EFFECT OF REINFORCEMENT ORIENTATION ON BEARING CAPACITY OF REINFORCED SOILS

N. Hataf, Visiting Associate Professor, Civil and Environmental Engineering Department, Carleton University, Canada formerly Shiraz University, Iran
T. K. Law, Professor, Civil and Environmental Engineering Department, Carleton University, Canada

ABSTRACT
The performance of shallow foundations located on granular soils is usually improved by placing one or several horizontal layer(s) of geotextiles or geogrids beneath the foundation base at different depth prior to constructing the footing. This technique of soil reinforcement is routinely used for several years. Previous researches on the behaviour of foundation built on granular soil reinforced as cited have shown the increase in bearing capacity of footing on reinforced soil and provided empirical, analytical and numerical relations to predict the bearing capacity improvement of the reinforced soil.
The quantity of bearing capacity improvement is shown to be dependent on the soil parameters, the reinforcement material parameters, depth of the first layer of reinforcement, the vertical distance between the layers and the number of reinforcement layers. In this paper a new parameter called reinforcement orientation angle is introduced. The effects of this parameter on the bearing capacity of circular and strip shallow foundations located on soils reinforced with inclined reinforcement are numerically studied. It is shown that a considerable increase in ultimate bearing capacity and foundation bearing stress corresponding to a given settlement may be obtained when reinforcement is placed as inclined layer(s).

RÉSUMÉ
La performance d'une fondation peu profonde située sur de la terre granulaire est habituellement améliorée par le placement d'une ou de plusieurs couches horizontales de geotextiles ou de geogrids en-dessous la base de la fondation à de profondeurs variées avant de construire cette fondation. Souvent, on se sert de cette technique de renforcement du sol pendant plusieurs années. La recherche antérieure sur le comportement d'une fondation bâtie sur du sol granulaire renforcé, comme cité, démontre l'augmentation de la capacité de portance de la fondation sur le sol renforcé. Aussi, elle nous informe aussi des relations empirique, analytique et numérique pour pouvoir prédire l'amélioration de la capacité de portance du sol renforcé.
On démontre que la quantité de l'amélioration de la capacité de portance dépend des paramètres du sol, des paramètres des matériaux de renforcement, la profondeur de la première couche de renforcement, la distance verticale entre les couches et le nombre de couches de renfort. Lors de cet article, un nouveau paramètre qui s'appelle l'angle d'orientation du renfort. On étudie numériquement les effets de ce paramètre sur la capacité de portance des fondations peu profondes circulaires et en bandes situées sur du sol renforcé avec des renforcements inclinés. On démontre qu'une augmentation considérable de la capacité de portance ultime et du stress sur la fondation correspondant à un règlement donné peut être obtenue lorsque le renforcement est placé comme une couche inclinée.

1. INTRODUCTION

Applications of geosynthetics have found a firm ground in civil engineering projects. Among numerous applications of geosynthetics, the use of these materials in bearing capacity improvements of soils has attracted full attention in recent years. This is because the advantages of this method of soil improvement over to the other conventional approaches. Being cost effective, multipurpose, easy construction, etc. are some of the benefits of using the geosynthetics. The use of geosynthetics for bearing capacity improvement may also lead in improved drainage, filtration, separation and change in the type of foundations.

The process of soil reinforcement for bearing capacity of weak soil is conducted by removing up the weak soil to a certain depth and replacing it by the reinforced soil with horizontal layer(s) of high tensile strength geosynthetics. Many researchers have experimentally and numerically studied the behaviour of shallow spread and strip foundations placed on reinforced soil (Binquet and Lee, 1975a; Akinmusuru and Akinbolade 1981; Fragaszy and Lawton 1984; Guido et al. 1986; Huang and Tatsuoka 1990; Dixit and Mandal 1993; Khing et al. 1993, 1994; Yetimoglu et al. 1994; Adams and Collin 1997; Hataf and Baziar, 2000; Kumar and Saran 2001; Boushehrian and Hataf 2003). In all these investigations the layer(s) of reinforcement were placed or considered horizontal. It was generally recognized that geosynthetic reinforcement could increase the ultimate bearing capacity of the foundation and the allowable stress of the footing corresponding to a given settlement.

In this paper it is shown that the orientation of reinforcement has a significant effect on the strength of soil-reinforcement system. The variation of bearing capacity of circular and strip footings with changing the orientation angle of the reinforcement is then investigated numerically.

