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Factors Affecting the Stability of Reinforced Earth Slopes

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الملخص
تحتاج الميول الطبيعية والميول المصنعة إلى تحليل إتزان لها وذلك عن طريق حساب معامل الأمان والذى يعتمد على الناحية الإقتصادية والأمان على سبيل المثال (الجسور وقطع التربة والحفر والردم، إلخ.) يناقش هذا البحث تأثير العوامل المختلفه على معامل الأمان باستخدام برنامج (بلاكسيس ثنائى الابعاد) وتتضمن هذه العوامل زاوية ميل التربة، نوع التربةمن حيث زاوية الاحتكاك الداخلى ، المسافة بين زاوية ميل التربة والحمل الموزع، ارتفاع الميل وقيم الحمل الموزع. وايضا درست العوامل فى حالتى الميول المسلحة بالجيوجريد والاخرى بودن تسليح.
بينت النتائج: أنه فى حالة زيادة زاوية الاحتكاك الداخلي للتربة والمسافة بين الميل والحمل الموزع يزيد معامل الأمان، بينما يقل فى حالة زيادة زاوية الميل وقيم الحمل الموزع وارتفاع الميل.

Abstract
The slope stability analyses are performed to assess the safe and economic design of man-made or natural slopes (e.g. embankments, road cuts, open-pit mining, excavations, and landfills). In the assessment of slopes, engineers primarily use factor of safety values to determine how close or far slopes are from failure. In the present paper, parametric study using finite element analysis PLAXIS 2D has been introduced to discuss the global factor of safety, FS, as a function of slope angle, state of soil, horizontal position and value of surcharge, and height of slope. The stability analysis of the slope was carried out for two cases, unreinforced earth slope and that of reinforced using geogrid. The results indicated that, with the increase of friction angle of soil, and the distance between top of slope and surcharge load, the factor of safety increases, while with increasing of slope angle, surcharge load, and height of slope, the factor of safety decreases in both cases.

Keyword: Factor of safety, Finite element, Geogrid, Slope stability, Soil type, Surcharge.

1. Introduction
Man-made earth slope such as railway embankments, earth dams, canal banks, road cuts etc., represents one of the important problem that faces geotechnical engineer. The failure of slope may cause human and economic losses, as well as, environmental disasters; especially, large and infrastructure projects such as earth dams, riverbanks, building on or beside slopes, etc. Therefore, the stability of slopes should carefully be evaluated under the worst loading conditions to avoid failure. A number of slope failures have been recorded in slopes at least thirty years after initial construction, although there are several studies on reinforced earth, investigations of footings on reinforced slopes are rather limited (Selvadurai & Gnanendran, 1989; Omar et al., 1993; Huang et al., 1994; Lee & Manjunath, 2000; Yoo, 2001; El Sawwaf, 2007; Alamshahi & Hataf, 2009).The slopes may fail due to change of stress in foundation soil, increase of pore water pressure, decrease of shear strength of soil, and dynamic effect of

earthquakes. Slope stability can be improved by taking the following actions; flattening or benching, weight providing at toe, lowering of ground water table to reduce pore pressure in the slope, using of granular piles, driven or cast-in Reinforced concrete, retaining wall or sheet piling provided to increase resistance to sliding. Finally, in recent years, reinforcement has been used to improve the engineering performance of soil such as metal strips and geosynthetics. Foundations are sometimes built on slopes or near the edges of slopes, knowledge of the treatment technique to reinforce slopes loaded with a surface footing is of practical importance to geotechnical engineers.
The design and behaviour of multilayer reinforced slopes differ from that of reinforced embankments constructed on weak foundations and reinforced retaining wall structures. For example, the type of failure mechanisms that can develop or the internal stress develops, in both the soil and the reinforcement, will be different for the case of multilayer reinforced soil slopes. Consequently, the analysis of a reinforced slope must be considered as a unique design problem, taking into consideration the effect of slope inclination and height, reinforcement spacing, and embedment length.
The main scope of the present work is to study the behavior of a reinforced slope using geogrid, and to evaluate the factor of safety based on the results of the unstable earth slope. A parametric study based on finite element analysis model using "PLAXIS V.8.2" program has been developed to simulate the field slope geometry and loading conditions.

2. Finite Element Analysis

In the current study, the analysis was performed using the finite element program Plaxis software package (Bringkgreve and Vermeer, 1998). Two-dimensional plain strain model was used in the analysis.

