Performance of Strip Footing on Sand Bed Reinforced with Multilayer Geotextile with Wraparound Ends

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Abstract. The land scarcity has built up the pressure on the engineers to bring a cost-effective and time-saving solution to utilize the ground with poor strength as a foundation bed for the various structures. With the recent progress in the area of ground reinforcing techniques using geosynthetics, the extensive usage of geotextile materials as a reinforcing element in the soil to strengthen the load-bearing capacity of the soil mass and reducing the anticipated settlement of the footing pushes the researchers to evolve new methods to maximize the advantages received from the reinforced earth beds. In the above-context, the provision of reinforcing layers with wraparound ends has brought additional improvement in the load settlement behavior of a strip footing resting over such reinforced soil mass but this recently developed technique lacks the appropriate guidelines/recommendations for the geometrical configuration parameters of the reinforcing layer to maximize the benefit from the reinforcing layer. Given the above, a comprehensive numerical study has been conducted to propose some recommendations on the geometrical configurations of the reinforcing layers. Furthermore, this study also investigates the influence of the geogrid-soil interface on the load-settlement response of the reinforced bed under vertical footing load. From the findings of the study, it is concluded the width of the geogrid layers, governs the overall load-bearing capacity of the reinforced soil mass system, besides it, also suggests an optimum width of the geogrid layers, equals 1.5 times the width of the footing should be used to maximize the effective utilization of the wraparound technique. Furthermore, it was also noted that appropriate assessment of the interface between soil and geogrid may bring an optimized design of the reinforced soil mass as a foundation bed for the footings.

Keywords: Geogrid, Reinforced soil mass, Strip footing, Normalized settlement ratio, Strength reduction factor, Finite element method

1 Introduction

The concept of bearing capacity of the soil mass was put forward by Terzaghi [1] for the very first time, and thereafter numerous researchers have proposed various analytical models to predict the bearing capacity of a footing resting over an isotropic and homogenous soil mass. Reinforcement of the soil mass and the usages of reinforced soil mass in the contemporary soil structures was proposed by Casagrande and its use as a composite material was presented by Henri Vidal for the first time in the mid of 19th century [2]. Usages of geogrid for enhancing the bearing capacity of the ground i.e. for improved ultimate load-bearing capacity and reduced settlement of the foundation, as a reinforcing material for the soils having poor strength have become a widely adopted solution for the utilization of poor strength ground as a foundation bed [3]. Moreover, apart from reinforcing action, geogrids may also serve the purpose of drainage control, erosion control, separation, etc. The tensile reinforcement in the form of geogrid can be used for the construction of load-bearing structures and also improve its overall stability when subjected to static as well as dynamic loadings [4]. The reinforced soil foundation has a considerable potential to support the shallow foundation as a cost-effective substitute for traditional approaches of construction [5].

In the past, various researchers have accompanied studies to assess the response of shallow foundation emphasized with metal strips and geogrid subjected to concentrated vertical loading [6]. The ultimate bearing capacity of circular and strip footings under vertical and inclined load was determined by using the limit equilibrium method [7]. In order to assess the performance of reinforced foundation, a series of large-scale testing was conceded to evaluate the influence of reinforcement on the bearing capacities and settlement criterion by using biaxial geosynthetics as horizontal reinforcement [5]. Furthermore, various field tests and small-scale laboratory tests had recommended that reinforcing the soil mass with single or multiple layers of geogrids under vertical concentrated load may result in higher ultimate-load bearing capacity of the reinforced soil mass ($q_{u,\,R}$) and reduced settlement of the foundation (s) [8, 9]. The geometrical parameters of the reinforcing layers (length and width), their depth beneath the footing, the elastic stiffness of geogrid are the key factors that sincerely affect the $q_{u,\,R}$. The available literature suggested that the width of the reinforcement layer should be 4 to 6 times of the footing width to maximize the benefits from the provision of the reinforcement in the foundation soil [9, 10]. Nevertheless, sometimes the availability of land on both sides of footing restricts the use of sufficient width of reinforcement than required. The above circumstances have been addressed by Kazi et al. [11, 12] and Shukla [13], in which a rearrangement in the placement of geogrid is introduced with the wrapping ends of the reinforcement on both the ends along its width. The practice of wraparound ends has improved the bearing capacity of soil mass along with the saving in land space. In the recent past, the concept of using reinforcing layer with full wraparound ends has been introduced which does not only improve the bearing capacity of the soil mass additionally compared to a reinforced bed with reinforcement without wraparound ends but also confined the soil mass and restricted its lateral movement on the application of load over the footing [14].