2. BEHAVIOUR OF SHALLOW FOUNDATIONS ON REINFORCED SOIL

The previous researches revealed that it is possible to assume that the failure mechanisms of reinforced foundations are the same as that of non-reinforced foundations such as the mechanism proposed by Terzaghi (Terzaghi and Peck 1948).

Binquet and Lee (1975a, b) were the first who studied the bearing capacity of shallow foundations on reinforced earth slabs and proposed a rational failure mechanism and design method. Through the observations in extensive model tests they proposed three modes of failure for the reinforced soil foundations as depicted in Figure 1.

According to their conclusion, provided that the first layer of reinforcement is placed at a considerable depth ($u/B > 0.67$) the failure occurs at the uppermost layer of reinforcement, Figure 1(a). Pull-out failure of reinforcement may occur if reinforcement layers with insufficient length (or width) are placed beneath the footing, Figure1 (b). Reinforcement break failure occurs if the frictional pull-out force is more than the rupture strength of the reinforcement, Figure 1(c).

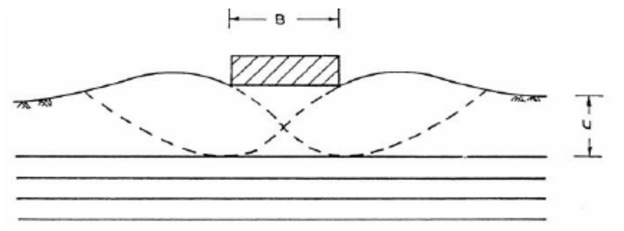
Since the reinforcement layers are usually placed at shallow depth beneath the foundation, the failure mode (a) is not the case in practice. For failure modes (b) and (c) in Figure 1 as it can be seen the shear plane makes an angle with the reinforcement. This angle varies along the critical failure surface of the reinforced soil. The orientation angle ranges from zero degrees for the lowermost layers to about ninety degrees for the uppermost reinforcement layers.

3. EFFECT OF ORIENTATION ANGLE ON SHEAR STRENGTH

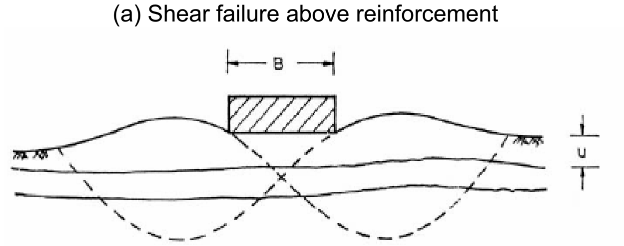
Several researchers have studied the effect of the orientation angle on shear strength and deformation behaviour of the reinforced soil (Jewell 1980; Gray and Ohashi 1983; Palmeira and Milligan 1989; Zhao 1993). Zhao (1993) by conducting a comprehensive direct shear and pull-out tests on reinforced soils concluded that the maximum shear strengths were observed in the test when the reinforcement was inclined at 30˚ to the normal of the shear plane while minimum shear resistance were obtained when the geogrid was placed in the shear plane (i.e. 90˚ to the normal of the shear plane). According to his findings the reinforcement, if possible, should be placed close to the direction of the minor principal stresses.

4. NUMERICAL ANALYSIS

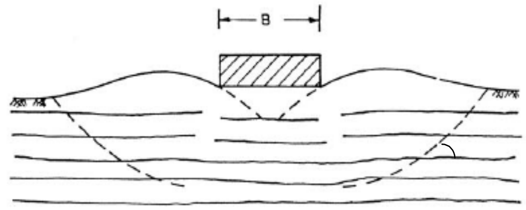
To investigate the effect of reinforcement orientation on bearing capacity of footings on reinforced soil a numerical study has been performed using the finite element program PLAXIS (version 8). PLAXIS is intended for the analysis of deformation and stability in geotechnical engineering projects. The Mohr–Coulomb model was used for soil, the axi-symmetric or plane strain conditions and 15-node triangular elements were used for the analysis. Reinforcement layers were modeled using the options already built into the program. They are simulated in PLAXIS by the use of special tension elements. To model the slip between the soil and the reinforcement these elements are combined with interfaces.



(a) Shear failure above reinforcement



(b) Pull-out failure



(c) Break failure

Figure 1. Modes of reinforced soil failure under foundation loading (After Binquet and Lee, 1975)

Reinforcements are slender objects with a normal stiffness but with no bending stiffness. Reinforcement can only sustain tensile forces and no compression. These objects are mostly used to model soil reinforcement for example geogrids or woven geotextiles. When 15-node soil elements are employed then each reinforcement element is defined by 5-nodes. The only material property of reinforcement is elastic normal (axial) stiffness EA. Other parameters used in the analysis are tabulated in Table1. A relatively high value of elastic normal stiffness of reinforcement was used to ensure the break failure does not occur during foundation loading.