2.1 Geometry and Boundary Conditions

The geometry of the simulated earth slope is presented in Fig(1-a), the finite element mesh is composed of 15-node isoparametric triangular elements. The mesh coarseness was set as "very fine". Horizontal fixities (rollers) were applied to the vertical face. This allowed the slope to settle at in the vertical direction but prohibited the nodes along the boundary from moving laterally. Total fixities were placed at bottom of the foundation. Plane strain was assumed to solve the three-dimensional problem with a two-dimensional analysis.

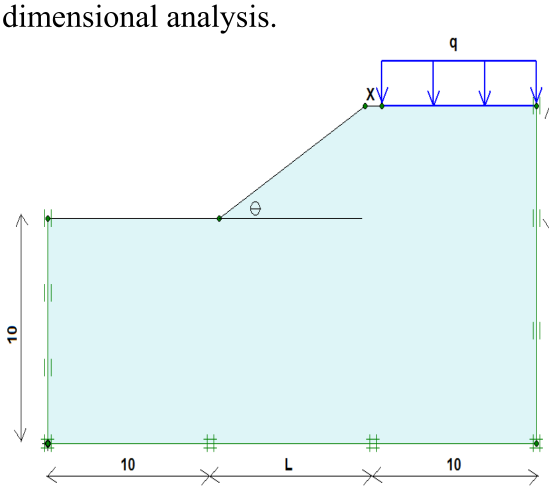

Figure (1-a) Finite Element Model for earth slope

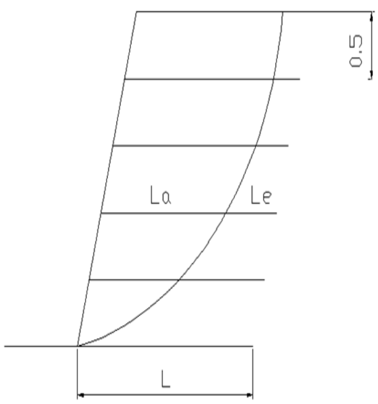

Figure (1- b) Length of reinforcing

elements (L) in reinforced case

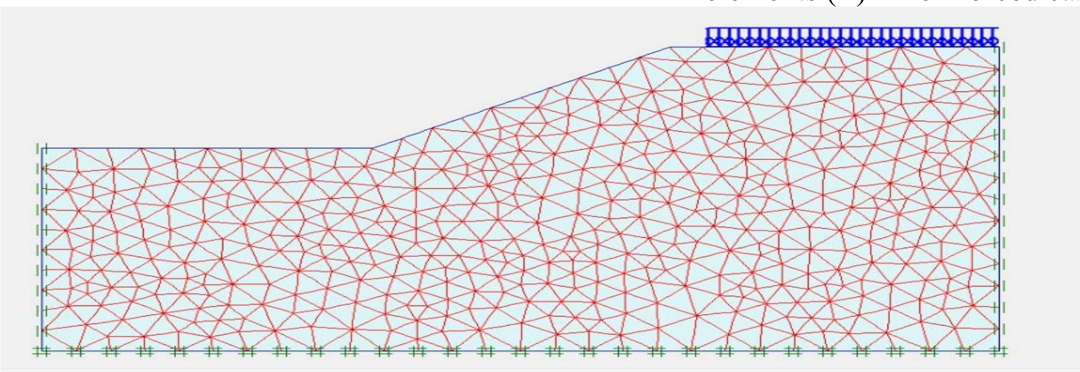

Fig. (1-c): Mesh generation using Plaxis.

As shown in Fig. (1- b) the length of reinforcing elements (L) consists of two parts (La), and (Le). The first part (La) represents length of reinforcing elements in failure zone, and the second part (Le) represents effective length of reinforcing elements to resist pullout force. The second part (Le) was obtained by using the following equation as recommended by B.S. (1995).

$$L_e = \frac{F_p * F_n * T_J}{2(\gamma * h_J + ws)\dfrac{a \tan \phi'_p}{F_{m_s}}} \tag{1}$$

Where:

L_e: Minimum calculated reinforcement length at level j in the slope.

$F_{b:}$: Partial factor governing reinforcement pull out, equals 1.3.

F_n: Partial factor governing the economic ramifications of failure, equals 1.1.

h_j: Height of fill above level j in slope.

W_s: External surcharge due to dead and live load.

$\grave{a}$: Coefficient of interaction relation soil reinforcement angle with $\tan \phi'_p$.

F_{m_s}: Partial material factor applied to $\tan \phi'_p$.

γ : The soil density above level j in slope.

T_J : Maximum reinforcement tensile load at any level j in slope, where:

$$T_j = (F_{f_s} * \gamma * h_{j+} F_q * W_s) * K * S_{v_j} * 1 \tag{2}$$

F_{F_s} : Partial load factor applied to soil unit weight, equals 1.5.

