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Experimental and Numerical study of earth slope reinforcement using ordinary and rigid stone columns

Mohammad Hajiazizi [a, *], Masoud Nasiri [a]

[a] *Department of Civil Engineering, Razi University, Taq-e Bostan, Kermanshah, Iran*

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ABSTRACT

Earth slopes stabilization is one of the main issues in geotechnical engineering. The use of stone columns is one of the approaches for properly increasing the safety factor of earth slopes of the soil embankments. Furthermore, it is economically efficient and is easy in implementation. The present paper aims at an experimental comparison of the Ordinary Stone Column (OSC) and Rigid Stone Column (RSC) behaviors in sandy slopes. These tasks were carried out by constructing an embankment sandy slope, and then, saturating it with rain and, finally, loading increment. The experimental results of laboratory modeling have been also verified through the three-dimensional finite difference method. Laboratory modeling and numerical analyses results showed that the existence of rigid stone column in the middle of the slope (as the optimal placement location) enhances the sandy slope stability up to 1.36 times compared with a slope reinforced by ordinary stone columns.

Keywords : *Earth Slopes, Ordinary Stone Column, Rigid Stone Column, Stability*

1. Introduction

Earth slopes stabilization is one of the peculiar and practical issues for researchers and has attracted an extensive attention. Generally, stabilization methods applied by geotechnical researchers are classified into experimental, numerical and analytical categories [1-2]. Stabilization methods incorporate particular techniques, which are required to be well recognized, and they are also, needed to be scientifically capable of being modeled [3]. Various methods can enhance the earth slope stabilization, such as changing the geometry of the slope surface, using soil fortifiers or installing reinforcing structures including stone columns. Among these approaches, cutting slope upstream and/or filling slope downstream and/or changing slope angle are the primary and effective methods in slope stabilization and solidification [4]. Internal erosion of soil induced by seepage flow is the main cause of major hydraulic works failures such as earth dams [5]. The use of stone columns has been proposed as a method for stabilizing the earth embankments and increasing their factor of safety. Moreover, it has been proved to be cost-effective in respect of other executive methods besides the simplicity it offers in its implementation on highly dangerous slopes. Many researchers including Nazari Afshar and Ghazavi [6] have studied the effectiveness of stone columns. Increasing the loading capacity, reducing the subsidence, enhancing the shear strength, liquefaction control and drainage are among the factors contributing to the stone columns' appropriateness. Stone columns act as resistant limbs exposed to lateral forces and their performance can be improved through various methods, and their large-scale pressure can be enhanced besides their displacement resistance. One of these methods is creating rigidity in the stone columns by injecting grouts into the column and constructing a Rigid Stone Column (RSC). Stone column was first applied in France in 1830 [7]. Stone column technique became popular in European countries since early 1960s and they found extensive use in the entire world afterwards [8-9]. Stone columns undergo various forms of disintegration when subjected to compressive loads among which column bulging [10-11], total shear failure [12] and sliding can be pointed out [13]. Stone columns are applicable in a wide range from soft cohesive soil to rigid as well as in silt sandstones [14]. When applied in soft soil, stone columns act like piles except that the need for constructed structures and subtle infiltration into denser layers is removed [15]. In addition, stone columns are more competent for bearing more compressive forces in contrast to piles. Under loading conditions, the bulged stone columns deform in the bottom layer, distribute the tensions over the upper sections of the soil profile, and create a shield to protect the soil [16]. Stone columns acquire their bearing capacity from the peripheral ground surrounding pressure [17]. Balaam et al [18] studied the stone column hardness effect on the deformation behavior subject to loading. Munfakh [19] and Han and Ye [20] demonstrated that the solidification rate increases with the stone column and the compression on the peripheral ground is mitigated as well. Many researchers [21-23] have investigated the effect of stone columns within the format of field studies and they have proved the efficiency of this method in reinforced soil. Numerous researchers have proposed laboratory and theoretical solutions [24-29] to estimate the bearing capacity and the reinforced soil subsidence behavior when stone columns are applied. Stone columns increase the bearing capacity [30], reduce the total and relative settlement rates [31-32], decline the liquefaction potential [33], improve the soil slopes stability [34-35] and higher the resistance to shear stresses [36]. Laboratory studies and numerical tests show that the major reason behind the improvement obtained through strengthening the soil by stone columns is the higher hardness of the stone column as compared to the soil at its vicinity [37-42]. Through field investigations, Bergado et al [41] reported that stone columns increase the slopes factor of safety up to 25%. The results of their studies indicate that besides allowing for drainage, the stone columns play roles as dike fortifiers. Vekli et al. [43] experimentally investigated the stone column effect on the slope stability. The results obtained by them indicate that the stone column increases slopes

