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3D Numerical investigation of excavation in sandy ground reinforced using different types of geosynthetics

Masoud Nasiri [a, *], Hassan Sharafi [a]

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

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ABSTRACT

Stabilization of excavations and retaining walls are important issues in the geotechnical field. The use of new and novel methods in excavation sites, and providing safe conditions for the final aim of the project is one of the challenging matters in this regard. Excavation in sandy soils, due to lack of enough cohesion for its stability, faces serious problems. In order to solve this problem, using special techniques to improve stability is a very important subject. Geosynthetics (i.e. geotextile, geogrid, and geocell) are among the new techniques, which could enhance the stability and performance of sandy soils. In this research, 3D finite different analysis was performed to investigate unreinforced and reinforced excavations using geotextile, geogrid, and geocell elements and their comparison. Results indicated that in the case of using geotextile, geogrid and geocell the critical depth of excavation increased up to 3.125, 2.75, and 2.25 times of unreinforced excavation, respectively.

Keywords: *Excavation, Sandy Soil, Geotextile, Geogrid, Geocell*

1. Introduction

Each digging occurred under the natural surface of the earth or the baseline of the adjacent building foundation, known as excavation. The common examples of excavation are diggings in order to construct the basement, cutting trenches for tubing, and soil removal in order to construct roads and highways.

The loss and damages of excavation can be the cause of the following matters; optimistic and unrealistic prediction of site condition, underestimation of buildings settlements, misunderstanding of stabilization methods limitations, loading, and environmental conditions, misinterpretation of static and dynamic forces such as traffic loads and so on [1]. Reinforced soil walls were investigated by various researchers [2-6]. To enhance the site performance, different methods for reinforcing excavations were proposed and investigated [7-10], which among these approaches, the use of geosynthetics is one of the applicable methods.

Geosynthetic reinforced excavations have been widely used in both practice and research [11-12]. This technique can significantly decrease the cost of the project and improve the overall stability and performance of excavation walls. The selection of an appropriate excavation method plays a significant role in civil engineering projects [13]. The first use of geotextile to reinforce the earth was back in 1953 in the Netherland, in which a high tide killed 2000 people [14].

Selection of an appropriate excavation necessarily considers many factors such as construction budget, allowable construction period, the existence of adjacent excavations, availability of construction equipment, area of the construction site, condition of adjacent buildings, and foundation types of adjacent buildings [15].

The results of Hsiung's [16] study on an excavation in sandy soil show that the creep rate of wall movement caused in the non-supported stage of the excavation varies between 0.14 and 0.38 mm/day. Hsiung et al. [17] indicate that the soil modulus E plays a key role in predicting the wall displacement induced by an excavation. Settlement in sandy soils caused by dewatering is a kind of irreversible settlement, so the ground settlement of a deep excavation caused by good dewatering cannot be ignored during the design and construction of excavation engineering [18]. Konai et al. [19] performed a series of shake-table tests on an excavation in sands. The results of their research indicate that in a post-seismic condition, when other factors were constant, lateral displacement, bending moment, strut forces, and maximum ground surface displacement increased with excavation depth and the amplitude of base acceleration. According to the results of Bahrami et al. [20] analysis, the error rate in 2D analysis increases with decreasing depth of excavation and increasing soil stiffness. Therefore, 2D analysis is not a suitable approach to analyze the behavior of retaining walls in excavations up to depths of 10m or shallower or in dense sand, and a 3D analysis is recommended for such excavations. Shi et al. [21] showed that by increasing the relative sand density 30–90%, the pile settlement decreases by up to 66%. It is found that the excavation in loose sand, did significantly increase the ground movements induced by the excavation [22].

The finite difference approximations for derivatives are one of the simplest and oldest methods to solve differential equations. The advent of finite difference techniques in numerical applications began in the early 1950s and their development was stimulated by the emergence of computers that offered a convenient framework for dealing with complex problems of science and technology. Theoretical results have been obtained during the last five decades regarding the accuracy, stability, and convergence of the finite difference method for partial differential equations. The principle of finite difference methods is close to the numerical schemes used to solve ordinary differential equations. It consists of approximating the differential operator by replacing the derivatives in the equation using differential quotients. The domain is partitioned in space and in time and approximations of the solution are

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* Corresponding author. *E-mail address:* nasiri.ma@razi.ac.ir (M. Nasiri).

computed at the space or time points. The error between the numerical solution and the exact solution is determined by the error that is committed by going from a differential operator to a different operator. This error is called the discretization error or truncation error. The term truncation error reflects the fact that a finite part of a Taylor series is used in the approximation [23].