F_q : Partial load factor applied to external surcharge load, equals 1.3.

S_{V_j}: Vertical reinforcement spacing level j in slope.

K : Active earth pressure of Coefficient.

The values of F_n , $F_{b:}$, F_{F_s} , F_q are taken tables specified by B.S. (1995).

2.2 Backfill Model Properties

Hardening soil model was selected to simulate the nonlinearly plastic response. The Hardening soil model is a stress-dependent hyperbolic model based on the flow rule and plasticity theory. It was believed that Hardening soil model had better ability to match the stress-strain curves of granular soil at working stress conditions than the Mohr-Coulomb model, a linear elastic and perfect plastic model (manual of Plaxis). Angle of dilatancy (Ψ), was used to account for the dilatation of sand during shearing. The value was calculated by the empirical equation $\Psi \approx \varphi - 30°$ (Bolton, 1986). The adapted hyperbolic model parameters for the backfill soil are shown in Table 1. These parameters were selected to simulate the properties of loose, medium dense, dense, and very dense sand.

Table (1): Input Parameters for the Backfill Soil

Type of soil	Unit Weight, γ kN/m^3	Friction Angle, $\Phi°$	Cohesion c, kN/m^2	Elastic Modulus E, kN/m^2	Dilatancy angle, $\Psi°$
Loose sand	17	30	1	20000	0
Medium sand	18	35	1	40000	5
Dense sand	19	40	1	70000	10
Very dense sand	20	45	1	70000	15

2.3 Reinforcement

The reinforcements were modeled as membrane elements with a normal stiffness but without bending stiffness. In addition, line elements could only sustain tensile forces but no compression. An elastoplastic model was selected to mimic the breakage of reinforcement. The input parameters for the reinforcements were the elastic axial stiffness EA and maximum axial tension force, Np.

Table (2) Reinforcement properties

Property	Value
Elastic Axial Stiffness (EA) kN/m	1800
Max. Axial Tension force (Np) kN/m	120

3. Methodology of Analysis

The factor of safety is defined as the ratio of average soil shear strength to the average shear stress developed at the potential failure surface. When this ratio is greater than one, resistive shear strength is greater than the driving shear stress, and the slope is considered stable. When this ratio is close to one, shear strength is nearly equal to shear stress and the slope is close to failure, if factor of safety, FS, is less than one the slope should have already fail, however, minimum F.S. of 1.5 is recommended in common practice to ensure the stability of slope. Effect of slope angle (θ), type of soil, and distance between slope and surcharge load (X), surcharge load, (q), and height of slope (H), on safety factor of earth slope were investigated. A numerical study using Plaxis 2D was carried out on plane strain model of earth slope; the items of parametric study are listed in Table (3).

Study	Variable parameter	Other constant parameters	Figure of Results
Factor of Safety	θ =30°, 35°, 40°, 45°.	Type of soil, X, q, H	Fig. 2
	ϕ =30°, 35°, 40°, 45°. (Type of soil from loose to very dense sand)	θ, X, q, H	Fig. 3
	X =0.5, 1, 1.5, 2 m.	Type of soil, θ, q, H	Fig. 4

	q = 20, 30, 40, 50 kN/m^2	Type of soil, θ, X, H	Fig. 5
	H = 5, 6, 7, 8 m.	Type of soil, θ, X, q	Fig. 6

Table (3) Range of parameters used in the study

4. Results of analysis

4.1 Effect of slope angle without surcharge load.

In this item the slope was analyzed for pure sand without surface surcharge load. In this model the used parameters are friction angle (ф) =40, height of slope (H)=5m, are listed in table (4) and plotted in Fig. (1).

Table (4) Effect of slope angle on the factor of safety without surcharge load

Slope angle (θ) without load		30	35	40	45
Factor of safety (F.S)	unreinforced	1.82	1.44	1.29	1.11
	reinforced	2.18	1.79	1.72	1.54
Equivalent (F.S)		1.2	1.24	1.33	1.39

