loaded area was selected based on the recommendation of Grizi et al. [48]. Figure 4 presnts deformed mesh of the model under the imposed embankment load.

In finite element analysis, accuracy of calculation is the function of mesh density and size [49]. Fine meshes apparently leads to development of more elements leading to prolonged iteration time thereby more accurate results [50]. Considering a large number of meshes with smaller sizes increases the processing time required to generate the calculation results [50]. Applying meshes having smaller sizes alleviates the problem of divergence in the results of the analysis. As mesh size decreases, the attributes such as maximum deformation converges towards the calculated

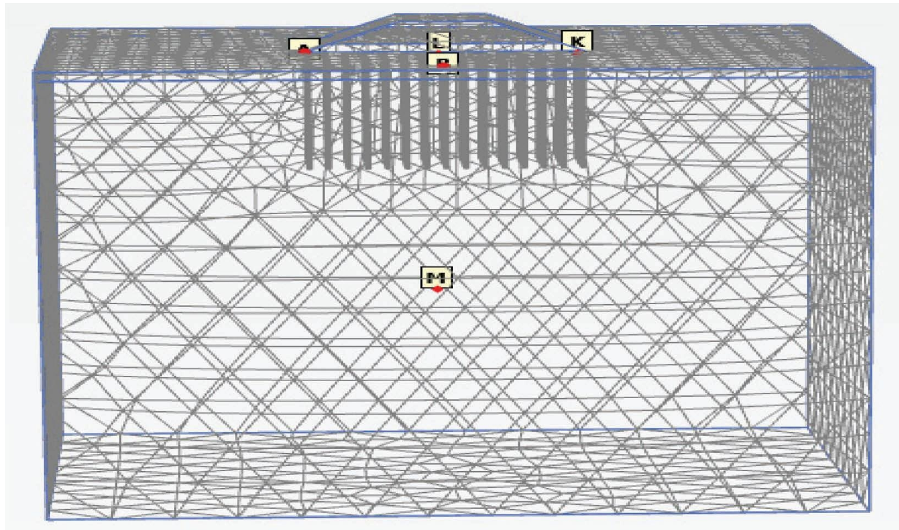
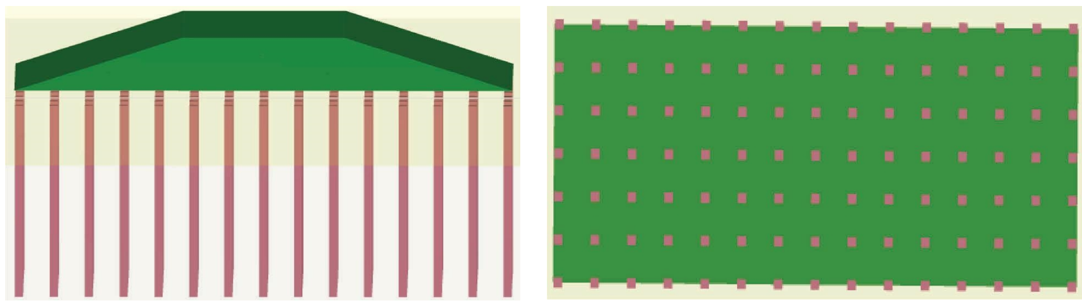


FIGURE 4: The deformed mesh under the applied boundary conditions.

value [51]. However, the analysis run time rises exponentially which in turn provides diminishing marginal returns in terms of calculation accuracy. Calculation accuracy hence depends on degree of refinement of the mesh [52]. For accuracy in calculation, not only the size of meshes matter but also shape of the meshes has its own impact. For the 3D model, there are four mesh elements commonly used, which include tetrahedral, bricks, prisms, and pyramids whereas triangular and quadrilateral elements are used in the two-dimensional model [51]. For discretization purposes, prism element was considered in the current study, that the generated meshes assume prism geometry.