From the widespread literature survey, it has been noted that the width of the reinforcing layer (b), the vertical length of the wrapping ends (d), lap length of the overlapping portion (L), placement of the first layer of reinforcement (u), the vertical spacing between consecutive layers (h), and the number of reinforcing layers (N) are the governing factor in controlling the bearing capacity and settlement criterion. From the available literature, it is perceived that the following parameters have been recommended in order to have maximum reinforcement benefits for a strip footing of width (B): $b/B = 6$ [9]; $L/B = 0.6$ [12]; $h/B = 0.2\text{-}0.4$ [8]; $d/B = 0.2$ [11]; $u/B = 0.25\text{-}0.5$ [9]; $N = 4$ [8, 15].

From the available research related to the numerical approach of determining the ultimate load-bearing capacity of the strip footing, no discussion had been done on the interaction parameters between the soil and geogrid. The force transfer mechanism between soil and reinforcing material is measured through the behavior of interface, and the assessment of the interface behavior is essentially required to understand the interaction between two dissimilar materials i.e. soil and geogrid. Numerical models for defining the performance based on the laboratory and/or field tests are called constitutive models, which are suitable for the realistic characterization of the mechanical behavior of the solid materials and interfaces, which is essential for the appropriate solution of the practical problems. “In the traditional plasticity models such as Drucker-Prager and Mohr-Coulomb, it is assumed that the behavior is elastic until the material reaches a certain yield point, often defined by the yield stress. Subsequently, the material reaches into a plastic region governed by conditions such as a yield criterion and flow rule that defines the plastic flow, like a liquid.” Considering the above, the present research aims to analyze the effect of the interface parameter between soil and geogrid on the $q_{u, R}$ of the footing. Also, it is noticed that the discussion on the effect of reinforcement parameter i.e. elastic stiffness (EA, where E is young’s modulus and A is the cross-sectional area) is absent in the available literature.

Most of the studies were relevant to the behavior of footing which was resting on the surface, which is not the actual situation in the practice, however, this is close to Terzaghi’s [1] original derivation for the bearing capacity determination, where he has assumed that overburden due to the surrounding soil is zero. Concerning the above, align with the actual site condition all the foundations are embedded one, therefore this particular study is highlighting the behavior of embedded footing resting over the reinforced soil mass.

In view of the above, a detailed parametric study has been performed using a finite element method based program Optum G2 [16], for a strip footing of width B, by varying the width of reinforcement (b) and the results thus obtained from the present analysis are compared with the available data. Moreover, the elastic stiffness (EA) of the geogrid reinforcement has been varied to analyze its effect on the $q_{u, R}$ and the responsiveness of EA towards the settlement and the soil deformation has been discussed comprehensively in the subsequent section. The objective of conducting the present research work is to focus on the significance of interface parameters that guide the interaction between soil and geogrid, which has been discussed by varying the strength reduction factor (R_{int}) in between the soil and the geogrid reinforcement.

The previous findings stated that for simulation of the actual behavior of soil, the Mohr-Coulomb (M-C) yield criterion has been used frequently for the evaluation of the ultimate load-bearing capacity of the footing. Few researchers had reported that the Mohr-Coulomb criterion produces singularities due to an irregular pyramid in the bay of principal stresses while computing numerical equations intended for operating the plastic flow at the corner of the yield surface [17]. To overcome the above situation, the Drucker-Prager (D-P) yield criterion is taken into consideration in the present study. A comparison of the Drucker-Prager yield criterion and Mohr-Coulomb yield criterion has also been discussed in the consequent section of this paper. The Drucker-Prager yield criterion uses slightly different expressions for characterizing plastic and yield potential function. The following Eqs. 1 and 2 can be used to obtain the parameters for the Drucker-Prager model with the help of shear strength parameters.

$$M = \frac{3\sin\phi}{\sqrt{3+\sin^2\phi}} \tag{1}$$

$$k = \frac{3c\cos\phi}{\sqrt{3+\sin^2\phi}} \tag{2}$$

where c and ϕ are the cohesion and the internal friction angle of the soil that is used in the M-C model to define soil strength. Moreover, k and M are the Drucker-Prager parameters which signify the cohesion and the friction coefficient, respectively.