5. BEHAVIOUR OF SHALLOW FOUNDATIONS ON REINFORCED SOIL

To evaluate the increase in bearing capacity, the bearing capacity ratio (BCR) which is defined as bellow is often used.

$$BCR_u = \frac{q_{u(r)}}{q_u} \qquad [1]$$

$$BCR_s = \frac{q_{(r)}}{q} \qquad [2]$$

where, BCR_u is the BCR with respect to the ultimate load and BCR_s is BCR at a given settlement, $q_{u(r)}$ is the ultimate bearing capacity of reinforced soil, and q_u is the ultimate bearing capacity of unreinforced soil. As previously mentioned, the effect of horizontal reinforcement in increasing bearing capacity of foundation soil is reported by several researchers (Binquet and Lee 1975a, b; Akinmusuru and Akinboladeh 1981; Guido et al. 1985; Yetimuglu et al. 1994; Adams and Colin 1997; Boushehrian and Hataf 2003). It was shown that by placing the reinforcement layers horizontally beneath the foundation a BCR value greater than unity is obtained. The value of BCR was reported to depend on the soil parameter, the reinforcement parameter, depth of the first layer of reinforcement (u), the vertical distance between the layers (z) and the number of reinforcement layers (N). During this investigation, the cited parameters, shown in Table 1, kept constant. Besides these parameters, the angle of reinforcement layers with respect to horizontal plane called the angle of orientation (θ) was introduced and varied, Figure 2.

Table 1. Parameters used in the numerical analysis

Parameter	Value
Angle of internal friction (residual)	30^o
Cohesion (kPa)	1
Modulus of elasticity (kPa)	10000
Poisson's ratio	0.33
Unit weight (kN/m3)	16
Elastic normal stiffness of reinforcement (kN/m)	150
Depth of the first layer of reinforcement at the center of the footing(u)	.30 m
Vertical distance between the layers (z)	0.20 m
Number of reinforcement layers (N)	7
Diameter (or width) of footing (m)	1.00

Negative values of the angle of reinforcement orientation, i.e. the layers sloping opposite to the direction shown in Figure 2 were not used due to the fact that in this case the reinforcement are in pressure rather than in tension. Using the rigid plastic finite element analysis built in PLAXIS for different values of (θ) the load-settlement curves were obtained for both circular and strip footings on reinforced and unreinforced sand. Rigid footings were used to study the behaviour of soil only.

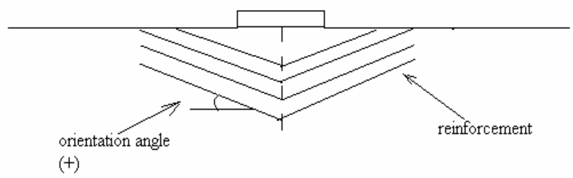


Figure 2. Foundation on soil reinforced with inclined reinforcement layer

The values of bearing stresses at settlements equal to 2.5 cm and the values of ultimate bearing capacities for both unreinforced and reinforced soil were determined from the load-settlement curves.

5.1 Circular footing

The results of numerical investigation for circular footings in terms of bearing capacity ratios at settlements equal to 2.5 cm and the value of ultimate bearing capacity ratios are tabulated in Table 2. The values of BCRu and BCRs and the ratio of BCRu/BCRs are presented in each case. As it is depicted in this Table the use of reinforcement has improved the bearing pressure capacity of the soil, but this improvement is dependent on the value of reinforcement orientation angle. This is therefore might be concluded that angle of orientation is a new parameter which should be considered in foundation design on reinforced soil. However it needs to be studied more in future.

Table 2. Variation of bearing pressure for circular rigid footing against reinforcement orientation

Condition	BCRs at 2.5 cm settlement	BCR_u	BCR_u/BCRs
Unreinforced Soil	1.0	1.0	1.00
Reinforced soil (θ=0)	1.08	1.45	1.34
Reinforced soil (θ=3.5º)	1.1	1.61	1.46
Reinforced soil (θ=5.0º)	1.06	1.65	1.56
Reinforced soil (θ=10.0º)	1.14	1.11	.97
Reinforced soil (θ=15.0º)	1.055	1.07	1.01
Reinforced soil (θ=30.0º)	1.25	1.59	1.27

The values of BCR_u are plotted against the angle of orientation in Figure 3. It can be seen that there is a maximum reinforcement effect at certain value of (θ) and then the effect decreases for higher values of (θ). This may be due to the fact that for further inclination of reinforcement the angle between the reinforcement and shear failure surface changes unfavourably. This pattern however can not be seen for footing stresses at 2.5 cm settlement, Table 2.

