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Optimization of Tension Absorption of Geosynthetics through Reinforced Slope

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ABSTRACT

A series of direct shear tests were carried out on a sandy soil to evaluate the effect of optimum reinforcement orientation through the geosynthetic reinforced slopes. The main aim of the research was to find out how reinforcement should be installed through the shear box with respect to shear plane and regarding to absorbing maximum tension forces. For finding this optimization angle, a large-scale direct shear box was used. The reinforced soil specimens (30.4 × 30.4 × 15.0 cm) were installed through the shear box in five different forms including 0, 30, 45, 60, 90 degree of reinforcement respect to vertical axis of shear box. Based on the results gained from the research, the optimization angle of reinforcement that both shear displacement and soil dilation have caused the most tension stress in dry sandy soils was between 45 and 60 degree with respect to shear failure plane. It was because of the better interaction of the coarse granular soils with geogrid apertures. Finally, a series of two-dimensional finite element simulations were carried out using the results of optimum direction to describe the behavior of reinforced slope under different reinforcement directions with respect to shear failure plane.

KEYWORDS: Reinforced slope, Optimum Direction, Shear Behavior, Numerical Modeling

INTRODUCTION

Reinforced slopes are basically compacted fill embankments that incorporate geosynthetic tensile reinforcement arranged in horizontal planes. The tensile reinforcement holds the soil mass together across any critical failure plane to ensure stability of the slope (Koerner, 1986). On the one hand, geosynthetic reinforced soil has gained considerable popularity due to its wide application in the construction of geotechnical structures such as retaining walls, foundations, embankments, pavements, etc. Since Vidal first employed it in 1966, significant advances have been made in the design and construction of the system. The use of geosynthetics increases bond in the soil system due to the interlocking of the soil particles with the reinforcement aperture as well as enhancing the bearing resistance of the transverse members of the reinforcement. The effectiveness of the reinforcements in contributing an increase in the shear resistance is highly dependent on the orientation of the reinforcements with respect to the failure plane (Smoltczyk, 2003). Commonly, direct shear test used in order to model the failure shear plane in intersection with reinforcement. Furthermore, the direct shear test data can be used in the design of geosynthetic applications in which sliding may occur between the soil and the geosynthetic. Note that the direct shear test can also be conducted to study the geosynthetic–geosynthetic interface frictional behavior by placing the lower geosynthetic specimen flat over a rigid medium in the lower half of the direct shear box and the upper geosynthetic specimen over the previously placed lower specimen (Saran, 2006). It should be noted that the direct shear test is not suited for the development of exact stress–strain relationships for the test specimen due to the non-uniform distribution of shearing forces and displacement. Total resistance may be a combination of sliding, rolling, and interlocking of soil particles and geosynthetic surfaces, and shear strain within the geosynthetic specimen. Shearing resistance may be different on the two faces of a geosynthetic and may vary with direction of shearing relative to orientation of the geosynthetic. The direct shear test data can be used in the design of geosynthetic applications in which sliding may occur between the soil and the geosynthetic. Note that the direct shear test can also be conducted to study the geosynthetic–geosynthetic interface frictional behavior by placing the lower geosynthetic specimen flat over a rigid medium in the lower half of the direct shear box and the upper geosynthetic specimen over the previously placed lower specimen (Shukla and Yin 2006). The present study is aimed to investigate the load transfer mechanism between geogrids in different directions respect to shear failure plane and soil by direct shear strength increase. Then, by using the same method in case of reinforced slope a series of two-dimensional finite element simulations will be used in order to evaluate the effect of changing reinforcement direction respect to shear failure plane on stability parameters and tension absorption of reinforcement layer.

Idealized Failure Element in Reinforced Slope

The action of reinforced soil can also be understood by visualizing two steep slopes one of which is reinforced and other unreinforced as shown in Figure 1. In unreinforced system it is apparent that the shear resistant that can develop on a failure surface is given by Eq. 1.

$$P_{\text{resisting}} = P_{\text{v}} \tan\phi \tag{1}$$

Where: P_v is the vertical load in the shear box or the normal load in the failure surface in an unreinforced slope. If a reinforced soil element as shown in Figure 1 is now considered in a similar manner, the corresponding shear box analogy is as given in Figure 2 (Jewell, 1996).

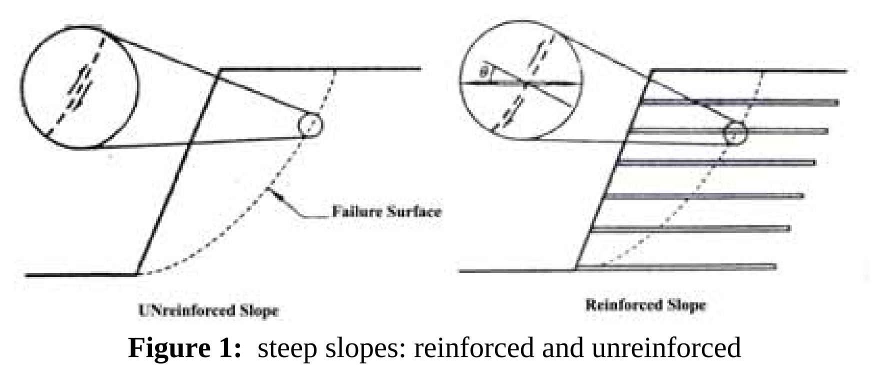

Figure 1: steep slopes: reinforced and unreinforced

Form the resolution of forces within the reinforcement and shearing soil element, it can be seen that the reinforcement has two beneficial effects on the shear resistance of the reinforced soil mass.