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* Corresponding author Tel: +988334283264, *E-mail address:* mhazizi@razi.ac.ir (M. Hajiazizi).

bearing capacity up to 1.25 to 1.71 times the unreinforced embankment and the factor of safety decreases by an increase in slope angle. Stabilization of the embankments, at the periphery of the highways in Alaska, California, Florida, Iowa, Kentucky, Mississippi, New York, Texas, South Dakota, Virginia and Wisconsin, has been conducted by means of stone columns [44]. Wang et al. [45] examined the slope stability by considering the rainwater infiltration effect on soil's effective stress and they found out that the soil percolation to soil skeleton reduces the soil's effective stress strength, which is quantitatively defined by a decline in the equivalent compressive surrounding pressure. The infiltration of the precipitation into the dikes, as a result of textual suction, causes a reduction in the unsaturated soil's shear strength. Abusharar and Han [46] conducted a two-dimensional analysis on stone column effect on earth embankments to evaluate various parameters such as stone column spacing, friction angle, cohesion, water effects, embankment height and diameter of column. Examining stone columns in stratified soils, Mohanty and Samanta [47] indicated that the stone column behavior in inhomogeneous soils strongly depends on the upper layer and the layer conditions determine the stone column behavior. There are other methods, as well, proposed and applied for slopes stabilization among which the use of cement slurry, the use of stone column reinforced with geo-textile covers and sand compaction piles can be highlighted. Vieira [48] by introducing a method based on limit equilibrium showed that the required forces for stabilizing unbalanced slopes are derived from reinforcement systems. Other introduced and used methods for stabilization of slopes are using cement grout [49], using stone column reinforced by geotextile layers [50] and using piles [51-52].

Despite the numerous aforementioned studies, no experimental research has been carried out up to the present time regarding the study of soil slopes strengthened by rigid stone columns and the use of the latter method has been introduced as a novel method in the current research. This study aims at providing a better and more broadened understanding of the ordinary as well as rigid stone columns' behavior and mechanism in improving the soil slopes stability. The primary objective in the present research is gaining insight regarding the slope disintegration and plastic deformation; small yields or elastic deformations have not been considered in slopes. Accordingly, a series of laboratory modeling was undertaken, the results were compared using the 3D finite difference, and it was shown that the results highly match.

2. Laboratory Modeling

2.1. Laboratory equipment and material used

2.1.1. Test box

The test box consists of five parts: water supply system, modeling section, drainage part, Piezometeric tables, and loading system (Fig. 1). The transparent glass sides were built sufficiently rigid to maintain a plane strain condition for prevention of lateral displacements and the sample could be seen during model preparation, precipitation, and Loading. Before beginning, the inside walls of the box are lubricate to reduce friction with sand as much as possible. The loading system consists of a hand operated hydraulic jack and a loading ring.

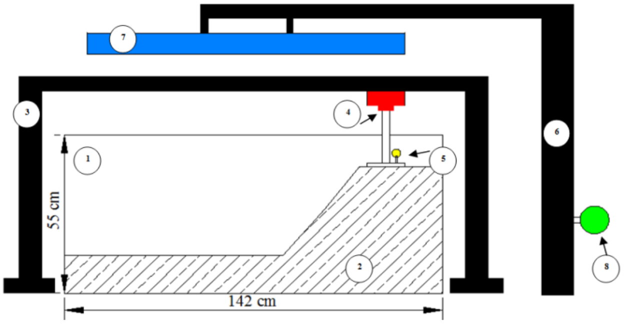


Fig. 1. Schematic view of the experimental apparatus.

2.1.2. Sand

The sand used in this research is a washed type. A series of direct shear test in dry and saturated conditions were performed to evaluate the shear strength parameters of the sand (Table 1). The particle size distribution was determined using the dry sieve method and the results are shown in Fig. 2 (the amount of fine particles in the sand was about 0.285%). The sand was placed in 50 mm-thick beds by the raining technique in which sand raining follows a given and controlled height to lead to a uniform density. Dike density was controlled in the course of the experiment through collecting samples with certain volumes from different positions of the test box. No visible movement was observed during the implementation and installation processes.