Figure 4 shows the variation of axial force in each layer of geogrid for different angles of reinforcement orientation (θ). It is depicted in Figure 4 that induced forces in reinforcement layers also depend on the values of angle of orientation (θ).

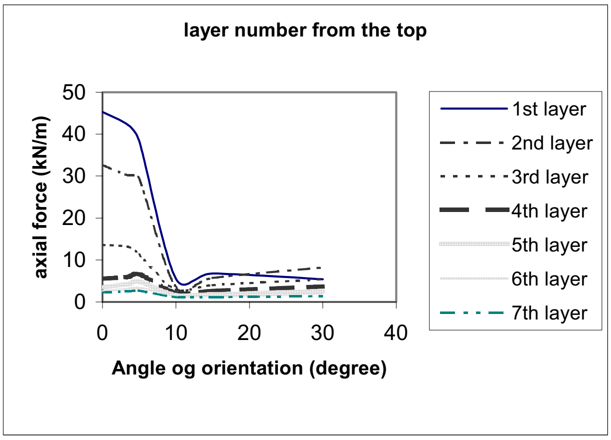


Figure 4. Variation of axial force in reinforcement layers for circular footing against reinforcement orientation.

The variations of ultimate axial force with depth for circular footing for different reinforcement orientation angle are plotted in Figure 5. This figure depicts that the first layers experience higher values of axial forces indicating that increasing the number of reinforcement layers would not lead to further bearing capacity improvement.

The variations of BCR_u/BCR_s ratio with (θ) for circular footing is plotted in Figure 6. This figure depicts that this ratio is not constant, as some previous researches have shown (Binquet and Lee 1975a, b) and the maximum value is reached at certain value of (θ).

5.2 Strip footing

The variation of BCRs for 2.5 cm settlement and ultimate condition for rigid strip footing against different values of (θ) are presented in Table 3. The ultimate values of BCR are also plotted against (θ) in Figure 7. It can be seen that the values of BCR are generally increasing with (θ). However it is not practically feasible to use high values of (θ).

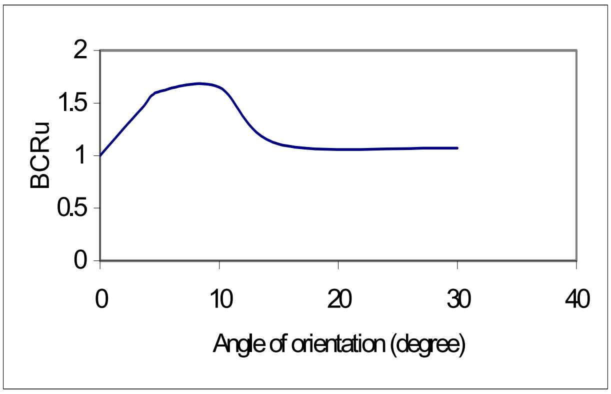


Figure 3. Variation of ultimate BCR_u for circular footing against reinforcement orientation

The values of axial forces in the reinforcement layers against the values of (θ) are shown in Figure 8. The minimum values of axial force are induced in the layers at (θ) equals to 10 degrees which compares well with the results for circular footing. The first two layers in this case are again bearing the higher values of axial forces.

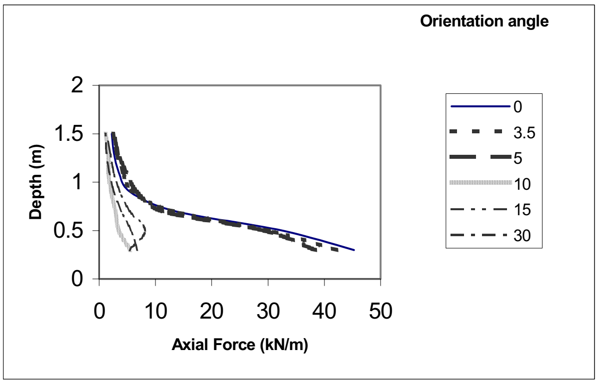


Figure 5. Variation of ultimate axial force with depth for circular footing for different reinforcement orientation

The variation of axial forces with depths of reinforcement layer for different values of (θ) are shown in Figure 9. As it can be seen the force increases with depth and then decreases after reaching its maximum.
The values of BCR_u/BCR_s ratio with (θ) for strip footing is not constant either as for circular footings, Table 3.