- There is a reduction in the shear force through the horizontal component of the tensile force in the reinforcement.
- There is an increase in the normal force applied to the shear surface, and hence an associated increase in the shear resistance derived from the vertical component of the tensile force in the reinforcement.

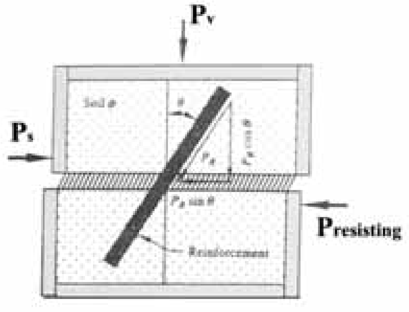

Figure 2: Idealized failure element in reinforced slope, (Resistant Forces) (Jewell and Worth, 1987)

The shearing resistant of the element of reinforced soil is increased from that given in Eq. 1 to that given in Eq. 2.

$$P_{resisting} = P_v \tan\varphi + P_R(\sin\theta + \cos\theta\tan\theta) \tag{1}$$

Fundamental studies have shown that the reinforcement is most effective when aligned in the direction of tensile strain in the soil, so that a tensile reinforcement force develops (McGown et al., 1978). The orientation (θ in Figure 2) of the reinforcement with respect to the potential shear plane is the only geometry variable in Eq. 3 (Jewell & Worth, 1987). It should be mentioned that in Bauer and Zhao (1993) research, θ has selected the angle between reinforcement layers and tangent line along the shear failure surface in intersection of reinforcement and potential shear plane.

Hence it is apparent that the inclination of the reinforcement is the governing factor for determining how much additional shear resistance is generated by the inclusion of the reinforcement. Figure 3 demonstrates the variations of the function given in Eq. 2 with respect to different θ and φ angles. The optimum angle can also be obtained analytically by differentiating Eq. 2 with respect to θ, as follows.

$$\frac{dP_R}{d\theta} = P_R\cos\theta - P_R\sin\theta\tan\varphi = 0 \tag{2}$$

$$\Rightarrow \cos\theta = \sin\theta\tan\varphi$$

$$\Rightarrow \cos\theta = \tan\varphi$$

$$\Rightarrow \tan(90-\theta) = \tan\varphi$$

$$\Rightarrow \text{Hence } \theta_{opt} = (90-\varphi)$$

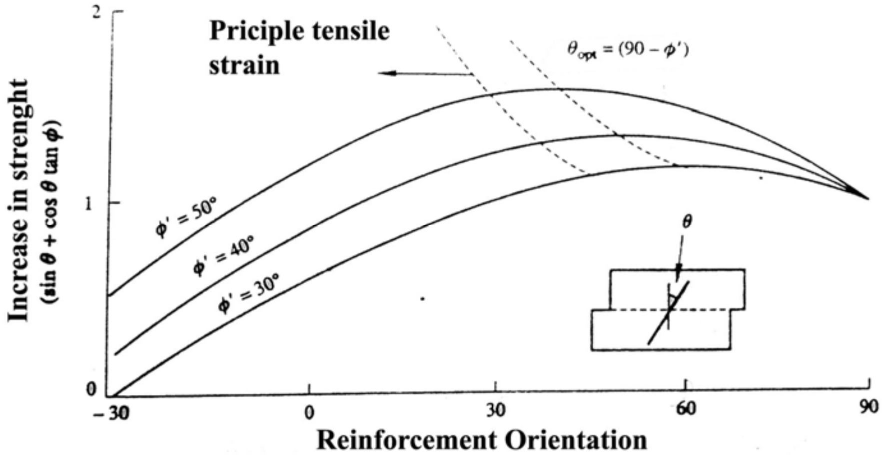

Figure 3: shear resistance versus reinforcement orientation (Jewell, 1996)

