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Suitability analysis of vertically installed scoria gravel drains for enhancing consolidation performance of clayey ground

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ABSTRACT

In alleviating challenges associated to long-lasting consolidation of clay, highly permeable materials such as sand and crushed aggregate are used as drain. Despite the fact that granular vertical drains are effective in shortening the prolonged consolidation period of clay, limited information exist regarding applicability of scoria gravel as vertical drain that no concisely documented information is observed in literatures. This study hence aimed at evaluating suitability of scoria gravel as vertical drain in perpetuating consolidation process of soft clay under road embankment. Finite element-based simulation was used to model the drains. To incorporate the effect of gradual load increment on consolidation rate, staged construction approach was employed. Various dimensions of scoria vertical drain (SVD) have been considered to investigate the effect of dimension parameters. Besides, comparison has been made between performances of SVD and crushed aggregate drains (CAD) in impacting the consolidation process. The numerical analysis result revealed that provision of group of SVD considerably accelerated consolidation rate. With increase in drain diameter, the consolidation rate goes increasing whereas it is inversely related to increase in drain spacing. For SVD installed at spacing of 2 m, diameter of 0.4 m and length of 8 m any arbitrary settlement magnitude is achieved 25 days earlier than the case without drain. No considerable difference was witnessed in performance of the square and triangular installation patterns though the consolidation rate remains slightly faster in the case of triangular installation. In speeding up consolidation rate, SVD was observed to perform slightly better than the CAD.

1. Introduction

Clay soil is typically known for its poor workability that embankment loads results in bearing failure and excessive deformation after construction [3]. Conventionally, the engineering properties of clay soil are modified via application of chemical and mechanical stabilization approaches [78,79]. Clayey ground underlying road embankments commonly experiences a long-lasting deformation that takes considerable time duration for consolidation process to be fully accomplished [1]. Upon placement of external loading, the excess pore pressure begins rising which is typical characteristics of clayey foundations [2]. In many practical cases, removal of massive clay deposits down to larger depths is technically and economically not feasible. In the move to overcoming this challenge, employment of vertical drains to purposely speed up 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 aggregate, sand, and prefabricated vertical drain are commonly provided without removing the massive volume of unsuitable clayey soil [6–8]. Vertical drain improves permeability of low permeable soils through reducing the drainage path [9]. Negesa AB [4] stated that vertical drains are fundamentally installed in group to accelerate soil consolidation process by shortening the drainage path and activating radial drainage, thereby increasing the shear strength of the soil while reducing its post construction settlement [10–12]. In addition to its drainage role, vertical drain also plays reinforcing role that is pertinent in improving the overall load bearing capacity of soft grounds [13,80–82]. With rapid consolidation process, soft soils gain shear strength rapidly which allows 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 [14,60–69]. The water flow into vertical drain is affected by the degree of saturation of soil surrounding the drain [75–77].

Scoria is a highly porous pyroclastic material made of solidification

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of volcanic lava [15,16]. Ethiopian rift valley is known for large coverage of volcanic materials like pumice, scoria and cinder [17]. Melese DT and Newill D et al. [18,19] reported that scoria is one of the materials abundantly found in volcanic prone areas of Ethiopian rift. From application point of view, scoria gravel is widely used for improvement of weak subgrade materials and as replacement material for production of light weight concrete. Use of scoria as additive when blended with other materials is recently becoming common practice especially in improving highway sub grade. Conventionally, it does not meet requirements of pavement materials without blending with other materials [20]. Gomes F and October S [21] 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 used in production of construction blocks as well [15]. It is also similarly, used as cement additive in construction of reinforced concrete structures to improve engineering properties of concrete [22–24]. Hossain KMA and Hearn GJ et al. [25,26] reported that blending of scoria as additive material in concrete works proved effective in improving strength, durability and heat insulation properties of the concrete. Saltan M and Ozen FS [27] in the experimental study on usability of scoria as sub base material reported appropriateness of scoria as a partial replacement. Finding of the study revealed that scoria is effective in improving Californian bearing ratio and lessening the plastic index of pavement sub base.

Many studies have documented the wide application of scoria material as road subgrade and sub base and as 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 suitability and applicability of scoria as vertical drain. In this study hence the potential use of volcanic scoria as vertical drain is explored. The study specifically focuses on the consolidation and deformation attributes of soft clay subgrade under impact of highway embankment and vertically installed scoria drains. Besides, the performance and suitability of scoria material as vertical drain is compared with that of crushed aggregate columns. Its effectiveness in shortening 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. Material characterization

For the numerical analysis conducted in the current study, five different materials namely soft clay, volcanic scoria, crushed aggregate, sand blanket and natural gravel fill were considered. 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 vertically installed scoria gravel and crushed aggregate drains. The clay soil is of massive thickness under lied by relatively hard strata situated at large depth. Samples of clay soil for determination of physical properties were collected from outskirt of Jimma city, Ethiopia. As observed from the conducted laboratory tests, permeability of the clay soil is considerably insignificant which a typical characteristic of problematic expansive soil is. The materials considered in the study have the properties summarized in Table 1 and Fig. 1.

Scoria gravel was used as a cylindrical vertical drain for the prior intention of shortening radial drainage path in a clay soil. The considered scoria material was sampled from 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 cinoscoidal material [23,28,59]. 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 provision of vertical drains load bearing capacity, permeability and deformation characteristics of soft clay are improved [20,27]. Accordingly, scoria drains having various diameter and lengths are vertically installed at different spacing. Permeability of scoria in horizontal direction is usually several times larger than that in vertical direction. Hence, the rate of consolidation becomes considerably faster compared to conventional soil system [15,21].

Crushed basalt aggregate is the second alternative used as vertical drain. Apart from its drainage role by reducing radial path of drainage, crushed aggregate is also well known for its reinforcing role as stone column [70,71]. Crushed aggregate drains are commonly provided in group and can be floating or end bearing type [72]. The applicability and suitability of materials as vertical drain is basically affected by permeability of the material [73,74].

