

Reinforced Granular Foundation Beds- A Review

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ABSTRACT: A commonly adopted technique to improve the bearing capacity of weak soil is the inclusion of polymeric reinforcements into the soil-foundation system; which is generally done by placing one or more reinforcement layers of geosynthetics by determining optimum depth from foundation to create a composite material with improved performance characteristics. Experimental and numerical modeling using PLAXIS and FLAC had been used by researchers to investigate the behavior such foundations. This review paper highlights the research work in the area of behavior of foundations resting on granular bed with and without prestressing. Concept of prestressing, physical, analytical and numerical modeling is also discussed.

KEYWORDS: Geosynthetics, Analytical modeling, prestressed reinforced soil, numerical modeling, non linear analysis, oblique pull, extensible and inextensible reinforcement

I. INTRODUCTION

The use of geosynthetics to improve the bearing capacity and settlement performance of shallow foundations has proven to be a cost-effective foundation system. In low-lying areas with poor foundation soils, the geosynthetic reinforced granular bed can be placed over the weak soil. The resulting composite ground (reinforced granular bed) will improve the load carrying capacity of the footing and provide better pressure distribution on top of the underlying weak soils, hence reducing the associated settlements. During the past 30 years, the use of reinforced soils to support shallow foundations has received considerable attention. Many experimental and analytical studies have been performed to investigate the behavior of reinforced foundation beds for different soil types. In the study of prestressed reinforced sand bed, it is clear that Geosynthetics are extensible reinforcements and require some strain for mobilizing the required tensile stress. The strain in reinforcement occurring due to initial settlement is not sufficient to mobilize the required tensile stress in it. Prestressing the reinforcement is a promising technique to increase the load bearing capacity of a geosynthetic reinforced soil without the occurrence of large settlements.

In analytical modeling of geogrid reinforced soil foundation, it aims at developing analytical solutions for estimating the ultimate bearing capacity of geogrid reinforced soil foundations (RSF) for both sand and silty clay soils. Failure mechanisms for reinforced soil foundations are proposed based on the literature review and the results of experimental study on model footing tests conducted by the authors. New bearing capacity formulas that incorporate the contribution of reinforcements to the increase in bearing capacity are then developed for both reinforced sand and silty clay soil foundations based on the proposed failure mechanisms. Reinforced earth fills; ground and slopes counteract the destabilizing forces by mobilizing tensile forces in the reinforcement. In most studies, the pull-out resistance due to only axial pull is considered in the analysis for stability. Parametric study quantifies the contributions of depth of embedment, length and interface characteristics of the reinforcement, stiffness of the ground, etc. on the overall response. It is established that reinforcement in dense granular fills subjected to a transverse pull generates pull-out resistances larger than purely axial pull-out capacity in reinforced earth construction.

From the numerical and nonlinear analysis of geosynthetic reinforced bed, response of a multilayer extensible geosynthetic reinforced granular fill-soft soil system has been studied with incorporates the nonlinear behavior of the granular fill and soft soil and the overall behavior of the multilayer extensible geosynthetic- reinforced soil is assessed and comparisons are done with previous models. .

II. ANALYTICAL MODELLING

Several researchers [1], [3], [4], [7] have presented the analytical models for estimating the ultimate bearing capacity of strip footing on reinforced soil. Most of the analytical solutions available in literature assume that all reinforcement layers either fail by tension rupture or by pull out. This assumption implies that the tensile force developed in reinforcement increases with increasing depth of reinforcement of reinforcement.

The proposed reinforcement mechanisms for analytical solution can be categorized as follows:

- (1) Rigid boundary: when the depth of the first layer of reinforcement is greater than a certain value, the reinforcement would act as a rigid boundary, and the failure would occur above the top layer reinforcement.
- (2) Membrane effect: with the applied load, the footing and soil beneath the footing move downward; the reinforcement is deformed and tensioned. Due to its stiffness, the curved reinforcement develops an upward force to support the applied load. A certain amount of settlement is needed to mobilize tensioned membrane effect, and the reinforcement should have enough length and stiffness to prevent it from failing by pull out and tension.
- 3) Confinement effect or lateral restraint effect: due to relative displacement between soil and reinforcement, the friction force is induced at the soil-reinforcement interface. Furthermore, the interlocking can be developed by the interaction of soil and geogrid. Consequently, lateral deformation or potential tensile strain of the reinforced soil is restrained. As a result, vertical deformation of soil is reduced. Since most soils are stress-dependent materials, improved lateral confinement can increase the modulus or compressive strength of soil, and thus improve the bearing capacity of reinforced soil.

