JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Numerical Modelling of the Behaviour of 3D Geogrid Reinforced Soil Foundation

[1] Femy M. Makkar, [2]Sreya M.V.

[1]Assistant professor
[1]Department of Civil Engineering,
[1]Amaljyothi College of Engineering, kanjirappally, India

Abstract: This paper presents the results of numerical studies carried out on a square footing resting on sand reinforced with three dimensional geogrid using Plaxis-3D software. The performance of 3D geogrid reinforced sand bed was compared with the planar geogrid reinforced sand bed and unreinforced sand bed. The foundation soil was modelled by Mohr coulomb model and the reinforcements were modelled using geogrid structural element available in the software. The numerical models of unreinforced sand bed, planar geogrid reinforced sand bed and 3D geogrid reinforced sand bed were validated with the laboratory plate load test results. The experimental results and numerical results were found to be in good agreement with each other. Using the validated model, parametric studies were carried out to quantify the effect of various parameters on the performance of reinforced soil. The results showed that 3D geogrid reinforced sand bed performed better than conventional planar geogrid reinforced sand bed. Planar geogrid with an optimum number of layers improves the bearing capacity of sand bed by 3.7 times compared to unreinforced soil, whereas, of 3D geogrids gives a BCR value of 6.30.

***IndexTerms* – 3D geogrid, Bearing capacity, Geosynthetics, Reinforced soil foundation**

I. INTRODUCTION

Geosynthetics of various types such as geotextiles, geogrids, geocells, and geomembrane etc. has been used very often for various applications in the field of geotechnical engineering. Its suitability as a reinforcing material for the construction of embankements, shallow foundations, retaining walls, and pavements etc. are well established. However, the performance of a reinforced soil structure greatly depends on the form in which it is incorporated in the soil. Geotextiles are planar sheet like polymeric material in which the friction between the surface of the material and soil mobilizes the interfacial strength and thereby improves the bearing capacity. Geogrids are another type of planar reinforcement which is having a grid like structure. The friction between soil and surface of the geogrid ribs along with the interlocking of soil particles within the apertures impart strength to the geogrid reinforced soil. In the case of geocell reinforced soil, the all-round confinement provided by the geocells prevent the lateral spreading of the soil [1] and improve its strength and stability.

The bearing capacity and settlement characteristics of model footing resting on soil reinforced with above mentioned type of planar geosynthetics have been studied experimentally and numerically by various researchers [2–9]. The performance of geocell reinforced soil has also been studied [10–14]. A few studies have been reported on the behaviour of soil reinforced with reinforcements in three dimensional forms [15–18]. Makkar et al. [19] conducted an experimental study to understand the performance of geogrids in three dimensional form (3D geogrids) in improving the bearing capacity and settlement characteristics of reinforced soil foundation. They reported that 3D geogrids perform better than conventional planar geogrids due to the additional confinement provided by the cells of 3D geogrid. In the present investigation, an attempt has been made to numerically simulate the 3D geogrid reinforced soil foundation.

The results obtained from the numerical simulations of 3D geogrid reinforced sand bed using Plaxis 3D software are presented in this paper. The unreinforced and geogrid reinforced sand bed are also numerically simulated to compare it with 3D geogrid reinforced soil. The numerically obtained results were validated with the laboratory model tests results. Also a detailed parametric study has been done to understand the effect of various parameters such as effect of embedment depth of first layer, width of reinforcement, stiffness of reinforcement, vertical spacing between adjacent layers, and number of layers.

II. TYPE STYLE AND FONTS LABORATORY MODEL TESTS

A series of laboratory scaled plate load tests were carried out to investigate the bearing capacity and settlement characteristics of a square footing resting on 3D geogrid reinforced and conventional planar geogrid reinforced sand bed. The details of the test set up, preparation of test bed, formation of 3D geogrid, testing programme and the results obtained were described by Makkar et al. [19].Only the required features are explained here in.

The model test bed was prepared in a steel tank with dimensions 0.75 m x 0.75 m x 0.75 m. The model footing used was made of mild steel with 0.15 m x 0.15 m square in size and 0.025 m thickness. The soil used in the experimental study was locally available river sand with an average particle size (D_{50}) of 1 mm. The sand has a uniformity coefficient (C_u) of 3.7, coefficient of curvature (C_c) of 1.07, maximum dry unit weight (γ_d max) of 16.28 kN/m^3 and minimum dry unit weight (γ_d min) of 13.73 kN/m^3. According to the Unified Soil Classification System (USCS), the sand was classified as poorly graded sand (SP).