Sand blanket is placed on top of the clay mass right after installation

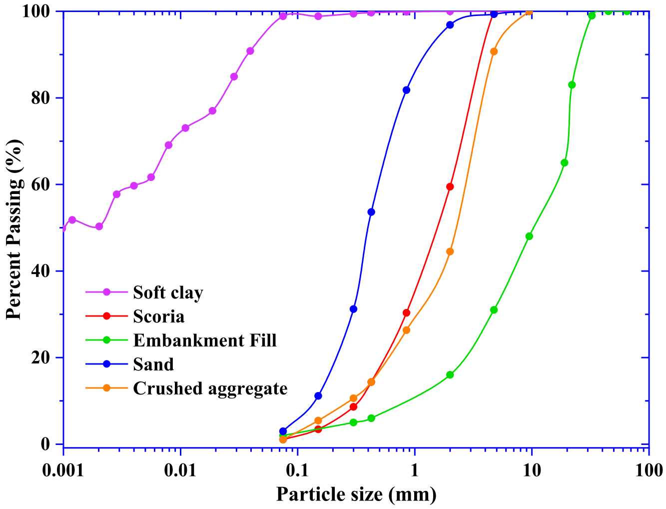


Fig. 1. Particle size distribution of the soft clay, scoria, embankment fill and sand envelope.

Table 1
Physical properties of the materials required.

Properties/Parameters	Unit	Clay soil	Scoria	Crushed aggregate	Sand	Embankment
Moisture Content (w_c)	%	48.75	–	–	–	21
Liquid limit (LL)	%	88	–	–	–	44
Plasticity index (PI)	%	53	–	–	–	16
Soil classification (USCS)		CH	GP-GM	GP-GM	–	GP-GM
Activity (A)		0.64	–	–	–	–
Specific gravity (G_s)		2.72	2.50	2.78	2.63	2.64
Bulk unit weight (γ)	kN/m^3	16.11	13.78	22.62	18.60	19.76
Unconfined Compressive Strength (UCS)	kPa	39.52	–	–	–	–
Secant Young's modulus (E_{50})	MPa	–	41.5	62.17	38	35.5
Compression index (C_c)		0.42	–	–	–	–

of the vertical drains to allow 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 road side 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 road side ditch without disturbing moisture content of the fill material [4]. Coarse sand is commonly preferred over fine sand to be used as horizontal drain because of development of relatively large voids between solid grains [8]. The voids are hence suitable room for fast flow of excess water which significantly contributes to rapid consolidation of the clay soil. Even though the primarily purpose of having sand drain for its drainage role, it is also beneficial in making the loading area leveled and uniform [6].

A natural granular selected material was used as road embankment material. For the purpose of material characterization, a sample for embankment fill was collected from the quarry site situated in the vicinity of Jimma city named Baddaa Bunaa. The embankment material is directly placed on top of the sand envelope. The material is hence the top layer used in the numerical simulation. In this specific study, the fill material will serve as both preloading and integral part of the pavement structure. Even though it plays a preloading role, the material is not removed at commencement of the actual construction work. Hence, it is a permanent part of the road embankment structure.

Mineral composition of the scoria material was determined using the analytical method of elemental analysis. Accordingly, X-ray diffraction (XRD) method was used to chemically characterize the scoria gravel material and the chemical composition of the material is illustrated Fig. 2. X-ray diffraction is basically employed to measure the average spacing and orientation between layers and crystals [29]. Besides, the size, shape, crystal structure and internal stress of small crystalline region is investigated [30]. 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.

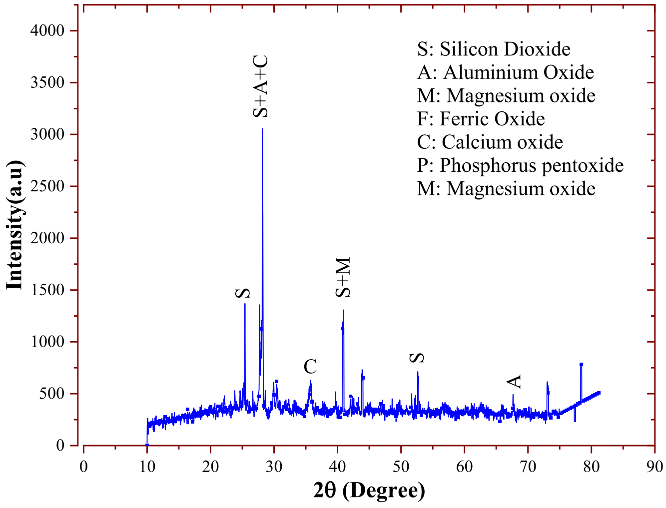


Fig. 2. Chemical composition of volcanic scoria via XRD.

2.2. Numerical modeling

2.2.1. Definition of the problem of interest

In the current study, soft clay reinforced with a group of vertically installed scoria gravel and crushed aggregate drains was numerically modeled using the principle of finite element method. As scoria and crushed aggregate are highly permeable material, the materials were primarily used to presumably speed up consolidation process of the clay mass under embankment load. A group of drains were installed up to certain depth of 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 by using the three-dimensional version of Plaxis software. Under the imposed embankment load, the performance of vertical drains in perpetuating consolidation rate was investigated. The numerical model is also intended to simulate the deformation response and consolidation attributes of the soft clay.

2.2.2. Geometry of the model

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. Selection of the proper and suitable geometry for simulation of vertical drains depends on and 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 simulation of deformation and stress characteristics of soil material [13]. The 3D model can assume two forms namely full three dimensional and three-dimensional rows or slice 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, a portion of the road embankment only was modeled. In the current study hence the three-dimensional slice of rows was used to simulate a group of scoria gravel and crushed aggregate drains made of six rows and fifteen columns. The problem to be modeled is made of a number of material layers having their own thickness. The clay mass treated with installation of granular 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 (44.45% of the clay thickness). 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, a drain spacing of 1.5 m was considered. 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 drain diameter of 0.4 m was used. A 0.75 m thick sand blanket is provided on top of the soft clay as a horizontal drainage media. In addition to drainage role, the sand layer allows an even and leveled loading surface to develop. Fig. 3 (b) shows 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. 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 Fig. 3 (a).

