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Experimental and Numerical Investigation of Reinforced Sand Slope Using Geogird Encased Stone Column

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ABSTRACT: Among all of the slope stability methods, use of stone columns and geosynthetic elements can be a good way for stabilizing. One of the efficient ways in order to reinforce earth slopes is Geogrid Encased Stone Column (GESC). This technique can dramatically increase bearing capacity and decrease settlement rate. The aim of this paper is experimentally to investigate a comparison between the behavior of Ordinary Stone Column (OSC) and GESC for reinforcing of sand slopes. The slope was constructed using raining technique and reinforced using GESC. The slope saturated through precipitation and loading procedure applied. The obtained results compared and verified with 3D Finite Difference Method (3DFDM). Both experimental and numerical analyses indicated that location of GESC in middle of the slope increases the bearing capacity of slope crown 2.17 times than OSC.

Keywords: Geogrid Encasement, Sand Slope, Stabilization, Stone Column.

INTRODUCTION

Earth slope stabilization is one of the fundamental issues in advances of human lives. Stone columns could increase bearing capacity, decrease settlement rate, increase shear strength of surrounding soil, control liquefaction, and provide drainage condition. Stone columns act as a stiff element, which occasionally subjected to lateral forces, so use of geogrid as an encasement around these columns results in increase of stone column shear strength, and better and further stabilization of surrounding soil.

Earth slopes bearing capacity categorized as an important issue, which researchers have been dealing with (Mofidi et al., 2014; Haghbin and Ghazavi, 2016). The history of stone column first use go back to France in 1830 (Dheerendra et al., 2013), this technique widely use in European countries and all around the globe since 1960s (Han and Ye, 2001). Stone columns have three main failure mechanism under compression loads: bulging (Hughes et al., 1975), general shear failure (Greenwood, 1970), and sliding (Aboshi et al., 1979). Stone columns can serve as a function of increasing bearing capacity (Gueguin et al., 2015), decreasing total and differential settlement (Castro et al., 2013), decreasing liquefaction potential (Han and Ye, 2002), improving slope stability (Connor and Gorski, 2000; Marandi et al., 2016), and bearing much shear stresses (Madhav and Miura, 1994).

Stone columns bearing capacity depends

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on lateral stresses, due to this matter, is necessary to provide additional confining in some soils. In this regard, different techniques presented which one of them is use of geogrid layers as encasement. Efficiency of using geogrid encasement around stone columns investigated and confirmed by various researchers (Fattah and Majeed, 2012; Lai et al., 2014; Zhang et al., 2016; Fattah et al., 2016; Gu et al., 2017; Debnath and Dey, 2018). Kempfert (2003) indicated that reinforced stone columns have better function in comparison to ordinary stone columns. Sivakumar et al. (2004) by conducting a series of triaxial test on sand columns in ordinary and reinforced conditions confirmed the efficiency of encasement. Results of Choobasti et al. (2014) showed that encasement role in decreasing surface settlement is more significant due to higher confining pressure around stone column. Encasement of stone columns decrease settlement rate, increase load bearing capacity, reduce lateral displacement. By increasing the stiffness of encasement, GESC can significantly improve performance of surrounding soil (Khabbazian et al., 2014). Only after loading intensity is heighten, the effects of encasement are significant (Yoo, 2015).

In spite of extensive researches performed in this regard, there is a dearth of literature on the use of GESC in slopes in order to increase their stability. The present study aimed to better and further understanding of behavioral mechanisms for geogrid encased stone columns in sand slopes improvement. A series of experimental modeling performed and 3DFDM applied to verify the obtained results, and it illustrated that results of both experimental and numerical methods were consistent with each other. Experimental models were reinforced using OSC and GESC and saturated through artificial rainfall process.

EXPERIMENTAL EQUIPMENT

Test Box

The test box consists of four parts, which are water supply system, modeling part, drainage section, and piezometer boards (Figure 1). Box sides were rigid enough to maintain plane strain conditions to prevent lateral movements. Glass walls allow seeing the model during construction, precipitation, and loading process. Size of this box is as follow: 20 cm in width × 55 cm in height × 142 cm in length.

Sand (Slope Material)

Kermanshah washed sand used in this investigation and the properties of applied sand using direct shear test presented in Table 1 (The elastic modulus obtained based on the stress-strain curve from direct shear test, and Possion's ratios was obtained using reference of textbooks with regard to modulus of elasticity, friction angle, and type of material). Grading conducted using dry sieve analysis and the result shown in Figure 2.

Table 1. Properties of Sand

Dry unite weight (kN/m^3)	**16**
Friction angle (°)	38
Cohesion (kPa)	≈ 0.0
Elastic modulus (MPa)	30
Poisson's ratio	0.3
Specific gravity	2.65
Maximum void ratio	0.6
Minimum void ratio	0.3