It can be seen from Figure 3 that the optimum orientation for the reinforcement is given by θ_{opt} = (90 – φ). In practice, the degree of improvement is critically dependent upon the magnitude of the mobilized reinforcement force (P_R) (Jewell, 1996). It is observed that two physical factors require consideration in evaluation of P_R. The maximum force that the reinforcement can carry ultimately is governed by the bond between the soil and reinforcement. The bond is at maximum when the maximum compressive stress in the soil acts perpendicular to the plane of the reinforcement. The stiffness of the reinforcement influences the soil shear deformation required to mobilize the reinforcement force. The maximum possible tensile strain in the reinforcement is equal to the tensile strain in the adjacent soil in the direction of the reinforcement. Thus, reinforcement oriented in the direction of maximum tensile strain will experience the greatest elongation for any given shear deformation in the soil (Babu, 2006). Moreover, such a result means that the maximum efficiency should be anticipated when the orientation of the reinforcement coincides with the direction of the tensile strain of the soil. The use of geogrids as reinforcement will also increase the bond between soil and reinforcement due to the bearing resistance of the transverse members of the geogrid as well as interlock of the soil particles with the geogrid apertures. However, the interaction mechanism between geogrid and soil and the mobilization of tensile strain in the reinforced soil are not yet well understood and this phenomenon needs additional experimental exploration (Koerner, 1986).

Factors Affecting Behavior and Performance

Reinforcing soil is essentially a construction technique. Hence, a number of factors influence the performance and behavior of reinforced soil, apart from external loading and the environmental conditions (Saran, 2006).

Reinforcement: the role of reinforcement in the behavior of reinforced soil is influenced by its form, surface properties, dimensions, strength and stiffness.

Geogrids depend on the interfacial friction and bonding besides the interlocking effect, which develops when aggregates occupy the space in the apertures of the geogrids. Surface properties play a crucial role in the mobilization of friction and tensile forces in the reinforcement. The higher the frictional force between the soil and the reinforcement more is the tensile force and hence more efficient is the effect of reinforcement in the reinforced soil structures.

Reinforcement distribution: factors relating to reinforcement distribution such as location, orientation, and spacing affect the behavior of reinforced soil. As demonstrated earlier, the effect of reinforcement is in maximum when placed in the direction of tensile strains. Tensile strains induce reinforcement force leading to increased stability.

Soils: the properties of the soil of a reinforced soil structure affect its performance considerably. Factors such as index properties, particle size, grading and mineral content need to be considered.

SAMPLE PREPARATION AND TESTING PROGRAM

As mentioned before, direct shear tests are a suitable mean to study the interaction between soil and reinforcement because they can simulate the shear mechanism along a potential failure plane in a reinforce earth structure (Mofiz et. al 2004). Direct shear tests were performed on dry sand reinforced with different types of discrete reinforcement. The effect due to the reinforcement orientation was investigated. In unreinforced case, the soil was then compacted in a 300 mm x 300 mm shear box mould by machine compaction to the desired height and unit weight at the dry condition. In the case of reinforced soil, the reinforcement consisted of 300 mm x 350 mm size geogrid that was cut from the sheet and placed inside the soil in different orientations. Five series of tests were carried out on both the unreinforced and reinforced soil at normal pressures varying between 50-200 kPa and the strain rate of 1.0 mm/min. This rate is in the range recommended in the research manual (Bauer and Zhao, 1993). All the tests were run following immediately the placement and compaction of soil in the shear box which represent mainly the short-term conditions developed in the corresponding field application. Moreover, the tests were conducted on Iran Azma shear box equipment using different load and deformation transducers.

Material Properties

Soil Properties

As can be seen from Figure 4 the soil which selected for the laboratory testing classified as sand. It is due to appropriate interaction between granular soils and geogrid reinforcement through the loading. Furthermore, It is well known that geosynthetic reinforced soil normally utilizes granular soil as its backfill material. Thus, most studies and design methods and charts are well established on the use of such materials

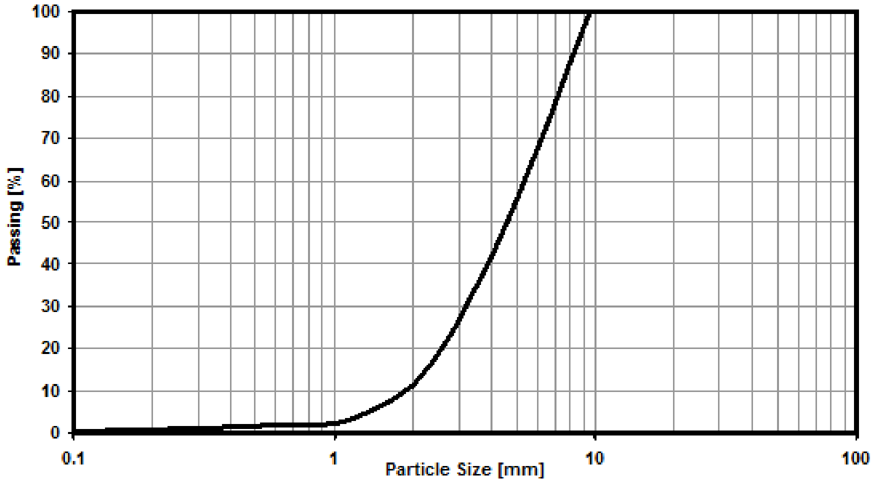

Figure 4: grain size distribution of sample sandy soils

It should be mentioned that the sandy soil which used in present study was completely non plastic. Also, because of both uniformity coefficient, C_u=2.75 and coefficient of curvature of grading, C_c=0.93 it was classified as a poorly graded. In addition, sandy soil was compacted through the shear box at 67% relative density.