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 hence is 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 [13,31]. The overall processes of the numerical simulation pass through two major phases of analysis. 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. Secondly, the clay mass is modeled after being treated with a group of vertically installed granular drains (scoria gravel and crushed aggregate). After installation of the drains, the sand blanket and the granular embankment material are permanently placed in a sequential

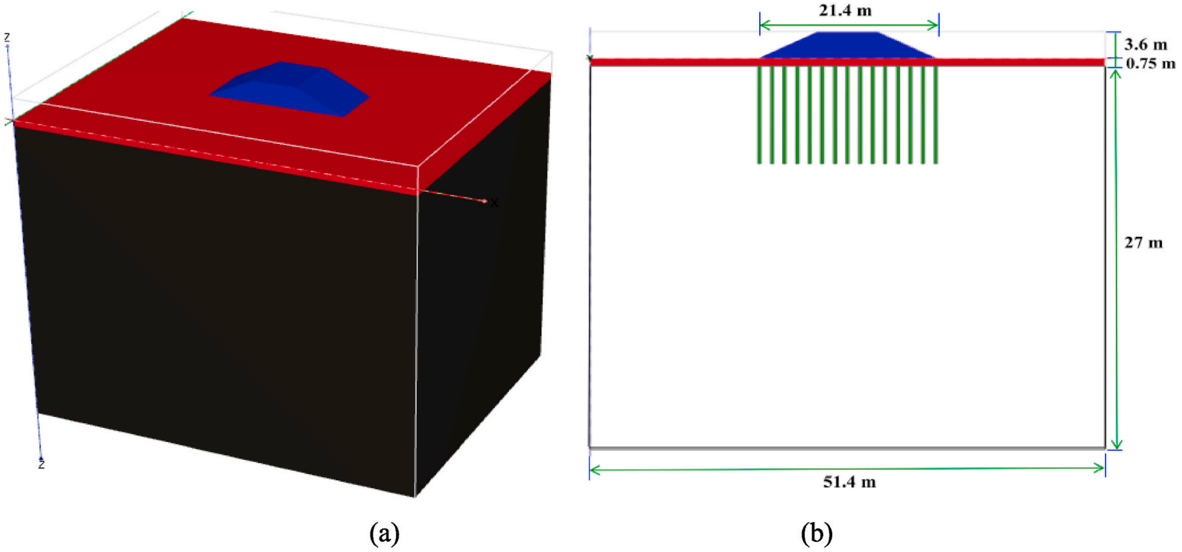


Fig. 3. a) 3D view of geometry of the model, b) Cross-section of the embankment and material layers.

manner for certain time duration. In this stage, the massive 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, the vertical drains, sand blanket and embankment fill. The material parameters used in the numerical model is summarized in Table 2. Mohr- Coulomb is one of the oldest widely used soil model to numerically simulate soil behaviors exhibiting linear interfaces and non-sophisticated boundary conditions [32]. Hardening Soil is an advanced and versatile material model that takes into account the key drawbacks existing within the Mohr- Coulomb model [33,34]. HS is a powerful soil model which overcomes some limitations associated with the Soft Soil (SS) model especially with regard to over consolidated soils [33,35].

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 can be solved. These boundary conditions are believed to numerically represent the actually existing 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 [36]. 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 are subjected to lateral fixity. With regard to drainage, a flow boundary was specified to take into account the presence of ground water table at a depth of 1 m from the surface. Summary of the flow boundary is presented in Table 3. Any stress boundary condition has not been considered in the numerical analysis. There is no quantified magnitude of external stress which the soft clay supports except self-weight of the sand and embankment layers. The pressure imposed by the fill material and sand drain is not specified as stress boundary since both materials are integral part of the model geometry.

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

Table 2
Input parameters used for the numerical model.

Properties/Parameters	Unit	Clay soil	Scoria	Sand	Crushed aggregate	Embankment
Initial void ratio (e_o)		1.321	0.5	0.5	0.64	0.5
Unit weight	kN/m^3	16.11	13.78	19.84	22.62	18.513
Over-consolidation ratio (OCR)		1	–	–	–	–
Lateral earth pressure coefficient at rest (K_o)		1	0.211	0.168	0.223	0.156
Natural moisture content (w_c)	%	48.75	–	–	–	21
Stiffness modulus for unloading/reloading (E_{ur})	MPa	–	124.4	114	210.17	106.5
Stiffness modulus for primary loading (E_{50})	MPa	–	41.5	38	68.31	35.5
Oedometric modulus (E_{oed})	MPa	–	41.5	114	93.34	106.5
Permeability in X direction (K_x)	m/s	$2*10^{-4}$	$3.64*10^{-1}$	$2.41*10^{-1}$	$3.32*10^{-1}$	3.499
Permeability in Y direction (K_y)	m/s	$2*10^{-4}$	$3.64*10^{-1}$	$2.41*10^{-1}$	$3.32*10^{-1}$	3.499
Vertical Permeability (K_v)	m/s	$2*10^{-4}$	$3.1*10^{-1}$	$2.41*10^{-1}$	$3*10^{-1}$	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	0.5
Strength reduction factor (R_{int})		1	1	1	1	1
Rint						
Cohesion (c)	kPa	24.27	0.00	1	0.00	3
Friction angle (Ø)	o	6.95	40.71	37	41.60	33
Dilation Angle (Ψ)	o	0.00	6.785	6.16	8.76	0.00

Table 3
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 = 0–61.4 m Y = 0–9 m Z = −1 m–0 m	Open	Open	Closed	Closed	Open	Open
Soft Clay	X = 0–61.4 m Y = 0–9 m Z = −52 m to -1m	Open	Open	Closed	Closed	Open	Open
Embankment (1st fill)	X = 20–41.4 m Y = 0–9 m Z = 0–1.2 m	Open	Open	Closed	Closed	Open	Open
Embankment (2nd fill)	X = 22.4–39 m Y = 0–9 m Z = 1.2 m–2.4 m	Open	Open	Closed	Closed	Open	Open
Embankment (3rd fill)	X = 24.8–36.6 m Y = 0–9 m Z = 2.4 m–3.6 m	Open	Open	Closed	Closed	Open	Open

boundary effect hence considerable clearance should be left between the exterior boundaries of the model and area of interest [1,37]. As stated by Grizi A et al. [38], 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 to significantly lower the boundary effect. 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, 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 transversal direction) boundaries from center of the loaded area were selected based on the recommendation of Grizi A et al. [38].