III. STUDIES ON REINFORCED SOIL FOUNDATION

Extensive experimental studies, including small-scale laboratory model tests and large-scale field tests, were conducted on geogrid reinforced sand and silty clay soils [1], [3], [4], [9]. The influences of different variables and parameters contributing to the improved performance of reinforced soil foundation were examined in these tests. These include the depth of the first layer, the total depth of reinforcement, the vertical spacing between reinforcement layers, and the tensile modulus and type of reinforcement. In the mean time, an instrumentation program with pressure cells and strain gauges was designed to investigate the stress distribution in soil mass with and without reinforcement and the strain distribution along the reinforcement.

Based on the literature review and the results of experimental study possible failure modes are identified for reinforced soil foundations: failure above top layer of reinforcement, failure between reinforcement layer, failure similar to footings on a two-layer soil system (strong soil layer over weak soil layer), and bearing failure within reinforced zone. The first two failure modes can be avoided by keeping the top layer spacing (u) and the vertical spacing between reinforcement layers (h) small enough. If the strength of the reinforced zone is much larger than that of the underlying unreinforced zone and the reinforcement depth ratio (d/B) is relatively small, a punching shear failure will occur in the reinforced zone, followed by a general shear failure in the unreinforced zone.

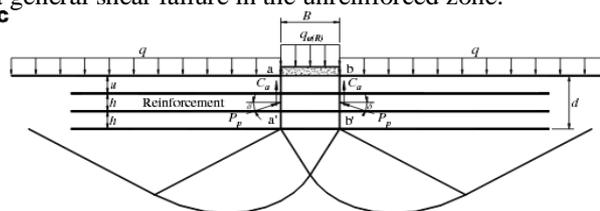


Fig 4. Failure similar to two layered soil system [9]

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To calculate the ultimate bearing capacity of reinforced soil foundation using proposed analytical solutions, it is critical to find a reasonable method to estimate the tensile force in reinforcement. For a given footing settlement, the vertical settlement distribution at a certain depth in reinforced soil is assumed to be the same as that in unreinforced soil. At a certain settlement level, the shape of deformed reinforcement should be compatible with the vertical settlement distribution of surrounding foundation soil.

The bearing capacity ratio (BCR) is used here to compare the results of laboratory model tests and the predicted values from analytical solutions. The predicted ultimate bearing capacity ratios for the reinforced soils were calculated based on aforementioned failure modes proposed for reinforced sand and reinforced silty clay.

IV. NON LINEAR AND NUMERICAL ANALYSIS

Placement of a relatively rigid granular bed reinforced with multiple layers of geosynthetics overlying a soft soil bed to increase the overall bearing and improved settlement performance is very common. Two methods of analysis are carried out, namely Non-linear and Numerical analysis conducted to investigate the behavior of multi layer geosynthetic reinforced granular bed overlying a soft soil. In the existing foundation models with multiple geosynthetic layers, geosynthetics are considered to be inextensible, but in reality geosynthetics may be extensible. The response of a multilayer extensible geosynthetic reinforced granular fill-soft soil system has been studied with incorporates the nonlinear behaviour of the granular fill and soft soil.

A granular bed containing several layers of geosynthetic reinforcement is placed on the soft soil as shown in Figure 5. The number of reinforcement layers is varied from one to three enmeshed within the sand bed such that it is equally divided

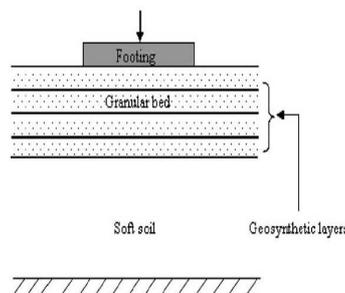


Fig. 5 Multilayer extensible geosynthetic reinforced granular bed on soft soil [3]

The behavior of such a system may be idealized by the proposed foundation model in the case of non-linear analysis shown Figure 6. In this model, the granular fill and soft soil have been idealized by the Pasternak shear layer and a layer of nonlinear springs, respectively. Stretched rough elastic membranes represent the geosynthetic reinforcement layers. Nonlinear behavior of soft soil and granular fill is considered. Plane strain conditions are considered for the loading and the reinforced foundation soil system.