2 Numerical modeling

A rigid strip footing has been analyzed by utilizing the Optum G2 program resting on a medium dense cohesionless soil [16]. The effect of reinforcement width, elastic stiffness of the geogrid material, and the interface parameters between the soil and geogrid has been studied for a footing having width B = 2m. The vertical boundary of the model is restrained in the normal direction and the horizontal bottom is fully fixed (as shown in Fig. 1).

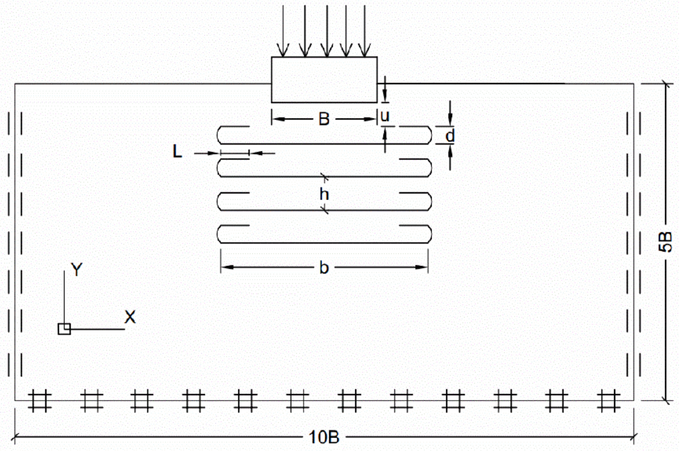


Fig. 1. Boundary conditions and geogrid reinforced soil using the wraparound technique

It has been reported in many studies that if the sufficient length and width is not provided to the mesh, the failure plane is being intercepted by the boundaries and inappropriate bearing capacities determination is shown in numerical analysis. To avoid this situation, the boundary limits in the present study are considered at 5B in the vertical direction and 10*B* in the horizontal respectively. The soil mass has been modeled using six node plane-strain triangular elements for achieving higher accuracy in the results. An elastoplastic constitutive model considering the D-P yield criterion with zero dilatancy, following associated flow rule has been used to model the soil. The reinforcement material is modeled using the structural geogrid elements having axial elastic stiffness, *EA*.

It has been recommended by various researchers, that the accuracy of any numerical model depends upon the appropriate number of elements present in the mesh as a lesser number of elements may lead to an inconsistent result and a high number of elements in a given mesh may pose problems to computational efficiency. Keeping this in mind, a sensitivity analysis has been performed for unreinforced soil mass, by varying the number of elements from 1000 to 8000 for the present mesh at an interval of 1000 each, and the results indicated that 5000 elements are sufficient for the current mesh, as a negligible change is observed in the ultimate load-bearing capacity of the unreinforced footing (q_u) after increasing the number of elements from 5000 (as shown in Fig. 2) [18].

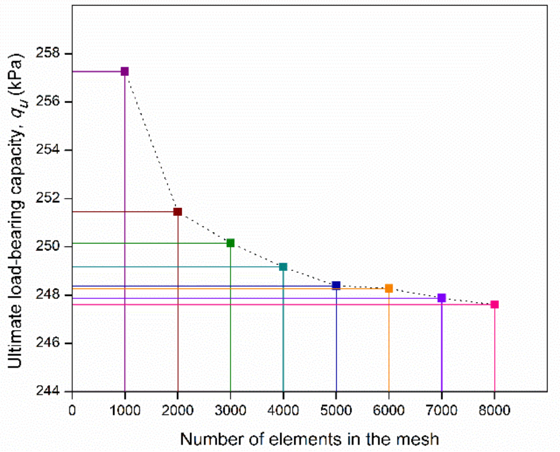


Fig. 2. Sensitivity analysis for the mesh considered in this study

The vertical length of geogrid (*d*) (used for wrapping geogrids at both ends) has been chosen in such a manner that it should always be lesser than the value of spacing between consecutive layers of geogrid (*h*). Therefore, a reinforced mass lying between two consecutive geogrids is such that two parallel reinforcing layers exist along with two wrapped around ends and vertical length of the reinforcement of length, *L* and *d* respectively are present over there. A unit cell of the reinforcement comprises two horizontal reinforcement, two small vertical reinforcement, and two small horizontal reinforcement i.e. lap length.