In finite element analysis, accuracy of calculation is the function of mesh density and size [39]. Fine meshes apparently leads to development of more elements leading to prolonged iteration time thereby more accurate results [40]. Considering large number of meshes with smaller size increases the processing time required to generate the calculation results [40]. Applying meshes having smaller sizes alleviates the problem of divergence in results of the analysis. As mesh size decrease, the attributes such as maximum deformation converges towards the calculated value [41]. 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 [42]. For accuracy of calculation not only 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 [41]. For discretization purpose, prism element was considered in the current study that the generated meshes assume prism geometry (Fig. 4 (a), Fig. 4 (b)).

2.2.5. *Pattern and methods of drain installation*

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 required time period is affected by the installation pattern and spacing between the drains [9,51,53,43, 44]. In the current study, installation of the scoria gravel drains in square grid pattern was considered (Fig. 5 (a),

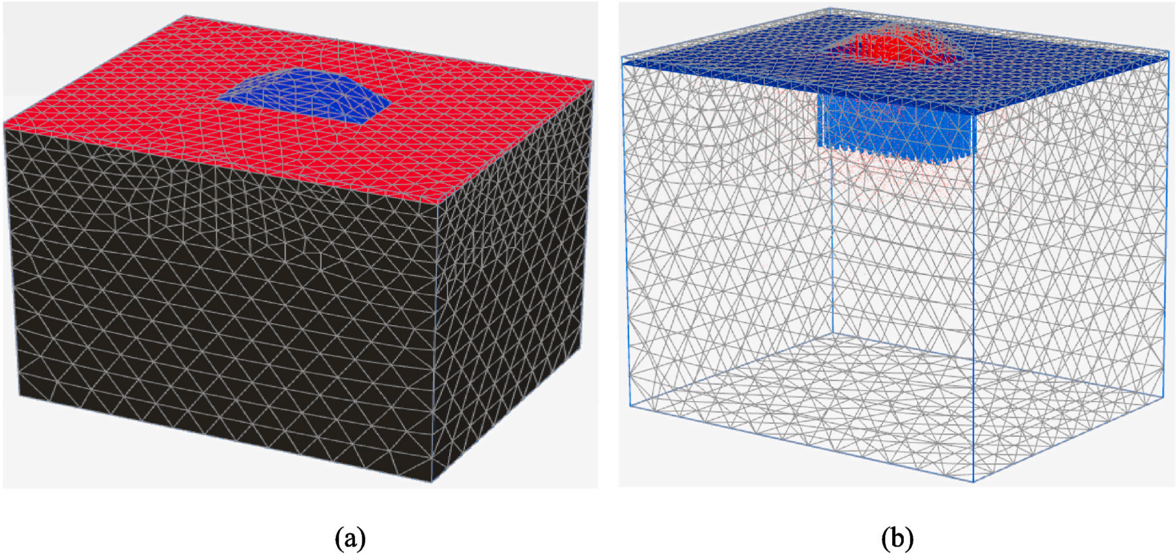

(a) (b)

Fig. 4. Meshing and boundary conditions applied to the model.

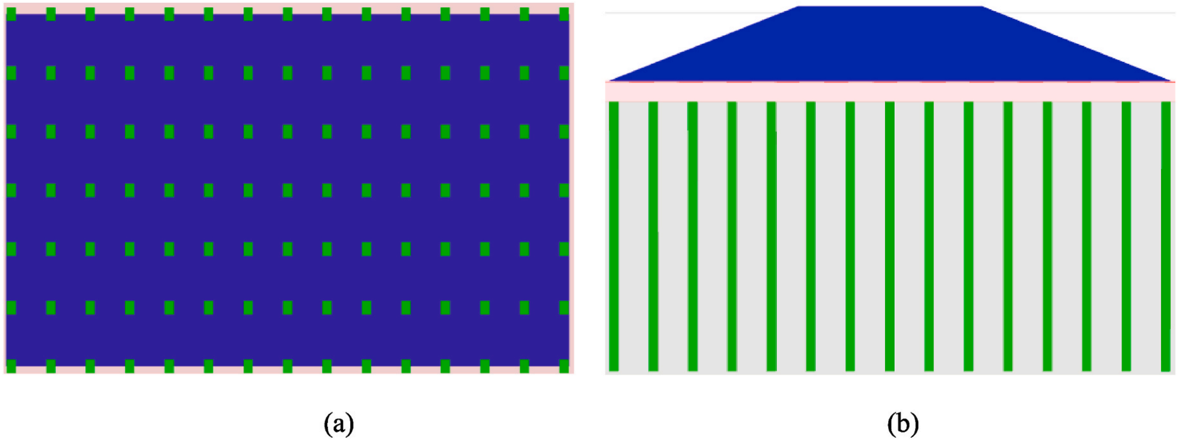


Fig. 5. a) Arrangement of drains in square pattern, b) Installation of drains in clay soil.