The reinforcements used in the study were planar geogrid and 3D geogrid. The planar geogrid used was commercially available biaxial geogrid having tensile strength of 100kN/m in both longitudinal and transverse direction. The aperture size was 30 mm x 30 mm. The 3D geogrid used was prepared from planar geogrid in a rectangular pattern. The photographs of the two types of reinforcement are shown in Fig. 1.

Fig.1. Photographs of reinforcements used (a) planar geogrid; (b) 3Dgeogrid

All the plate load tests were carried out at a relative density of 50%. In the case of reinforced sand bed, the reinforcements were placed at predetermined locations. A manually operated hydraulic jack supported against a rigid reaction frame was used to transfer the load to the footing. The load applied to the footing was measured from the pressure gauge connected to the hydraulic jack. Two dial gauges placed on diagonally opposite points on the footing was used to measure the footing settlement. Three series of tests were conducted to compare the performance of geogrid and 3D geogrid reinforced sand upon unreinforced sand, and to understand the various parameters such as depth of placement of first layer, spacing between two adjacent layers and number of layers.

III. Numerical modelling

In the present investigation, Plaxis 3D was chosen for the numerical simulation of loading test on reinforced soil bed. It is a three dimensional finite element program that is used for the analysis and design of deformation and stability problems in geotechnical engineering. The simple graphical input procedures in the software enables the quick generation of complex finite element models. The calculation is fully automated and it is based on robust numerical procedures. The enhanced output facilities provide a detailed presentation of computational results.

Table 1. Properties of different materials used in numerical modelling

Parameters	Value
Sand	
Unsaturated unit weight, γ_{unsat}	14.9 kN/m^3
Saturated unit weight, γ_{sat}	17 kN/m^3
Young's modulus, E	3600 kPa
Poisson's ratio, υ	0.3
Cohesion, C	1 kPa
Angle of internal friction, ϕ	40.4◦
Dialatancy angle,ψ	0◦
Model footing	
Thickness, d	0.025 m
Unit weight, γ	78.5kN/m^3
Young's modulus, E	2 x 10^6 kPa
Poisson's ratio, υ	0.3
Geogrid	
Axial stiffness, EA	250kN/m
Aperture size	0.03 x 0.03 m

To simplify the computational effort, only quarter portion of the test model was numerically modelled due to symmetry of the soil-footing reinforcement system. A soil grid with dimensions 0.375 m x 0.375 m x 0 .75 m was used to model the quarter portion of the actual geometry. In order to simulate the behaviour of foundation soil, a suitable material model and appropriate material parameters have to be assigned to the geometry. The Mohr Coulomb model was used to simulate the behaviour of infill soil. The linear elastic- perfectly plastic Mohr Coulomb model requires a total of five parameters, namely, Young's modulus, E (kN/m^2); Poisson's ratio, ν; cohesion, C (kN/m^2); friction angle. Φ (◦); and dilatancy angle, ψ (◦). The square footing was modelled as a plate element. The shear strength properties of the sand were determined from direct shear test. The Young's modulus of sand bed (3600 kPa) modelled is directly taken from the pressure- settlement curve of plate load test on unreinforced sand bed. Latha and Somvanshi [8] also used the same procedure to determine the Young's modulus of sand. The behaviour of plate element is defined by the parameters Young's modulus and Poisson's ratio.

The conventional geogrid and 3D geogrid of rectangular pattern (3DGR) were modelled in Auto CAD-3D and imported into Plaxis 3D software. Later, it was modelled using geogrid structural elements available in Plaxis 3D. The properties of different materials used in the numerical modelling are given in Table.1.

A uniformly distributed pressure was applied on the top of the plate in the vertical direction to simulate the load on the model footing. The displacement along the bottom boundary, which represents the tank bottom, was restrained in both horizontal as well as vertical directions. The side boundaries (which represent tank side) were restrained only in the horizontal direction, such that the displacements were allowed to occur in the vertical direction. Fig.2 shows the numerical models of unreinforced, geogrid reinforced and 3D geogrid reinforced sand bed. In this paper, the numerical analysis on the model footings are used to support the results obtained from the experimental study.