Fig. 1. Test box and piezometer panel used for experimental modeling of slopes

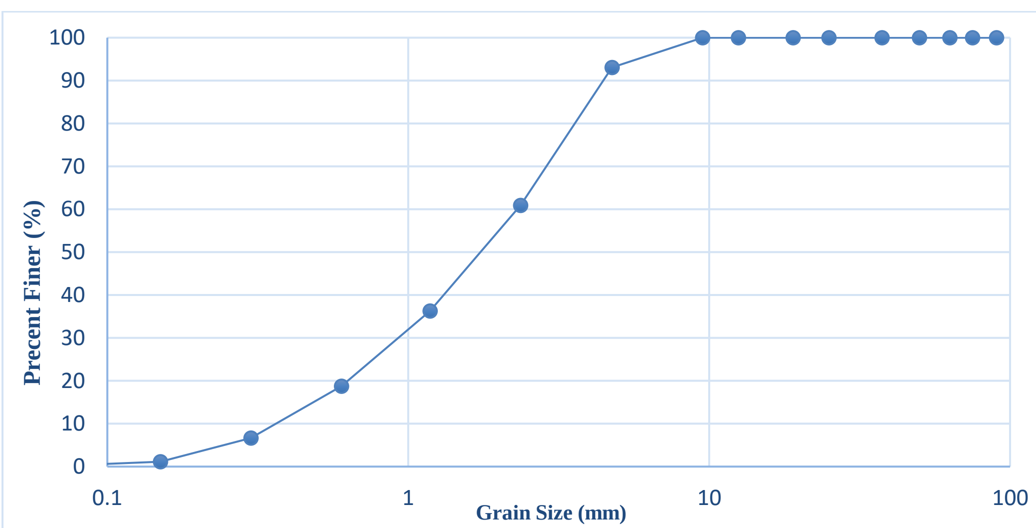

Fig. 2. Grain size distribution of sand

Gravel (Stone Column Material)

Table 2 illustrates the physical characteristics of the stone column provided by direct shear test. For construction of ordinary stone column, a plastic encase with a diameter of 3.6 cm were used (this diameter was chosen to eliminate the impact radius due to the limited width of the box, so that with a distance of 5 times greater than radius from the box sides, their effects on stone column can be eliminated). This encase was placed in the desired location before modeling and in each step during modeling the required amount of gravel, with regard to stone column density, poured into it and compacted with a specific bar. The stone column particles passed through 1.25 cm sieve but they left on sieve No. 4.

Geogrid (As Encasement Element)

The geogrid layer used in this research shown in Figure 3 and its properties (based on Manufacturer Company) presented in Table 3. Properties of geogrid used in 3D numerical analysis are as follows:

Isotropic material: Young's modulus (E) and Poisson's ratio (v). E obtained using the relationship ($J = E \times t$) in which, J: is tensile strength (kN/m); t: is geogrid thickness (1 mm), by solving the equation the amount of E obtained 7680 kPa. Poisson's ratio considered 0.2 (the common value used in numerical analysis related to geogrid analysis).

Coupling spring stiffness per unit area (k) is set equal to the slope of the pull out stress versus displacement plot. According to Beneito and Gotteland (2001) and the manual of 3D Finite Difference software, this relation is $k = \Delta S/\Delta U$ in which, S: is pull-out stress, and U: is pull-out displacement. In this research, we used the manual of software for the value of k, which is 2.3×10^6 (N/m^3). As summary; J = 7.68 kN/m; t = 2 mm; E = 7680 kN/m^2; ν = 0.2; K = 2.3×10^6 N/m^3.

Table 2. Properties of Stone Column

Dry unite weight (kN/m^3)	**17.5**
Friction angle (°)	42
Cohesion (kPa)	≈ 0.0
Elastic modulus (MPa)	100
Poisson's ratio	0.2
Specific gravity	2.60
Maximum void ratio	0.75
Minimum void ratio	0.35

Fig. 3. Geogrid layer used in experimental modeling

Table 3. Geogrid properties

Model name	**CE121C**
Opening dimensions (mm)	6 × 8
Weight (gr/cm^2)	730
Composed material	HDPE (High Density Polyethylene)
Ultimate tensile strength (kN/m) (based on ASTM)	7.68

EXPERIMENTAL MODELING

In order to study the effects of geogrid encased stone columns on slopes, three types of models built and examined. The first model was an unreinforced sand slope, and underwent raining operation and saturation. The second model included a reinforced slope used ordinary stone column (OSC) in the middle of the slope (as optimal location), raining operation, and then saturation. The third model was a sand slope reinforced using geogrid encased stone column (GESC) in the middle of the slope, and saturation same as before. In each phase of loading, its time duration maintained constant until the slope gained balanced, and then the next loading phase applied. The following conditions considered for all three models.

A. In order to eliminate friction effects of test box sides as much as possible, they lubricated.

B. In all three models, the length of slope crest, slope height, and the total height of the model were 15, 30, and 45 cm, respectively. The slope angle considered about 37 degrees, with regard to the internal friction angle of dry sand (38 degree), in order to balance out during construction.

C. After completion of construction, a thin layer of cement grout poured on the slope surface in order to prevent leaching (Since the role of this grout is just prevention of leaching of slope surface during saturation process, it has no effect on stability and strength of models. This is a common method in order to maintain stability of slope against surface leaching).

D. Artificial rainfall technique used to saturate models (with steady rate of 2 Lit/min).

E. Drainage in slope carried out through downstream section of the test box.

F. In reinforced slopes, bottom of the stone column have a distance of 5 cm (about 1.43 times the column diameter) to the box floor, in order to overcome the fixed end of the floor.

G. Sand slope constructed in one layer with a dry density of 16 kN/m^3 and stone column density in reinforced slopes was 17.5 kN/m^3.

H. The models built using raining technique in layers with a thickness of 50 mm (Raining technique or dry pluviation, used in this paper performed through a box in which at first sand poured into, then at specified height from the test box the sand poured into box. This technique allow us to obtain a uniform density all over the box).

I. Geogrid encasement constructed as a cylindrical shape with diameter of 3.6 cm, which filled with specified amount of gravel.