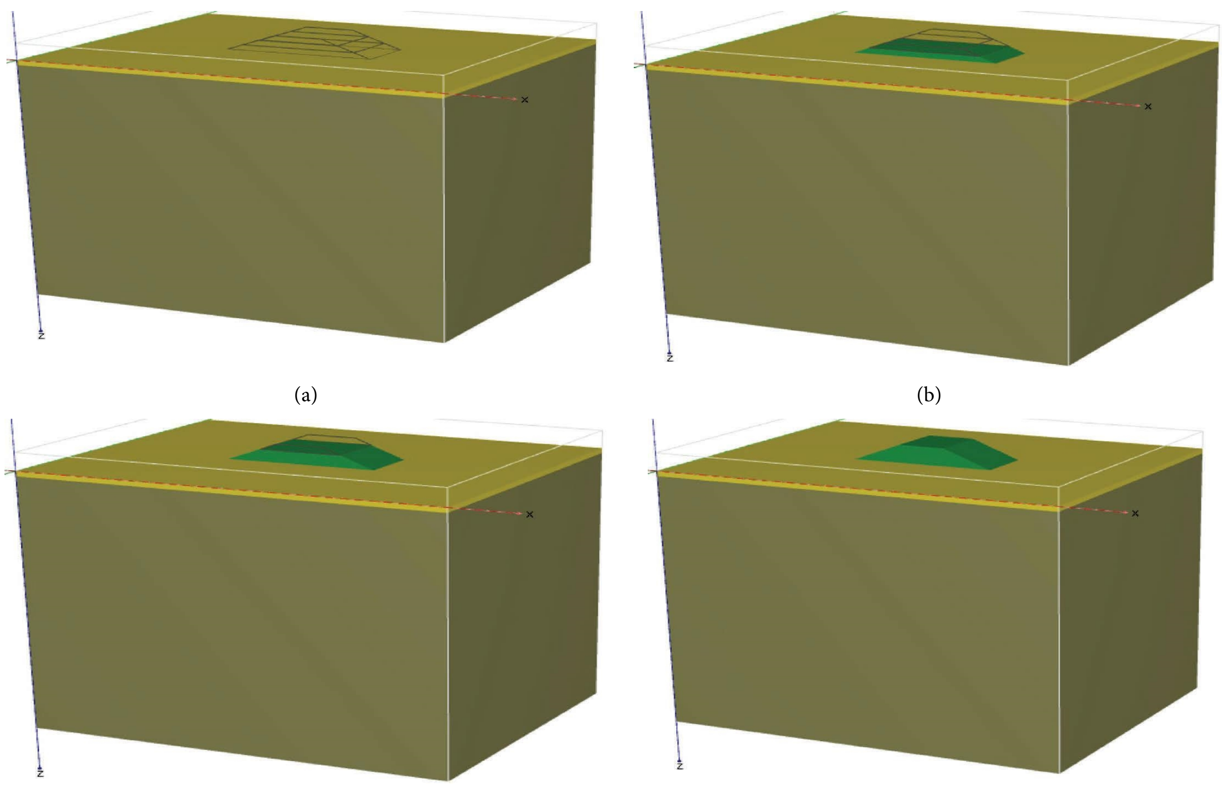
2.2.5. Installation of the Scoria Gravel Drains. Vertical drains are arranged either in square or triangular pattern. In some cases, however, drains can be installed by mixing the two patterns. The performance of drains in bringing about expected settlement within the required time period is affected by the installation pattern and spacing between the drains [9, 53–56]. In the current study, installation of the scoria gravel drains in square grid pattern was considered (Figures 5(a) and 5(b)). Besides, the comparison was made between performance of the two installation patterns (square and triangular grid) in speeding up the consolidation rate. The installed drains have a length (L) of 12 m, diameter (D) of 0.4 m, and situated at center-to-center spacing (S) of 1.5 m. The efficiency of a group of drains is a result of collective contribution of many factors such as drain diameter, length, spacing, smear zone, discharge capacity of the drain material, hydraulic conductivity, and installation method [13, 57, 58]. Installation of vertical drains causes remolding of the subsoil especially in the zone close to the drain face. As a result, the zone of less permeability and increased compressibility will develop, which significantly influences the effectiveness of drains. Remolding apparently retards the consolidation process [9]. In the current study, however, the effect of smearing was not considered. In the practical installation of vertical granular drains, there are three techniques commonly employed. These techniques are driven or vibratory closed-end mandrel, jetted, and hollow-stem continuous-flight auger [6].

2.2.6. The Consolidation Process and Staged Construction. A consolidation analysis introduces the dimension of time into the calculations that the process is dependent on time-based loading. In order to accurately perform a consolidation analysis, a reasonable time step has to be selected. Therefore, the analysis of clay consolidation should allow for a time-stepping procedure that takes into account time-based incremental loading [59]. In a specific context, the main intention of introducing drains to clay soil is to accomplish the consolidation process within predefined time duration, to attain a required minimum excess pore pressure, or to attain the required degree of consolidation [60, 61]. In relation to this, the analysis conducted in the current study targeted at completing the consolidation process within a certain time duration, which can possibly be achieved via the introduction of a staged construction approach. In a staged construction approach, step-wise incremental loading is considered to purposely allow clay soil to completely undergo consolidation within a certain fixed time frame. Every activity executed as part of the embankment construction was systematically simulated. The overall construction process of the test embankment encompasses six models including three cycles of granular material fill. First, the compressible clay mass was modeled in order to generate the in-situ deformation, pore pressure, and stress conditions. Second, the clay mass after getting treated with a group of scoria gravel drains was modeled in the absence of any fill material. The third model considered the simulation of the consolidation attributes after the placement of the horizontal sand drain. After the third model, three models were done for the three rounds of fill placement (1.2 m thick each). The construction phases of the model are presented in Figure 6. Following the first fill placement, consolidation process is expected to begin [9].