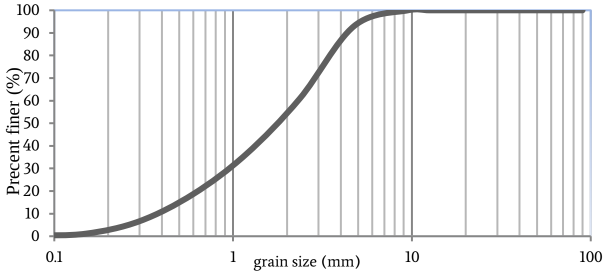


Fig. 2. Grain size distribution of the modeled sand.

Table 1. Sand properties.

Properties	Value
Unite weight (Dry condition)	$\gamma = 16\ kN/m^3$
Unite weight (Saturated condition)	$\gamma = 18\ kN/m^3$
Internal friction angle (Dry condition)	40 °
Internal friction angle (Saturated condition)	36°
Cohesion	0.0
Elastic modulus (E)	40 Mega Pascal
Specific gravity (G_s)	2.65
Poisson's ratio	0.3
D_{50}	1.8

2.1.3. Ordinary stone column

The stone column is composed of particles that pass through a 0.5-inch sieve but is blocked by sieve No. 4 (Fig. 3). Shear strength parameters of used gravel were obtained by using the direct shear test (Table 2). A plastic case with a diameter of 3.6 cm was used to construct an ordinary stone column. Before constructing the model, the plastic case was placed in the intended position and the required gravel was poured and compacted therein during construction in each phase with regard to stone column's unit weight. The rigid stone column was procured in a precast format to be installed in the intended place on the slope.

Table 2. Gravel properties.

Properties	Value
Unite weight (Dry condition)	$\gamma = 16\ kN/m^3$
Unite weight (Saturated condition)	$\gamma = 19\ kN/m^3$
Internal friction angle (Dry condition)	41 °
Internal friction angle (Saturated condition)	37°
Cohesion	0.0
Elastic modulus (E)	100 Mega-Pascal
Specific gravity (G_s)	2.60
Poisson's ratio	0.2

2.1.4. Rigid stone column

In this research, the rigid stone column was a prefabricated element and placed in a specified location (optimal position) on the slope. The cement used in construction of the RSC was Portland cement type II (Kermanshah Cement). According to the stress-strain test, the elasticity modulus of the RSC is 250 MPa.

Fig. 3. Gravel for stone column.

2.1.5. Rigid stone column

In this research, the rigid stone column was a prefabricated element and placed in a specified location (optimal position) on the slope. The cement used in construction of the RSC was Portland cement type II (Kermanshah Cement). According to the stress-strain test, the elasticity modulus of the RSC is 250 MPa.

2.2. Construction of experimental models

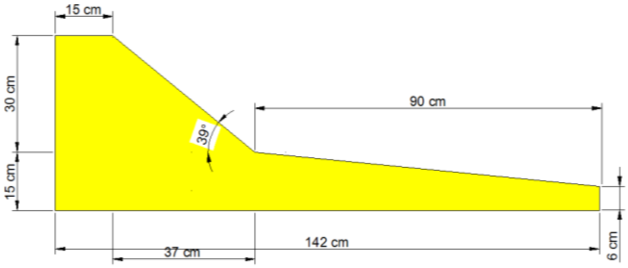
The models of interest in the current study were constructed by the raining technique and the slopes were observed through the box's glass walls. Three kinds of models were built and examined in order to investigate the effects of reinforced stone column in earth slopes; the first model, constructing unreinforced soil embankment; second model, constructing reinforced embankment by an Ordinary Stone Column (OSC) in the middle of the slope (as an optimal location [53-54]); the third model, constructing a reinforced embankment by the RSC in the middle of slope. In each phase of loading, the time duration of the exerted loads was kept constant for the slope to achieve balance subjected to them after which the next loading phase was initiated. Each model was repeated twice to ensure the obtained results. Characteristics and conditions listed below are similar and identical for all three models. (1) In order to diminish the friction effects exerted by the test box interior walls, they were lubricated. (2) The embankment's crest was 15-cm long in all models and the embankment's angle was 39 degree with regard to the dry sand internal friction angle (40 degrees). The slope was 30 cm high, and the total height of the model was 45 cm. (3) In order to prevent erosion of the embankment's surface by water, a thin layer of cement grout was poured thereon. (4) Model saturation was carried out by artificial precipitation and the discharge rate of precipitation was 2 lit/min. (5) Drainage operation and reservoir water outflow tests were implemented via the downstream section of the test box. (6) Stone column (ordinary and rigid) was 3.6 cm in diameter and it had a clearance for about 5 cm from the test box floor. (7) Sandy dike was implemented in a single-layer format and the sand and ordinary stone column's specific weight was 16 kN/m^3.