2. Modeling Characteristics

The objective of this research is to investigate the performance of excavation in unreinforced and geosynthetic reinforced sandy soil. The analysis was performed using the 3D Finite Difference Method (3D F.D.M.); the model dimensions (Fig. 1) are 10 × 10 × 10 meters. Due to the importance of excavated zone, the number of meshes in this section was finer than other parts as shown in this figure. Cutting in X and Y directions were 2 meters (cutting in Z direction was a variable parameter in this paper). Sensitivity analysis was performed in order to obtain optimal meshes, after analyzing various conditions, the optimal mesh in this research was gained 22500. To build a condition similar to a natural situation, soil used in this research was selected from a project with a retaining wall and geosynthetic elements (i.e. geotextile, geogrid, and geocell) selected from previous researches. In all models, two conditions for reinforcement were used. First, reinforcement which begins at the start of excavation (30 cm below the earth surface) with 30, 50, and 70 cm distance from each other (case A), and the second one which, reinforcing element placed at the level of 80 centimeters below earth surface (the critical excavation depth for unreinforced model), with the same distances (case B). In this research, for boundary conditions static states were implemented, in which, lateral boundaries were fixed along x and y axes, and the bottom boundary was fixed along x, y, and z axes. Sand characteristics are shown in table 1, and geosynthetic elements (i.e. geotextile, geogrid, and geocell layers) are presented in table 2. In all models, excavation steps were 10 cm. in this paper the total amount of 220 F.D. analysis was performed and compared.

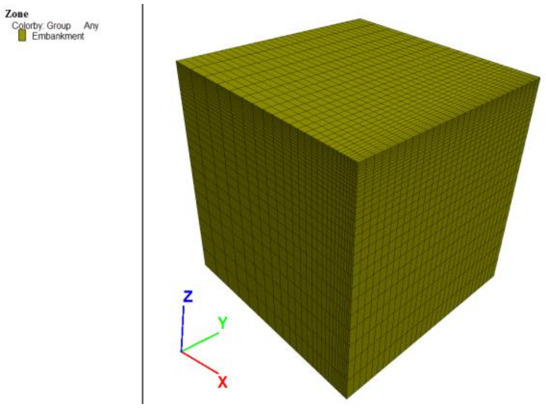

Fig 1. Excavation Model in 3D Finite Difference Method Analysis

Table 1. Sand Characteristics

	Unite Weight (kN/m³)	Young's Modulus (MPa)	Poisson's Ratio (-)	Friction Angle (φ)	Cohesion (kPa)
Embankment [24]	19	10	0.3	38	0.0

Table 2. Geosynthetic Characteristics

	Elastic Modulus (MPa)	Poisson's Ratio (-)	Interface Shear Modulus (MPa/m)	Interface Cohesion (kPa)	Interface Friction Angle (φ)	Thickness (mm)
Geotextile [25]	400	0.3	-	-	-	1
Geogrid [26]	210	0.33	2.36	0.0	18	1.5
Geocell [26]	275	0.45	2.36	0.0	30	1.5

3. Unreinforced Excavation

In this section, the behavior of unreinforced excavation is discussed. For this purpose, in each phase of 10 cm excavation, the results of displacements and factors of safety were obtained. Critical depth of excavation (the depth in which, stability of excavation remains), were obtained 80 cm (Fig. 2). The values of factor of safety are presented in Fig. 3, the depth in which instability occurred and the wall collapsed (i.e. the factor of safety dropped below 1), is 90 cm. Maximum displacements that occurred in X and Z directions are illustrated in Fig. 4. As it is indicated, up to 30 cm of excavation, the value of safety factor is practically having the same amount. However, by reaching 40 cm of excavation, the value of the factor of safety becomes one-fourth and finally, by reaching 90 cm of digging, the value of safety factor dropped below 1 (which means the failure of the excavated wall). Also, the amounts of displacements in X and Z directions are steady up to 50 cm of excavation, after passing this depth, the displacements will have a considerable increase.