3 Material properties

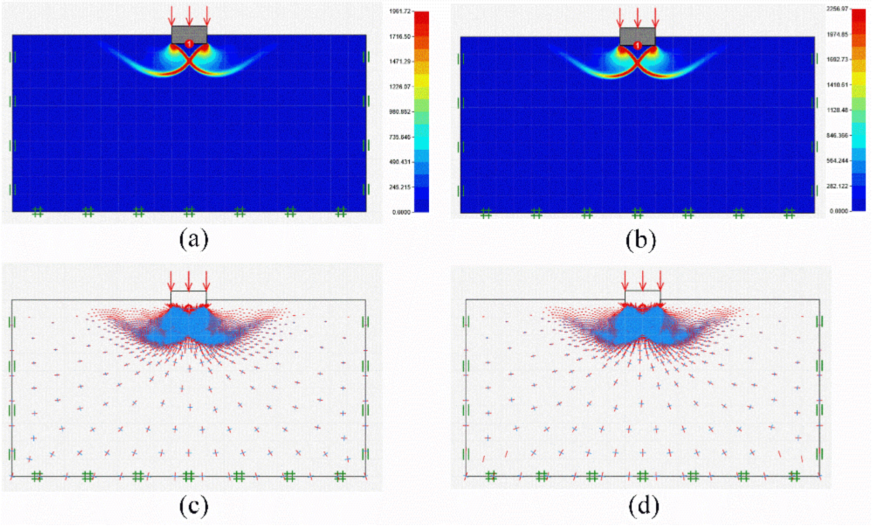
The assigned soil properties are $k = 0$, and $M = 0.736$, corresponding to the cohesionless soil having a dry unit weight of $\gamma_{dry} = 15$ kN/m^3 with shear strength parameters $\phi = 26°$ and $c = 0$ as per Mohr-Coulomb failure criterion. To examine the geometrical parameters of reinforcement, a parametric study has been conducted by varying the reinforcement width (b) from 3 m to 6 m at an interval of 1m. Following geometrical parameters of the geogrid are kept constant while performing the analysis: lap length (L) = 0.3B, vertical length of the wraparound ends (d) = 0.2B, depth of placement of first layer (u) = 0.3B, vertical spacing between consecutive geogrid layers (h) = 0.3B. Also, the axial elastic stiffness (EA) of the geogrid has been varied from 500 kN/m to 2000 kN/m at an interval of 500 kN/m for analyzing the settlement behavior and improvement in the bearing capacity of the footing resting over corresponding reinforced soil mass. With the above-mentioned evaluation, parameters are determined and while keeping the optimum reinforcement width and elastic stiffness fixed, the strength reduction factor (R_{int}) has been varied at 0.7, 0.8, and 0.9 to study the effect of soil-geogrid interaction on the behavior of footing resting over reinforced soil mass. With the use of multiplier elastoplastic analysis, the load-settlement behavior of the footing is evaluated for all the cases studied in the present study. The multiplier elastoplastic analysis involves the application of an incremental vertical surcharge till the state of incipient failure of the footing reaches and the corresponding $q_{u,\,R}$ of the footing is determined from the load-settlement curve by applying the double tangent method [19].

4 Results and discussion

As mentioned earlier, in this study numerical simulations have been carried out for the investigation of optimum width of reinforcement, the effect of elastic stiffness of geogrid, and also the impact of strength reduction factor (i.e. interface parameter) on the ultimate load-bearing capacity ($q_{u,\,R}$) and settlement of the footing. The results have been presented in the form of plots of load-bearing pressure versus normalized settlement of the footing and discussed in the following section.

To ascertain the efficiency of the Drucker-Prager model, the current model has been compared with the Mohr-Coulomb model by using an established computational technique i.e. limit analysis. A strip footing of width 2 m has been considered resting over an unreinforced soil mass in both the model i.e. M-C and D-P yield criteria and a vertical incremental surcharge has been applied on the footing in the downward direction followed by limit analysis. The results obtained from the above analysis are shown in the form of potential failure patterns and principal stresses vectors σ_1 and σ_3 in Fig. 3, where σ_1 and σ_3 are major and minor principal stresses, respectively.