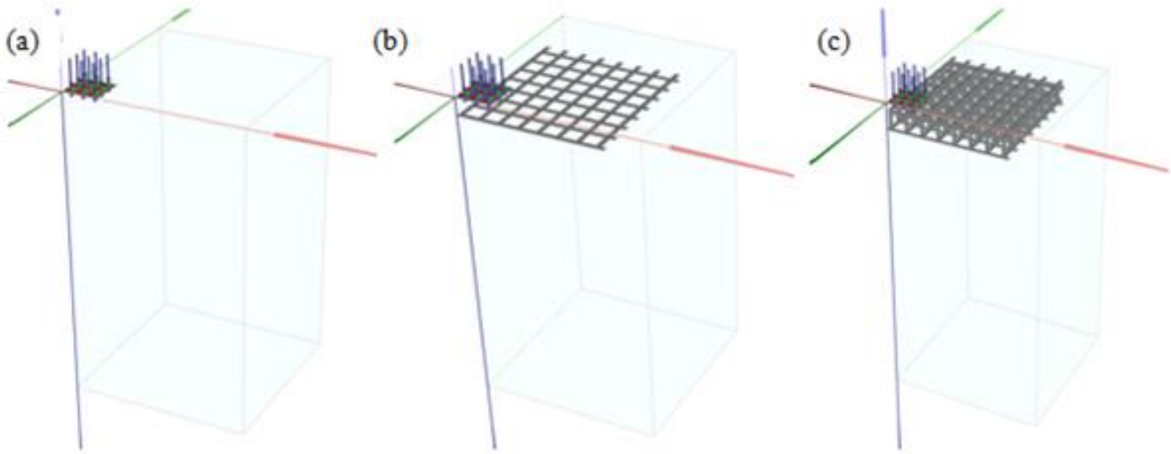

Fig.2. Plaxis 3D models of (a) unreinforced sand; (b) Geogrid reinforced sand; (c) 3Dgeogrid reinforced sand

IV. Validation

Before moving to the parametric study the numerical model was validated with experimental results. In the numerical analysis, uniform pressure was applied on the top of the plate and the corresponding settlements were found out. The numerical results were compared with experimental results reported by Makkar et al. [19]. Fig.3 shows the comparison of the bearing pressure- settlement curve obtained from experimental and numerical studies for unreinforced and reinforced sand bed. A fairly good match was observed between the numerical and experimental results. The bearing capacity of soil was taken as the bearing pressure corresponding to 25 mm footing settlement. In all the cases, the percentage variation between predicted and observed values was less than 10%.

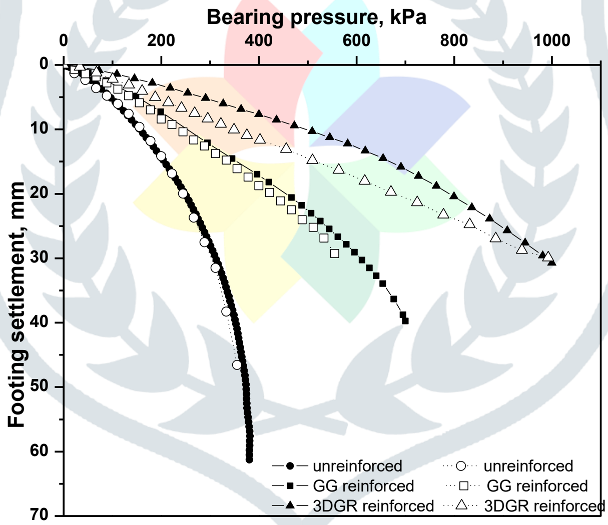

Fig. 3. Bearing pressure- settlement curve for unreinforced and reinforced sand bed

V. Parametric studies

The various parameters considered in the numerical analysis includes the embedment depth of first layer, width of reinforcement, tensile strength of reinforcement, vertical spacing between two consecutive layers, and number of layers. The parameters and its values chosen are given in Table 2.

Table.2. Parameters for numerical modelling of reinforced soil

Sl.no	Parameters	Value
1	Embedment depth of first layer	u/B =0.1, 0.25, 0.5, 0.75; b/B =4
2	Width of reinforcement	b/B =1, 2, 3, 4; u/B =0.25
3	Stiffness of geogrid	EA = 50, 250, 500 1000, 2000, 5000
4	Spacing between two layers	h/B =0.1, 0.25, 0.5, 0.75; u/B=0.25; b/B= 4
5	Number of layers	N =1, 2,3,4,5

VI. RESULTS AND DISCUSSIONS

The improvement in the performance of model footing due to the inclusion of planar geogrid or 3D geogrid in sand bed was quantified in terms of non-dimensional parameters, bearing capacity ratio (BCR) and settlement reduction factor (SRF), which are defined as follows:

$$BCR=q_r/q_0 \quad (1)$$

Where, q_r is the bearing pressure of reinforced soil at a given settlement and q_0 is the bearing pressure of unreinforced soil at the same settlement.