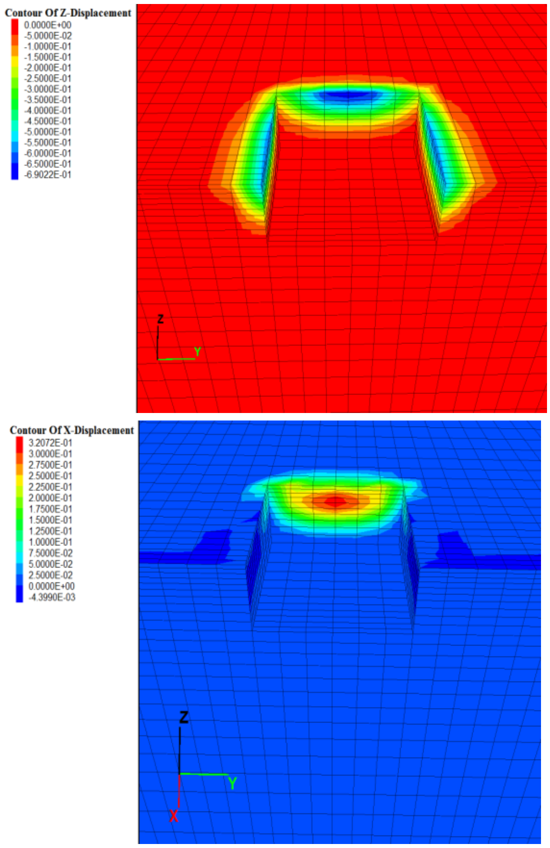

Fig 2. X and Z Displacement Occurred in Critical depth of Excavation in Unreinforced Model.

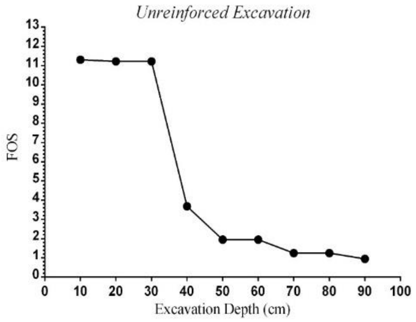

Fig 3. FOS Results of Different Excavation Depth for Unreinforced Model

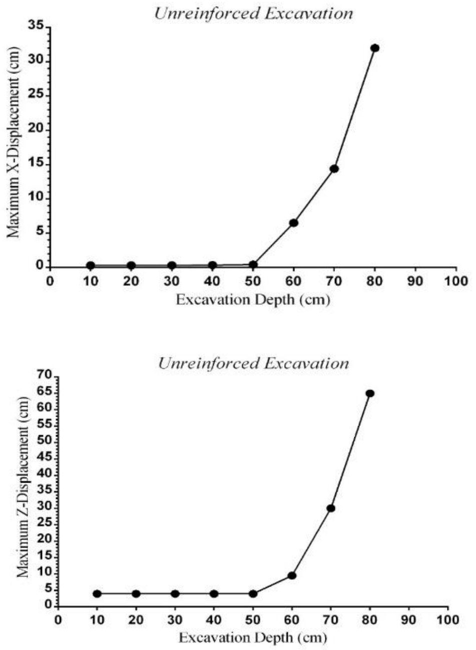

Fig 4. Maximum X and Z Displacement Occurred in Different Excavation Depth for Unreinforced Model

