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Reviews on Finite Element Modeling Practices of Stone Columns for Soft Soil Stabilization Beneath an Embankment Dam

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Abstract: This article reviews the numerical approach in stone column practices and presents the benefits of stone columns as a ground improvement of soft soil to support an embankment dam. In this article, the methodological approaches to numerically modeling stone columns in both 2D and 3D studies, as well as the selection of an appropriate constitutive model are discussed. The numerical practices for the installation of the stone column and the validation procedures used to ensure the accuracy of the numerical analysis are also explained. In addition to that, the study also presents the benefits of stone columns in improving settlement behavior, slope stability, and decreasing the end time of consolidation. Parameters that influence the performance of the stone column with their respective results are also assessed.

Keywords: embankment; soft soil; settlement; stone column; slope stability; consolidation.

1 Introduction

The characteristics of soft soil is that it withstands its self-weight and any additional load will cause greater deformation. These soils are well known for their low shear strength and high compressibility. Thus, it is necessary to improve this soil before loading it with any additional structure. Stone columns significantly reinforce such soft soils [1]. This type of improvement is widely used around the world due to their versatility and relatively broad applicability in different soil and foundation situations [2]. They are inexpensive and easy to construct. They essentially work by reinforcing the ground to increase bearing capacity, control settlement rate, reduce total and differential settlement, improve slope stability, and increase resistance to liquefaction [3].

Constructing embankments on soft soil is a difficult task for geotechnical engineers because of the possibility of failure, excessive settlement, and stability issues. Stabilizing soft soil using a stone column to support an embankment dam is effective, economic, and environmentally friendly [4].

A laboratory model of ground improvement technique using stone column was presented by Ayadat et al., Gniel et al., Black et al., Sivakumar et al., Ali et al., and Lee et al. [5-10]. It was revealed that stone columns are an effective ground improvement technique in increasing the stiffness, reducing the liquefaction potential, and increasing the bearing capacity of the host soil. The field load test conducted by Iman [11] also indicates that stone columns are used to reduce the total and differential settlement, improve the drainage conditions, control the deformation, and accelerate consolidation.

According to studies by Kousik et al. [12], the results of the analytical method are verified against several design methods and good agreement is observed. The effects of soil arching, stiffness of stone column, depth of soft soil, and tensile stiffness of the geosynthetic reinforcement are incorporated in the analysis. As the stiffness of the stone column increases, more stress is transferred from the soft soil to the stone column, and the use of reinforcement improves the stress transfer process. The stress concentration ratio also increases with the increase in modulus ratio (the ratio of elastic modulus of stone column to soft soil). The study finally concludes that the use of geosynthetic reinforcement reduces the total and differential settlement.

In the analysis of geotechnical problems, different methods ranging from closed-form analytical methods to a

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Table 1: Stone Column Installation Method.

Method of Construction	Construction Process	Recommendation	References
Displacement Method	A closed-tip steel tube is pushed down into the soft soil and then the cylindrical frame of geotextile and fills is inserted into the empty hole. After that, the tip opens, and the tube is pulled upward under vibration.	A very soft soil (for instance, cu < 15 kPa).	[15] Alexiew et al. (2005)
Replacement Method	An open steel pipe is installed into the soil until it reaches the hard layer, followed by the removal of the soil within the shaft via an auger boring.	The potential for vibration to influence adjacent buildings.	[16] Gniel et al. (2010)

numerical finite element (FE)-based method are practiced. Methods used to find a solution to a given problem have their own merits and limitations. In a field experiment, extraneous variables that could affect the results are difficult to control. Moreover, studies are expensive and time consuming. To limit the cost, many people turn to prototype testing. This still requires significant investment of time and resources and does not always yield the certainty sought. Advanced computational tools, such as FE analysis, can be used as an alternative solution.

The FE analysis is used to determine the complicated parameters that would be difficult to measure through experimental work. As mentioned, it is an effective way to use an alternative process for laboratory investigation studies, especially to save time and costs associated with the construction of physical models [13].

The fundamental benefit of FE analysis is that it produces a considerably more detailed set of results than experimental research, and it is frequently faster and less expensive. However, soft soil improved by a stone column is a complex composite material. Different phenomena that occur in reality can be captured using different numerical approaches. For this reason, it is appropriate to summarize and compare the various existing FE modeling practices.