2.2.1. Unreinforced slope

The slope's geometry has been illustrated in Fig. 4. First of all, the box's interior walls are lubricated. After the unreinforced embankment (Fig. 5), it showed no flaws in terms of stability, then the model was subjected to artificial precipitation and it displayed cracks in the middle of the embankment's section after termination of a 40-minute post saturation process, and the slope experienced total failure after a few minutes. Fig. 6 exhibits the embankment's total failure.

2.2.1. Reinforced slope using ordinary stone column (OSC)

According to the previous studies, the optimal location for stone column placement is in the middle of the embankment, for the same reason the stone column was placed in the middle of the embankment in order to carry out the tests on reinforced embankments. Therefore, at first, the box's interior glass casing and the inner and outer parts of pillar case were lubricated to allow the casing to be easily pulled out at the end. Before beginning, the casing was placed in the specified location (on the first 5-cm layer) and the pillar masonry was poured into the casing along with each layer of graveling and compacting. After completion of the model, the plastic case was pulled out gently and heedfully. Figs. 7, 8 and 9 show the slope's geometry, the constructed model and the stone column position, respectively. After the model was completed, the model was subjected to artificial precipitation and no cracks appeared on the slope's surface after about a 90-minute post precipitation, so it can be concluded that the slope's factor of safety has increased under the reinforced condition. Following the slope saturation, the slope was subjected to gradual loading (loading speed was approximately (1 Kg / 10 min), it showed a good resistance without undergoing any failure. The stone column's displacement was approximately about its diameter. After gradual loading on the crown, the slope failed under a pressure of 6.06 kPa. The embankment's slip surface can be observed in Fig. 10.



$\gamma = 16\ kN/m^3$

Fig. 4. The geometry of the unreinforced slope.

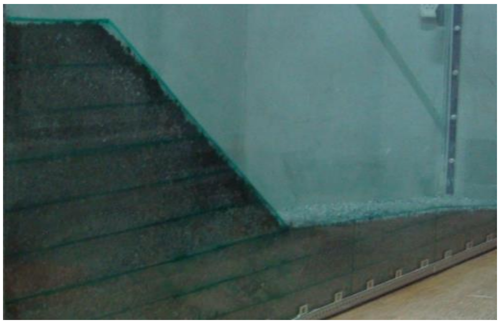
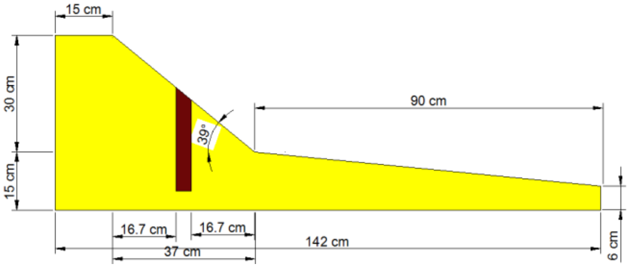


Fig. 5. The unreinforced slope.

Fig. 6. The unreinforced slope rupture.

2.2.1. Reinforced slope using rigid stone column (RSC)

In this model, the slope's geometry is exactly the same as the previous model, and as explained above, the box's sidewalls were lubricated. In addition, in this model, a prefabricated rigid stone column was used. The method applied for constructing this stone column is as follows. At first, a specified amounts of gravel with cement were poured in layers in a case with an internal annulus of 3.6 cm and the rigid stone column was constructed up to the intended height by adding water to each layer. Then, it was given a 48-hour resting period during which it solidified, and then, the casing was removed. The failed RSC at the end of the test is shown in Fig. 11. The obtained elasticity modulus using the stress-strain test was 250 MPa. The reinforced slope constructed by rigid stone column is shown in Fig. 12.