4. Geotextile Reinforced Excavation

In this part, the behavior of geotextile-reinforced excavation will be discussed. For this purpose, in each phase of 10 cm excavation, the results of displacements and factors of safety were obtained. In this research two-geotextile layers in two different conditions were used. First, reinforcement at beginning of excavation (30 cm below ground surface) with distances of 30, 50, and 70 cm. Second, reinforcement begins from 80 cm below ground surface (the critical depth of unreinforced excavation) with the same space of 30, 50, and 70 cm (all the calculations performed for excavation depth after 90 cm, in which, it was unstable in unreinforced case). Fig. 5 illustrated the results of safety factor analysis in the geotextile-reinforced ground. As it is indicated in this figure, a maximum factor of safety is dedicated to a space of 50 cm (in case of A); furthermore, this condition also has the least critical depth. Distance of 30 cm follows the same pattern. However, the drop of safety factor in this situation, is considerable (the critical depth is the same in both distances and it was 150 cm). The distance of 70 cm between layers, have the same value in seven steps, and finally failed in the depth of 190 cm. the main important point here, is that when using the case B of reinforcing (installation from the critical depth), a collapse occurred in the same depth (190 cm). In addition, the factor of safety is the same up to the depth of 180 cm and is less than the latter state. For 50 and 70 cm distances, the factor of safety is approximately the same, but they will collapse in 230 and 260 cm of excavation. This indicated that in order to reinforce excavation in sandy soil, the best arrangements of geotextiles are two-layer with 70 cm distance, which, install at the critical depth of the unreinforced ground. The maximum displacements, in this case, are presented in Fig. 6. As indicated, the maximum displacements are of 70 cm distance and the minimum ones are that of 50 cm distance (although in this case, the least amount of critical depth obtained). However, the behavior of reinforcing elements, which installed in the critical depth is different. They followed the specific pattern of increase up until they reach maximum displacement in collapse condition; the maximum displacement is that of 70 cm space, which prepares the highest stable depth for sandy excavation. This figure shows the optimal performance of using a two-geotextile layer with 70 cm distance, which installs at a critical depth of unreinforced excavation.

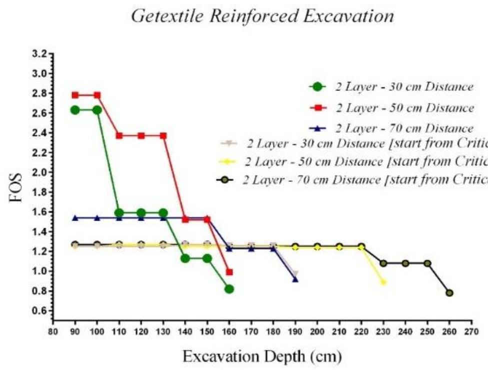

Fig 5. Results of Factor of Safety for Reinforced Models using Geotextile Layers with Different Excavation Depth

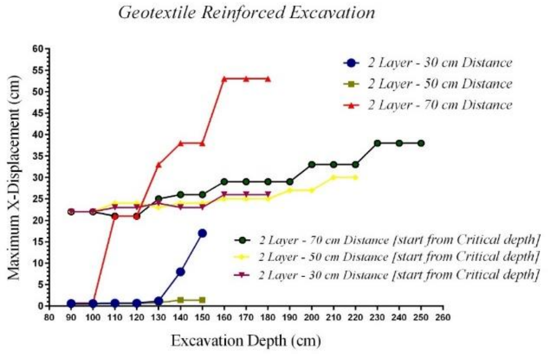

Fig 6. Results of Maximum X-Displacement in Different Excavation Depth for Reinforced Models using Geotextile Layers

5. Geogrid Reinforced Excavation

In this section, the behavioral analysis of excavation in the geogrid reinforced ground was investigated. In each phase of 10 cm excavation, the results of displacements and factors of safety were obtained. In this research two-geogrid layers in two different conditions (case A and B) were used. First, reinforcement was installed at beginning of excavation (30 cm below ground surface) with distances of 30, 50, and 70 cm. Second, reinforcement installation begins from 80 cm below ground surface (the critical depth for unreinforced excavation) with the same space of 30, 50, and 70 cm (all the calculations performed for excavation depth after 90 cm, in which, it was unstable in unreinforced condition). Fig. 7 illustrated the results of safety factor analysis for geogrid-reinforced ground excavation. As indicated in this figure, the maximum factor of safety belongs to a 30 cm distance among layers. However, this condition has the minimum critical depth. The distances of 50, and 70 cm, have a different patterns, but finally, they collapsed in one depth (in 160 cm of excavation). In the case of geogrid installation, beginning from critical depth, the behavior tends to be linear. However, the important point is that in contrast to geotextile (which this distance was the optimal arrangement); the space of 70 cm is the worst case of arrangements. There is no evident difference between 30, and 50 cm distances, and both were collapsed at the depth of 190 cm excavating. In Fig. 8 the maximum displacements occurred in X direction shown for geogrid-reinforced excavation. As indicated in this figure, the maximum displacement belongs to 70 cm space, and the least displacement belongs to 30 cm distance. In the case of reinforcing from the critical depth, having the same behavior, the maximum displacements in the x-direction for both 30 and 50 cm, are approximately the same. According to these results, the optimal arrangements in the case of using geogrid layers are one of 30 or 50 cm distance.