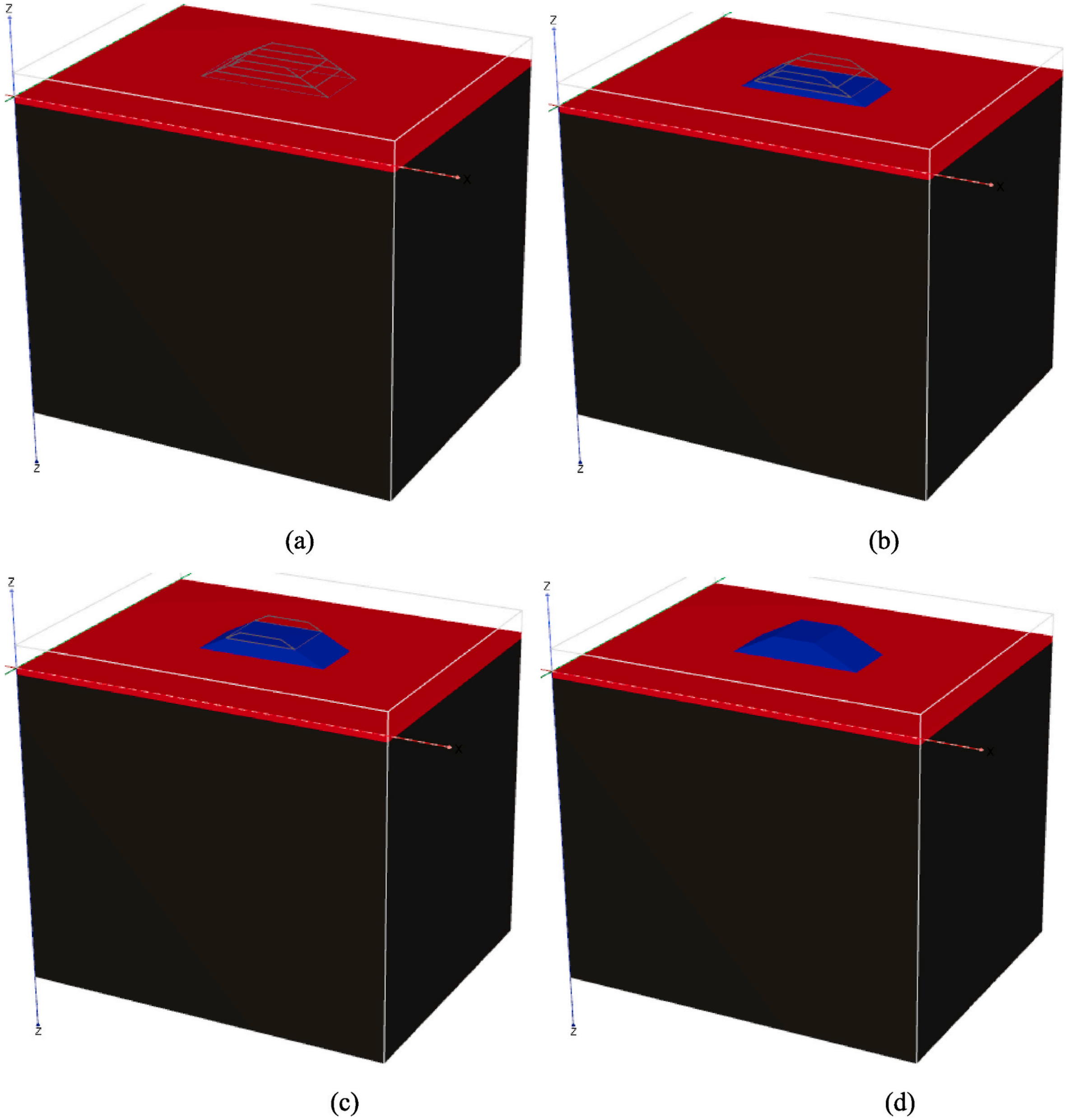
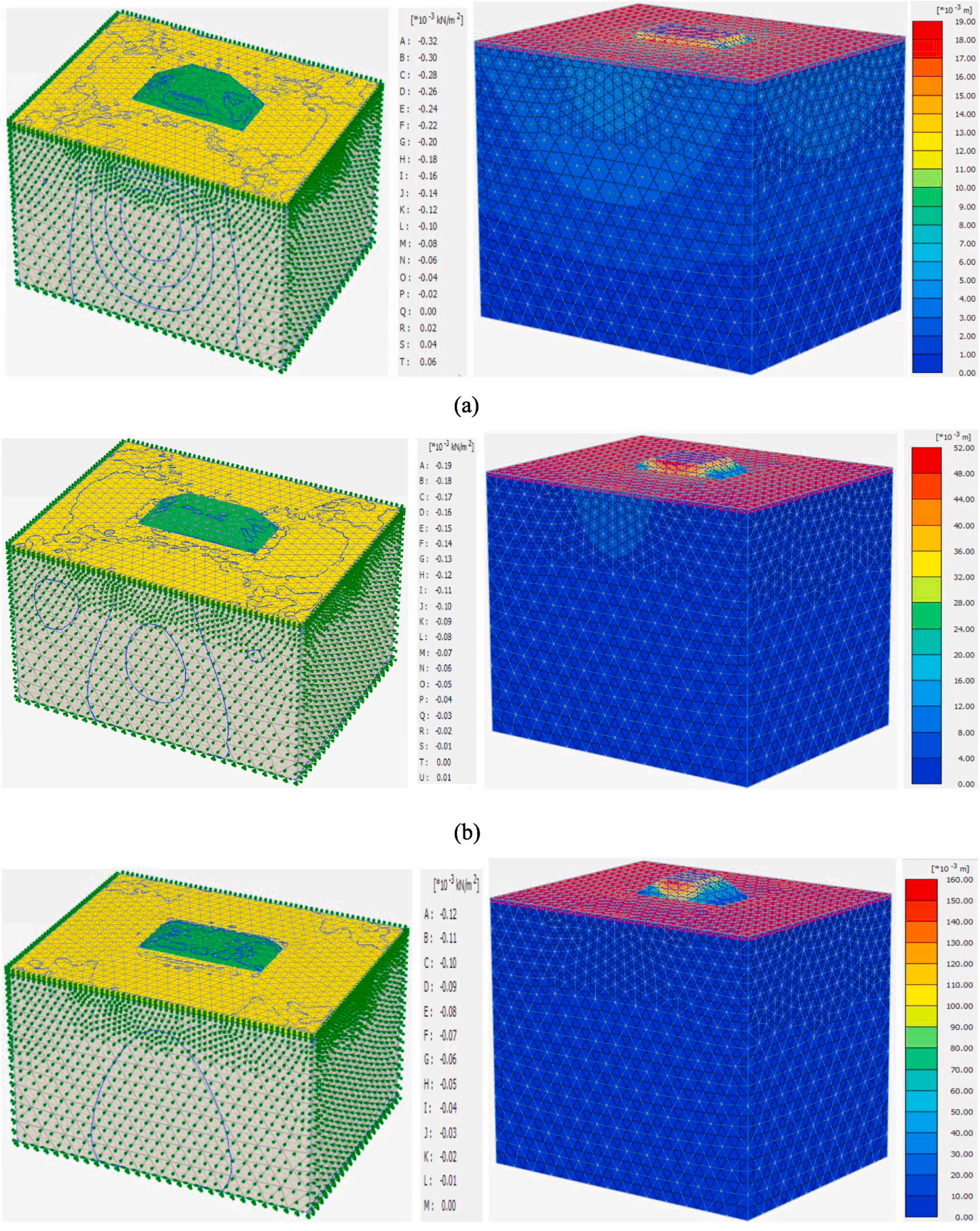


Fig. 6. Phases of the staged construction in presence of SVD; (a) Initial phase (no fill), (b) The 1st stage fill, (c) The 2nd stage fill, (d) The 3rd stage fill.