(a) (b)

Figure 5: (a) Installation of drains in clay soil. (b) Arrangement of drains in square pattern.



(a) (b) (c) (d)

Figure 6: Phases of the staged construction: (a) initial phase (no fill), (b) the 1st stage fill, (c) the 2nd stage fill, and (d) the 3rd stage fill.

The deformation magnitudes and pore water pressure changes with gradual increase in fill volume (Figure 7). After completion of the first round of fill, consolidation period of days was implemented to let the excess pore pressure dissipate. Similarly, after completion of each fill, another consolidation period was introduced from which the final consolidation settlements could be determined (Table 5).

3. Results and Discussion

3.1. Effect of SVD on Settlement and Pore Water Pressure (PWP). The rate of pore water dissipation for the soft clay was simulated with and without the installation of a group of vertical scoria drains (Figure 8(a)). The magnitude of excess pore water pressure in the absence of vertical drains is higher than in the case in which SVD was considered. During the whole duration of the consolidation process, no significant reduction in excess PWP was observed, as the artier of water dissipation from the clay mass is very less even after the considered consolidation time. This is because low soil permeability makes it difficult for pore water in the soil to freely dissipate, resulting in a lengthy final consolidation process. In contrast, the dissipation rate of pore water is relatively faster for the case with SVD. This is due to presence of SVD in the clay mass which can shorten the exit distance of soil pore water [4, 55, 62, 63]. Like other granular materials (sand and crushed aggregate) with high the permeability, introduction of scoria