Reinforcement Properties

Geogrid specimen was placed at the middle of two halves filled with specified soil. Required normal stress was applied and as mentioned the specimen was sheared at the rate of 1.0 mm/min. The various properties of geogrid are given in Table 1.

Table 1: Input parameters for geogrid.

Parameter	
Geogrid type	Huesker (Fortrac)
Polymer	polyethylene
Aperture shape	Rectangle
Aperture size (MD/XD)(mm)	20/20
Rib thickness (mm)	0.75
Junction thickness(mm)	2.8
Tensile strength at 5% strain (kN/m)	
MD	30<
XD	80<
MD=machine direction	
XD=cross machine direction	

As can be seen from the Figure 5 geogrid as a reinforcement was placed through the shear box and direct shear tests were carried out in order to find about shear behavior of soil-reinforcement interface. It should be mentioned that after each test, geogrid placement will change. It is due to shear displacements which cause obligatory shear force through the reinforced soil body. Not only relative displacement can be observed by drawing the initial and final position of reinforcement but also final displacement which causes failure into the reinforced soil body can be specified.

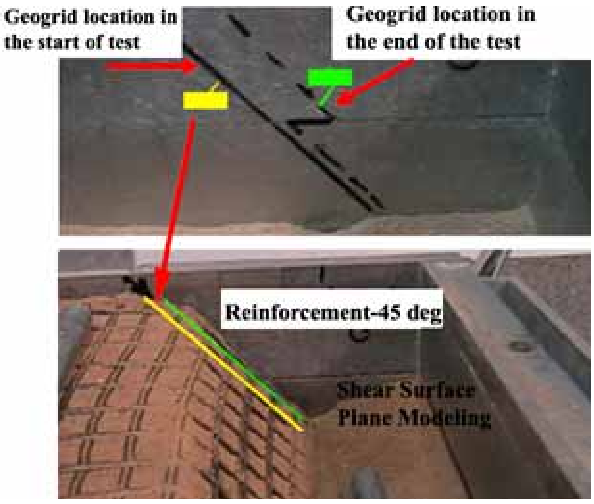

Figure 5: geogrid situation change after test, 45 degree reinforcement orientation

Results of Laboratory Testing

The test results of unreinforced soil with different interfacial normal stresses are shown in Figures 6 to 9. The shear stress-shear displacement plot indicates that the relative shear displacement corresponding to maximum shear stress increases with interface normal stress. Figure 6 to 8 show the shear stress versus horizontal displacement behavior for reinforced soil with different interface normal stress. As it was expected, the reinforced soil samples exhibit, except horizontal layer which showed lower shear interface parameter other ones showed higher shear strength than unreinforced samples. It is observed that, the maximum shear strength was attained at higher shear strains in reinforcement. The shear stress of unreinforced specimen was reduced after the post peak value. On the other hand for reinforced soil, strain-hardening behavior was observed due to conversion of brittle for the unreinforced soil to ductile behavior of the composite material. The shear stress and shear displacement of all unreinforced and reinforced samples at the initial shearing were similar since the effect of the reinforcement will only begin to function at some finite shear displacement.

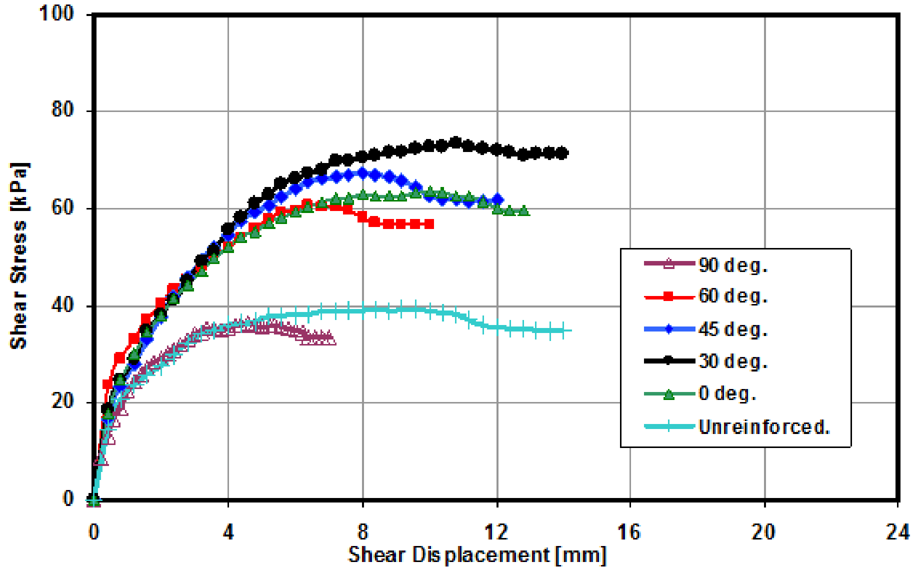

Figure 6: shear behavior of reinforced soil through shear box in normal stress equal to 50 kPa