Unreinforced Slope

Figure 4 shows the unreinforced slope. By constructing unreinforced slope in dry condition, and pouring the thin layer of grout on the surface (Figure 5), the slope was stable as expected. Afterward, this model underwent the artificial rainfall process. By passing about 45 minute of saturation process, some cracks appeared in the middle section of the slope and few minutes later, slope ruptured completely. This indicates that unreinforced sand slope is unstable in saturated state. Figure 6 shows the complete failure of unreinforced slope due to saturation.

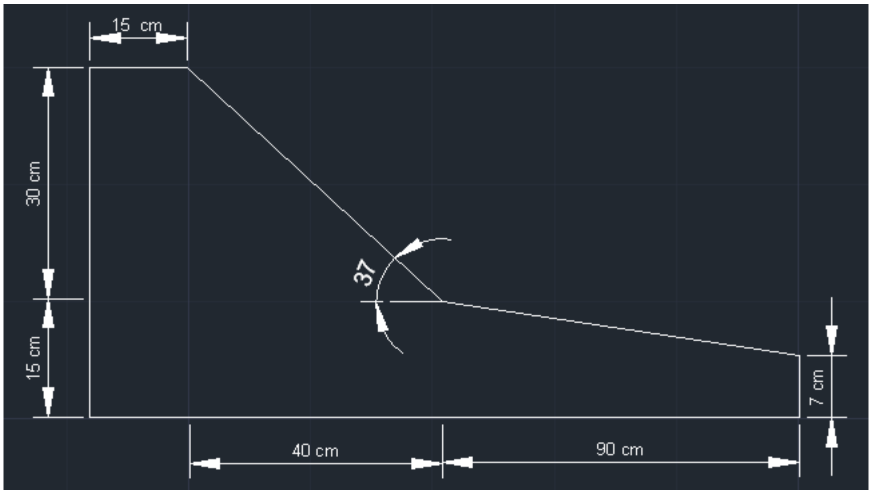

Fig. 4. Geometry of unreinforced slope

Fig. 5. Unreinforced slope modeled in test box

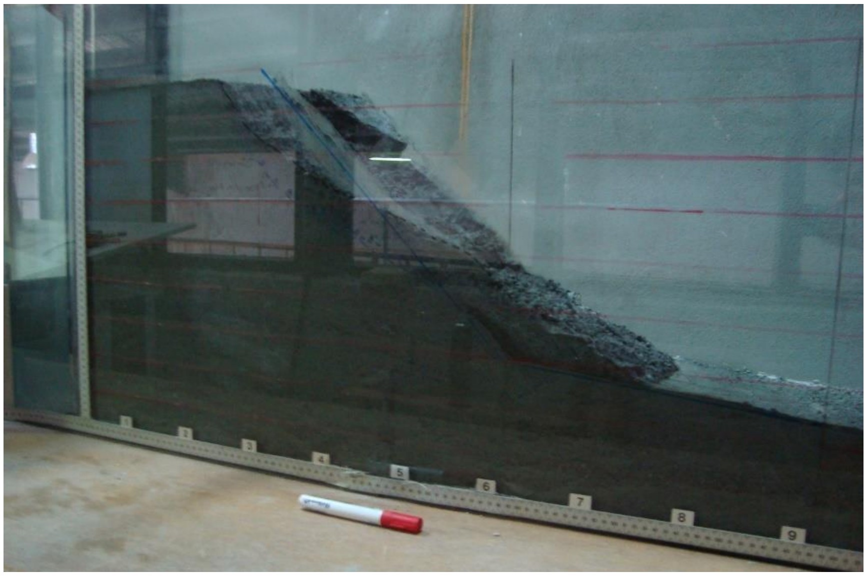

Fig. 6. Failure of unreinforced slope due to saturation

Reinforced Slope Using OSC

Based on the previous studies (Hajiazizi and Nasiri, 2016; Hajiazizi et al., 2018; Hajiazizi and Nasiri, 2018) in sand slopes, the optimal location for stone column placement is the middle of the slope. Therefore, the OSC (and GESC) placed in the middle of the slope in reinforced slope tests. At first inner and outer walls of the plastic encase were lubricated (in order to facilitation of the plastic encase pull out after construction). In beginning, this encase placed in the desired location (on the first 5 cm layer) and gravel were poured into it and compacted by each layer of embankment construction. Finally, this plastic encase pulled out gently and a thin layer of grout was poured on the slope surface to prevent leaching, same as before. Figures 7-9 show the geometry of slope, constructed model, and stone column location, respectively.

When the model was completed, the slope is saturated through precipitation. After about 120 minutes of the slope saturation, no visible cracks created on the slope surface, so it can be deducted that stone column reinforcement, increased safety factor of the sand slope. The slope crest was underwent gradually loading to reach failure (loading rate was approximately 1 kg per 10 minute). Ultimately, slope failed under a pressure of 6.26 kPa. In Figure 10 failed slope and slip surface illustrated.

Reinforced Slope Using GESC

In order to perform this test, geogrid encased stone column installed in the middle of the slope. At first, geogrid layer shaped as cylinder with diameter of 3.6 cm (Figure 11). Then the GESC placed in its location and slope model constructed (Figure 12) and same as before in order to prevent leaching under rainfall, thin layer of grout poured on slope surface.

Artificial rainfall process began and after about 120 minutes, the slope was completely saturated and slope was stable. In the next step, the slope crest was put under gradually loading same as before (loading rate was approximately 1 kg per 10 minute) to determine ultimate failure stress. The geogird encased stone column resisted very well during loading and finally, the slope failed under a pressure of 13.59 kPa. The important issue in this part is slip surface in reinforced slope using GESC, in contrast to slope reinforced using OSC, did not pass through stone column and it was ceased in upper part of stone column (Figure 13). In this condition, upper wedge of GESC failed, while lower wedge was stable.