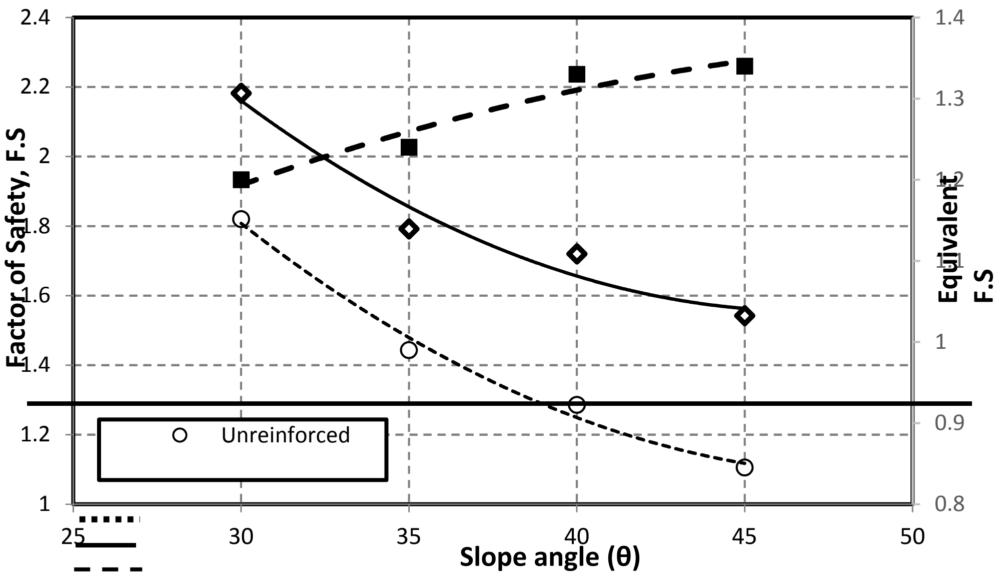

Figure (1) Relationship between slope angle, θ, and safety factor without surcharge load

For unreinforced slope: F.S = $2*10^{-2}\,\theta^2-2*10^{-1}\,\theta+6$ (R^2=0.9899)
For reinforced slope: F.S = $0.0021\theta^2-2*10^{-1}\,\theta+6.2$ (R^2=0.9588)
(Where, ϴ is in degrees)

For unreinforced sand slope without surface surcharge load, it will nearly be safe for slope angle less than 34°, whereas, for reinforced slope with geogrid at vertical interval of 0.5 m it will be safe even for slope angle equals 45°.
To evaluate the effect of geogrid on the F.S, the equivalent Factor of Safety defined as: (E.F.S = $\frac{F.S\,.\ With\,reinforcement}{F.S\,.\ without\,reinforcement}$), was computed and plotted in Fig (1)
From Fig (1), It can be observed that, with increase of slope angle (θ), The E.F.S. increase, that may be attributed to the effect of increase in Geogrid.

4.2 Effect of Slope Angle with Surcharge Load

To investigate the effect of variation of slope angle (θ) on the factor of safety under surcharge load, other factors are kept constant as friction angle (ϕ) =40, distance between slope and surcharge load (X) =1m, height of slope (H)=5m, surcharge load (q) =20 kN/$m^2$and geogrid at vertical interval=0.5m. Variations of factor of safety versus slope angle (θ) in the range of 30° to 45°are listed in table (5) and plotted in Fig. (2).

Table (5) Effect of slope angle on the factor of safety with load

Slope angle(θ)		30	35	40	45
Factor of safety (F.S)	unreinforced	1.78	1.43	1.28	1.05
	reinforced	1.84	1.51	1.42	1.29
Equivalent (F.S)		1.03	1.05	1.11	1.23

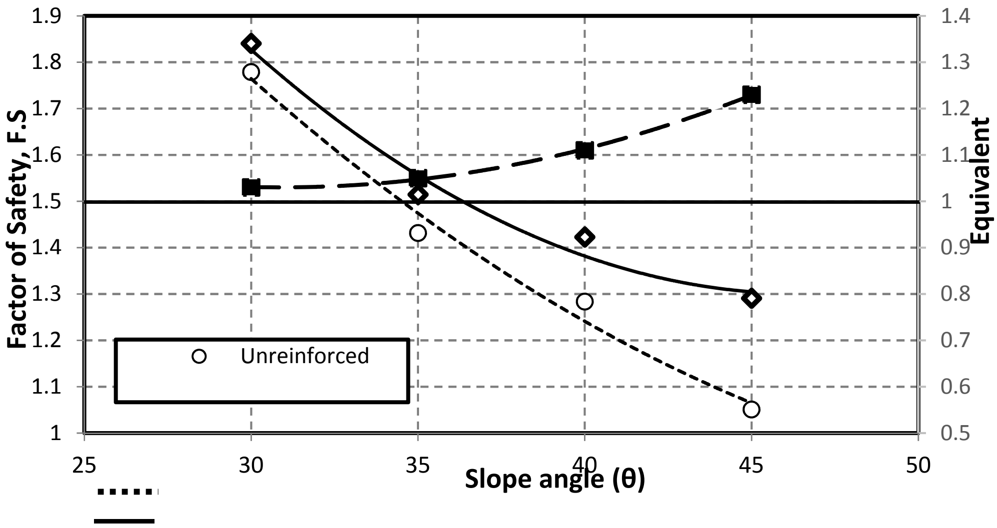

Figure (2) Relationship between slope angle, θ, and safety factor with surcharge load