6.1 Embedment depth of first layer

For understanding the effect of embedment depth of first layer of reinforcement, the distance of first layer of reinforcement from the bottom of the footing (u) was varied as 0.1 B, 0.25B, 0.5B, and 0.75B, where B is the width of the footing. In all the case of 3D geogrid reinforced soil, 'u' is taken as the distance from the bottom of the footing to the mid height of the 3D geogrid. The variation of bearing pressure with footing settlement for different embedment depth of first layer is plotted in Fig4. From the figure, it can be seen that the bearing capacity of the soil increases with the provision of reinforcement and the better performance has been shown by the 3D geogrid reinforced sand.

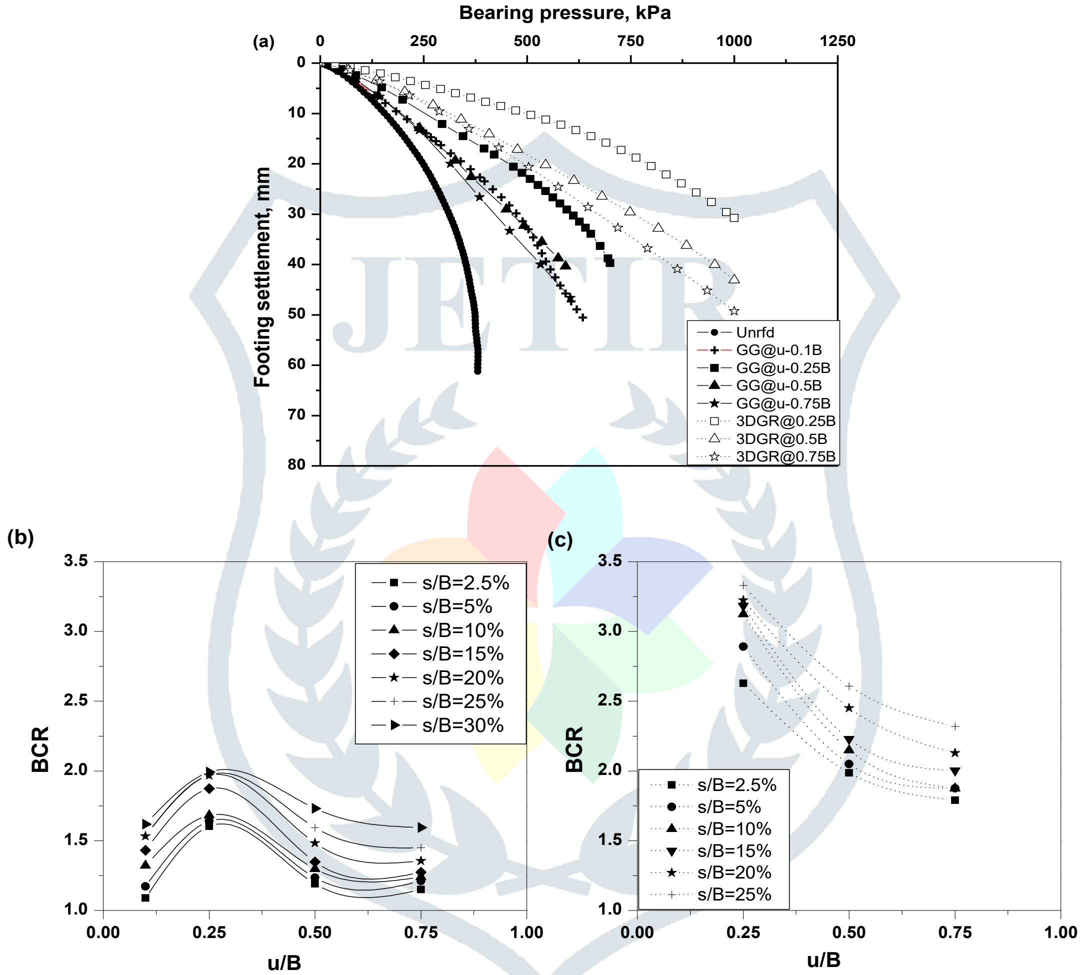

Fig. 4. (a) Bearing pressure-settlement curve for different u/B ratios; (b) Variation of BCR with u/B ratios for different settlement ratios for planar geogrid; (c) Variation of BCR with u/B ratios for different settlement ratios for 3D geogrid