NUMERICAL MODELING

The numerical analyses were performed using 3DFDM. The factor of safety is calculated using strength reduction technique. Strength reduction technique is typically applied for calculation of safety factor by reducing the shear strength of the cohesion and friction angle to obtain factor of safety equal to 1.

In order to determine optimal meshes for each case, sensitive analysis performed and final results are as below: unreinforced slope (3000 elements), slope reinforced by OSC (3240 elements) and slope reinforced using GESC (3311 elements). Mohr-Coulomb criterion considered as behavior model for sandy slope and stone column considered as cylindrical element same as laboratory model (Figure 14). Reinforcing stone column performed by wrapping geogrid layer around column element (Figure 15). Numerical results are compliant with laboratory modeling. Lateral boundaries were fixed along x and y axes, and the bottom boundary was fixed along x, y and z axes.

Numerical Analysis of Unreinforced Slope

By modeling unreinforced slope in saturated condition, safety factor obtained

0.96 (Figure 16). Slope was unstable in this state and it was what exactly seen in experimental modeling.

Numerical Analysis of Reinforced Slope Using OSC

The slope reinforced by OSC was analyzed using 3DFDM. The slope was modeled in saturated condition and results indicated that reinforce slope using OSC is stable in saturated condition. Finally, the slope analyzed under crest overburden loading and the critical pressure for slope failure obtained 6.01 kPa (Figure 17). As it is illustrated, critical slip surface pass through stone column (same as experimental modeling).

In Laboratory, ultimate bearing capacity of slope was 6.26 kPa, this amount in numerical analysis obtained 6.01 kPa, and the differences are about 1 percent.

Numerical Analysis of Reinforced Slope Using GESC

In final step, the reinforced slope using geogrid encased stone column numerically modeled. Same as before slope was stable in saturated condition. At last, the slope analyzed with overburden stress, and the slope failure stress obtained 13.17 kPa (Figure 18). As seen in this figure, critical slip surface, same as experimental modeling, did not pass through GESC and failure wedge was in upper part of column.

In Laboratory, the ultimate bearing capacity of this slope was 13.59 kPa, while in numerical result this amount obtained 13.17 kPa. Both analyses are compliant with each other and their differences were about 1 percent. Table 4 presents results of experimental and numerical modeling.

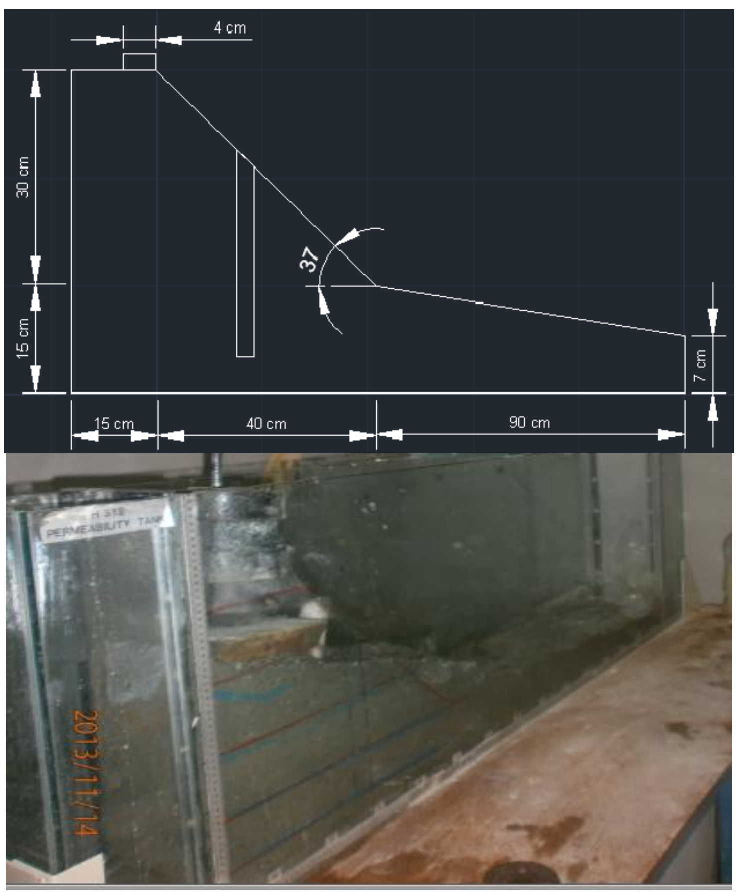

Fig. 7. Geometry of reinforced slope and position of loading

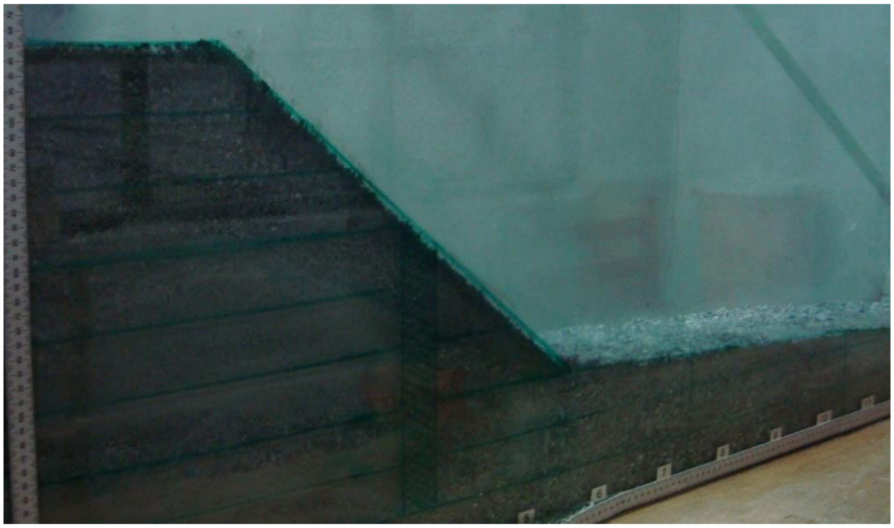

Fig. 8. OSC reinforced slope modeled in test box

Fig. 9. OSC location in reinforced slope

Fig. 10. Failure of OSC reinforced slope under overburden stress of 6.26 kPa

Fig. 11. Geogrid Encased Stone Column (GESC)