$\gamma = 16\ kN/m^3$

Fig. 7. The geometry of the reinforced slope using an ordinary stone column.

Fig. 8. The reinforced slope using an ordinary stone column.

Fig. 9. Stone column's location in the middle of the reinforced slope using an ordinary stone column.

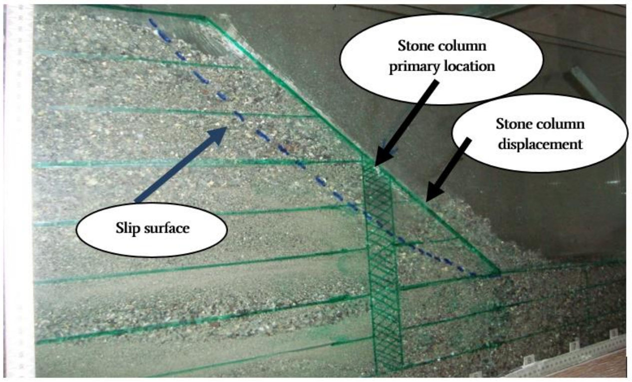


Fig. 10. Failure of the reinforced slope using an ordinary stone column under a pressure of 6.06 kPa.

After the model was completed, the embankment was subjected to artificial precipitation and no cracks appeared on the slope's surface 100 minutes after the complete saturation. In the next step, in order to develop rupture, the slope was subjected to gradual loading (with a rate of of approximately (1 Kg / 10 min). The embankment was subjected to loading and showing no failure demonstrated a higher resistance with respect to the slope reinforced by an ordinary stone column. After the exertion of gradual loading on the crown, the slope failed under a pressure of 8.52 kPa. Fig. 13 illustrates the slip surface in this reinforced slope.

Fig. 11. The rigid stone column.

Fig. 12. The position of the rigid stone column and the reinforced slope using a rigid stone column.

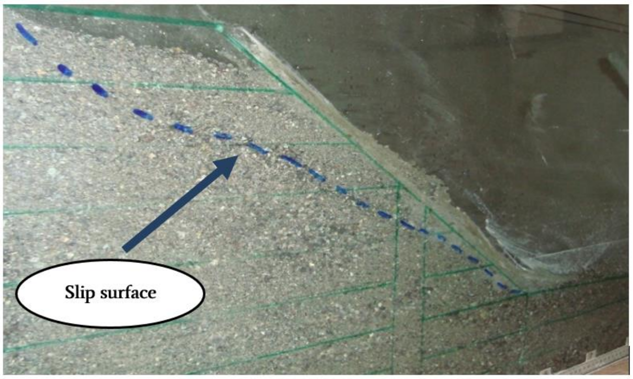


Fig. 13. Failure of the reinforced slope using a rigid stone column under a pressure of 8.52 kPa.

3. Numerical Modeling

Numerical modeling was carried out using FDM. Modeling was performed for all three types of unreinforced slope, reinforced slope using OSC and reinforced slope using RSC. Analytical results are compliant with laboratory modeling. The slope's properties are presented in Table 3.

3.1. Numerical modeling of unreinforced slope

After modeling the unreinforced slope in a dry condition, the obtained factor of safety was 1.12 and the embankment was found stable under such conditions. Then, the embankment was modeled under saturation that exhibited the failure and its obtained factor of safety was 0.97. These two states were the same as what was observed in laboratory. Figs. 14-16 show an unreinforced embankment model and its relevant analyses under dry and saturated conditions, respectively.

3.2. Numerical modeling of reinforced slope using ordinary stone column

In the next phase, the reinforced slope was numerically modeled using an ordinary stone column. In this model, the stone column was modeled as a cubic element, the validity of which has been proved in [55-56]. The model's geometry has been shown in Fig. 17. At first, the reinforced embankment was modeled under dry conditions and its obtained factor of safety was 1.44. Then the embankment was analyzed under saturation for which the factor of safety equals to 1.24. In the last step, the slope was analyzed under the crown loading state with the same specifications as before and the critical load resulting in the embankment's failure was 5.85 kPa (Fig. 18).

Table 3. Properties of slope.