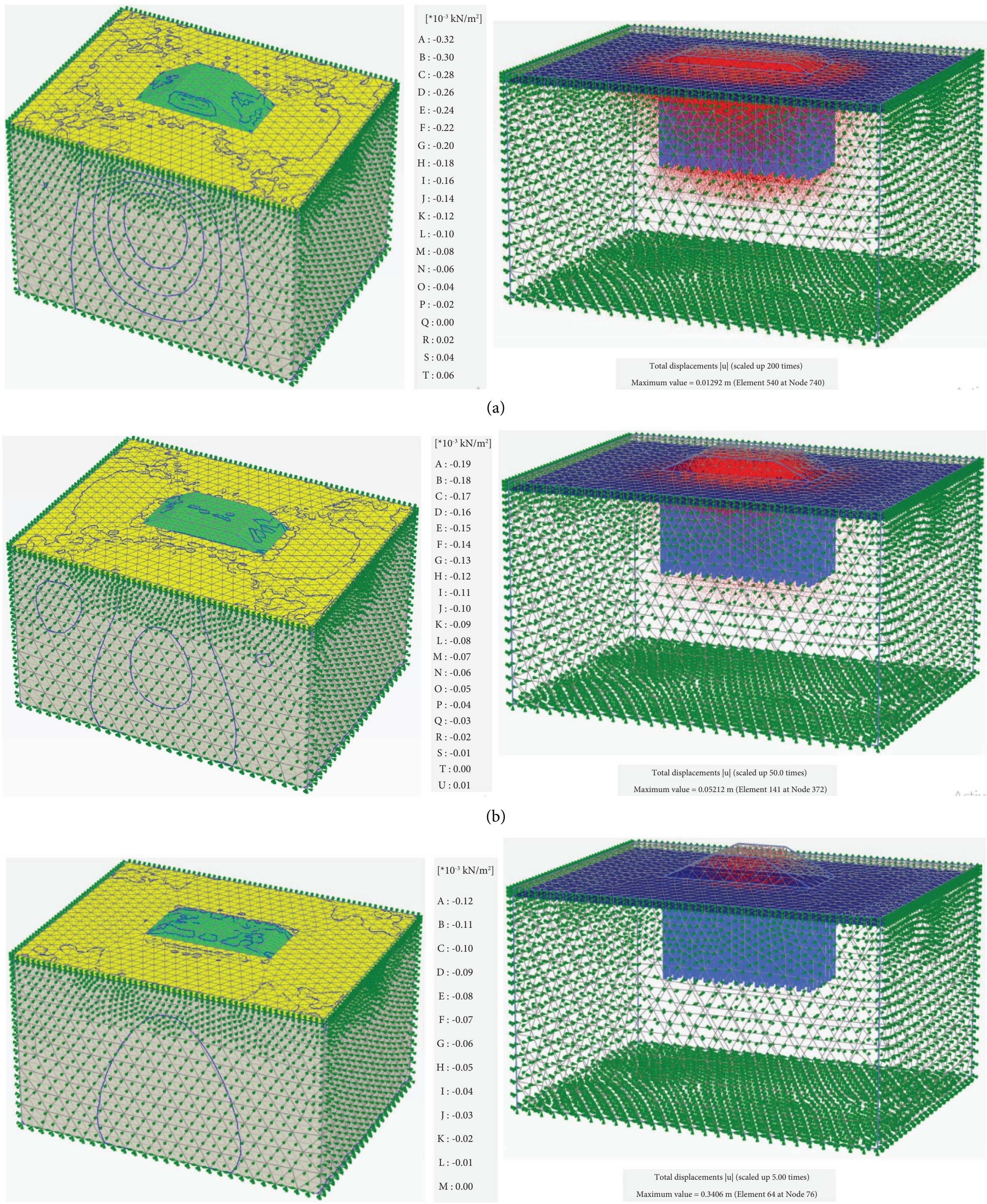


Figure 7: Mesh geometry indicating PWP and settlement variation: (a) the 1st round fill, (b) the 2nd round fill, and (c) the 3rd round fill.

gravel as a vertical drain performs well in facilitating and speeding up consolidation rate of clayey soil. The three peaks observed in the graph indicate that there is fluctuation in magnitude of PWP with placement of fill material in three rounds. The numerical analysis revealed that it takes a maximum of 244 and 376 days the excess PWP to be released under the 3.6 m thick embankment with and without SVD, respectively.

Table 5: The overall construction and consolidation process of the clay.

Loading/Construction phases	Duration (days)	Duration until the next construction stage (days)
Installation of drains	5	2
Placement of sand envelope	5	10
1st fill placement	10	50
2nd fill placement	10	80
3rd fill placement	10	250

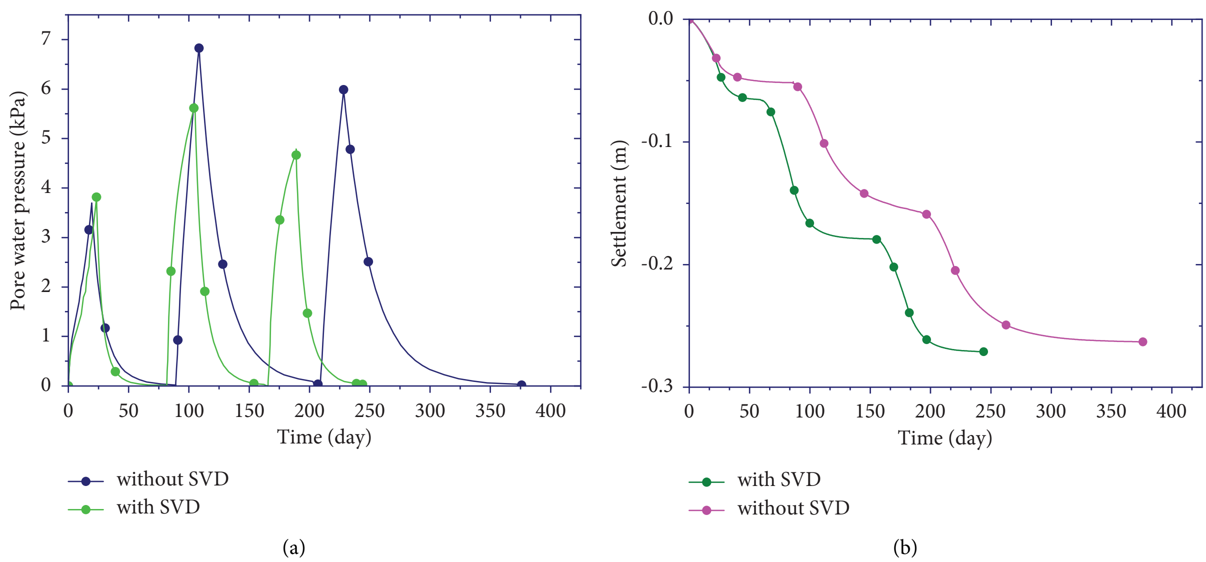


Figure 8: (a) The effect of SVD on PWP under embankment fill (for $D = 0.4$ m, $S = 2.5$ m, and $L = 8$ m). (b) The effect of SVD on settlement (for $D = 0.4$ m, $S = 2.5$ m, and $D = 8$ m).