The main objective of this review article is to summarize and compare existing FE modeling practices of stone columns for soft soil stabilization beneath an embankment dam. Additionally, it provides a better understanding of the benefits of stone columns in improving settlement behavior, slope stability, and decreasing the end time of consolidation.

2 Stone Column Installation

The primary notion of numerical modeling of the stone column is the installation method and its impact on the soil around the column. Each phase of column construction must be represented numerically to accurately model column installation.

2.1 Installation Technique of Stone Column

Tandel et al. [14] classify the installation method of an encased stone column as displacement method and replacement method, as summarized in Table 1.

Figures 1 and 2 show the stone column installation technique using the displacement method and the replacement method.

2.2 Modeling the Effect of Stone Column Installation

Each phase of the column construction must be represented numerically to accurately model the column installation. Using an axisymmetric 2D model, some authors, Guetif et al., Castro et al., and Kirsch [17-19] impose a uniform lateral displacement equal to the final stone column average diameter. The descriptions used by other scientists include uniform volumetric strain expansion of the stone column in 3D (Foray et al. [20]) and back analysis to determine field test behavior by altering the lateral to vertical stress ratio (K) (Elshazly et al. [21], Elshazly et al. [22]).

The majority of the numerical approaches were tested and calibrated on clays, where the vibrating probe's effect would be negligible, as in the displacement methodology. The main effect on clay would be generated by the lateral expansion of the stone column in a weak undrained soil. On the stone column, this would result in an increase in pore water pressure and an increase in the lateral to vertical stress ratio (K).

The density of the soil increases as the clay consolidates, and the stress ratio increases as the density of the mesh of columns increases (group effect). Foray

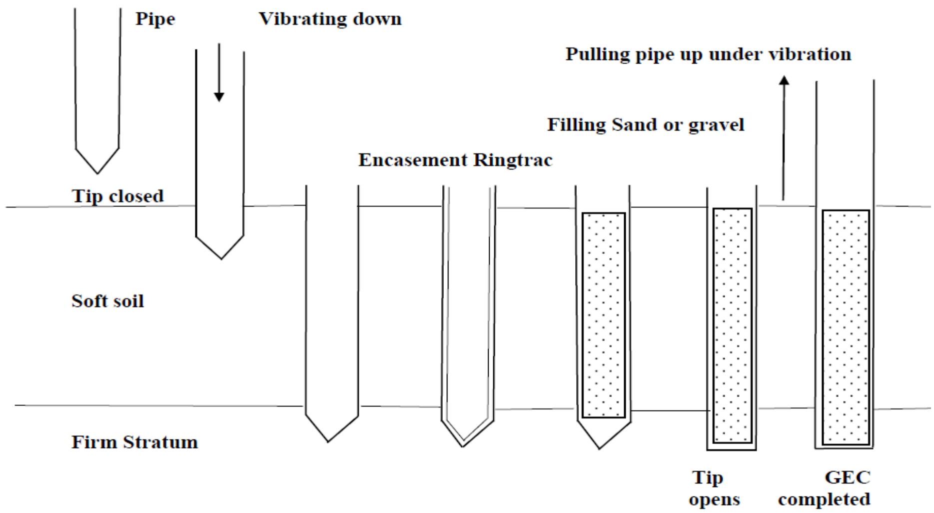

Figure 1: Displacement method (Alexiew et al. 2005).