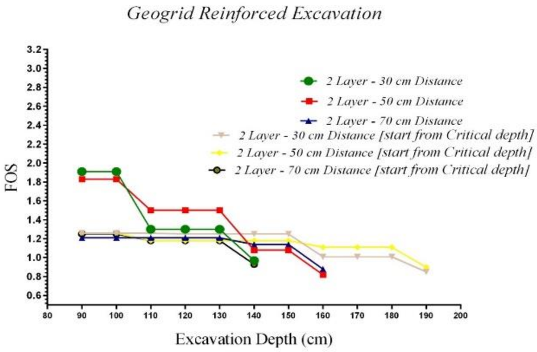

Fig 7. Results of Factor of Safety for Reinforced Models using Geogrid Layers with Different Excavation Depth

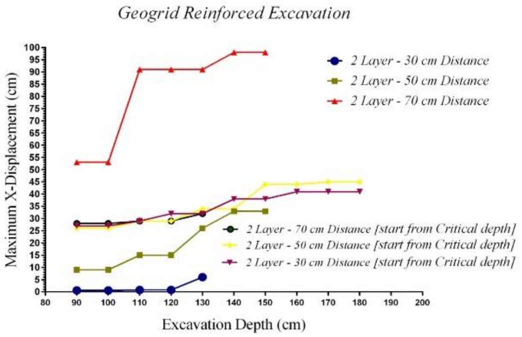

Fig 8. Results of Maximum X-Displacement in Different Excavation Depth for Reinforced Models using Geogrid Layers

6. Geocell Reinforced Excavation

This part investigates and discusses the behavior of geocell-reinforced excavation. To this aim, in each phase of 10 cm excavation, the results of displacements and factors of safety were gained and discussed. In this research two-geocell layers in two different conditions were used. First, reinforcement at beginning of excavation (30 cm below ground surface) with distances of 30, 50, and 70 cm. Second, reinforcement begins from 80 cm below ground surface (the critical depth for unreinforced excavation) with the same space of 30, 50, and 70 cm (all the calculations performed for excavation depth after 90 cm, in which, it was unstable in unreinforced case). Fig. 9 illustrates the results of safety factor analysis in the geocell-reinforced ground. As indicated in this figure, the maximum safety factor obtained from a distance of 30 cm, have the minimum critical depth among others and collapsed in the depth of 160 cm. Behavior and critical depth for 50 cm distance are the same as the later state. However, the distance of 70 cm and all three states in which the installation begins from critical depth, have a similar pattern. Distances of 70 cm (case A) and 30 cm of second condition (case B) have one critical depth (180 cm) and distances of 50 cm (case A) and 70 cm of second condition (case B) have the same critical depth (220 cm). Fig. 10 shows the maximum displacements that occur in the X direction for geocell-reinforced ground. According to this figure, we can understand that the maximum displacements belong to 70 cm space from the first state (case A) and the least displacements are belong to 30 cm distance in the first case (case A). The behavior of all three distances in case B is the same, although in this condition after one semi linear procedure in the adjacent of critical depth, the displacements experience an increasing jump in their values. Based on obtained results in this section, it can interfere that the optimal condition for using geocell layers in order to reinforce excavation in sands is the use of 50 cm distance in case B, in which displacements are less and have the maximum factor of safety.

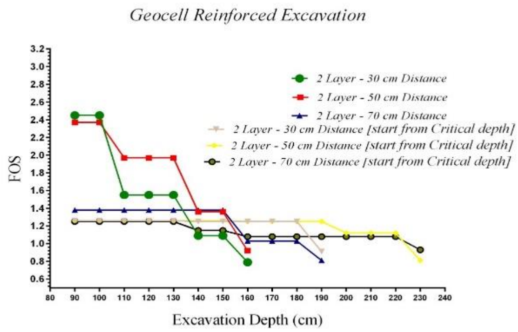

Fig 9. Results of Factor of Safety for Reinforced Models using Geocell Layers with Different Excavation Depth