The significance of drain installation is determined not only by how rapidly the consolidation process proceeds but also the amount by which the soft soil settles out. The comparison made between the embankment built with and without SVD revealed that the magnitude of vertical deformation in the presence of SVD is greater in magnitude than the case in which SVD is not provided (Figure 8(b)). Likewise, the reinforced clay mass settles more rapidly than the untreated one, as the provision of drains perpetuates the consolidation process. The soft clay undergoes a consolidation settlement of 0.272 m in the presence of SVD within 244 days, whereas a vertical deformation of 0.261 m was observed within 376 days of the consolidation period in the absence of scoria vertical drains. As reported by Warner and Gafoor et al. [64, 65], introduction of vertical drains to soft clays reduces the overall duration of consolidation process by more than four months.

3.2. Parametric Study

3.2.1. Influence of SVD Diameter. In order to investigate the effect of variation in drain diameter (D) on PWP and settlement of the clay mass, three diameters having a dimension of 0.4 m, 0.6 m, and 0.8 m were considered. The PWP and consolidation settlement were simulated for the three diameters. Obviously, the placement of fill material causes the generation of PWP due to the load from the embankment. The magnitude of PWP increases with decrease in diameter of the vertical drains that the excess PWP is significantly higher for drain diameter of 0.4 m than 0.6 m and 0.8 m (Figure 9(a)). The reason is that vertical drains with larger diameter enable pore water to freely dissipate at a relatively rapid rate, which in turn contributes to a reduction in the excess pore water pressure [62]. The rate of excess PWP dissipation increased together with the diameter of the scoria vertical drain. A maximum of 122, 78, and 51 days are required for excess pore water to be dissipated at mid-depth of the soft clay when using drain diameters of 0.4, 0.6, and 0.8 m, respectively. It was also observed that a very small variation in drain diameter considerably results in a noticeable change in PWP.

The variation in vertical deformation with change in drain diameter is presented in Figure 9(b). The variation in drain diameter influences not only the rate of deformation but also the magnitude of settlement [13]. A change in drain diameter altered the settlement rate of the soft clay. When drains with a smaller diameter are used, it takes long time to achieve a certain magnitude of settlement. Increasing the size of the SVD from 0.4 m to 0.6 m and 0.8 m leads to an increase in the settlement rate of 36% and 58%, respectively. The numerical analysis also reveals that the clay soil to undergo vertical deformation of 0.25 m, it takes 40, 65, and 95 consolidation days when using drain diameters of 0.8 m,

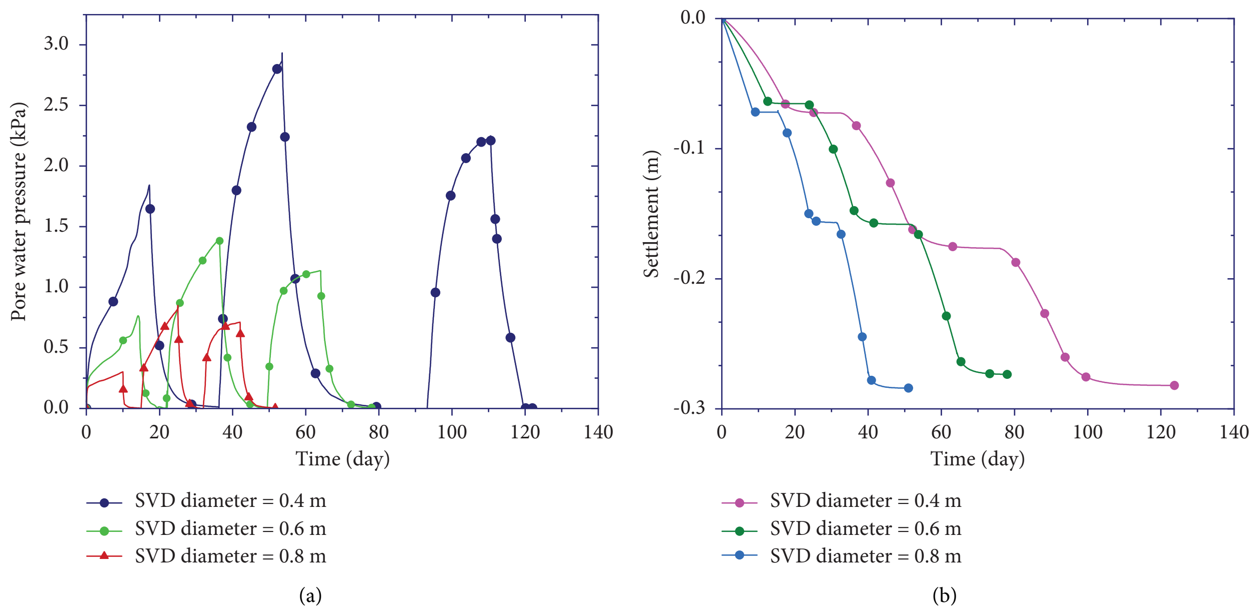


Figure 9: (a) The effect of SVD diameter on pore water pressure (for $S = 1.5$ m and $L = 15$ m). (b) The effect of SVD diameter on settlement (for $S = 1.5$ m and $L = 15$ m).