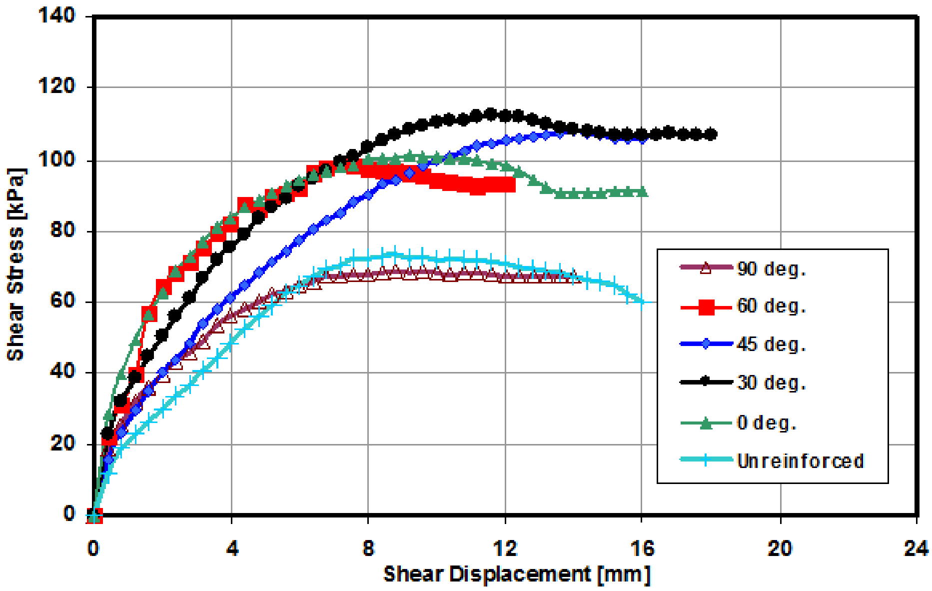

Figure 7: shear behavior of reinforced soil through shear box in normal stress equal to 100 kPa

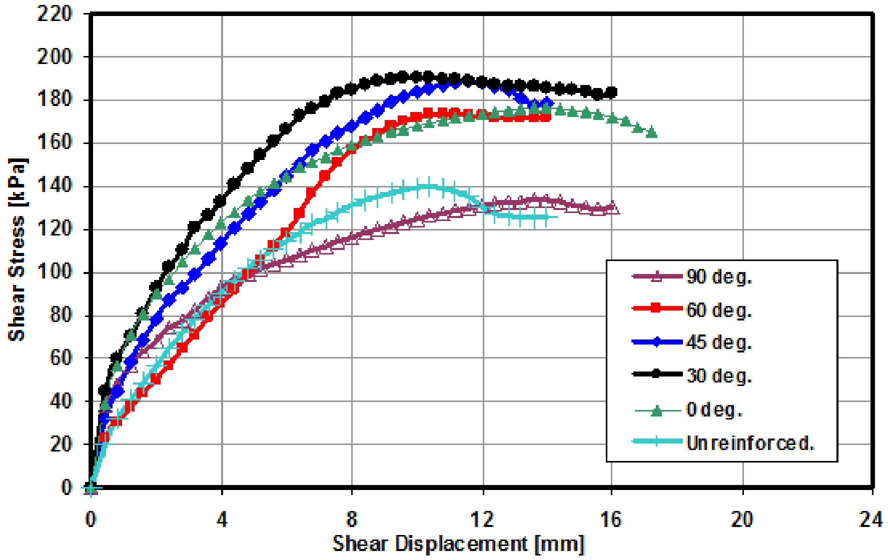

Figure 8: shear behavior of reinforced soil through shear box in normal stress equal to 200 kPa

Figure 9 shows the results of shear stresses versus normal stresses throughout samples. As mentioned before specimens were reinforced in different reinforcement orientation. Mohr-Coulomb stress space of each specimen has showed in Figure 9. As can be seen from this Figure $\theta = 30^{\circ}$ respect to vertical axis in shear boxes showed the highest strength and the lowest amount belongs to $\theta = 90^{\circ}$. Furthermore, such a result proved that in circular surface, reinforcements which are in the deepest point of slope do not reach to their sufficient tension strain and even they will cause of sliding through the reinforced soil slope. On the one hand embedded reinforcements in middle of failure surface (about midpoint of slope height) will show the highest amount of strength of absorption.