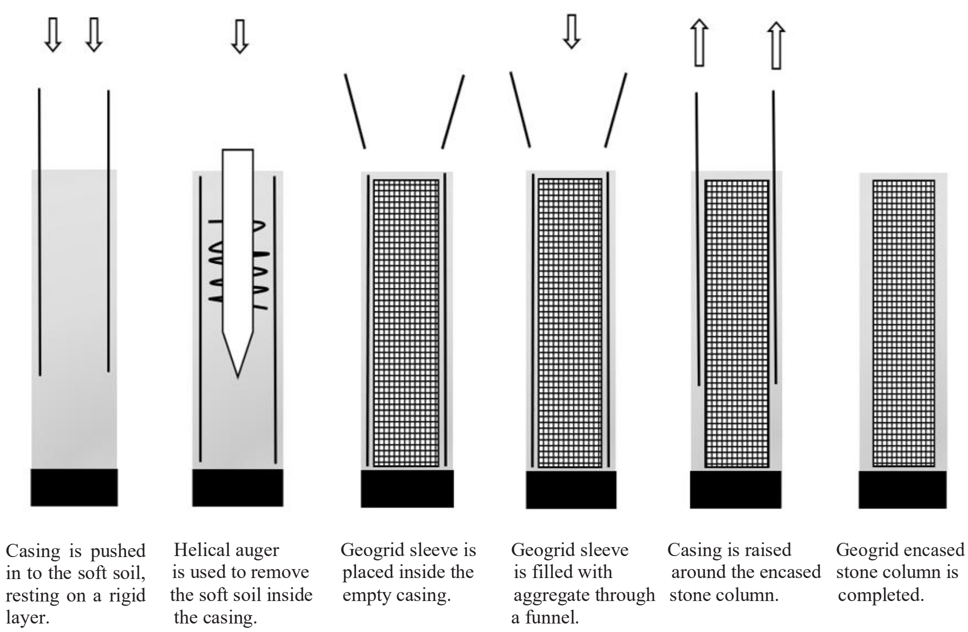

Figure 2: Replacement method (Gniel et al. 2010).

et al. [20] revealed that modeling in 3D rather than 2D is more appropriate to account for the effect of the group on the surrounding soil. Instead of an imposed lateral displacement, Egan et al. [23] recommend adopting a volumetric strain expansion of stone columns.

Kessler et al. [24] examined the modeling of vibration in dry sand, followed by Arnold et al. [25] in both 3D and 2D using ABAQUS. Because sand has no cohesion and a significantly higher permeability coefficient than clay, it will liquefy after installation. They depicted the vibrating probe as a source that generated a cyclic loading on the soil laterally. Although soil liquefaction during installation was not taken into account, they discovered that for this type of modeling, a 2D axisymmetric model is sufficient to analyze the influence of densification on the sand. In addition, the boundary condition might have a significant impact on the behavior of the soil during modeling.

The numerical modeling seeks to recreate the construction processes with certain simplifications. This simplification perceives the expansion of the cavity of the soil, the granular lateral loading of the surrounding soil caused by the insertion of the stone and the expansion of the stone column into the soil, and creates a group effect of columns representing the geometry of the mesh. Table 2

Table 2: Numerical Procedure for Installation of Stone Column.

No.	Name of Authors	Model Type	Numerical Procedure
1	[17] Guétif et al. 2007 [18] Castro et al. 2010 [19] Kirsch 2006	Axisymmetric model: 2D	By imposing a uniform lateral displacement, which is equal to the final stone column average diameter.
2	[20] Foray et al. 2009	Volumetric model: 3D	By using a uniform volumetric strain expansion of stone column.
3	[21] Elshazly et al. 2008 [22] Elshazly et al. 2006	Back analysis from field test	By varying the lateral to vertical stress ratio to obtain the field test behavior.

summarizes the state-of-the-art stone column installation technique developed by different authors.

3 Finite Element Modeling Practices of Stone Columns to Support an Embankment Dam

The finite element method (FEM) is a numerical analysis technique that can be used to obtain approximate solutions to various engineering problems. The FE model of the problem gives a piecewise approximation of the governing equation. The basic premise of the FEM is that the region of interest can be modeled by discretizing the domain into small parts called finite elements. Because these elements can be combined in many ways, they can be used to represent extremely complex shapes [26].

The simulation of reality remains an approximation, which involves some inevitable numerical and modeling errors and care should be taken in selecting the appropriate soil model. Thus, it is necessary to carry out several preliminary checks (such as mesh sensitivity, distance to the boundary, appropriate choice of constitutive model) to ensure the accuracy of the model [27]. FEM is still an approximate technique that idealizes real-life situations as a set of continuum components and uses a constitutive model to simulate soil behavior. Verification is used to check whether the computer model has been developed correctly, while validation is to ensure that the model fulfills its use. The verification techniques involves numerical methods, analytical solutions, experimental or physical models, actual case studies, and full-scale or field tests should be used to verify the numerical model.

The accuracy of the results in the analysis of FEs is measured by the size of the mesh.

According to the theory of FE analysis, a small element size results in high accuracy compared to a large element size. In addition, as the size of the element increases, the complexity of the model increases, and it is only used when great accuracy is required. Therefore, the selection of the mesh size plays an important role in the results of each study.