The soil parameters i.e. cohesion and angle of internal friction angle for both the models are kept similar by utilizing Eqs. (1) and (2). The results indicated that both the models produce a similar potential failure pattern as proposed by Terzaghi [1] and is in good agreement with each other. Also, the ultimate load-bearing capacity of the footing obtained for M-C and D-P yield criteria is 247.8 kPa and 247.6 kPa, respectively, in which the difference in ultimate values of bearing capacities is only about 0.08%, and the noted observation justifies the selection of the D-P model for analysis.



(a) (b)

(c) (d)

Fig. 3. Potential failure pattern (a) M-C yield criterion; (d) D-P yield criterion; and σ_1 and σ_3 vectors (c) M-C yield criterion; and (d) D-P yield criterion

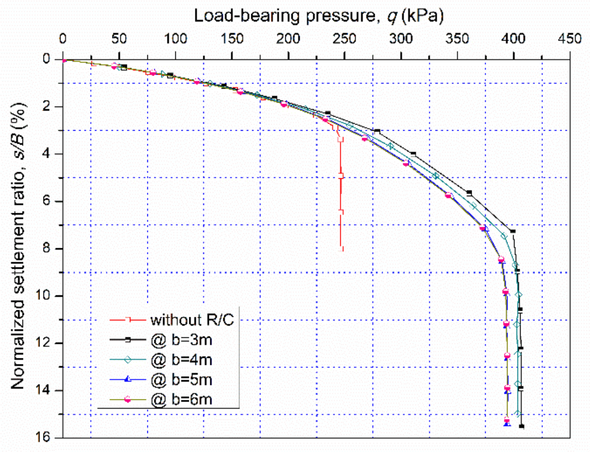


Fig. 4. Variation of load-bearing pressure versus normalized settlement ratio of the footing for varying width of the reinforcement

Furthermore, the ultimate load-bearing capacity ($q_{u, R}$) has been investigated for the parameters discussed in the trailing section for various width of reinforcement. The ultimate load-bearing capacity of thein the unreinforced case (q_u) is found to be 248.6 kPa, however, with the inclusion of geogrid in the soil bed, a severe increase in the magnitude of ultimate bearing capacity has been noticed due to the presence of the tensile member beneath the footing. Moreover, to ensure the minimum width of reinforcement required for the sufficient increase in the $q_{u,R}$, *b* has been varied from 3 m to 6 m (as shown in Fig. 4). The results indicated that the maximum improvement in $q_{u,R}$ is observed at *b* = 3m i.e. 403.3 kPa and no further significant improvement in the load-bearing pressure is observed beyond the 3m wider reinforcing layer. The above-noted behavior may be attributed to the virtue of the confinement effect which is being introduced by the wraparound ends of the geogrid, however, the maximum improvement in the bearing capacity with 3m wide geogrid was due to the proximity of the wraparound ends of the reinforcing layer with the footing, which restrains the possible lateral movement of the stressed soil mass near the footing. With a further increase in the width of the reinforcing layer, the distance of the wrapping ends of geogrid from the footing increases, and the confinement effect decreases, and due to this a marginal reduction in the $q_{u,R}$ is observed in all the other cases. Based on the above observation, it can be easily concluded that for a strip footing of width *B* = 2m, the width of reinforcing layers must be kept 3m for the maximum benefit of reinforcement, which is 1.5 B only. Previously, the researchers had reported the optimum width of reinforcement based on the regression model for footing resting on pond ash to be 5*B* to 7*B* [20]. In a similar study, utilizing the full wraparound ends of geogrids, the optimum width of reinforcement is reported to be 2*B* [14]. The optimum width of reinforcement using the wraparound ends of geogrid, the present study suggests a reinforcement width of 1.5B, where *B* is the width of footing.