Parameters	**Value**
Sand dry unite weight	16 KN/m^3
Sand saturated unite weight	18 KN/m^3
Ordinary stone column dry unite weight	16 KN/m^3
Ordinary stone column saturated unite weight	19 KN/m^3
Rigid stone column unite weight	22 KN/m^3
Sand Bulk modulus	3.3×10^7 N/m^2
Sand Shear modulus	1.5×10^7 N/m^2
Ordinary stone column Bulk modulus	5.6×10^7 N/m^2
Ordinary stone column Shear modulus	4.2×10^7 N/m^2
Rigid stone column Bulk modulus	1.4×10^8 N/m^2
Rigid stone column Shear modulus	1.04×10^8 N/m^2
Sand cohesion	0
Sand friction angle in dry condition	40°
Sand friction angle in saturated condition	36°
Ordinary stone column cohesion	0
Ordinary stone column friction angle in dry condition	41°
Ordinary stone column friction angle in saturated condition	37°
Rigid stone column cohesion	50
Rigid stone column friction angle	50°

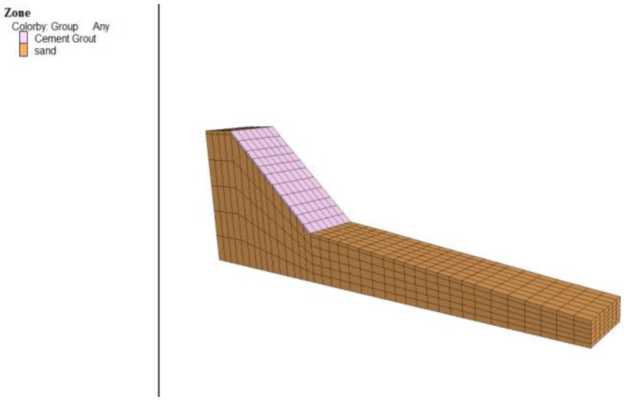


Fig. 14. Unreinforced slope model.

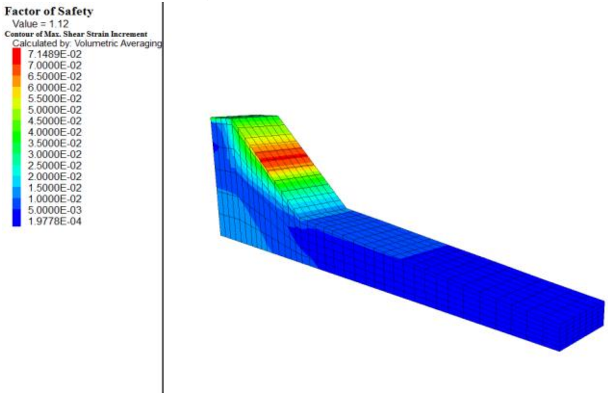


Fig. 15. Dry unreinforced slope, FS=1.12.

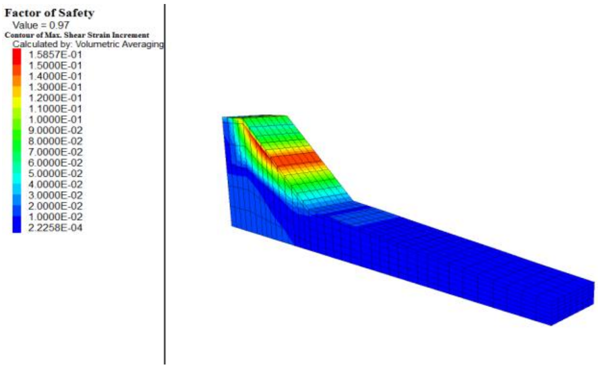


Fig. 16. Saturated unreinforced slope, FS=0.97.

The amount of the load leading to the embankment's failure in the laboratory was 6.06 kPa that was obtained equal to 5.85 kPa in numerical analyses, providing a difference less than 1 percent. The laboratory modeling had some uncontrollable errors, such as the sidewall effects (even after lubrication), the drainage performance of stone column, and the assumption of the stone column in numerical modeling being a cubic element whereas stone column in the laboratory was a cylindrical element.