The variation of bearing capacity ratio (BCR) with u/B ratio for planar geogrid reinforcement at different settlement ratios are shown in Fig.4(b). It can be seen that the bearing capacity of the soil increases upto a u/B ratio of 0.25; and there after it decreases for all levels of settlement. In planar geogrid reinforced soil, in order to develop maximum frictional resistance between soil and the reinforcement, sufficient overburden pressure is required above the reinforcement [6, 19-20]. In the present study, the sufficient overburden pressure was attained at a depth of 0.25B from the bottom of the footing. Further increase in depth of reinforcement reduces the bearing capacity due to excessive settlement. Fig.4(c) shows the variation of BCR with u/B ratios for 3D geogrid reinforced sand bed. When the 3D geogrid was placed at a depth of 0.25B, the BCR value is maximum for all levels of settlements. As the depth increases further, the BCR value decreases. So the optimum depth of single 3D geogrid layer can be taken as 0.25B from the base of the footing. A single layer 3D geogrid placed at an optimum depth gives a BCR value of 3.21; while, planar geogrid layer at optimum depth gives a BCR value of 1.9 times. Along with the beneficial advantages of planar geogrid, the confinement and interlocking of sand particles within the cells of 3D geogrid contributes to the better performance of 3D geogrid reinforced soil. Fig. 5(a) - 5(c) shows the vertical displacement profiles of unreinforced sand bed , single layer planar geogrid reinforced sand bed and single layer 3D geogrid reinforced sand bed at the optimum depth of 0.25B. It shows that the vertical displacement reduces with provision of geogrid reinforcement.

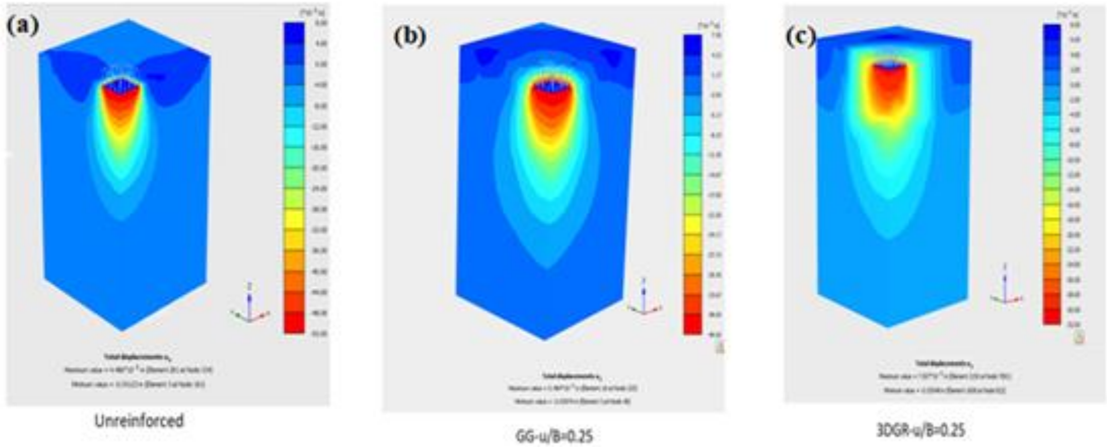

Fig.5. Displacement profile for (a) unreinforced sand; (b) planar geogrid reinforced sand; (c)3D geogrid reinforced sand

6.2 Effect of width of reinforcement

To find out the optimum width of reinforcement, the analysis was carried out by varying the width of reinforcement (b) as 1B, 2B, 3B, 4B and 4.5B. The variation of bearing capacity ratio with width ratio at different settlements for planar geogrid and 3D geogrid are plotted in Fig. 6(a). It can be seen that the BCR value increases with increase in width of reinforcement upto 4B for both planar geogrid and 3D geogrid. With further increase in width of reinforcement beyond 4B, the bearing capacity of the soil starts to decrease. Latha and Somvanshi [8] reported that the optimum width of reinforcement is the sum of the width of shear zone and anchorage zone on both the sides; and any additional width of reinforcement beyond this value will be ineffective and does not result in any improvement in the bearing capacity of footing. Hence from the numerical analysis, the optimum width of reinforcement can be taken as 4 times the width of the footing.