Non-linear differential equations are developed for the mobilized tension and normalized shear stress and pressure intensity on the top of each layer and a computer program has been developed using finite element method to solve these equations and solutions are obtained using Gauss elimination technique.

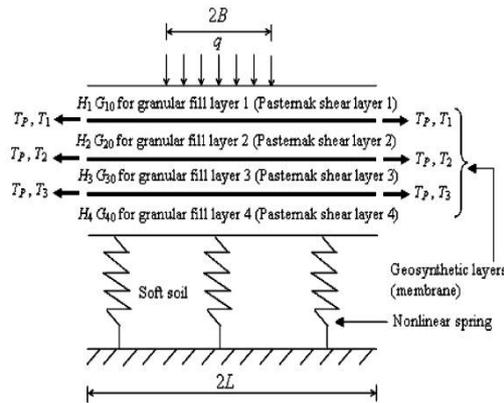


Fig. 6 Proposed Foundation Model [3]

Figure 7 shows that in inextensible reinforcements, settlement is decreased with a decreasing rate as the number of reinforcement layer is increased, whereas in extensible reinforcement the reduction rate is almost constant.

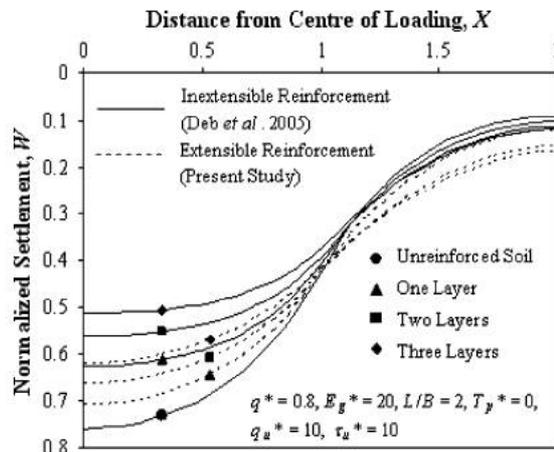


Fig. 7 Settlement profiles of extensible and inextensible reinforcement [3]

V. SHEET REINFORCEMENT SUBJECTED TO TRANSVERSE AND OBLIQUE PULL

In the study done by [8] the reinforcement is considered to be inextensible. The front-end displacement is assumed to be small and hence the inclination of reinforcement, θ with the horizontal is assumed to be very small and negligible. The linear normal stress–displacement relation of the soil is characterized by the relation $q = k_s w$. Full shear resistance (rigid plastic behaviour) is developed along the interface irrespective of its horizontal displacement i.e. $q_t = \tau_t \tan \phi_r$ and $q_b = \tau_b \tan \phi_r$. The full interface shear resistance is considered to have been mobilized even at infinitesimally small displacements. The analysis is done and final equations are obtained. The transverse force, P^* is then obtained and a parametric study is carried out for quantifying normalized displacement, $W^* = (w/L)$; normalized tension, T^* ; normalized transverse force, P^* ; normalized maximum tension at right end, T^*_{max} ; normalized pull-out force, $T^*_{max} \cos \theta_L$; slope or inclination of reinforcement at right end, θ_L ; in terms of μ, ϕ_r and W_L . The variations of these parameters with the effect of μ and w_L are plotted.

Reinforcement in reinforced earth constructions and nails in nailed soil structures are rarely subjected to pure axial pull-out force. The kinematics of the problem often dictates a non-axial movement of the sliding soil and an imposition of an oblique force on the reinforcement. Conventionally reinforcement is considered to be subjected to an axial pull-

out force only, though in few stability analyses non-axial reinforcement forces are included. In this paper, an analysis of a reinforcement sheet embedded in soil at depth to a transverse force is proposed modeling the soil response by a set of linear Winkler springs. The governing differential equation is normalized and solved numerically to obtain normalized force versus normalized tip displacement relationships and normal displacement profiles for a range of parameters considered. Results of a parametric study are presented.