6. CONCLUSIONS

In this paper a new parameter affecting the bearing capacity of reinforced soils is introduced. This parameter is reinforcement orientation angle, which is the angle that reinforcement layers make with respect to horizontal plane. It was shown numerically that an optimum value for this angle might exist for which the BCR is maximum for shallow footings. The values of axial forces in reinforcement layers were also found to be affected by this parameter.

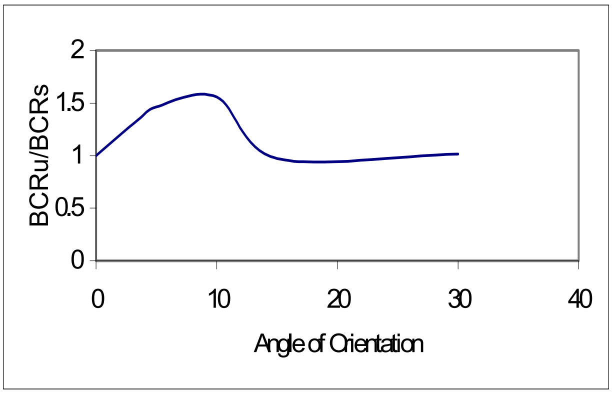


Figure 6. Variation of BCR_u/BCR_s ratio for circular footing for different reinforcement orientation.

Table 3. Variation of bearing pressure ratios for rigid strip footing against reinforcement orientation

Condition	BCRs at 2.5 cm settlement	BCR_u	BCR_u/ BCR_s
Unreinforced soil	1.0	1.0	1.0
Reinforced soil (θ=0)	1.07	1.51	1.41
Reinforced soil (θ=3.5°)	1.05	1.60	1.52
Reinforced soil (θ=5.0°)	1.05	1.66	1.58
Reinforced soil (θ=10.0°)	1.08	1.38	1.27
Reinforced soil (θ=15.0°)	1.07	1.82	1.7
Reinforced soil (θ=30.0°)	1.17	2.46	2.1

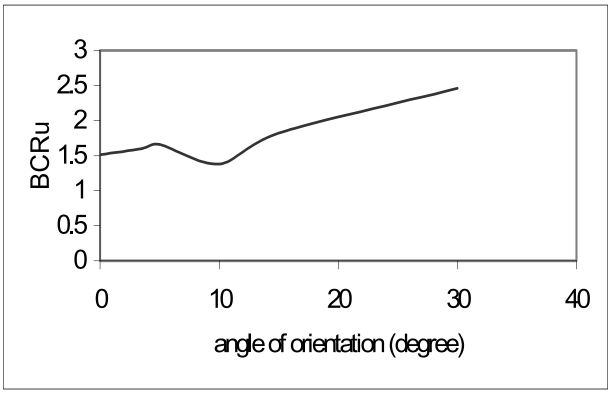


Figure 7. Variation of ultimate BCR_u for strip footing against reinforcement orientation

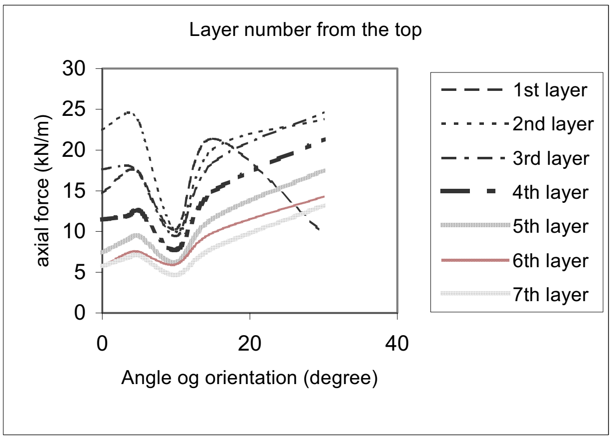


Figure 8. Variation of axial force in reinforcement layers for strip footing against reinforcement orientation

7. REFERENCE

Adams, Michael T. and Collin, James G. 1997. Large model spread footing load tests on geosynthetic reinforced soil foundations, J. Geotechnical and Geoenvironmental Eng., ASCE 123 (1), pp. 66–72.

Akinmusuru, J. O. and Akinbolade, J. A. 1981. Stability of loaded footings on reinforced soil, J. Geotechnical Eng. Div. ASCE, 107(GT6) , pp. 819–827.