For unreinforced slope: F.S = $11*10^{-4}\Theta^2-13*10^{-2}\Theta+5$ (R^2=0.9856)

For reinforced slope: F.S = $0.0019\Theta^2-2*10^{-1}\Theta+5$ (R^2=0.9772)

Where (ϴ) is in degrees

For unreinforced or reinforced sand slope with or geogrid at vertical interval of 0.5 m, under surface surcharge load of 20 kN/m^2 it will nearly be safe for ϴ not more than 35 degrees, after which it may fail. It is noticed that, in both cases the factor of safety significantly decreases with increasing the slope angle. In case of unreinforced earth, when the slope angle increased from 30° to 45°, the factor of safety decreased by about 41%, while for reinforced case the reduction was about 30%. The slope will not be stable if the inclination angle is more than 30° and 35° for unreinforced and reinforced slopes respectively. On the other hand, the equivalent F.S indicates the significant effect of geogrid regardless the un stability of reinforced slope.

4.3 Effect of friction angle of soil.

As shown in Fig. 3., linear proportional relationship friction angle, Φ, and safety factor. it was found that the safety factor increases significantly with increasing the friction angle, Φ, in both cases. The constant parameters are slope angle equal 30°, distance (X) equal 1m, surcharge load(q) equal 20 kN/m2 and height of slope(H) equal 5m. The results are listed in table (6).

Table (6) Effect of friction angle on the factor of safety

Friction angle (Φ)		30	35	40	45
Factor of safety (F.S)	unreinforced	1.24	1.49	1.78	2.09
	reinforced	1.30	1.54	1.84	2.15
Equivalent (F.S)		1.05	1.03	1.03	1.03

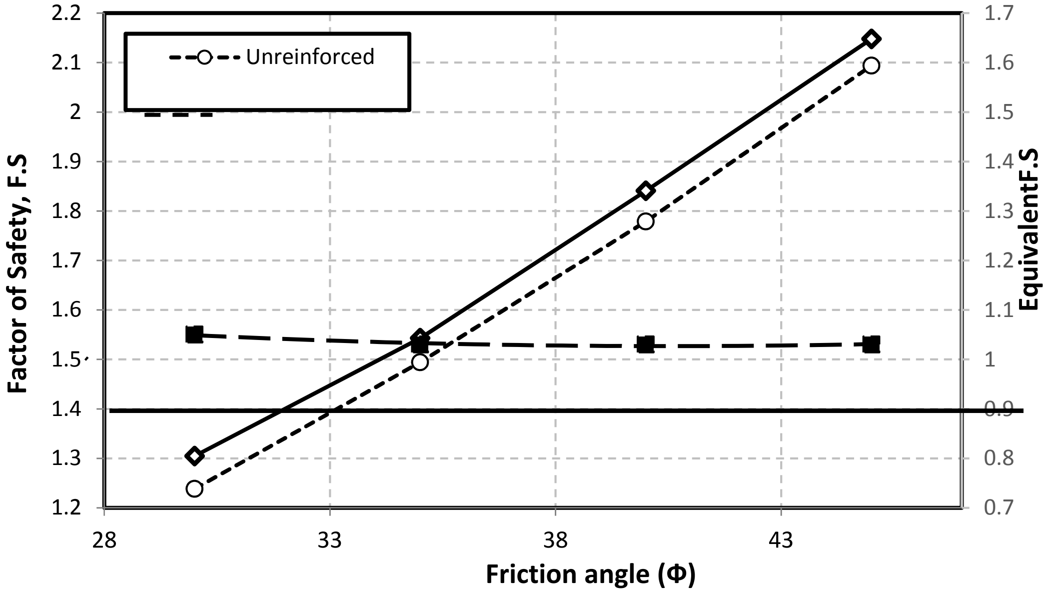

Figure (3) Relationship between friction angle, Φ, and safety factor

For unreinforced slope: F.S = -6*10^{-4} ϕ^2+12*$10^{-3}\phi$+0.3 (R^2=0.9982)
For reinforced slope: F.S = 7*10^{-4} ϕ^2+5*$10^{-3}\phi$+0.5 (R^2=0.9997)
Where (ϕ) is in degrees

For unreinforced or reinforced sand slope with geogrid at vertical interval of 0.5 m, under surface surcharge load of 20 kN/m2, it will nearly be safe for earth material with angle of friction (ϕ) more than 35°, before which it may fail.
The increase in factor of safety from 1.24 to 2.09 (i.e. the increase in factor of safety will be about 69.1%) when angle of friction of soil increased from 30° to 45° in unreinforced case. The increase in factor of safety from 1.30 to 2.15 (i.e. the increase in factor of safety will be about 64.6%) when angle of friction of soil increased from 30° to 45° in reinforced case. An increase in the safety factor will be attained for the shear strength of soil increases with increasing the friction angle, Φ, and that lead to decreasing of factor of safety. On the other hand, the equivalent F.S indicates the slight effect, that may be attributed to the constant effect of Geogrid with increase of soil friction.