Fig. 5 (b)). Besides, the comparison was made between performance of the two installation patterns (square and triangular grid) in speeding up 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 and spacing, smear zone, discharge capacity of drain material, hydraulic conductivity and installation method [13,45,46]. Installation of vertical drains causes remolding of the sub soil 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



(a)

(b)

(c)

Fig. 7. Mesh geometry indicating PWP and settlement variation in presence of SVD: a) The 1st round fill, b) The 2nd round fill, c) The 3rd round fill.

[6].

2.2.6. The consolidation process and staged construction

Consolidation analysis introduces the dimension of time in 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 [47]. In 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 [48,49]. 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 introduction of staged construction approach. In staged construction approach, step wise incremental loading is considered to purposely allow clay soil completely under goes 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. Secondly, the clay mass after getting treated with a group of drains was modeled in absence of any fill material. The third model considered simulation of the consolidation attributes after 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 Fig. 6. Following the first fill placement, consolidation process is expected to begin [9]. The deformation magnitudes and pore water pressure changes with gradual increase in fill volume (Fig. 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 4).

3. Results and discussions

3.1. Effect of SVD on settlement and pore water pressure (PWP)

Rate of pore water dissipation for the soft clay with and without installation of group of vertical scoria drains was simulated (Fig. 8 (a)). The magnitude of excess pore water pressure in the absence of vertical drains is higher than the case in which SVD is considered. During the whole duration of 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 in which the clay is reinforced with SVD. This is due to presence of SVD in the clay mass which can shorten the exit distance of soil pore water [4,50–52]. Like other granualr materials (sand and crushed aggregate) with high permeability, introduction of scoria gravel as vertical drain performs well in facilitating and speeding up consolidation rate of clayey soil. The three peaks observed in the graph indicates 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 4

The overall construction and consolidation process of the clay.

Loading/Construction phases	Duration (day)	Duration until the next construction stage (day)
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

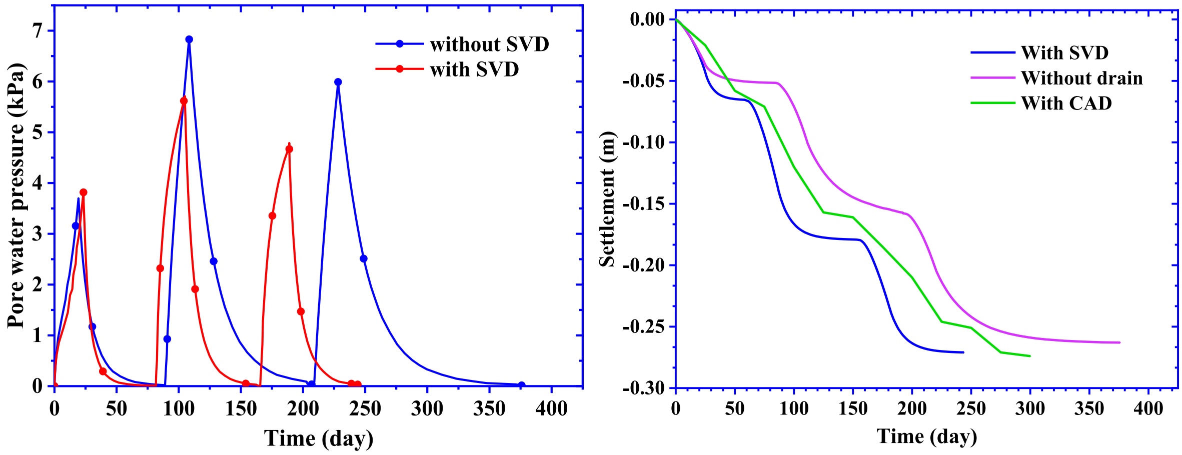
The significance of drain installation is determined not only by how rapidly the consolidation process proceeds, but also the amount by which the soft soil settle out. The comparison made between the embankment built with and without SVD revealed that the magnitude of vertical deformation in the presence of SVD is greater in magnitude than the case in which SVD is not provided (Fig. 8 (b)). Likewise, the reinforced clay mass settles more rapidly than the untreated one as the provision of drains perpetuates 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 is observed within 376 days of consolidation period in the absence of SVD. As reported by Warner J and Zaika Y [54,55], introduction of vertical drains to soft clays reduces the overall duration of consolidation process by more than four months. The magnitude of consolidation settlement in the presence of crushed aggregate is relatively lower than the case in which scoria gravel drains are installed. The gradation and the permeability of the two materials is almost similar even though crushed basalt aggregate is obviously denser than scoria. The numerical analysis revealed that the performance of scoria gravel drains in perpetuating the consolidation rate of clay soil is slightly better than the crushed aggregate drains (CAD).

3.2. Parametric study

3.2.1. Influence of drain diameter

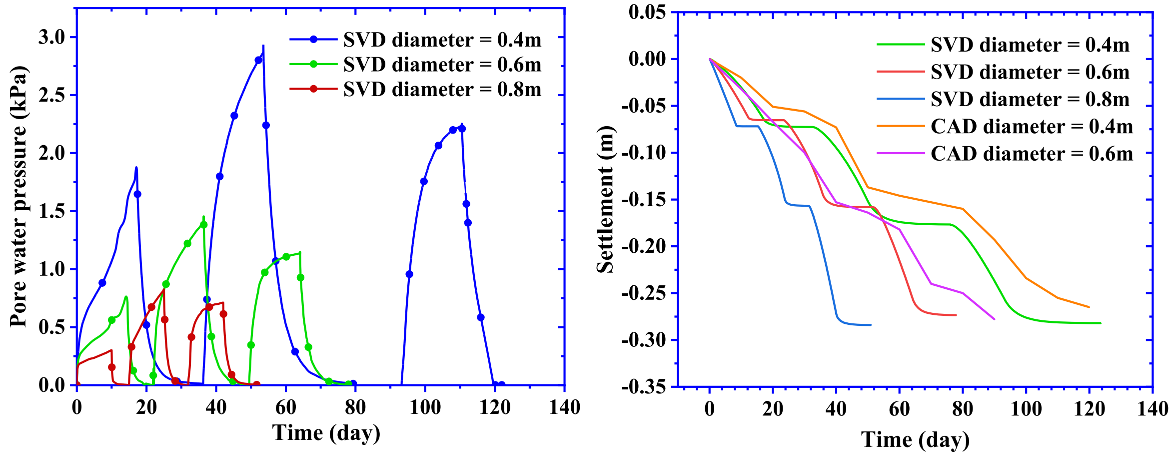
In order to investigate the effect of variation in drain diameter (D) on PWP and settlement of the clay mass, three diameters 0.4 m, 0.6 m and 0.8 m were considered. The PWP and consolidation settlement were simulated for the three diameters. Obviously, placement of fill material causes generation of PWP due to the load from 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 (Fig. 9 (a)). The reason is that vertical drains with larger diameter enable pore water to freely dissipate at relatively rapid rate which in turn contributes to reduction in the excess pore water pressure [50]. The rate of excess PWP dissipation increased together with the diameter of the scoria vertical drain. 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 very small variation in drain diameter considerably results in noticeable change in PWP.