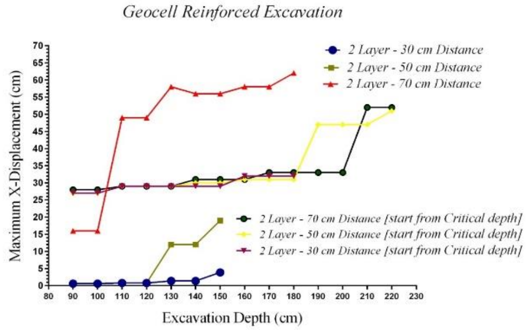

Fig 10. Results of Maximum X-Displacement in Different Excavation Depth for Reinforced Models using Geocell Layers

7. Discussion

In this research, the behavior of excavation in the sandy ground was investigated. The novel findings of the presented paper are the comparison of three geosynthetic layers as excavation reinforcements, their arrangements, and the critical depth in each case. Three reinforcing elements (i.e. geotextile, geogrid, and geocell) were used in order to reinforce excavation walls of sandy ground. In the case of the unreinforced model, the critical depth was 80 cm and after excavating 90 cm, the walls collapsed and the safety factor dropped below 1. Two cases of reinforcement (case A and case B) were used in this paper, to enhance the stable excavation depth of sandy soils. In case A, installation of reinforcing elements starts from the beginning of excavation (30 cm below the ground surface) with distances of 30, 50, and 70 cm. In the second case (case B), these reinforcing elements start from an elevation of 80 cm below ground surface (the critical depth in state of the unreinforced ground) with the same spaces of 30, 50, and 70 cm. Each reinforcing elements have their own special behavior and provide a different stable condition for excavating in sandy ground. In all models, the steps of excavation were 10 cm. In this research, the total number of 220 models were performed using the 3D finite difference method (3D F.D.M.). The numerical analysis indicated that for geotextile-reinforced excavation, using a two-geotextile layer with 70 cm distance in case B is efficient, in the case of using geogrid, either 30 or 50 cm distance (case B) is effective, and for geocell reinforced excavation, 50 cm distance of case B is the optimal arrangements. In the unreinforced model, up to 30 cm excavation in the sand, the FOS value did not change. However, after this elevation, the value of FOS dropped sharply and decreased approximately 3.5 times. In the Geotextile reinforced model, (in the case of optimal arrangement) while the value of the safety factor did not change significantly, the excavation depth in the safe zone is approximately twice of other layers' arrangements. This result indicates that the higher value of FOS does not necessarily provide higher critical depth. The same pattern followed in the case of reinforcement using geogrid and geocell layers, in which for optimal arrangements the value of safety factor did not change significantly but the excavation depth in the safe zone is higher than that of other layers. In the case of reinforcing sand beds using geosynthetic layers (i.e. geotextile, geogrid, and geocell) besides FOS value, the displacements that occurred in the sidewalls should also be considered carefully, in order to find the critical depth of excavation. The obtained results of the presented paper indicate that both FOS value and displacements in excavating area should be carefully considered since merely one of these parameters could be misleading in the final judgment.

8. Conclusion

The obtained results of 3D F.D.M. analysis for excavating in sandy ground reinforced using geotextile, geogrid, and geocell elements are presented below:

1-In excavating the unreinforced sandy ground, the maximum critical depth can be found 80 cm, in which, by reaching half of this depth (i.e. 40 cm), the value of the safety factor decreases to one-fourth of the first half excavation.

2- The best type of reinforcing element among these three geosynthetic is geotextile layers (it improve the depth of excavation up to 250 cm). The value of the safety factor using this technique is the highest among all three geosynthetics.

3-The second reinforcement element in the case of increasing critical excavation depth belongs to geocell layers which ensure the safety of excavating walls up to 220 cm.

4-The last one in this ranking is geogrid layers in which we can reach the maximum depth of 180 cm.

5-In the case of using geotextile, geocell, and geogrid layers, the critical depth of excavation becomes 3.125, 2.75, and 2.25 times of unreinforced ground, respectively.

6-Since merely one of the displacements or FOS values could not perfectly estimate the critical depth of excavation in sand beds, when using geosynthetic layers as reinforcements, both of these parameters should consider carefully.

Each case of reinforcement (i.e. geotextile, geogrid, or geocell layers) has its own optimal arrangement. In order to find the best location and distance of each layer using 3D analysis is strongly suggested

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