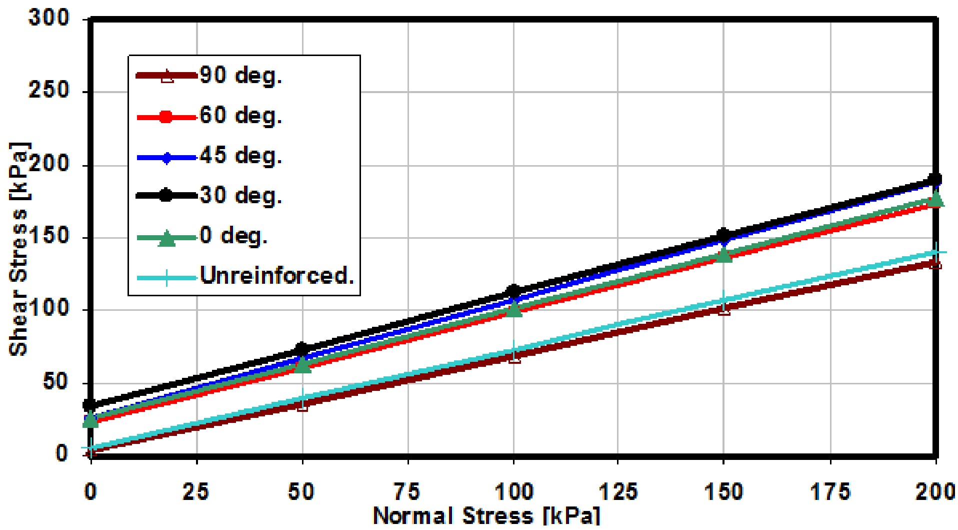

Figure 9: Mohr-Coulomb stress space

Figure 10 provides information about effect of reinforcement orientation with respect to vertical axis in shear box for sandy soil. It is due to shear behavior of reinforced sandy soil regarding different reinforcement direction. As can be seen from this table the highest amount of internal friction angle and cohesion belongs to both 45 and 60 degree and the lowest strength is belongs to unreinforced system.

Moreover, it is mentioned that the stress transfer mechanisms at the interface between the soil and the reinforcement involve the mobilization of shear resistance on the top and bottom surfaces of the reinforcement and bearing resistance on the transverse members (Jewell et al. 1985).

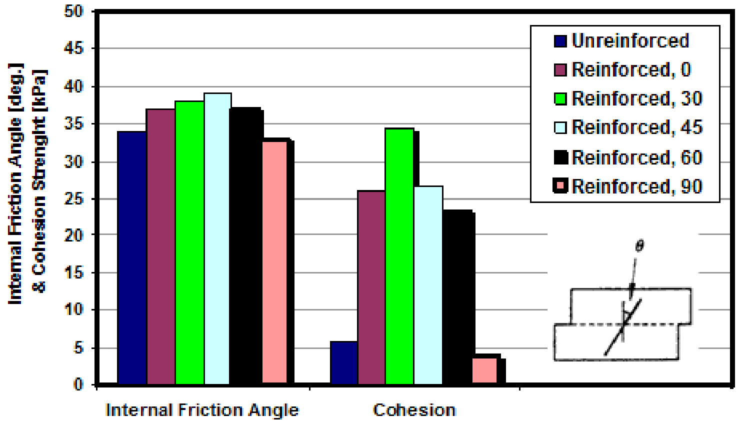

Figure 10: effect of reinforcement orientation respects to vertical axis in shear behavior of sandy soil

Numerical Modeling

Figure 11 shows initial proposal pattern for changing reinforcement orientation respect to shear potential failure based on height of slope. As it observed from the laboratory tests, those reinforcements which placed through the middle of slope's height show the highest shear resistant amount. On the other hand the lowest amount of resistance belongs to those reinforcements which located in bottom of slope. Due to the experimental results for 90 degree inclusion orientation which has smaller shear resistant than unreinforced system, it should be mentioned that, the longer reinforcement length in bottom of slope actually lead to the more vulnerable slippage failure along to bottom reinforcement.

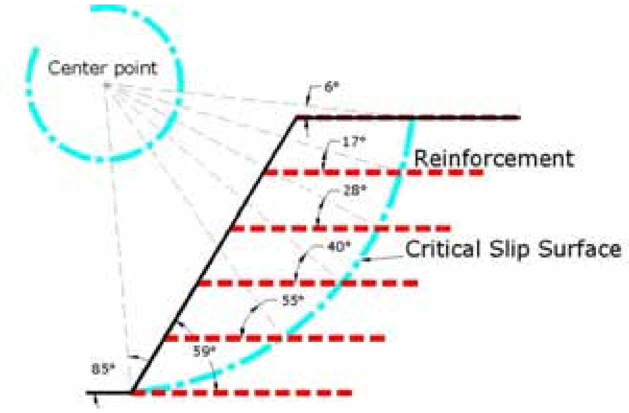

Figure 11: changing reinforcement orientation based on potential failure surface in reinforced slope

Simplifying models

As mentioned before, reinforcement orientation should be changed because it is deeply depends on slip surface shape. Moreover, such an angle will be changed by changing in height of slope from the lowest position in toe of slope to the highest position in the top of slope. So, in order to evaluate the effect of reinforcement orientation respect to shear failure, model simplified based on Culman method, as a wedge which is susceptible to slipping (Cullman, 1875). Critical slip surface in Culman method which called θ_{cr} and observed by following formula;

$$\theta_{Slope_{cr}} = \frac{\beta + \varphi}{2} \tag{4}$$

As can be from the Figure 12, reinforcement orientation θ_{re} is equal to 45 degrees with respect to potential shear failure. Similar to Figure 1, it can be seen that the shear behavior in soil-geosynthetic interface modeled in direct shear test. Hence, it can be modeled through the slide by using the results of large direct shear test.