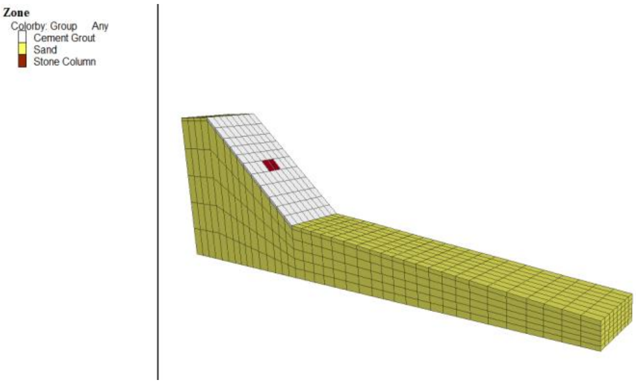


Fig. 17. Reinforced slope using an ordinary stone column.

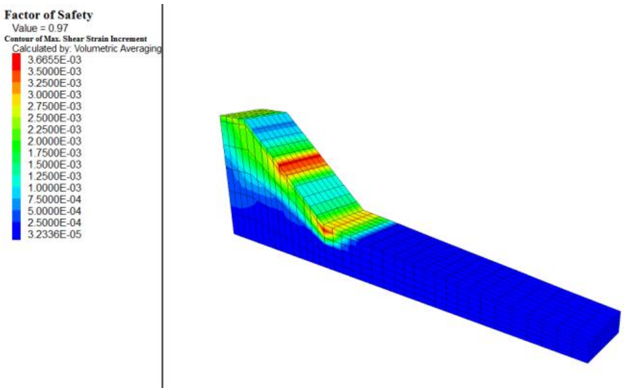


Fig. 18. Saturated reinforced slope using an ordinary stone column, FS=0.97 (loading=5.85 kPa).

3.3. Numerical modeling of reinforced slope using a rigid stone column

The geometry of the reinforced slope modeled using a rigid stone column is exactly the same as the previous model. At first, the slope stability was analyzed under dry conditions and a factor of safety equal to 1.50 was gained (Fig. 19). Then, the model was analyzed under saturation for which a factor of safety equal to 1.36 was attained. In the last step, the slope analysis was implemented under the crown loading condition and the critical load contributing to the slope collapse was obtained equal to 8.36 kPa (Fig. 20). The amount of the load causing the embankment failure was 8.52 kPa in the laboratory, and as compared to a value of 8.36 kPa found in the numerical analysis, the difference between was less than one percent.

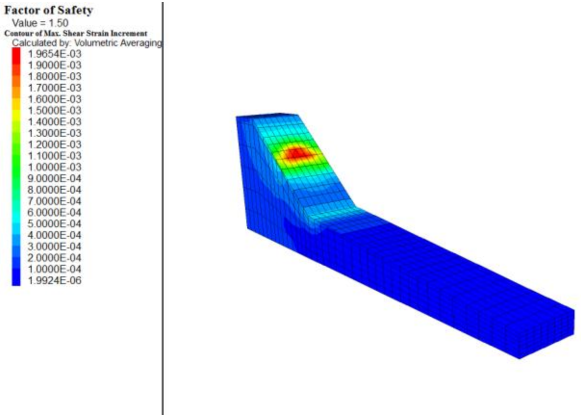


Fig. 19. Dry reinforced slope using a rigid stone column, FS=1.5.

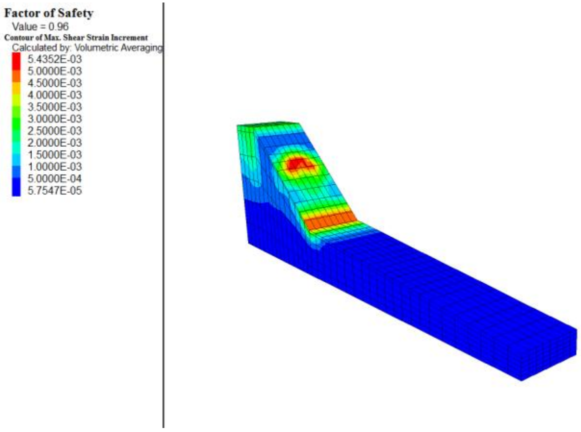


Fig. 20. Saturated reinforced slope using a rigid stone column, FS=0.96 (loading=8.36 kPa).

4. Results and Discussion

Several laboratory tests were conducted for sandy slopes reinforced using the OSC and RSC. The rigid stone column increases the bearing capacity of reinforced slope about 1.41 times of the reinforced slope using an ordinary stone column. This increase in the bearing capacity stems from high elasticity modulus that is provided by the rigidity of the stone column for the embankment.