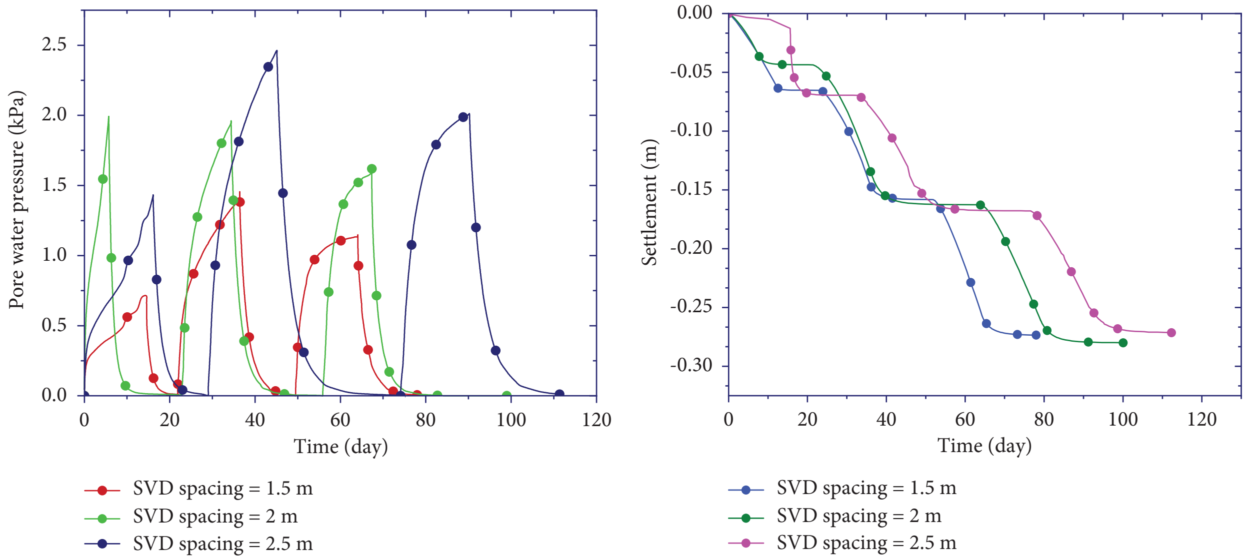
0.6 m, and 0.4 m, respectively. Increasing the diameter of the vertical drain provides suitable space for pore water to freely dissipate, which in turn increases the rate of vertical deformation [7]. The result of the study with regard to the effect of drain diameter has good agreement with the work of Hammad [13] in which a direct relationship between drain diameter and deformation rate was reported.

3.2.2. Effect of SVD Spacing. Not only drain diameter but also interdrain spacing (S) matters in consolidation process of soft clay. For comparative purposes, three spacing (1.5 m, 2 m, and 2.5 m) of drains were considered for a 0.6 m diameter of drains. Figure 10(a) shows the distribution of the excess PWP at a mid-depth of the soft clay during the three stages of fill placement. Placement of SVD close to each other reduces the developed excess PWP via perpetuating the water dissipation rate from the clay soil. The analysis indicates that when SVD is placed at spacings of 1.5 m, 2 m, and 2.5 m it takes 73, 90, and 112 days to complete the dissipation of excess pore water from the soft clay. It is evident that the excess PWP can be sufficiently reduced as long as a shorter drainage path is provided [4, 12]. Installation of vertical drains at narrower spacing shortens the drainage path, and the PWP generated due to embankment loading is lowered [14, 54, 66].

Similarly, the effect of SVD spacing on settlement was examined using the stated three spacings. With increased SVD spacing, the rate of consolidation rate reduces resulting in prolonged dissipation of pore water (Figure 10(b)). From the figure, it is observed that the rate of consolidation appears to increase with the reduction in SVD spacing. When the SVD spacing is reduced from 2.5 m to 2 m, the consolidation time drops by 10.8%, and when it is reduced further from 2 m to 1.5 m, it decreases by 21.21%. The soft clay undergoes settlement of 0.27 m in 70 days when a group of SVD is installed at spacing of 1.5 m. However, it waits at least for additional duration of one month if the drains are provided at spacing of 2.5 m. Hence, it can be inferred that using a spacing of 1.5 m over 2.5 m saves 30 days of consolidation time. Similarly, Ali and Ansary [67] reported that as the diameter of vertical drains is reduced, the rate of consolidation increases.