4.4 Effect of distance between slope and surcharge load.

Results of analysis for varying distance between slope and surcharge load, (X), on the safety factor are plotted in Fig. (4). The constant parameters are type of soil is dense sand, slope angle(θ) equal 30°, surcharge load(q) equal 20 kN/m2 and height of slope(H) equal 5m. there are listed in table (7).

Table (7) Effect of distance between slope and surcharge load on the factor of safety

Distance (X)		0.5	1	1.5	2
Factor of safety (F.S)	unreinforced	1.73	1.78	1.83	1.87
	reinforced	1.84	1.84	1.92	2.00
Equivalent (F.S)		1.06	1.03	1.05	1.07

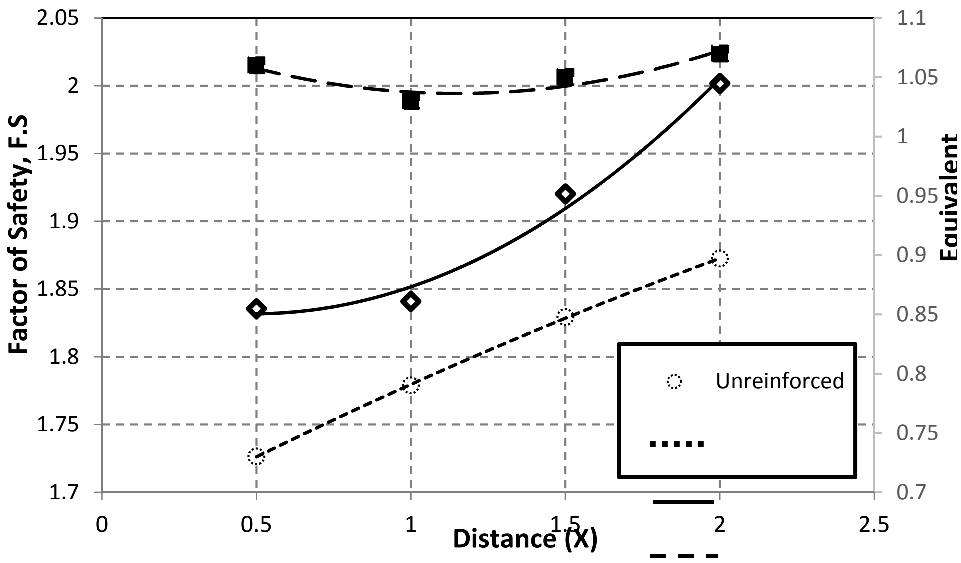

Figure 4. Relationship between distance between slope and surcharge load, X, and safety factor.

For unreinforced slope: F.S = -9*10$^{-3}X^2$+12*10^{-2}X+1.5 (R^2=0.9999)

For reinforced slope: F.S = 7*10$^{-2}X^2$-7*10^{-2}X+1.5 (R^2=0.986)

Where (X) is in meter

For unreinforced or reinforced sand slope with geogrid at vertical interval of 0.5 m, under surface surcharge load of 20 kN/m2, the slope will be safe for distance (X) from 0.5 to 2 m, with high factor of safety for greater distance between top of slope and surcharge load. It is noticed that the factor of safety increases with increasing the distance between slope and surcharge load, (X), in both cases. The increase in factor of safety in unreinforced slope is from 1.73 to 1.87 (i.e. the increase in factor of safety will be about 8.00 %) when the distance between slope and surcharge load increased from 0.5 to 2 meter. In reinforced case, the increase in factor of safety is from 1.84 to 2.01 (i.e. the increase in factor of safety will be about 9.0%) when distance between slope and surcharge load increased from 0.5 to 2 meter. On the other hand, the equivalent F.S indicates the slight effect, that may be attributed to the constant effect of Geogrid with increase of soil friction and surcharge load is few.

4.5 Effect of surcharge load

The results of factor of safety with variation of surcharge load are listed in Table (8), and their relationship for unreinforced and reinforced are plotted in Fig. (5). The constant parameters are type of soil is dense sand (γ) equal 40 kN/m2, slope angle(θ) equal 30°, distance (X) equal 1m and height of slope (H) equal 5m.