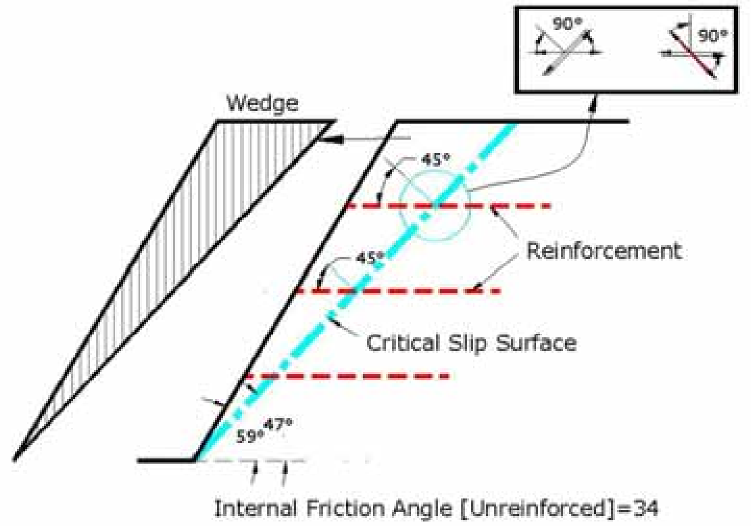

Figure 12: Prescribed failure surface; (Cullman, 1875)

LIMIT EQUILIBRIUM ANALYSIS

A plane strain analysis was carried out using Mohr-Coulomb's criterion. Geogrid has been used as a strain absorption interlayer system. Perkins, (2001) demonstrated that in most of these analyses the Geosynthetic reinforcement membrane is considered as an isotropic elastic material. Due to suitable interaction between soil particles and selected reinforcement, interface elements have not been used at the interface of the geogrid. This will not allow the relative deformation between the geogrid and gravel and sand layers. In order to analyze reinforced slope models, Slide 5.0 software modeling was carried out. *Slide* is a 2D limit equilibrium slope stability program for evaluating the safety factor or probability of failure, of circular or non-circular failure surfaces in soil or rock slopes. Figure 13 shows the schematic view of reinforced slope in case of $\theta = 30^{\circ}$ respect to prescribed shear potential surface.

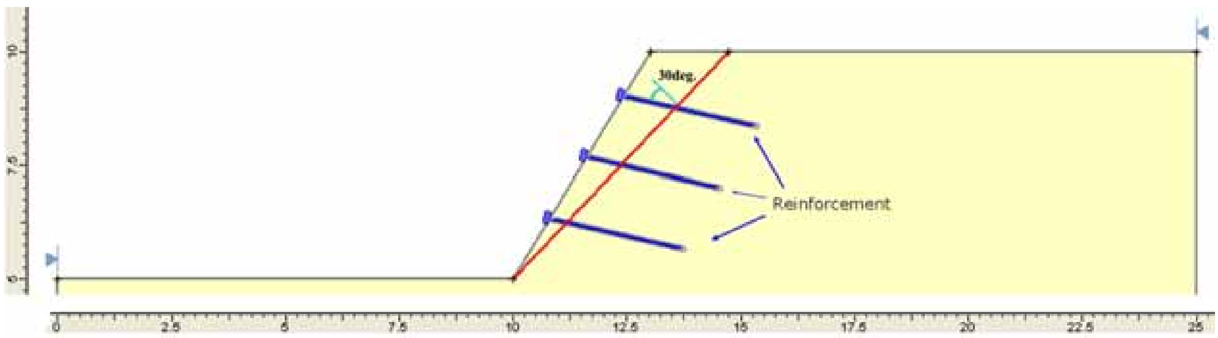

Figure 13: Schematic view of reinforced slope, case of $\theta = 30^{\circ}$ respect to prescribed shear potential surface

ANALYSIS OF THE RESULTS

Figure 14 compares reinforcing slope regarding different amount of orientation based on three analytical methods which were Bishop simplified, Janbu Simplified and Spencer. As it can be seen from following graph optimization orientation respect to prescribed shear failure plan, θ_{re} is equal to 30 degree. Results which come from the limit equilibrium analysis are exactly the same as the large direct shear test in lab. However, by changing in prescribed slip surface, results will be changed and it is due to different reinforcement orientation. Moreover, such a practice is more logical if the slip surface in unreinforced model specified and then based on the unreinforced slip surface shape, reinforcement orientation considered. Here, the main objective was to comparing the results based on laboratory testing and it is worth being mentioning that large centrifuges tests are needed.