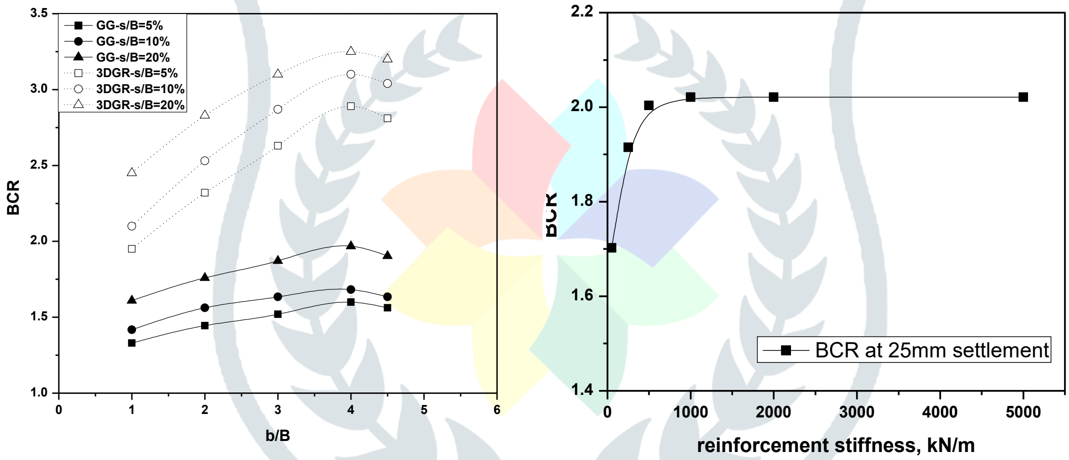

Fig.6. (a) Variation of BCR with width ratio for different settlement ratios; (b) Variation of BCR with reinforcement stiffness

6.3 Effect of stiffness of reinforcement

To analyse the effect of axial stiffness of the reinforcement on the bearing capacity, the stiffness value has been varied between 50kN/m and 5000kN/m. Fig.6(b) shows the variation of bearing capacity ratio (BCR) with axial stiffness of reinforcement for geogrid reinforcement. It can be seen that increasing reinforcement beyond an axial stiffness of 500kN/m would not results in any significant improvement in the BCR value. From the practical point of view, it shows that selecting reinforcement with higher stiffness does not always lead to better results in terms bearing capacity ratio. Since the 3D geogrids are prepared from the planar geogrids itself, the effect of reinforcement stiffness will be same as that in the case of planar geogrid.

6.4 Effect of spacing between two consecutive layers

To understand the effect of spacing between two adjacent layers of reinforcement, the first layer of reinforcement was placed at the optimum depth and the adjacent layer at various spacing ratios (h/B) as given in Table 2. Due to the height of 3D geogrid, the spacing variation between two layers of 3D geogrids was limited to 0.5B and 0.75B. Table.3 shows the BCR value for different spacing ratios. Two layers of geogrid gives higher bearing capacity, when they were placed at a spacing ratio of 0.25. As in the case of single layer geogrid, sufficient overburden pressure is required in between the geogrids to mobilize the interface resistance in the second layer. It was achieved at a spacing of 0.25B between two adjacent layers. Further increase in the spacing ratio reduces the bearing capacity of planar geogrid reinforced sand. In the case of 3D geogrid reinforced sand bed, the spacing between two adjacent layers were varied as 0.5B and 0.7B. It is seen that two layers of 3D geogrid at a spacing of 0.75B gives higher bearing capacity. Since the 3D geogrids are placed at desired locations in the test tank with respect to its mid height, sufficient amount of soil is required in between the base and top of the first and second layer to get maximum benefit, which is attained at a higher spacing ratio[19]. Therefore 0.75B could be taken as the optimum spacing between two consecutive layers. The BCR value for two layer planar geogrid reinforced and 3D geogrid reinforced sand bed at optimum depth and spacing gives a BCR value of 2.52 and 5.40 respectively.

Table 3. BCR value for different spacing ratios

Sl. No	Spacing ratio (h/B)	BCR	
		Planar geogrid	3D geogrid
1	0.1	1.90	-
2	0.25	2.52	-
3	0.5	2.10	4.70
4	0.75	1.93	5.40

6.5 Effect of number of layers

In the case of planar geogrid reinforced sand bed, the effect of number of layers was studied by placing the reinforcements at optimum embedment depth (u/B) and optimum spacing (h/B) and increasing the number of layers from 1 to 5. From the pressure-settlement curve shown in Fig. 7 (a), it can be seen that the bearing capacity of the planar georid reinforced sand increases with increase in number of layers. Fig. 7c shows the variation of bearing capacity ratio (BCR) with number of layers. From the graph, it is clear that the BCR value increases proportionally with increase in number of layers up to N=4, which is located at a depth of 1.0B. Beyond N=4, BCR value slightly increases, but the rate of increase is very small. When the number of layers increases from 3 to 4, the BCR value increased by 18%; while from 4 to 5, the increase in BCR value is only less than 2%. Several researchers had similar observation that increasing number of layers beyond a certain number would not increase the BCR significantly [2 - 3, 8 - 9, 21]. So the optimum number of layers for planar geogrid reinforced sand bed can be taken as 4.