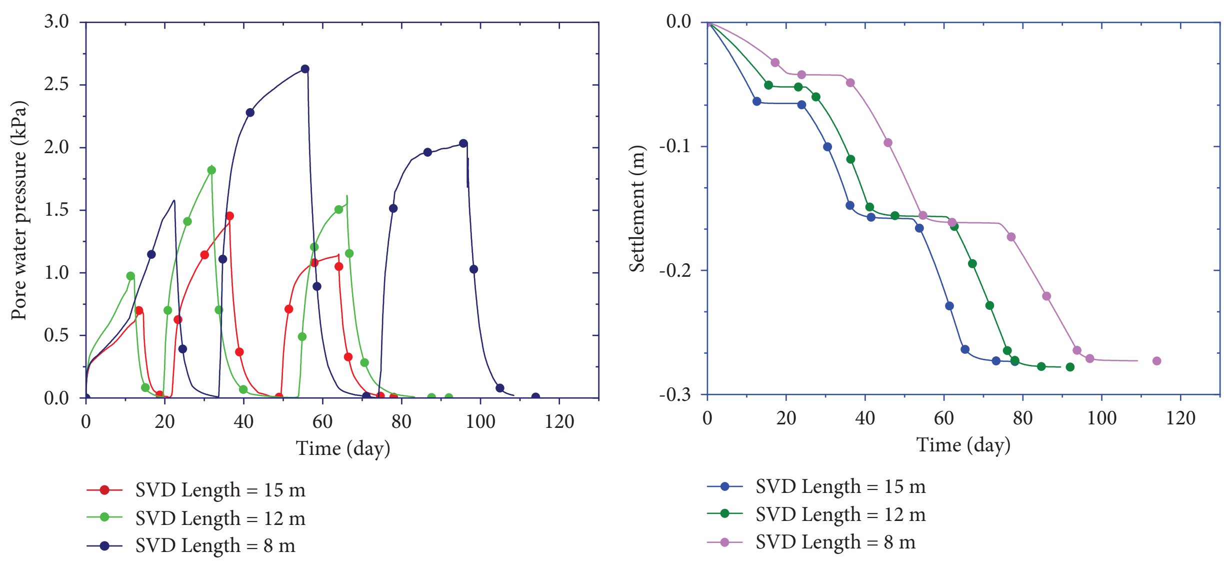
3.2.3. Influence of SVD Length. In order to investigate the critical influence of SVD length (L) on PWP and settlement rate, three lengths of SVD were considered. Figure 11(a) depicts the change in PWP for drain lengths of 8 m, 10 m, and 15 m. Unlike diameter and spacing, a change in SVD length has a moderate effect on the dissipation of pore water pressure. The numerical model demonstrates that an increase in SVD length leads to a slight increase in the dissipation rate of excess pore water. Accordingly, a decrease in drain length from 15 m to 12 m increased the consolidation period by 17.95%. When the length was further reduced to 8 m, a 46.16% increment in consolidation time was observed. From the study, it can be deduced that higher magnitude of PWP develops when vertical drains of short length are installed in soft clay. In contrast, the PWP is minimized when the drains are installed relatively deeper in the clay mass.

By examining the impact of the drain length on both the time rate of pore pressure and settlement, the effectiveness of the floating SVDs is examined. As indicated in Figure 11(b), settlement rate is higher for higher depth of SVD. This is due to the fact that higher the length of drain, higher is dissipation rate of excess pore water and so is rate of settlement. In relation to this, Hammad and Lou et al. [13, 59, 68] pointed out that the time it takes for pore water to dissipate



(a) (b)

Figure 10: (a) The effect of SVD spacing on pore water pressure (for $D = 0.6$ m and $L = 15$ m). (b) The effect of SVD spacing on settlement (for $D = 0.6$ m and $L = 15$ m).



(a) (b)

Figure 11: (a) The effect of SVD length on pore water pressure (for $D = 0.6$ m and $S = 1.5$ m). (b) The effect of SVD length on settlement (for $D = 0.6$ m and $S = 1.5$ m).

and the prolonged settlement decrease as the length of vertical drains grows.