In this paper, a rational analysis of an extensible sheet reinforcement subjected to a high oblique end force has been presented assuming a nonlinear elasto-plastic vertical stress-displacement relationship for the backfill soil and a nonlinear elasto-plastic shear stress-displacement relationship for the soil-reinforcement interface. Under the action of the oblique end force, the soil beneath the reinforcement experiences additional normal stresses as the reinforcement deforms transversely and as a result, additional friction stresses are mobilized. Equilibrium equations have been applied to the final deformed shape of the reinforcement after considering proper variation in normal and friction stresses with the deformed shape and extended length of the reinforcement. The resulting equations are first non-dimensionalized and then solved using the finite difference method. The results have been compared with finite-element analysis of pullout tests and back analyses of test data on model reinforced soil walls. Several known features of reinforced soil behavior are successfully linked and explained by this analysis. The results can be used for internal design of geosynthetic reinforced walls against the pullout failure and the tension failure.

VI. PRESTRESSED REINFORCED SOIL

One technique yet to be comprehensively studied is the effect of prestressing the geosynthetic layer before implementing them as reinforcement in field applications [5]. The strain in reinforcement occurring due to initial settlement is not sufficient to mobilize the required tensile stress in it. Hence geosynthetics demonstrate their beneficial effects only after considerably large settlements, which is not a desirable feature for shallow foundations. Prestressing the reinforcement is a promising technique to increase the load bearing capacity of a geosynthetic reinforced soil without the occurrence of large settlements.

In order to prestress the geogrid in a reinforced soil structure three different methods were developed [6]:

- a. Prestressed reinforced soil by compaction: PRSc
- b. Permanently prestressed reinforced soil: PRSp
- c. Temporarily prestressed reinforced soil: PRSt

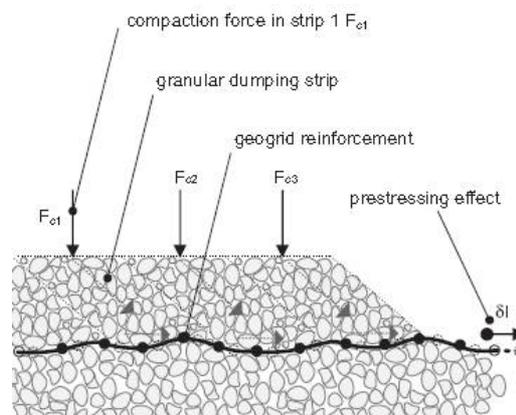


Fig 1. Prestressing by Compaction [6]

The concept of PRSp (permanent prestressing) highly improved the vertical and horizontal displacement behaviour of the soil element versus time t . Settlements measured during testing the PP geogrid reinforced soil elements are smaller compared to the ones measured while testing reinforced soil elements with woven PET geogrids. This was due to the higher tensile stiffness of the welded PP geogrids. The high displacements can be visualized above the geogrid layer. Below the geogrid layer the settlements decreased rapidly.

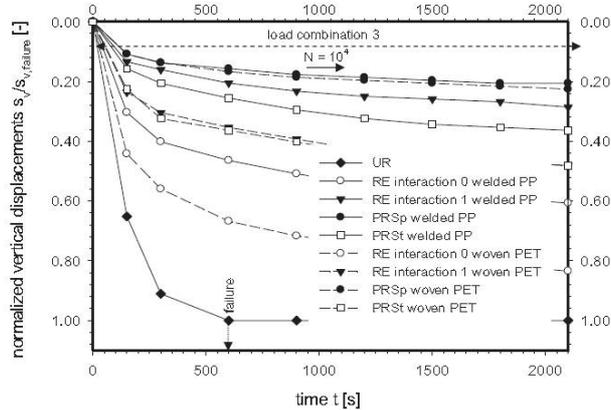


Fig 2. Normalized Vertical Settlement vs Time [6]

The improvement in bearing capacity depends upon the thickness of granular bed, magnitude of prestress, direction of prestress, number of layers of reinforcement and type of reinforcement [2]. The improvement in bearing capacity increases with thickness of granular bed. In moist soil, the bearing capacity ratios obtained with geotextile reinforcement are slightly higher than that with geogrid reinforcement for almost all the cases. In submerged soil, geogrid gives better BCR during uniaxial prestressing whereas during biaxial prestressing, geotextile is giving a higher value of BCR..