The variation in vertical deformation with change in drain diameter (both SVD and CAD) is presented in Fig. 9 (b). The variation in drain diameter influences not only rate of deformation but also the magnitude of settlement [13]. When drains with smaller diameter are used, it takes long time to achieve a certain magnitude of settlement. In relation to this, increasing the size of the SVD from 0.4 m to 0.6 m and 0.8 m leads to growing rate of settlement by 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 SVD diameters of 0.8 m, 0.6 m and 0.4 m respectively. Increasing diameter of the vertical drain provides suitable space for pore water to freely dissipate which in turn increases the rate of vertical deformation [7]. Result of the current study with regard to effect of drain diameter has good agreement with work of Hammad MS [13] in which a direct relationship between drain diameter and deformation rate was reported. Like in the case of scoria gravel drains, the consolidation rate drops with decrease in diameter of the CAD. Even though similar increment pattern in consolidation settlement is observed between SVD reinforced and CAD reinforced clay, the rate of consolidation is yet higher for scoria



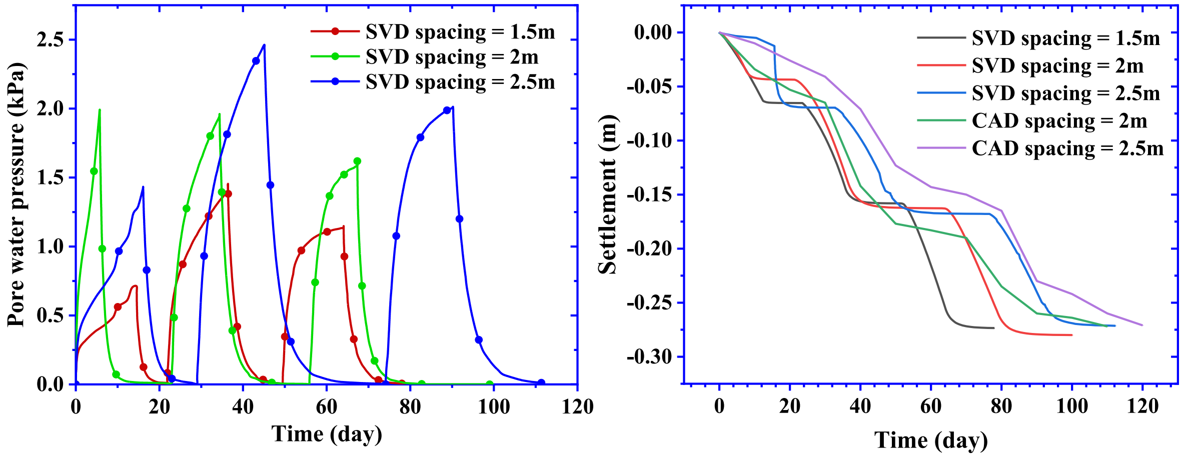
(a) (b)

Fig. 8. a) Effect of SVD on PWP under embankment fill (for D = 0.4 m, S = 2.5 m, L = 8 m), b) Effect of SVD and CAD on consolidation settlement (for D = 0.4 m, S = 2.5 m, L = 8 m).



(a) (b)

Fig. 9. a) Effect of SVD diameter on pore water pressure (for S = 1.5 m, L = 15 m), b) Effect of SVD diameter on consolidation settlement (for S = 1.5 m, L = 15 m).



(a) (b)

Fig. 10. a) Effect of SVD spacing on pore water pressure (for D = 0.6 m, L = 15 m), b) Effect of SVD and CAD spacing on consolidation settlement (for D = 0.6 m, L = 15 m).

drains (Fig. 9 (b)).

3.2.2. *Effect of drain spacing*

Not only drain diameter but also inter drain spacing (S) matters in consolidation process of soft clay. For comparative purpose, three spacing (1.5 m, 2 m and 2.5 m) of drains were considered for 0.6 m diameter of drains. Fig. 10 (a) shows, 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 spacing of 1.5 m, 2 m, and 2.5 m it takes 73, 90 and 112 days to complete dissipation of excess pore water from the soft clay. It is evident that the excess PWP can sufficiently be reduced as long as a shorter drainage path is provided [4,12]. Installation of vertical drains at narrower spacing shortens drainage path and PWP generated due to embankment loading is lowered [14,44,56].

Similarly, the effect of SVD spacing on settlement was examined using the stated three spacing. With increased SVD spacing, the rate of consolidation rate reduces resulting in prolonged dissipation of pore water (Fig. 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 spacing of 1.5 m over 2.5 m saves 30 days of consolidation time. Similarly, Ali AB [57] reported that as the diameter of vertical drains is reduced, the rate of consolidation is lowered. Comparison of the settlement rate has been made between the SVD and CAD for 2 m and 2.5 m spacing of the drains. The scoria reinforced clay undergoes 0.266 m consolidation settlement within 80 days of consolidation duration whereas it takes about ten extra days for the CAD reinforced clay to undergo the same magnitude of settlement for the drain spacing of 2 m. Similarly, the clay mass in the presence of SVD experiences vertical deformation of 0.275 m on the 100th consolidation day. In the presence of CAD however the clay should wait for about 118 days for drain spacing of 2.5 m.