3.3. Effect of the SVD Installation Pattern on PWP and Vertical Deformation. A numerical model was performed for both triangular and square installation patterns of vertical drains in order to compare the performance of installation patterns on the consolidation process of the clay soil. Even though the boundary conditions, material properties, and dimension parameters (spacing, diameter, and length) remain the same, the arrangement in which the drains are installed differs. The analysis result reveals that the triangular pattern has a marginally better influence on the reduction of both the duration of consolidation and excess PWP than the square grid pattern. However, the difference in magnitude of the two parameters (PWP and consolidation rate) between the two installation patterns is of minimal effect as the two curves are very close to one another (Figures 12(a) and 12(b)). The findings of the

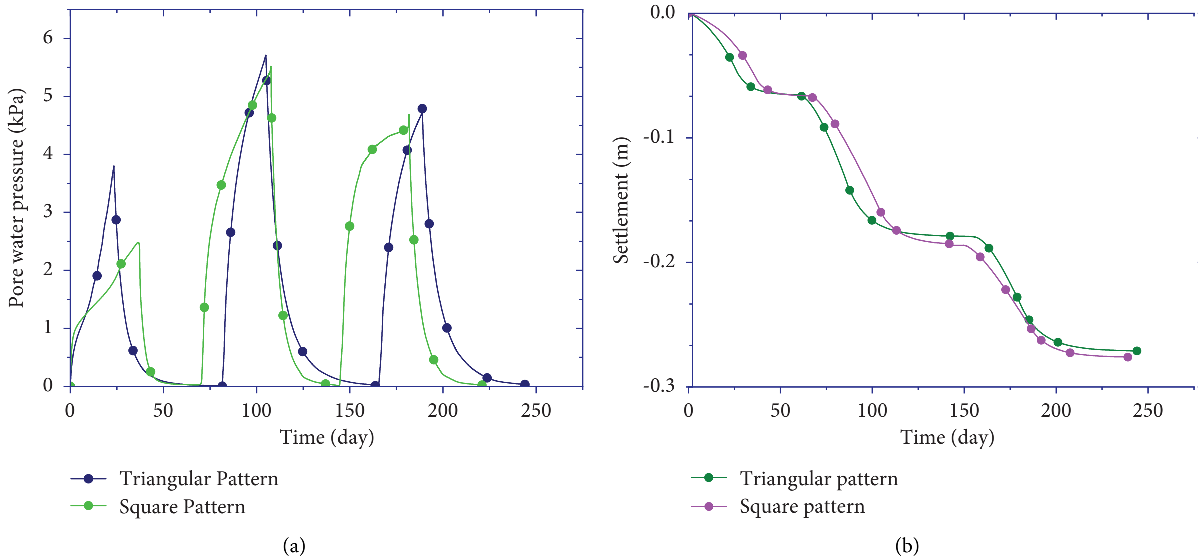


FIGURE 12: (a) The effect of the installation pattern of SVD on pore water pressure (for diameter = 0.4 m, S = 2.5 m, and L = 8 m). (b) The effect of the installation pattern of SVD on settlement (for D = 0.4 m, S = 2.5 m, and L = 8 m).

study with regard to drain installation perfectly agree with the works of Hammad [13], in which it was concluded that no significant difference exists between the performance of square and triangular patterns.

4. Conclusions

The numerical analysis revealed that a group of SVD when installed into soft clay performs well in improving the consolidation process of the soil via shortening the drainage path. Based on the obtained findings, the following conclusions can be drawn:

(i) The effect of SVD dimension parameters on PWP and rate of settlement is more significant for drain diameter and spacing over length. The consolidation process is sensitive to the variation in dimensions of drain spacing and diameter, whereas the effect of drain length is not as influential as spacing and diameter. With an increase in the diameter of drains, the pore water dissipation rate and rate of settlement go fast. Besides, the narrower the spacing between drains, the faster its consolidation would be. The maximum vertical deformation attained at the 80th consolidation day was found to be 27 mm, 21 mm, and 16 mm for the 1.5 m, 2 m, and 2.5 m spacing of drains, respectively.

(ii) The length of SVD affects the dissipation of excess pore water and hence the settlement rate. Lowering length of SVD leads to a lower rate of dissipation of pore water pressure and rate of settlement. In contrast, the decrement rate in excess PWP and vertical deformation increases with increase in SVD length. Decrement in the drain length from 15 m to 8 m leads to rise in consolidation duration by 21.14%.

(iii) The installation pattern of drains has an impact on dissipation rate of excess pore water. However, no noticeable difference in the magnitude of rate of settlement is observed between square and triangular drains arrangements. Hence, drain installation insignificantly influences the consolidation process of clay.

Data Availability

The data used to support findings of the study are included within the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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