Table 4. Experimental and numerical results in saturated condition

Model	Bearing capacity (experimental)	Bearing capacity (numerical)
Unreinforced slope	(Unstable) Zero	(Unstable) Zero
Reinforced slope using OSC	6.26 kPa	6.01 kPa
Reinforced slope using GESC	13.59 kPa	13.17 kPa

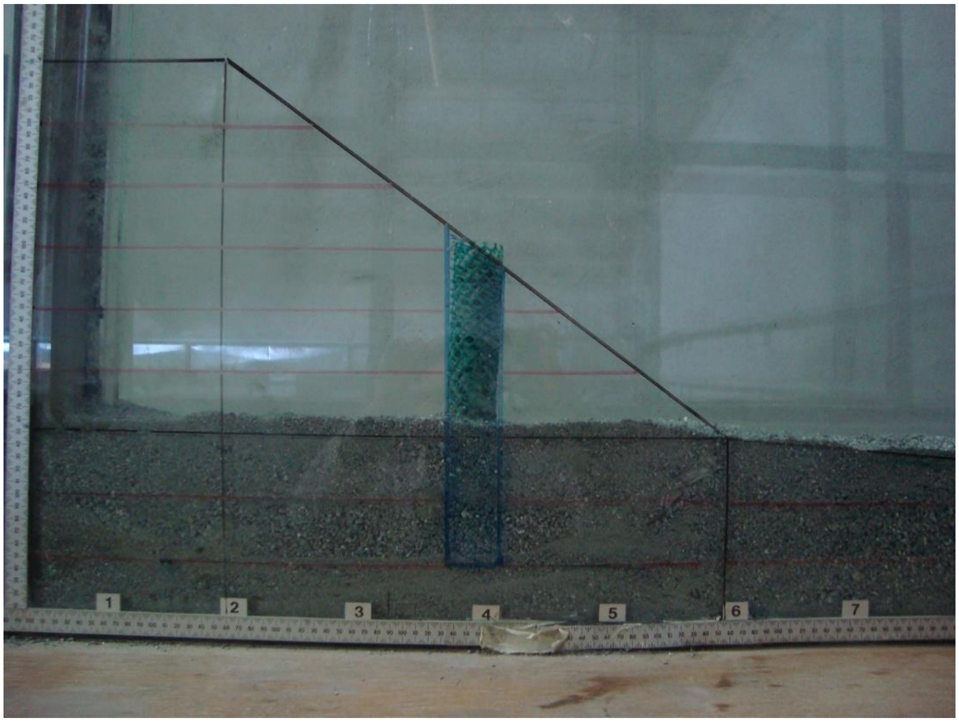

Fig. 12. GESC placement in reinforced slope

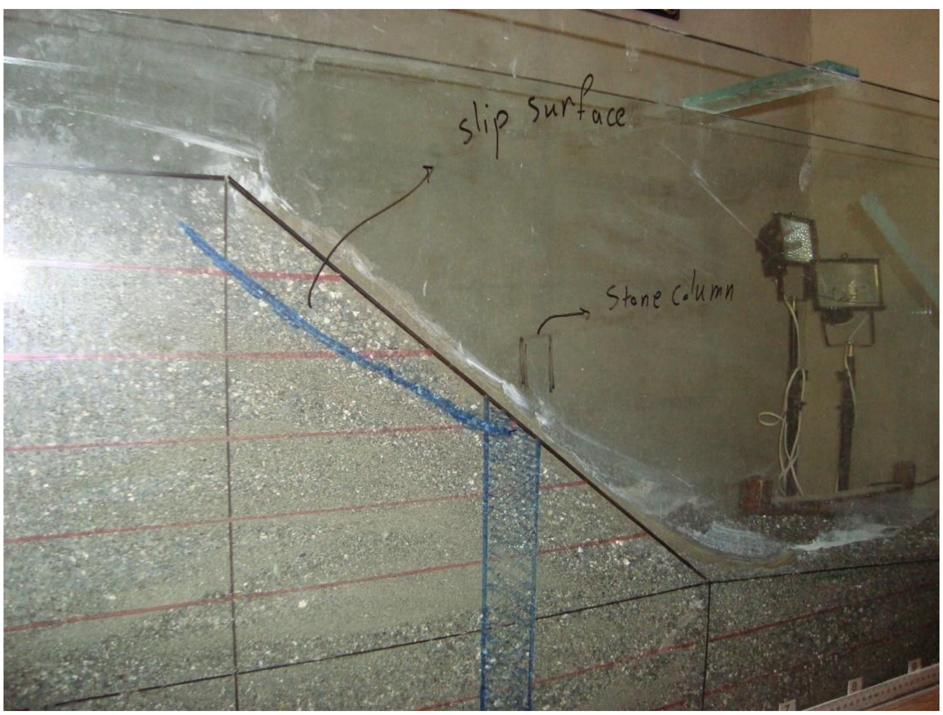

Fig. 13. Failure of GESC reinforced slope under overburden stress of 13.59 kPa

RESULTS AND DISCUSSION

Experimental modeling and numerical analysis performed for unreinforced sandy slopes, reinforced slopes using both OSC and GESC. It is notable that GESC increases bearing capacity of the slope up to 2.17 times than OSC. After installation of geogrid encased stone column, critical slip surface changed and in contrast to OSC, did not pass through stone column. This encasement cause scission of slip surface (as result increase in shear strength and bearing capacity of reinforced slope) and in case of GESC, upper wedge of stone failed. The bearing capacity enhancement caused by high elastic modulus and confinement of stone, which provided by geogird layer.

Under overburden pressure, after displacement of the stone column. Geogird encased stone column prevents the development of failure plane and resists to lateral deformations until the slope failed. Using geogrid encasement increases resistance to applied loads and lateral displacements significantly and enhances stability of the sand slope.

Comparison between OSC and GESC

In this study, the failure of the OSC observed as a shear failure whereas, sliding failure occurred to the GESC, which increased slope stability. Encased stone column increased bearing capacity of the slope up to 2.17 times the ordinary stone column and enhanced stability of the slope significantly. The results of this research indicated that, unreinforced saturated sandy slope is unstable and failed and if geogrid encased stone column installed to reinforce this slope, its stability increased in such a way that bearing capacity increase up to 13.59 kPa. Use of encased stone column significantly helps stabilization of sand slopes.