The following subsections review the numerical approach to the application of stone columns to support an embankment dam in relation to the effect of geotextile encasement, slope stability, and influential parameters.

3.1 Reviews on Ordinary Versus Geosynthetic-Encased Stone Columns to support an

3.1.1 Embankment Dam

The performance of ordinary stone columns (OSC) and geosynthetic-encased stone columns (GESC) with different types of column materials (sand, gravel, and construction waste) and encasement materials (by varying the stiffness) was studied by Alkhorshid [28]. Intensive laboratory tests that are supported by FEM numerical analysis were carried out. The result of this study shows that encasing a stone column has a paramount role in improving the column performance (in increasing the load-bearing capacity). The numerical analysis result indicates that the maximum settlement occurs at the center of the embankment. The maximum lateral displacement occurs below the embankment slope (at the toe of the embankment). The reinforcements applied to the stone column had also significantly increased the stability of the embankment dam.

The FEM was applied by Elsawy [29] to study the behavior of soft ground (Bremerhaven clay) improved by a conventional and geogrid-encased stone column under embankment loads. The study shows that encasing the stone column with geogrid increases the overall stiffness of the stone column. The geosynthetic encasement increases the overall stiffness of the stone columns,

Table 3: Reviews on OSC and GESC.

No	Name of Author	Year of Publication	Software Used	Constitutive Model **			Validation Method	Focused Area
				Soft Soil	Stone Column	Embankment Dam		
1	[28] Alkhorshid	2017	PLAXIS 3D	SS	MC	MC	Scaled Laboratory Test	Settlement Lateral deflection
2	[29] Elsawy	2013	PLAXIS 2D	SSC	MC	MC	Literature	Consolidation
3	[30] Belayneh	2020	PLAXIS 3D	MC	MC	MC	Literature (Field Test)	Consolidation Settlement
4	[33] Shafiqu et al.	2015	PLAXIS 3D	HS	MC	HS	Literature (Experimental)	Settlement Lateral displacement Consolidation
5	[32] Imad et al.	2020	PLAXIS 2D	HS	MC	MC	Analytical Method	Settlement Lateral deformation
6	[11] Iman	2015	PLAXIS 2D v.10	HS	MC	MC	Analytical Method	Settlement and lateral displacement
7	[35] Sim	2017	PLAXIS 3D	HS	MC	MC	Field Load Test	Settlement and consolidation

Where ** MC: Mohr-Coulomb SS: Soft Soil mode, HS: Hardening Soil, SSC: Soft Soil Creep

leading to a greater increase in the effective stress and the stress concentration in the encased stone columns, compared to conventional stone columns. This stress concentration, in turn, results in a reduction in the total stress and contributes a significant percentage in the dissipation of excess pore pressure, which accelerates the consolidation process.

Recent research on the behavior of OSCs and GESCs in collapsible soil was conducted by Belayneh [30]. This article studies the consolidation end time, excess pore water pressure versus time, and settlement versus time for an embankment dam that is constructed on untreated soil, OSC-stabilized soil, and GESC-stabilized soil. PLAXIS 3D consolidation analysis method was used. The use of GESCs decreases the amount of settlement of unreinforced soil by 12%. It also accelerates the consolidation end time by 56%. Obaide [31] also studies the treatment of collapsible soils using encased stone columns. The outcomes of his studies show that encasing a stone column increases both the ultimate bearing capacity and reduction of compressibility.

Another problematic soil, which is called Sabkha (salt flat), was reinforced by an encased stone column to support an embankment dam. It's studied by Imad et al. [32]. This soil has frequent small areas of very soft soils that are locally weak zones (has low strength and high compressibility). Numerical simulations using PLAXIS 2D were performed to evaluate lateral deformation, settlement behavior, and stress distribution between the stone column and the surrounding soil. Because of intensive bulging, OSCs were ineffective, caused by a lack of lateral pressure. Thus, encased stone columns reduced the bulging and settlement to a reasonable amount to build an embankment dam.

The study focused on the analysis of embankment supported by stone columns encased with geosynthetic material was conducted by Shafiqu et al. [33]. A scaled-down experimental work of Al-Shammarie [34] was taken to evaluate the percentage decrease in settlement and lateral displacement. The result of the study indicates that encasing the stone column with geosynthetic material relative to untreated soil has a great impact in decreasing the settlement, which ranges from 50% to 33%.