3.2.3. *Influence of drain length*

In order to investigate the critical influence of SVD length (L) on PWP and settlement rate, three lengths of SVD were considered. Fig. 11 (a) depicts the change in PWP for SVD lengths of 8 m, 10 m and 15 m. Unlike diameter and spacing, change in SVD length has a moderate effect on the dissipation rate of pore water pressure. The numerical simulation demonstrates that an increase in SVD length leads to slight increase in dissipation rate of excess pore water. Accordingly, a decrease in SVD length from 15 m to 12 m increases consolidation period by 17.95%. When the length is further reduced to 8 m, 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 to the clay mass.

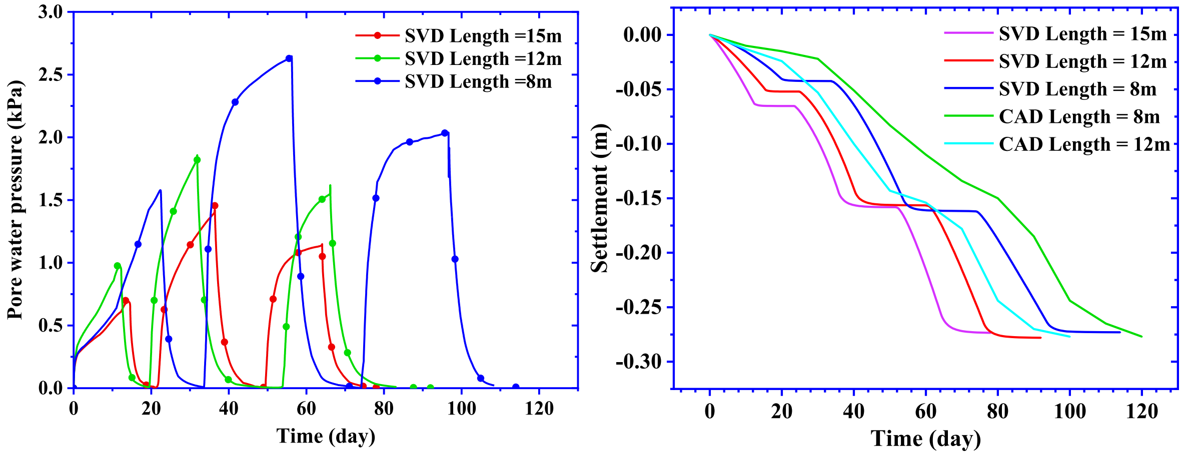
By examining the impact of the drain length on both time rate of pore pressure and settlement, the effectiveness of the floating SVD and CAD was examined. As indicated in Fig. 11 (b), settlement rate is higher for higher lengths of SVD and CAD. This is due to the fact that higher is the length of drains, the faster rate of settlement will be. In relation to this, Hammad MS and Lou C et al. [13,47,58] pointed out that the time it takes for pore water to dissipate and the prolonged settlement decrease as length of vertical drains grows.

3.3. *Effect of SVD installation pattern on PWP and vertical deformation*

Numerical model was performed for both triangular and square installation patterns of SVD in order to compare the performance of installation patterns on 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 marginally better influence on 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 (Fig. 12 (a), Fig. 12 (b)). Finding of the study with regard to drain installation perfectly agrees with works of Hammad MS [13] in which it was concluded that no significant difference exists between the performance of square and triangular patterns.

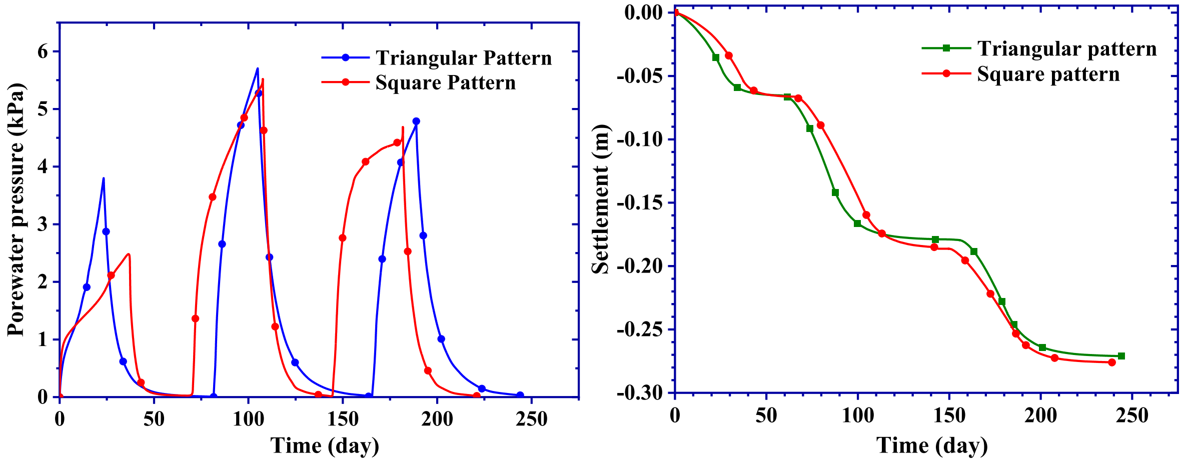
4. Conclusions

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.



(a) (b)

Fig. 11. a) Effect of SVD length on pore water pressure (for D = 0.6 m, S = 1.5 m), b) Effect of SVD and CAD length on consolidation settlement (for D = 0.6 m, S = 1.5 m).



(a) (b)

Fig. 12. a) Effect of installation pattern of SVD on pore water pressure (for Diameter = 0.4 m, S = 2.5 m, L = 8 m), b) Effect of installation pattern of SVD (for D = 0.4 m, S = 2.5 m, L = 8 m).

- The effect of SVD dimension parameters on PWP and rate of settlement is more significant for drain diameter and spacing over the length. The consolidation process is sensitive to the variation in dimension of drain spacing and diameter whereas the effect of drain length is not as influential as spacing and diameter. With increase in diameter of drains, the pore water dissipation rate and rate of settlement go fast. Besides, the narrower spacing between drains, the faster its consolidation would be.
- The length of SVD affects the dissipation of excess pore water and hence the settlement rate. Lowering of the d 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.
- 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.
- For the considered consolidation duration, the performance of SVD in enhancing consolidation rate is slightly higher than that of CAD. Settlement pattern of the clay in the presence of SVD has good agreement with its consolidation settlement in the presence of CAD.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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