Table (8) Effect of surcharge load on the factor of safety

Surcharge load (q)		20	30	40	50
Factor of safety (F.S)	unreinforced	1.78	1.75	1.71	1.67
	reinforced	1.84	1.80	1.79	1.69
Equivalent (F.S)		1.03	1.03	1.05	1.01

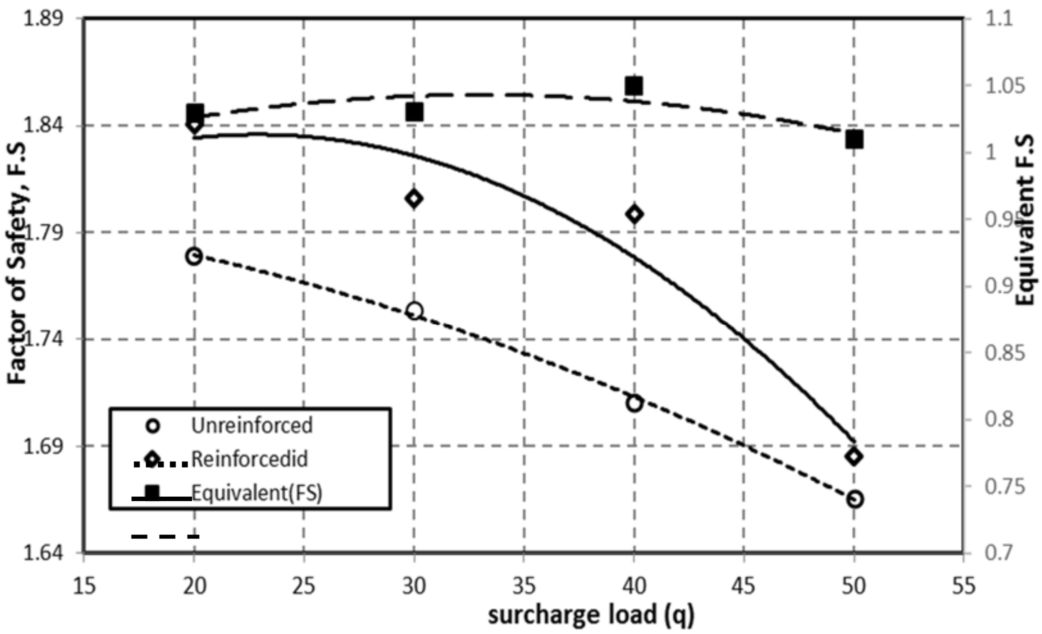

Figure 5. Relationship between surcharge load, q, and safety factor

For unreinforced slope: F.S = -5*$10^{-5}q^2$-3*10^{-3}q+2 (R^2=0.9982)
For reinforced slope: F.S = -2*$10^{-5}q^2$+9*10^{-3}q+1.75 (R^2=0.9356)
Where (q) is in kN/ m^2

For unreinforced or reinforced sand slope with or geogrid at vertical interval of 0.5 m, under surface surcharge load from 20 to 50 kN/m2, it will be safe when the slope angle of sand balanced and equal 30°, where greater the surcharge load the lesser the safety factor. Results of analysis for varying surcharge load, (q), on the safety factor are plotted in Fig. (5). It can be observed that, the safety factor decreases significantly with increasing the surcharge load in both unreinforced and reinforced cases, the decrease in factor of safety from 1.78 to 1.67 is about 6.35% when surcharge load increased from 20 to 50kN/m2 in unreinforced case. While the decrease in factor of safety from 1.84 to

1.69 is about 8.43% when surcharge load increased from 20 to 50 kN/m2 in reinforced case. On the other hand, the equivalent F.S indicates the slight effect, that may be attributed to the constant effect of Geogrid, soil friction, surcharge load, and the slope angle.