Other similar laboratory studies and field tests supported by a numerical analysis that has been a good agreement with the above studies were also performed by Iman [11], Sim [35], and Kahayoglu et al. [36]. Table 3 summarized and presented a review of OSCs and GESCs.

In general, as can be seen from Table 3 above, the authors used different models. However, when selecting this constitutive model, it takes into account a different perspective. For example, the soft-soil model is good for very soft surrounding soil. It also provides quite more appropriate results in the case of excess pore water pressure around the column. In addition to the hardening soil model, it is one of the most advanced and latest models for simulating and modeling soil behavior, and it includes several features of soil behavior that are relevant for many practical applications, such as: stress dependence of stiffness and strength, strain dependence of stiffness (modulus reduction), memory of preloading, distinction between primary loading and unloading or reloading stiffness, realistic nonlinear behavior instead of bilinear stress–strain response, and more accurate pore pressure development in undrained loading.

3.2 Reviews on Slope Stability Analysis of an Embankment Dam on Stone Columns

Several studies also report on the stability analysis of an embankment dam stabilized using a stone column. For example, Shaymaa et al. [37] conducted a 2D finite difference analysis using FLAC/SLOPE to analyze the stability of embankments supported by GESCs. This study mainly focuses on quantifying the embankment factor of safety against deep-seated failure under short-term conditions. Among the parameters that are considered, increasing the geosynthetic encasement stiffness, decreasing the spacing of the column, and increasing the height of the column enhances the stability of the stone column.

NG et al. [38] studied the slope stability analysis of embankment over stone column improved ground using a 2D limit equilibrium analysis and validated by a 3D FE program PLAXIS 3D. In authors opinion, the 2D limit equilibrium method can produce similar results as the 3D FEM in terms of factors of safety and failure modes with minor differences. Among the parameters, the embankment height, area replacement ratio, and undrained shear strength are the most influential factors in determining the stability of the embankment. The friction angle of the stone column material has an insignificant factor.

The stability analysis of an embankment dam that rests on soft clay stabilized using a stone column was done by Akhila et al. [39]. This study conducts a comparative study of an embankment that rests on the soft clay and stone column–stabilized soft clay. The use of a stone column as a stabilized material improves the properties of soil clay, reduces the deformation of the embankment, and changes the state of the soil from collapsing to increasing the bearing capacity.

The study that mainly focuses on the investigation of the effect of fine content present in the embankment soil on the response of stone column improved ground was conducted by Amit et al.

[40] with a title of “Response of Stone Column-Improved Ground Under c-φ soil embankment.”

The study reveals that there will be a great reduction in the stress concentration ratio that results in an increment in the vertical settlement due to the presence of a large number of fine contents in the embankment soil. This increment of the number of fines in the embankment soil also results in the differential settlement at the ground level and at the embankment top. This differential settlement takes less time to become stable compared to the vertical settlement.

The analysis of the failure mechanism of the GESC-supported embankment was carried out by Mohapatra et al. [41] using FLAC 3D. The research finally concluded that the accuracy of the continuum analysis approach is higher than the conventional slip circle analysis for the stability analysis of slopes supported by stone columns. For the failure mechanism, deep-seated failure is predominant for the OSC-supported embankments, whereas toe failure is predominant for the GESC-supported embankments. Encasing a stone column with geosynthetic material also helps to mobilize a higher factor value of safety. This is because the encasement provides greater resistance for lateral soil movement.

The stability analysis of road embankments supported by stone columns with the presence of a water table under short-term and long-term conditions was studied by Shaymaa et al. [42]. A 2D FLAC/SLOPE software was used to evaluate the stability of the embankment fill, which is built on stone column–stabilized soft soil. A column wall and an equivalent improved ground method are used to convert the 3D model into plane strain conditions. The effect of different parameters was also taken into consideration to determine the factor of safety against the embankment instability. Decreasing the spacing and increasing the height and diameter of the stone column improves the embankment stability. The factor of safety increases when the cohesion of soil is less than 25 kPa for short-term conditions and when the angle of internal friction is less than 20° for long-term conditions. The studies reviewed on the slope stability analysis of an embankment dam on stone columns are summarized and presented in Table 4 below.