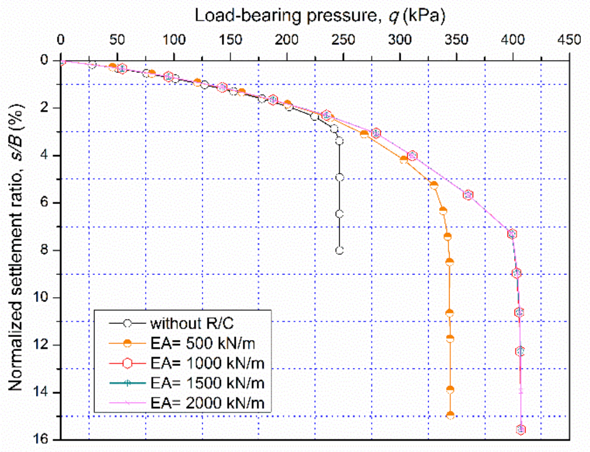


Fig. 5. Variation of load-bearing pressure versus normalized settlement ratio to investigate the effect of elastic stiffness, *EA*

For an economic design of any reinforced structure, the consideration of the overall cost of the geogrid material is an important consideration that depends upon the amount of length, kind of product, durability, stiffness, cross-sectional area, and many other factors also. In this study, only the width and stiffness of the geogrid is considered. Also, higher stiffness leads to a higher cross-sectional area or a stiffer material being used for the production of the geogrid. So, it is always preferable to study the effect of stiffness of the geogrid on the overall bearing capacity to ensure the use of a minimum quantity of material with increased stiffness for a safer and cost-efficient design.

In the present study, to evaluate the influence of *EA*, it has been varied from 500 kN/m to 2000 kN/m at an interval of 500 kN/m each, keeping all the other parameters and properties constant and its effect on the ultimate load-bearing capacity ($q_{u,\ R}$) as well as the footing settlement have been studied (as shown in Fig. 5). It is evident from Fig. 5, that inclusion of geogrid enhances the $q_{u,\ R}$, also it increases with an increase in *EA*. However, this improvement is noteworthy only when the stiffness of the geogrid changes from 500 kN/m to 1000 kN/m and the curve shown in Fig. 5 remains virtually constant for higher values of *EA*, a similar result was reported by Benmebarek et al. [14]

Based on the laboratory experiment, Martin et al. [21] had reported that the texture of the reinforcement material is the key element for the mobilization of the frictional forces in between the reinforcement material and surrounding soil. Based on the above, the R_{int} has been varied from 0.7 to 0.9 in an interval of 0.1 keeping all the other parameters invariable, even in some cases (nonwoven-needle/concrete sand) R_{int} = 1 has been observed. This interprets the fact that the mobilization of shear stresses depends on the behavior of the geogrid-soil interface. The vertical surcharge applied on the footing is being taken by the tensile forces generated in the geogrid and the fundamental cause for the generation of tensile stresses in the geogrid is due to the mobilization of the shear stress (friction forces) at the interface of the soil and reinforcing material. This is the reason that R_{int} is an important characteristic to understand whether the alteration in the texture of a geogrid material having identical elastic stiffness can lead to substantial improvement in the ultimate bearing capacity and maximize the mobilization of soil along with the reinforcing material. Therefore, it is essential to understand the effect of R_{int} on the overall bearing capacity of the soil mass reinforced with geogrid.

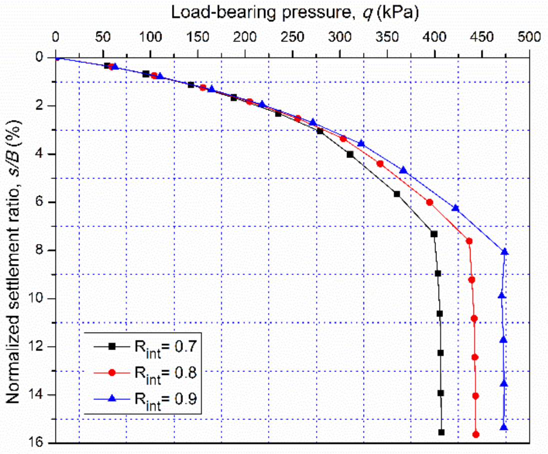
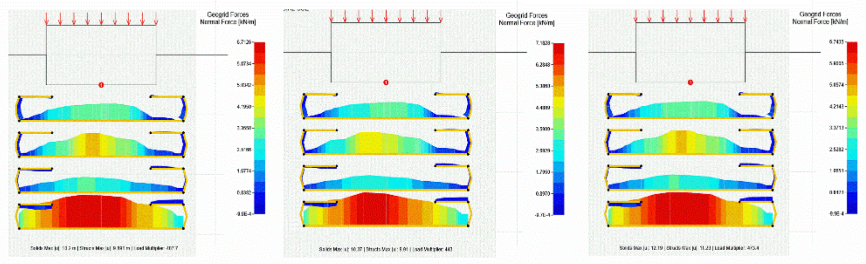