SCALE EFFECTS

Sawwaf (2005) suggested that 1-g models could be useful only in prediction of general behaviors of prototypes. In this regard, Hegde and Sitharam (2015) conducted that small-scale 1-g model tests help to approximate information about general behavior of the prototypes quicker and simpler than the large-scale tests. However, the large-scale tests have better control over key parameters of the model. It should mentioned that, scale effects affect the results of small-scale tests and results obtained from g-1 models are not directly applicable to the prototypes. As proposed by Fakher and Jones (1996), the results of the small-scale tests can extrapolated to prototype by applying scaling law carefully. They also showed that, it is not possible to create completely similar conditions for model and prototype due to involvement of several complex factors and it should left to judgment of the researchers to decide about these influencing factors. The numerical analysis performed in this paper were based on scale effects information, which obtained 1 to 100 (i.e. the numerical models dimensions were 100 times of small-scale experiments) (Hajiazizi and Nasiri, 2016). According to the items listed above and Sawwaf (2005) proposal, it is recommended to carry out further investigations using large scale tests or centrifuge model tests in order to compare with the results obtained from this research.

The mechanical properties of earth slope and geogrid such as cohesion, friction angle, etc. are fixed in the experimental model and the actual model. Differences in the experimental model and the actual model are in length, area, time, force, and mass that are converted according to the Table 5 (Hajiazizi and Nasiri, 2016).

Table 5. Converting any experimental model into a real with scale ratio S (Hajiazizi and Nasiri, 2016)

	Time	Length	Area	Force	Mass
Real	T	L	A	F	M
Experimental model	$\sqrt{S}T$	SL	S^2A	S^2F	S^3M

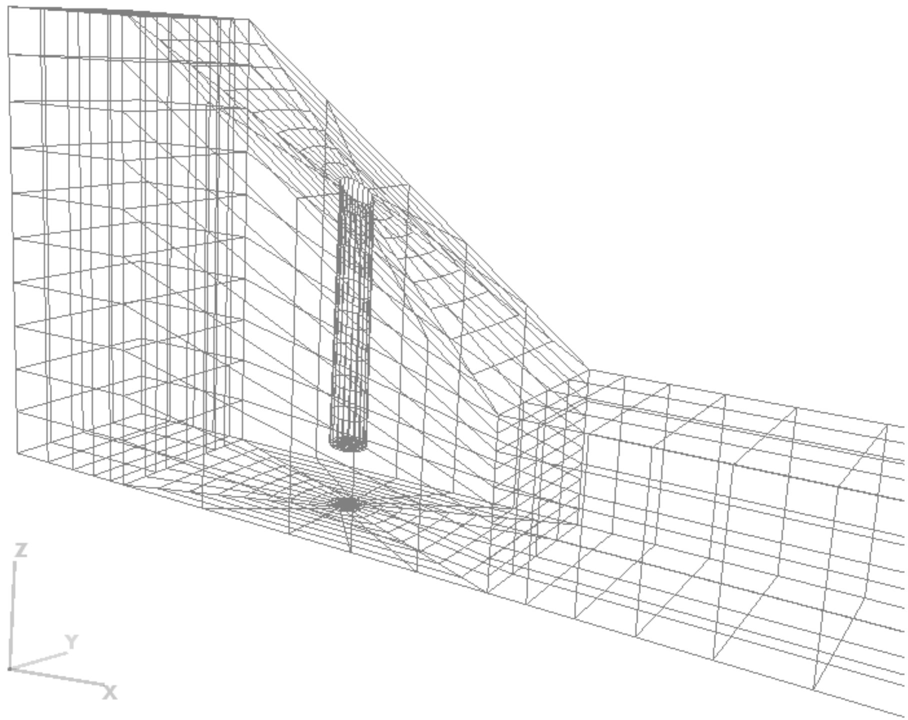

Fig. 14. Geometry of reinforced slope in numerical analysis (stone column location and distance from bottom of model illustrated)