3.3 Reviews on the Parametric Study of Stone Columns beneath an Embankment Dam

A parametric study on varying the stone columns height and spacing in alluvial soils under an embankment dam was conducted by Sajjid et al. [43]. The study reveals that utilization of the stone column reduces consolidation

Table 4: Reviews on Slope Stability Analysis of an Embankment Dam on Stone Columns.

No	Name of Author	Year of Publication	Software Used	Constitutive Model ***			Validation Method	Focused Area
				Soft Soil	Stone Column	Embank Ment Dam		
1	[37]Shaymaa et al.	2015	FLAC/ Slope	MC	MC	MC	Literature	Slope stability
2	[38] NG et al.	2019	PLAXIS 3D	MC	MC	MC	Literature and 2D limit equilibrium method	Slope stability
3	[39] Akhila Shaji et al.	2016	PLAXIS 3D	MC	MC	MC	Not mentioned	Slope Stabilization
4	[40] Amit et al.	2019	FLAC 3D	MC	MC	MC	Laboratory model test	Settlement
5	[41] Mohapatra et al.	2016	FLAC 3D	MC	MC	MC	Field Study (Literature)	Slope stability
6	[42] Shaymaa 2018 et al.	2018	FLAC/Slope	MC	MC	MC	Not mentioned	Slope stability

Where, *** MC: Mohr-Coulomb

time; hence the stone column plays a great role in the dissipation of excess pore water pressures. In addition to that, it concludes that there will be a considerable reduction in settlement by increasing the height and decreasing the spacing between the stone columns. It also recommends the use of a stone column as an effective ground improvement technique for enhancing the bearing capacity of the soil.

A comparative study between the axisymmetric and plane strain model approach for the ground improvement using stone column was studied by Maryam et al. [44] to see the difference of each model. Diameter, spacing, friction angle of the stone column, and undrained cohesion of the soft soil were taken as a governing factor. A series of models are simulated to evaluate the settlement improvement factor excess pore water pressure. Among this model, the stone column with a higher friction angle, bigger diameter, and lower spacing has a better settlement improvement factor and dissipation of water pressure in both axisymmetric and plane strain models. However, the axisymmetric showed a lower peak value of excess pore water pressure than the plane strain model. In the plane strain model, the settlement was improved more than twice while in the axisymmetric model the settlement improvement factor did not exceed 1.53. This article finally recommends that care should be taken in choosing the appropriate method for simulation in analyzing and designing methods (especially for projects with higher groundwater levels).

A numerical investigation into the performance of GESCs in embankment construction was carried out by Chungsik [45]. For constitutive modeling, the soft soil was represented by the modified Cam clay material. A 3D FE model was employed to carry out a parametric study on the geosynthetic encasement stiffness and length, the consistency of soft ground, the embankment fill height, and the area replacement ratio. The study found that the stiffness of the stone column will be enhanced by the additional confinement provided by the geosynthetic encasement so that there will be a reduction in the degree of embankment load transferred to the soft ground and decrease in the excess pore water pressure generation, thereby decrease in the overall settlement.

3D finite analysis of an embankment construction on a geosynthetic-reinforced stone column with a proposal of design method was conducted by Yogendra et al. [46]. The study considers the parameters such as geosynthetic stiffness, the spacing of the stone column, the stone column to diameter ratio, the height of the embankment, the thickness of the soft clay, and deformation modulus of the stone column material and embankment fill. Thus, increasing the geosynthetic stiffness, and reducing the column spacing to diameter ratio reduces the excess pore water pressure. The stone column spacing to diameter ratio, and a nondimensional diameter that relates soil modulus, stone column diameter, and geosynthetic stiffness have a significant effect on settlement improvement factor. This study also presents an equation for settlement improvement factor, which is defined as the ratio between the settlement of embankment that rests on untreated soil and soil treated with the geosynthetic-reinforced stone column.

According to the studies by Carreira et al. [47], the soft soil and stone column material were simulated using the soft soil (SS) and hardening soil (HS) models, respectively. The study also examined the critical height of embankments supported by geotextile-encased stone columns. A comprehensive numerical analysis was performed by increasing the height of the embankment to study the compressibility and thickness of the soft

Table 5: Reviews on the Parametric Study of Stone Columns Beneath an Embankment Dam.