Fig. 6. Variation of load-bearing pressure versus normalized settlement ratio for varying R_{int}

It has been noted that at a given footing settlement ratio, the ultimate load-bearing capacity of the embedded footing resting on the reinforced soil mass ($q_{u,\,R}$) has been improved by 9% when the R_{int} has been changed from 0.7 to 0.8 and it is improved by 16.2% when R_{int} is varied from 0.7 to 0.9 (as shown in Fig. 6). This is a significant improvement in $q_{u,\,R}$, where the same geogrid material having an only difference in the surface texture can lead to the maximum utilization of the reinforcing action. However, most of the studies recommend the value of R_{int} which is $\delta = 2/3$ of ϕ, where δ is the interface friction angle of two dissimilar materials (in the present case, soil and geogrid) [11, 12]. Therefore, it can be concluded that the alteration in the surface texture of the geogrid can enhance the R_{int} and subsequently increase the efficiency of reinforced soil bed to bear the load even for the same capacity of reinforcement for a given soil bed can be utilized in by the reinforcing material. However, taking $R_{int} = 2/3$ is leading towards a very conservative design, where one cannot expect to utilize the full capacity of the reinforcement and that is why it gives rise to a very costly design. Though, before proceeding with designing any structure it is recommended that the material intended to use for the reinforcement should always be tested laboratory for the determination of R_{int} value in the presence of actual backfill material/foundation material.



(a) $R_{int} = 0.7$ (b) $R_{int} = 0.8$ (c) $R_{int} = 0.9$

Fig. 7. Normal forces in reinforcing layer for interface strength reduction factor, R_{int} (a) 0.7; (b) 0.8; and (c) 0.9

The normal forces generated in the geogrid are shown in Fig. 7 for the various value of strength reduction factor (i.e. R_{int}). It is evident from the above observation that as the value of R_{int} increases, the ultimate load-bearing capacity of the reinforced bed also increases, and subsequently the normal forces generated in the geogrid increase. It can be noticed from Fig. 7; in all the cases the maximum normal forces are generated in the bottom-most layer (farthest from the footing), which is due to the overburden pressure lying above the reinforcing layer contributed by the weight of overlying soil mass and the applied surcharge.

5 Conclusions

This paper presents the numerical study of a strip footing to investigate the effects of wraparound ends of the geogrid on the ultimate load-bearing capacity ($q_{u,\,R}$) and footing settlement (*s/B*), in which the soil is modeled by using the Drucker-Prager yield criterion. A parametric study has been carried out to evaluate the influence of the width of reinforcement (*b*) and elastic stiffness (*EA*) of the geogrid. Furthermore, this study also highlights the effect of the interface between geogrid and soil mass, on the load-settlement response of a footing resting over a reinforced earth bed. Based on the findings and discussions of the present study, the following conclusions can be made:

1. The Drucker-Prager (D-P) model is an appropriate model for determining the load-settlement behavior and the ultimate load-bearing capacity of a foundation as the occurrence of singularity is avoided, which is seen in the case of the Mohr-Coulomb model.
2. The width of the geogrid layers, *b* governs the overall load-bearing capacity of the reinforced soil mass system. The finding of the present study suggests an optimum width of the geogrid layers, *b* equals to 1.5 B for maximizing the effective utilization of the wraparound technique.
3. The elastic stiffness, *EA* of a geogrid is an influential parameter, which affects the ultimate load-bearing capacity of the reinforced soil mass ($q_{u, R}$) and also the controls of the settlement of the footing. The maximum improvement in the $q_{u, R}$ is observed at *EA* = 1000 kN/m, and the curves between the load-bearing pressure and the normalized settlement remain virtually constant for higher values.
4. Strength reduction factor for the interface between geogrid and earth bed (R_{int}) creates a better resemblance of the numerical simulation with the actual site condition imparts an important role in deciding the $q_{u, R}$. This study recommends for the precise assessment of the $R_{int,}$ for the appropriate assessment of the response of reinforced earth mass under footing load.

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