4.6 Effect of height of slope.

Variations of factor of safety and height of slope, (H), are plotted in Fig. (6). The other constant parameters are type of soil is dense sand(γ) equal 40 kN/m2, slope angle(θ) equal 30°, distance (X) equal 1m, and surcharge load (q) equal 20 kN/m2

Table (9) Effect of height of slope on the factor of safety

Height of slope (H)		5.00	6.00	7.00	8.00
Factor of safety (F.S)	unreinforced	1.78	1.72	1.70	1.65
	reinforced	1.84	1.81	1.81	1.73
Equivalent (F.S)		1.03	1.05	1.06	1.05

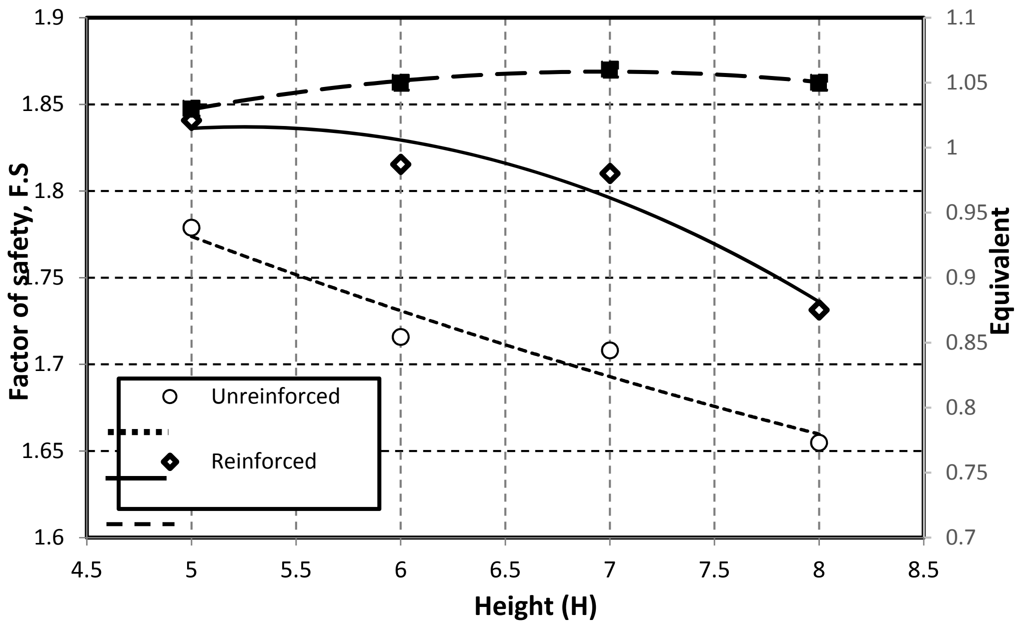

Figure 6. Relationship between height of slope, H, and safety factor

The equation for unreinforced slope: F.S = 2*10$^{-3}H^2$-7*10^{-2}H+2 (R^2=0.9346)
For reinforced slope: F.S = -13*10$^{-3}H^2$+14*10^{-2}H+1.5 (R^2=0.9348)
Where (H) is in meter

For unreinforced or reinforced sand slope with geogrid at vertical interval of 0.5 m, under surface surcharge load of 20 kN/m^2 it will be safe for heights from 5.00 to 10.00m. It is noticed that the factor of safety decreases with increasing the height of slope, (H), in both cases. The decrease in factor of safety is very small; for F.S. corresponding H=5 to 8m, the decrease is about 6.85% in case of unreinforced, while for reinforced slope it is about 5.94%. The increase in resistance is lesser than the increase in the mass driving force.

5. Conclusion:

The following conclusions could be drawn from the obtained finite element analysis results in slope with or without Geogrid:

1- For unreinforced sand slope without surface surcharge load, it will nearly be safe for θ not more than 34°. Whereas, for reinforced slope with geogrid at vertical interval of 0.5 m it will be safe even for slope angle equals 45°. For unreinforced or reinforced sand slope with geogrid at vertical interval of 0.5 m, under surface surcharge load of 20 kN/m^2 it will nearly be safe for (θ) not more than 35°, after which it may be fail.
2- For unreinforced or reinforced sand slope with or geogrid at vertical interval of 0.5 m, under surface surcharge load of 20 kN/m^2 it will nearly be safe for (ϕ) more than 35°, before which it may be fail.
3- For unreinforced or reinforced sand slope with geogrid at vertical interval of 0.5 m, under surface surcharge load of 20 kN/m^2 it will be safe for (X) from(0.5 to 2m),where greater the distance between slope and surcharge load increased the safety factor.
4- For unreinforced or reinforced sand slope with geogrid at vertical interval of 0.5 m, under surface surcharge load from 20 to 50 kN/m^2 it will be safe when the slope angle of sand balanced and equal 30°, where greater the surcharge the lesser safety factor.
5- For unreinforced or reinforced sand slope under surface surcharge load of 20 kN/m^2 it will be safe when the slope angle of sand to equal 30°, the slope is stable because the friction angle is high and equal 40°, where greater the height decreased the safety factor.
6- The Equivalent Factor of Safety reveals that, the rate in increase of slope stability is significient with slope angle, due to the increase in reinforcement by Geogrid, while for other parameters the rate in nearly the same.

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