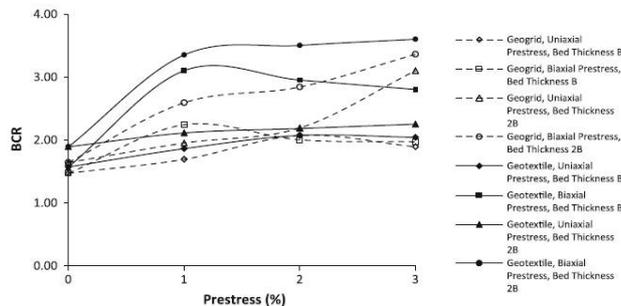


Fig 3. Variation of Bearing Capacity Ratio with Prestress [2]

From experimental studies as well as finite element analyses, it is observed that after a certain percentage of prestress, the BCR decreases with the increase in prestress. The improvement in bearing capacity depends upon the stress at the interface between reinforcement and granular soil. The tensile stress gets mobilized in the reinforcement due to the applied prestress and due to the friction developed between the reinforcement and surrounding granular soil. Results of finite element analysis indicated that in most of the cases, as the prestress increases, the normal stress at the interface between reinforcement and granular soil decreases.

Initially as the prestress is applied, the BCR increases due to an increase in the tensile stress in reinforcement and due to an increase in the interface stress. But as the applied prestress is further increased, the stress transfer between reinforcement and surrounding granular soil reduces resulting in a reduction of BCR. [7].

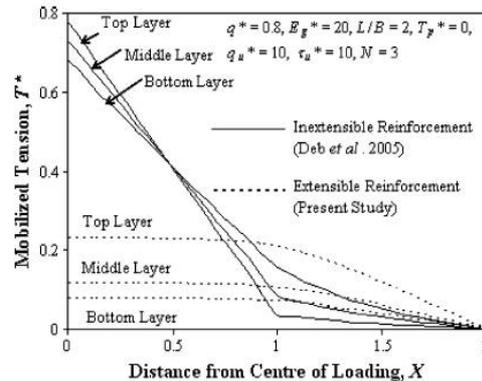


Fig.8 Mobilized tension in extensible and inextensible reinforcement [3]

Figure 8 shows that for multilayer reinforcement system the difference of mobilized tension in different reinforcement layers is very small in case of inextensible reinforcement, whereas in case of extensible reinforcement the difference is more.

VII. CONCLUSIONS

1. Reduction in settlement due to the use of extensible geosynthetic reinforcements is less as compare to the same for inextensible reinforcements.
2. As the number of reinforcement layers increase, the vertical stresses in the loaded region decreases causing maximum settlement reduction at a decreasing rate.
3. In case of inextensible reinforcements as the number of reinforcement layer is increased the settlement is decreased with a decreasing rate. In case of extensible reinforcement the reduction rate is almost constant.
4. The mobilized tension in the top extensible reinforcement layer is more throughout the length of the reinforcement
5. Use of multiple geosynthetic reinforcements reduce the total and differential settlements of the loaded region and are very effective for higher loading intensity and for very soft soil.
6. The addition of prestress to the geotextile reinforcement significantly improved the settlement response and load bearing capacity of the soil.
7. It can be stated that the system of prestressed reinforced (PRSi) soil has been experimentally, statically and cyclically, validated. By using the same materials, soil and reinforcement, and by prestressing the geogrid reinforcement with the explained concepts, the load displacement behavior of reinforced soil structures improved tremendously.
8. A rational analysis of an extensible sheet reinforcement embedded in soil subjected to an oblique end force is presented that properly accounts for complex soil-reinforcement interaction and involves a stress-deformation relationship implicitly.
9. The improvement in bearing capacity depends upon the thickness of granular bed, magnitude of prestress, direction of prestress, number of layers of reinforcement and type of reinforcement. The improvement in bearing capacity increases with the thickness of granular bed.

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