Binquet, J. and Lee, K. L. 1975a. Bearing capacity tests on reinforced earth slabs, J. Geotechnical Eng. Div. ASCE 101(GT 12), pp. 1241–1255.

Binquet, J. and Lee, K. L. 1975b. Bearing capacity analysis of reinforced earth slabs, J. Geotechnical Eng. Division, ASCE 101(GT 12), pp. 1257–1276.

Boushehrian, J. H. and Hataf, N., 2003. Experimental and Numerical Investigation of Bearing Capacity of Model Ring Footings on Reinforced Sand, Geotextile and Geomembrane J., Vol. 21, No.4, pp. 241-256.

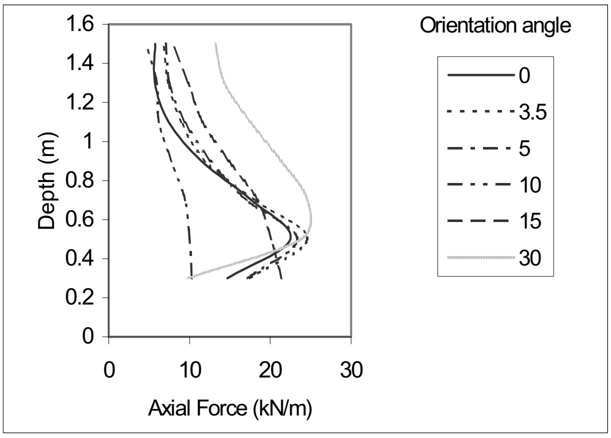


Figure 9. Variation of ultimate axial force with depth for strip footing for different reinforcement orientation

Dixit, R. K. and Mandal, J. N. 1993. Bearing capacity of geosynthetic reinforced soil using variational method, Geotextile and Geomembranes 12 (1993), pp. 543–566.
Fragaszy, R. J. and Lawton, E. 1984. Bearing capacity of reinforced sand subgrade, J. Geotechnical Eng. Div. ASCE 110(10), pp. 1500–1507.
Gray, D.H. and Ohashi, H. 1983. Mechanics of fiber reinforcement in sand, J. Geotechnical Eng. Division, ASCE 109(GT 3), pp. 335-353.
Guido, V. A., Chang, D. K. and Sweeney, M. A. 1986. Comparison of geogrid and geotextile reinforced earth slabs, Can. Geotech. J., Vol. 23, pp. 435–440.
Hataf, N. and Baziar, A., 2000. Use of tire shreds for bearing capacity improvement of shallow footings on sand, Proc. of the 3rd Int. Conf. on GROUND IMPROVEMENT TECHNIQUES, Singapore, pp. 189-194.
Huang, C. C. and Tatsuoka, F. 1990. Bearing capacity of reinforced horizontal sandy ground, Geotextiles and Geomembranes, 9, pp. 51–80.
Jewell, R. A. 1980. Some effects of reinforcement on the mechanical behaviour of soils, Ph. D. Thesis, Cambridge University, Cambridge, England.
Khing, K. H., Das, B. M., Puri, V. K., Cook, E. E. and Yen, S. C. 1993. The bearing capacity of strip foundation on geogrid reinforced sand, Geotextiles and Geomembranes, Vol. 12, pp. 351–361.
Khing, K. H., Das, B. M., Puri, V. K., Yen, S. C. and Cook, E. E. 1994. Foundation on strong sand underlain by weak clay with geogrid at the interface, Geotextiles and Geomembranes, Vol. 13, pp. 199–206.
Kumar, A. and Saran, S. 2003. Isolated strip footing on reinforced sand, J. Geotechnical Engineering, SEAGS, Vol. 32, No.3, pp. 177–189.
Palmeira, E.M. and Milligan, G.W.E. 1989. Scale and other factors affecting the results of pull-out tests of grid buried in sand. Geotechnique, Vol. 39, No.3, pp. 3511-3524.
Terzaghi, K. and Peck, R. B. 1948. Soil Mechanics in Engineering Practice, 1st Ed., John Wiley and Sons, New York.
Yetimoglu, T., Wu, J. H. and Saglamer, A. 1994. Bearing capacity of rectangular footings on geogrid reinforced sand, J. geotechnical Eng. ASCE, Vol. 120, No. 12, pp. 2083–2099.
Zhao, Y. 1993. Strength and deformation behaviour of geogrid reinforced soils, Ph.D. Thesis, Carleton University, Canada.