No	Name of Author	Year of Publication	Software Used	Constitutive Model****			Validation Method	Focused Area
				Soft Soil	Stone Column	Embankment Dam		
1	[43] Sajjid et al	2012	PLAXIS 2D	MC	MC	MC	Literature	Settlement and consolidation end time
2	[44] Maryam et al.	2018	PLAXIS 2D	MC	MC	MC	Literature (Laboratory result)	Consolidation analysis settlement
3	[45] Chungsik	2010	Abaqus	MCC	MC	MC	Literature (Load test)	Settlement
4	[46] Yogendra et al.	2013	PLAXIS 3D	MC	MC	MC	Not mentioned	Settlement
5	[47] Carreira et al.	2016	PLAXIS 2D	SS	HS	MC	Literature (Full-scale test)	Critical height of the embankment

Where, *** MC: Mohr-Coulomb, MCC: Modified Cam Clay, SS: Soft Soil, HS: Hardening Soil

clay layer and the influence of the tensile stiffness of the encasement. Based on the findings, the diameter and spacing of the stone column are the basic parameters for the development of critical height. A remarkable comparison was also made of an embankment dam that was anchored in soil treated with a geotextile-encased stone column and piles. The geotextile-encased stone column–stabilized soft soil was found to be a more flexible system than the one associated with piles. For critical height, there are insignificant differences between the piled embankment and the embankment supported by a GESC.

A case study on the performance of an embankment supported on soft soil reinforced by a stone column was carried out by Mohammedzein et al. [48]. Different analytical and numerical methods are compared with the FEM for the prediction of settlement reduction factor. The FEM with proper modeling of geometry and material properties predicts the measured value well. For deep deposits of soft soil, the study recommends floating stone columns with a length to depth ratio of 0.5 (which would be as effective as end-bearing stone columns). Moreover, the settlement reduction factor decreases with the increase in the area replacement ratio. The summarized studies on a parametric study of stone columns beneath an embankment dam are presented in Table 5.

4 Discussion

For this study, different FE modeling practices have been assessed. It seems that FE modeling is the most popular and efficient method of simulating a stone column to stabilize soft soil beneath an embankment dam. In summary, this review study emphasizes the importance of paying close attention to the following factors.

4.1 Constitutive Models

The FEM software is equipped with different types of constitutive model to be selected based on different conditions, such as soil type, construction method, and liquefaction phenomena. Mohr-Coulomb, Hardening Soil, Soft Soil, and Soft Soil Creep material models have been used by different scholars in order to model the soft soil beneath an embankment dam. This constitutive law employed to describe the soils' behavior of nonlinear elasticity, elasto plasticity, and elasto visco plasticity. Although different soil models have been applied for the numerical analyses, there are no studies reported about the influence of soil models to the performance of a stone column under an embankment. Intuitively, there should be a difference to load transfer mechanism as different soil models use different assumption for the stiffness and yielding behavior of the soil. For example, the Mohr-Coulomb model, which incorporates one stiffness for the entire soil, will produce different stress field due to arching compared to advanced soil models, which consider stress level dependency. Hence the embankment load transfer should be different as well. To what extent that they are different still needs to be studied. Even though the capabilities and shortcomings of these models are not always easy to ascertain, and the requirements for determination of parameters are not uniform, it is consequently crucial to select the appropriate model for a particular task.

In the case of the surrounding soil (granular or cohesive), it is preferable to employ an elastoplastic model such as the Modified Cam-Clay or the Hardening Soil Model to adequately reflect loading and unloading behavior in the context of numerical modeling of stone column installation. This will allow the user to track the density and resistance of the column as it is built. Additionally, in the vicinity of the stone column, the areas of native soil prone to plasticity, that is, the most persistent deformations and failure, can be recognized. Because the soil does not have time to disperse the increased pore water pressure, the installation procedure is analyzed under undrained conditions.

Laboratory experiments, including physical tests, triaxial tests, and oedometer tests, should be performed to collect all the critical characteristics of soil compression and shearing behavior. Additionally, the soil model should be calibrated using sensitivity analysis to determine the best meshes, boundary conditions, type of analysis (drained or undrained), and soil interface interaction to use in numerical analysis.