To study the effect of multi-layered 3D geogrid reinforced sand bed, the reinforcement layers were placed at an optimum embedment depth of 0.25B and optimum spacing of 0.75B. The number of layers increased up to 3. From Fig. 7 (b) it is clear that the bearing capacity of 3D geogrid reinforced sand increases with increase in number of layers. The variation of BCR with number of 3D geogrid layers can be seen in Fig.7(c). The improvement in bearing capacity ratio, when the number of layers increases from 1 to 2 was 68%; and from 2 to 3 is only 17%. The effect of maximum depth of influence of the vertical load is governed by the depth of pressure bulb, which is equal to 2B in the case of square footing. In this analysis, the third 3D geogrid layer was located at a depth of 1.75B from the base of the footing, which was very close to the depth of pressure bulb. This may be the reason for smaller rate of improvement in the BCR value when the number of layers increased from 2 to 3. Hence it will be insignificant to provide one more 3DGR layer beyond 2B depth. So the optimum number of 3DGR layers can be taken as 3.

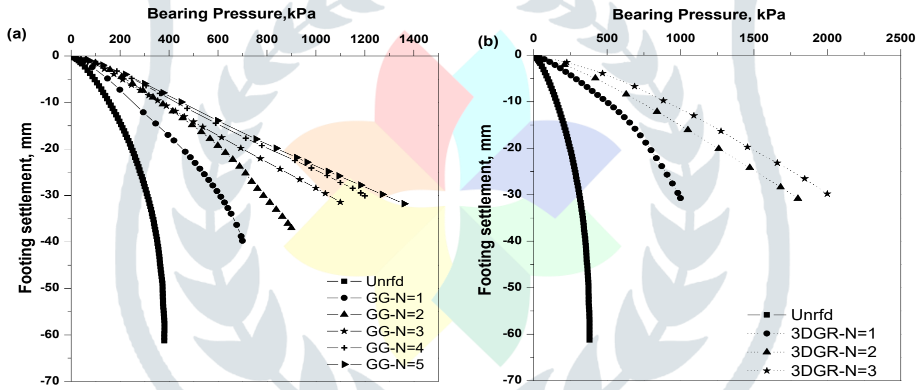

Fig.7. (a) Bearing pressure- settlement cure for different number of planar geogrid layers; (b) Bearing pressure-settlement cure for different number of 3D geogrid layers;

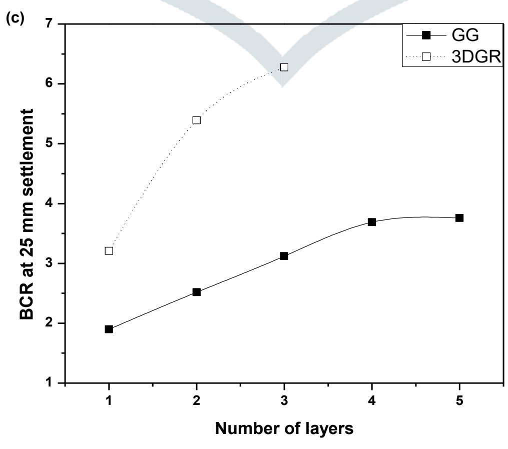

Fig.7. (c) Variation of BCR with number of layers

VII. Conclusions

This paper presents the results of a numerical analysis carried out to understand the behaviour of square footing resting on 3D geogrid reinforced sand bed using a finite element software Plaxis 3D. The performance of 3D geogrid reinforced sand bed is compared with unreinforced and geogrid reinforced sand bed. Detailed parametric study has been done to understand the effect of various parameters on the bearing capacity of reinforced sand. From the numerical study, the following conclusions can be drawn.

- The numerically simulated model was validated with the experimental results and found that the results are in good agreement with each other.
- The bearing capacity of the square footing resting on 3D geogrid reinforced sand bed increased significantly compared to unreinforced and planar geogrid reinforced sand.
- A single layer of 3D geogrid at an optimum depth of 0.25B from the base of the footing gives a BCR value of 3.21; while, single planar geogrid layer gives a BCR value of 1.92 only. The percentage improvement in bearing capcity for 3D geogrid reinforced sand is 67% compared to planar geogrid reinforced sand.
- The bearing capacity of reinforced sand bed increases with reinforcement width up to 4B for both 3D geogrid and planar geogrid.
- Increasing the reinforcement stiffness beyond 500kN/m would not result in any significant improvement in the BCR vale.
- The optimum spacing between two adjacent layers of reinforcement has been obtained as 0.25 B and 0.75 B for planar geogrid and 3D geogrid respectively.
- The optimum number of planar geogrid layers was obtained as four with a BCR value of 3. 69, while 3 layers of 3D geogrid reinforced sand bed gives a BCR value of 6.30.