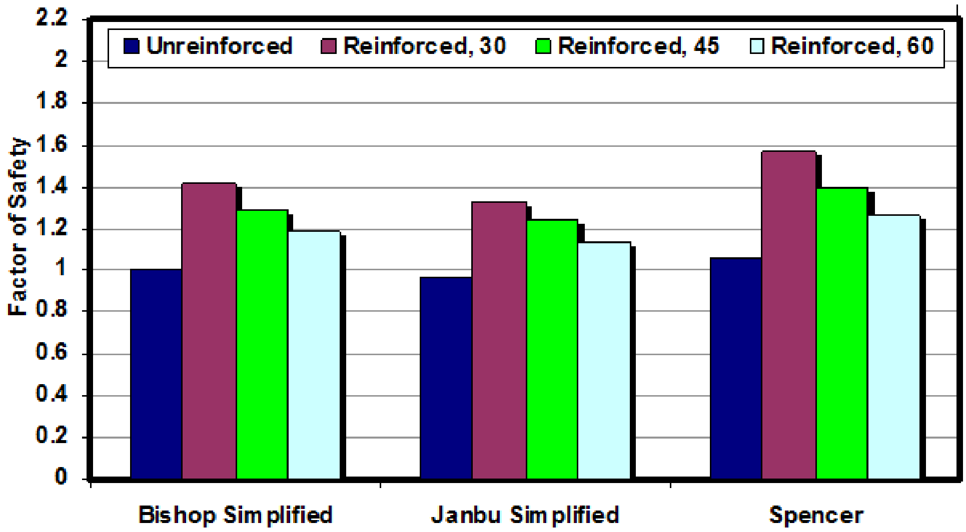

Figure 14: Factor of safety in three different analysis methods

Figure 15 shows the variation of tensile strength of geogrid versus factor of safety for Bishop simplified method analyzing. It is observed that increasing in tensile strength did actually lead to increasing in factor of safety. The most rising belongs to $\theta = 60^{\circ}$ and the least belongs to $\theta = 45^{\circ}$.

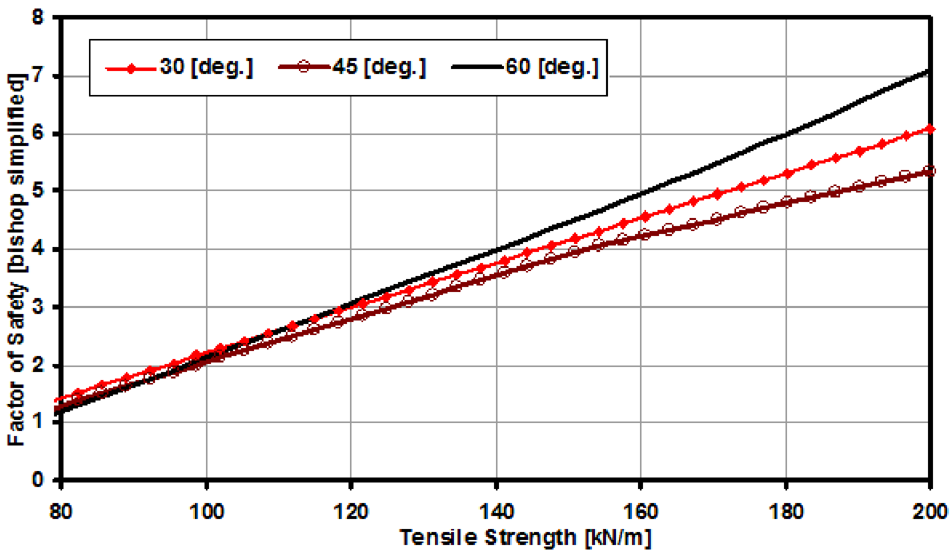

Figure 15: Effect of reinforcement tensile strength on factor of safety

CONCLUSIONS

The laboratory test results show that the orientation of geogrid with respect to shear plane has a significant effect on the increase of shear strength of the composite. The maximum increase occurs when the geogrid is orientated at 30° to the shear plane. At this orientation the combined effect of shear displacement and soil dilatancy will mobilize the most tension in the reinforcement. The average tensile strain in the geogrid indicates that when the geogrid inclines to 30° respect to shear failure plane's perpendicular line, the maximum tensile stain is mobilized. This inclination coincides with the direction of minor principal strain in the soil. Therefore, if practically possible, the alignment of the reinforcement elements should be as closely as feasible along the direction of minor principal strains mobilized in the soil. In future design of reinforced earth structures the orientation effect might be taken into consideration. However, present design in case of reinforced walls and slopes, the failure plane intersects most reinforcement elements at angles from 0 to 45. This means that according to the test and analytical results presented, a substantial increase in shear strength is realized.

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