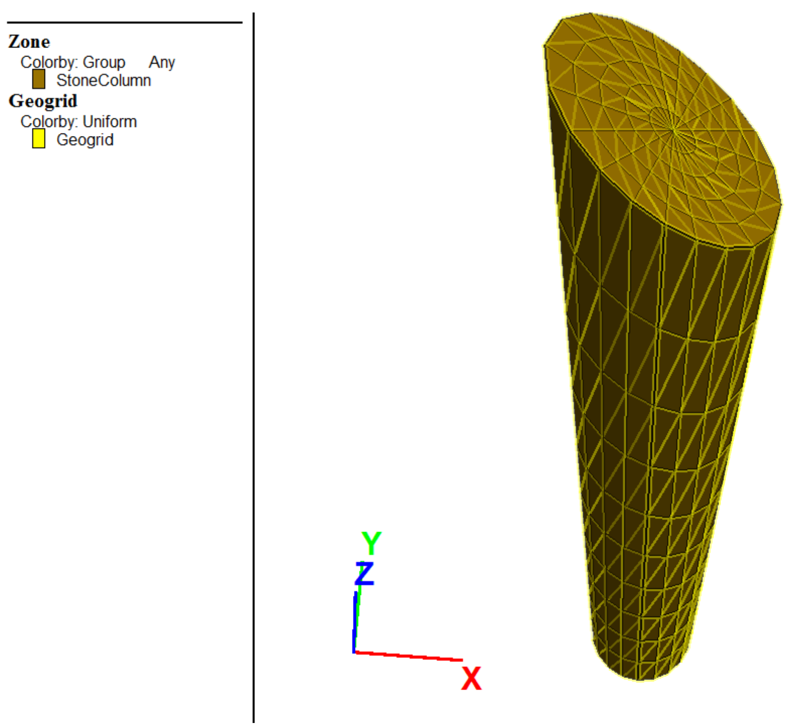

Fig. 15. Wrapping geogrid layer around stone column in order to model GESC

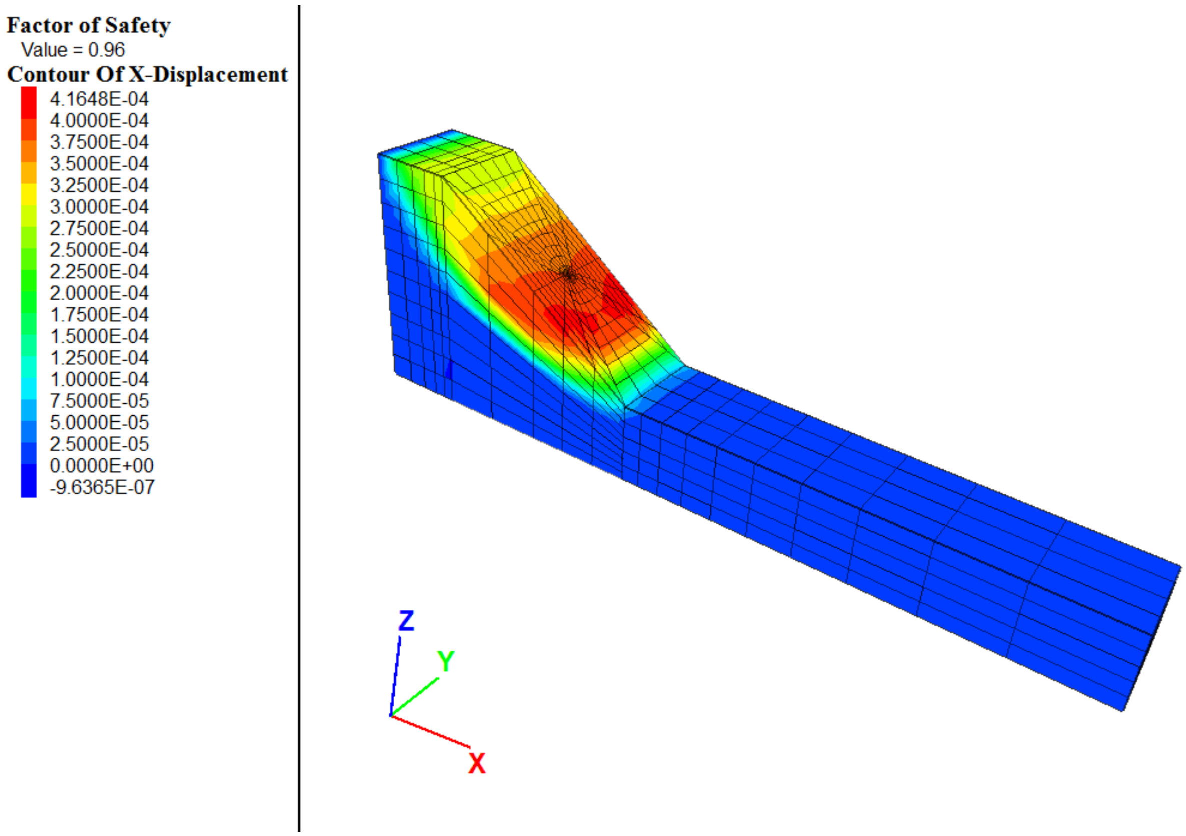

Fig. 16. Unreinforced slope F.S. in saturated condition

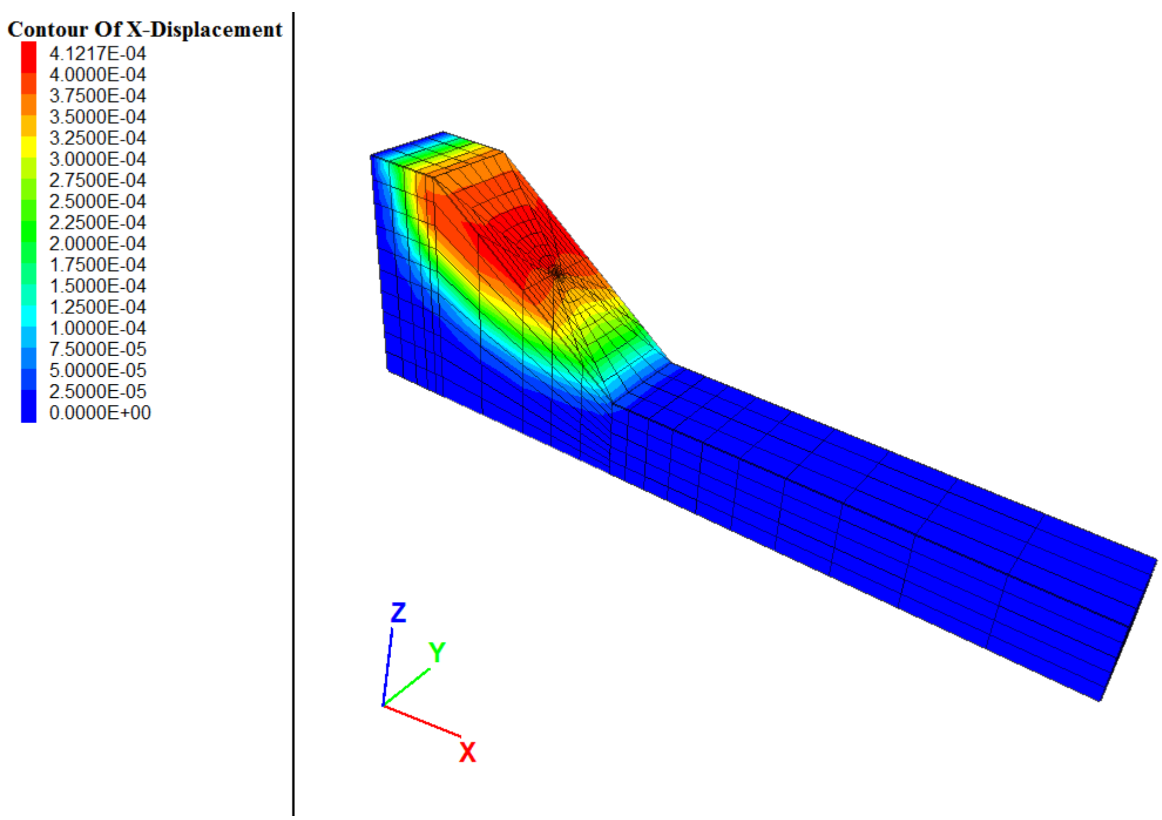

Fig. 17. Failure of reinforced slope using OSC under overburden stress of 6.01 kPa

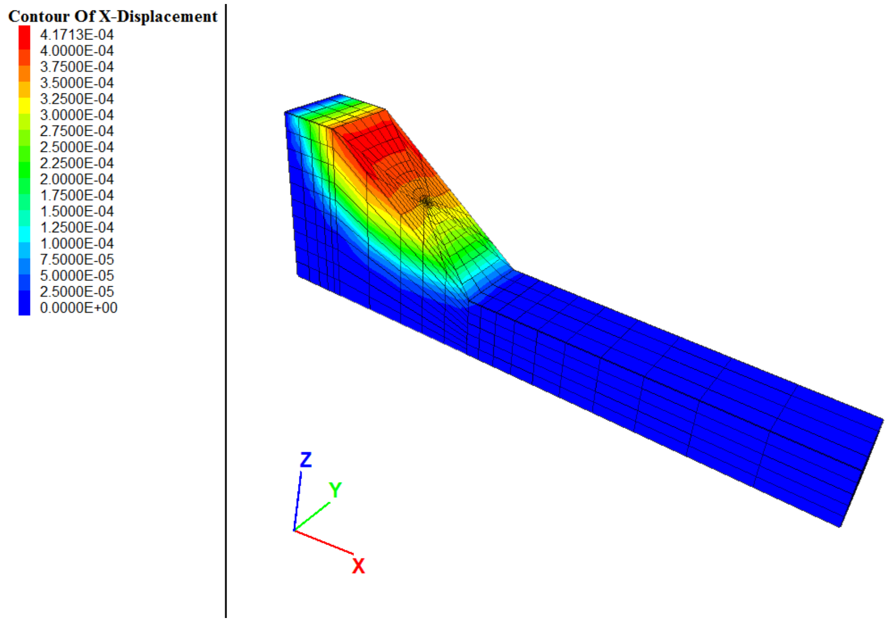

Fig. 18. Failure of reinforced slope using GESC under overburden stress of 13.17 kPa

CONCLUSIONS

The aim of this paper was experimentally to investigate a comparison between the behavior of OSC and GESC for reinforcing of sand slopes. A series of experimental modeling and 3DFDM analyses performed. Results of experimental models are properly consistent with the results obtained by 3DFEM. There are several results, which are considering:

1. GESC is an efficient way in order to reinforce earth slopes to increase the bearing capacity of slope crown.
2. The GESC resisted very well during loading and the slope failed at pressure of 13.59 kPa while the slope failed at pressure of 6.26 kPa using OSC.
3. GESC increases shear strength of slope up to 2.17 times than OSC.
4. Encased stone column changes the failure mode from shear failure to sliding failure.

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