4.2 Geosynthetic Encasement

In the reviewed articles, the geosynthetic encasement is modeled as a flexible membrane that does not support compressive stresses, has a negligible thickness, and behaves as a linear elastic material with a modulus of elasticity (J) ranging from 1000 to 5000 kN/m. The tensile strength values of 100 to 300 kN/m were taken because it usually reached for circumferential strains of around 5–10%. Common geosynthetics for column encasement are woven geotextiles. It is common that geosynthetic may be anisotropic and then different properties should be input for each direction.

4.3 Stone Column–Soil Interface

Interface elements are available in FE software to model the interaction between smooth and rough surfaces (such as piles/basement walls and soil). These elements can simulate the gap and slip displacements, which are normal and parallel to the interface, respectively. However, the zone of interface between the stone column and the soil is a zone with a high difference in the magnitudes of Young's modulus, and the shear strength properties of this zone also depend on the method of stone column installation. However, during the loading stages the stone column undergoes bulging and induces lateral displacement of soil in radial direction, where the shearing phenomenon is nearly absent. Hence, to make the analysis simple, many scholars do not consider the interface element. But, since this interface gives the frictional resistance along the length of the stone column, it is essential to model the interface and assign the friction angle of the interface and the cohesion properties on either side of the geosynthetic material to obtain good agreement with the experimental results. Thus, by ignoring the interface, one cannot capture the actual magnitude of the stress transfer from the stone column to the soil.

4.4 Mesh Size

There are several factors to consider when choosing a mesh size for FE software. For example, in terms of geometrical parameters of problems such as the thickness of the soil, the width of the embankment, the height of the embankment, the side slope of the embankment, the length of the stone column, the diameter of the stone column, the spacing between the stone columns, and the number of stone columns. According to the studied articles, numerical analysis of a very fine mesh is accurate because stresses and displacements are very high. In addition to this, finer meshes are used mainly for stone columns and soil below the embankment, where higher shear stress is expected to be mobilized due to deep-seated failure. Comparatively, coarser meshing is used for embankment soil. Owing to the large dimensions of the model of an embankment dam, in order to minimize computational time, some authors practice creating finer meshes around the stone column and coarse meshes on the surroundings to achieve greater precision in results. In addition to that, the soil model should be calibrated through sensitivity analysis to define the most appropriate meshes, boundary condition, type of analysis (drained or undrained), and soil interface interaction that will be utilized in the numerical analysis. In general, to establish a suitable

FE size, the selected analysis should be solved for a few different mesh sizes and the performance should be checked. Then note where high deformations or high stresses occur; perhaps it is worth refining the mesh in those regions. Therefore, understanding and selecting the appropriate size and arrangement of the mesh is extremely important, which will greatly affect the results if not properly considered.

4.5 Comparison of 2D versus 3D model

In terms of analysis, a 2D plane strain and 3D were performed to study the influence of critical parameters such as area replacement ratio, encasement stiffness modulus, soil thickness, embankment loading, and reinforcing modes briefly described in the study articles. It is obvious that the 3D provides more precise results at all desired angles, compared to 2D, which only presents the result based on the plane strain model. However, 3D analyses require longer time to get the results compared with the 2D approach. Thus, in selection of this analysis, it is critical to know how much accurate results are required from the numerical modeling compared to the actual geotechnical problem. Therefore, further step of the analysis is required as a validation and verification. This can be done using analytical method, experimental method, physical modeling or actual case study, and full-scale field test.

5 Conclusion

In this review, recent studies have been thoroughly reviewed on FE modeling practices of stone columns for soft soil stabilization beneath an embankment dam. On the basis of the issues raised, the following conclusions are drawn.

– When choosing the mesh size, it is projected that higher shear stress is mobilized due to deep-seated collapse, and hence finer meshes are needed to be employed primarily for stone columns and soil below the embankment. However, the embankment soil can be modeled by a coarser mesh than other soil types.
– The interface elements can simulate the gap and slip displacements that are normal and parallel to the interface, respectively. Because the frictional resistance along the length of the stone column is provided by this interface, it is necessary to model the interface and assign the friction angle of the interface as well as the cohesion properties on both sides of the geosynthetic material to achieve good agreement with the experimental results.
– The stability of the embankment can be greatly enhanced when increasing the stiffness of geosynthetic encasement due to the effect of apparent cohesion.

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