A stone column acts as a barrier to the development of the failure plane and it resists lateral deformation due to the displacement in the position of the stone column during loading. The use of cement in stone columns and the creation of a rigid load-bearing limb increase the resistance against the exerted loads and enhance the slope stability.

The slope's factor of safety depends on many factors, such as the size of the slope failure, the type of soil, the geometry of slope, the height of slope, and the stiffness of stone column. All parameters except the stone stiffness are the same in this research, and the stiffness is increased in rigid stone columns because of which the slope stability is enhanced. Shear failure is the mechanism of the OSC rupture under loading, and bending failure is the main failure mode in the RSC under loading. This change in the mechanism of failure causes an enhancement of slope stability. Reinforced stone column increased the soil's shear strength up to 1.41 times the ordinary stone column and enhanced the stability of slope up to 40.6 percent. The results of this research indicate that an unreinforced embankment is unstable under saturation and it consequently fails. If an ordinary stone column in its middle position reinforces the earth slope, then its stability will be enhanced in a way that its bearing capacity can be increased to 6.06kPa. In case of a rigid stone column, the bearing capacity of slope can be increased up to 8.52kPa. The use of both ordinary and rigid stone columns significantly contributes to augmentation of earth slope stability, but the effect of rigidity is about 40 percent higher in improving the stability and safety. The experimental and numerical results are presented in table 4.

Table 4. Experimental and numerical results.

	Experimental analysis results	Numerical analysis results
Unreinforced saturated slope	Unstable	Unstable
Bearing capacity of the unreinforced slope	0.0	0.0
Reinforced saturated slope using OSC	Stable	Stable
Bearing capacity of reinforced slope using OSC	6.06 Kilopascal	5.85 Kilopascal
Reinforced saturated slope using RSC	Stable	Stable
Bearing capacity of reinforced slope using RSC	8.52 Kilopascal	8.36 Kilopascal

5. Scale Effects

It is obvious that due to the scale effects and the nature of soils, especially granular soils, they may not play the same role in the laboratory models as in the prototype. These differences occur primarily because of the differences in stress levels between the model tests and field tests [57]. Regarding this issue, Sawwaf [58] proposed that using 1-g models could be useful only in prediction of general trends of the behavior of a particular prototype. In this regard, Hegde and Sitharam [59] explained that small-scale experiments under 1-g conditions help experts more quickly and more simply to obtain appropriate approximations in terms of the information about the general behavior of the prototype compared to the full-scale tests. However, full-scale tests provide a better control over key parameters of the model. It is worth mentioning that the results of 1-g model tests can be influenced by scale effects and are not directly applicable to the prototype case. As mentioned by Fakher and Jones [60], the results of the small-scale tests can be applied for prototype cases by a careful use of scaling law. They also warn that it is not possible to use complete similarity between the model and prototype due to the involvement of several complex factors and it should be left for the judgment of the researchers to decide about these influencing factors to scale up considering the accuracy and the nature of the problem. According to the above-mentioned cases and based on the recommendations made by Sawwaf [58], it is suggested that further researches should be undertaken using full-scale tests or centrifuge model tests in order to ascertain and compare the obtained results in this research.

6. Conclusion

The objective of this paper is a comparison between ordinary and rigid stone columns in the stability enhancement of a sandy slope. For this purpose, a series of experimental modeling was carried out. Stabilizing the earth slope using a stone column, in addition to being compatible with the environment, is also a useful and economically efficient method causing the endangered slopes to become stabilized to a great extent. According to tests accomplished and confirmed by numerical analysis, the following results were obtained:

- The results showed that the optimal location for the stone column is in the middle of the slope, because the maximum displacements are occurred in the middle of the slope.
- The factor of safety increases significantly by the use of rigid stone columns.
- The RSC causes shear strength enhancement up to 1.41 times the OSC.
- The RSC enhanced the slope stability up to 40.6 percent compared to that of the OSC.

- The use of cement grouts inside a stone pillar changes the failure mode and the rigid stone column failure occurs as bends while the rupture in an ordinary stone column takes place as the shear failure. This rigidity caused by cement grout enhances the stability and bearing capacity of the slope.

Using ordinary and rigid stone columns is an effective and useful method, which is highly capable of stabilizing the slopes exposed to risk.

However, natural slopes behave differently from what was shown in the present research. Therefore, further research is recommended using full-scale tests or centrifuge model tests.

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