REFERENCES

[1] G. M. Latha, S. K. Dash, K. Rajagopal, "Numerical Simulation of the Behavior of Geocell Reinforced Sand in Foundations," Int. J. Geomech.vol. 3641, (2009).
[2] M. T. Omar, B. M. Das, S. C. Yen, "Ultimate bearing capacity of shallow foundations on sand with geogrid reinforcement," *Can. Geotech. J.*, vol. 30, 545–549, (1993).
[3] A. Yetimoglu, T,Wu J.T.H, Saglamer, "Bearing capacity of rectangular footings on geogrid-reinforced sand," *J. Geotech. Geoenvironmental Eng.*, vol. 120, no. 12, 2083–2099, (1994).
[4] C. G. Collin, M.T. Adams, "large model spread footing load tests on geosynthetic reinforced soil foundations," *J. Geotech. Geoenvironmental Eng.*, vol. 123, no. 1, 66–72, (1997).
[5] H. A. Alawaji, "Settlement and bearing capacity of geogrid-reinforced sand over collapsible soil," *Geotext. Geomembranes*, vol. 19, 75–88, 2001.
[6] A. Ghosh, A. Ghosh, A. K. Bera, "Bearing capacity of square footing on pond ash reinforced with jute-geotextile," *Geotext. Geomembranes*, vol. 23, 144–173, (2005).
[7] W. Chung, G. Cascante, "Experimental and numerical study of soil-reinforcement effects on the low-strain stiffness and bearing capacity of shallow foundations," Geotech. Geol. Eng., Vol.25, 265–281, (2007).
[8] G. M. Latha, A. Somwanshi, "Bearing capacity of square footings on geosynthetic reinforced sand," *Geotext. Geomembranes*, vol. 27, no. 4, 281–294, (2009).
[9] M. Abu-farsakh, Q. Chen, R. Sharma, "An experimental evaluation of the behavior of footings on Geosynthetic -Reinforced Sand," *Soils Found.*, vol. 53, no. 2, 335–348, (2013).
[10] S. K. Dash, K. Rajagopal, N. R. Krishnaswamy, "Behaviour of geocell-reinforced sand beds under strip loading," *Can. Geotech. J.*, vol. 44, 905–916, (2007).
[11] T.G . Sitharam, S. Sireesh, S.K. Dash, "Performance of surface footing on geocell- reinforced soft clay beds," *Geotech. Geol. Eng.*, vol. 25, 509–524, (2007).
[12] S. Saride, S.Gowrisetti, T. G. Sitharam, A.J.Puppala, "Numerical simulation of geocell-reinforced sand and clay," *Gr. Improv.*, vol. 162, no. G14, 185–198, 2009.
[13] A. Hegde, T. G. Sitharam, "3-Dimensional numerical modelling of geocell reinforced sand bed *Geotext. Geomembranes* s," vol. 43,171–181, (2015).
[14] A. Hegde, T. G. Sitharam, "Experiment and 3D-numerical studies on soft clay bed reinforced with different types of cellular confinement systems," *Transp. Geotech.*, vol. 10, 73–84, 2017.
[15] M. X. Zhang, A. A. Javadi, X. Min, "Triaxial tests of sand reinforced with 3D inclusions," *Geotext. Geomembranes* , vol. 24, 201–209, (2006).
[16] M. Mosallanezhad, N. Hataf, A. Ghahramani, "Three dimensional bearing capacity analysis of granular soils reinforced with innovative grid-anchor system," *Iranian J. Sci.Tech.*, vol. 34, 419–431, (2010).
[17] M. Harikumar, N. Sankar, S. Chandrakaran, "Behaviour of model footing resting on sand bed reinforced with multi-directional reinforcing elements," *Geotext. Geomembranes*, vol. 44, 568–578, (2016).
[18] N. Hataf, M. Sayadi, "Experimental and numerical study on the bearing capacity of soils reinforced using geobags," *J. Build. Eng.*, vol. 15, 290–297, (2018).
[19] F. M. Makkar, S. Chandrakaran, N. Sankar, "Behaviour of model square footing resting on sand reinforced with three-dimensional geogrid," *Int. J. Geosynth. Gr. Eng.*, vol. 3, 1-10, (2017).
[20] P. Vinod, A. B. Bhaskar, S. Sreehari, "Behaviour of a square model footing on loose sand reinforced with braided coir rope," *Geotext. Geomembranes*, vol. 27, no. 6, 464–474, (2009).
[21] P. K. Basudhar, S. Saha, K. Deb, "Circular footings resting on geotextile-reinforced sand bed," *Geotext. Geomembranes*, vol. 25, 377–384, (2007).