Numerical analyses of the failure of geosynthetic-reinforced soil beneath shallow foundations subjected to inclined load

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ABSTRACT: The use of geo-reinforcements under shallow foundations is aimed to increase the soil mechanical properties and, consequently, to improve the footing load carrying capacity reducing the associated settlements. Simplified approaches generally rely on corrective factors, allowing the analysis of reinforced foundation starting from the knowledge of the performance of the unreinforced one.

A critical aspect refers to the applied load: for footings subjected to inclined loads, it is not possible to assess the bearing capacity and the displacements by using simplified methods referred to vertical loading conditions. The paper reports the results of numerical FEM analyses, aimed to investigate the limit conditions for a shallow strip footing subjected to inclined load and to highlight how the failure envelope (in the plane of vertical V and horizontal H load components) of the reinforced foundation modifies (in size and shape) in comparison with that of the unreinforced one. The use of the failure envelope approach, instead of the usual bearing capacity corrective factors, allows a more rational analysis of the interaction phenomena occurring in the reinforced soil. The numerical analyses enable to consider different cases as to the reinforcement arrangements and types.

1 INTRODUCTION

The use of geo-reinforcements under shallow footings is aimed to increase the mechanical properties of soil and, consequently, to increase the foundation bearing capacity and to reduce the settlements.

As suggested by Huang & Tatsuoka (1990) «In some engineering practices, the bearing capacity of ground has to be improved in an economical way. One of the promising methods is to place tensile-reinforcement layers horizontal beneath the footing».

Many remarkable studies have been performed to highlight these aspects, most of them referred to experimental data obtained from small-scale laboratory model tests, generally adopting vertical load conditions. The reinforced soil performance is analyzed taking into account all those factors influencing the overall behaviour (number of reinforcements, placement depth, spacing, reinforcement length, mechanical characteristics, etc.).

In this framework, a critical aspect refers to the applied load: for a footing subjected to combined vertical (V) and horizontal (H) loads, it is not possible to assess the bearing capacity and the displacements by using simplified methods usually referred to vertical loading conditions.

The paper reports the results of numerical FEM analyses, aimed to investigate the limit conditions for a shallow strip footing, subjected to inclined load, above a geosynthetic reinforced sandy soil. It has been possible to consider different cases as far as the reinforcement arrangements and types are concerned.

The foundation response has been analyzed resorting to the failure envelope approach (in the V-H plane) since it allows a more rational evaluation of the interaction between the different load components.

For the cases considered in the paper, the observed difference (in size and shape) between the unreinforced and reinforced foundation failure envelopes enables to point out the relevant role played by the reinforcement system.

2 LIMIT CONDITIONS

Many experimental, analytical and numerical studies have been carried out in order to investigate the behaviour of a foundation resting on geosynthetic reinforced soil (see, e.g., the reference list in Geo-Institute 2004). As a result, careful indications about the design parameters (placement and features) of the reinforcements have been provided, especially in order to optimize their use (Wayne et al. 1998).

The literature review indicates that two different ways could generally be followed in order to take into account the role played by the reinforcements in the bearing capacity assessment.

The first one refers to the Bearing Capacity Ratio (BCR) which has been introduced in order to quantify the effectiveness of the reinforcement (Binquet & Lee 1975). This corrective factor, which depends on the geosynthetic arrangement, allows the evaluation of the bearing capacity of the reinforced foundation, multiplying the bearing capacity of the unreinforced one by BCR.

In the second one the limit condition of a reinforced foundation is assessed by analytical approaches leading to relationships similar to those adopted for unreinforced foundations, but properly modified to account for reinforcement presence and characteristics (e.g. introducing confinement effects and the geosynthetic tensile strength). The different analytical approaches depend on the failure modes developing beneath the foundation, inside the reinforced soil (Palmeira 1998; Patra et al. 2006; Sharma et al. 2009).

Both BCR correction and analytical relationships are usually adopted for vertically loaded foundations. When a shallow footing is subjected to general loading (inclined and/or eccentric load) the prediction of ultimate conditions can be effectively accomplished considering failure envelopes relating load components. This kind of approach avoids the addition, in a bearing capacity formula, of some corrective factors whose significance and validity are often questionable.

When dealing with footings resting on geosynthetic reinforced soil bed, this uncertainty increases to a great extent; thus the applicability of failure envelope approach and the possibility of defining shape and size of the limit curves are both interesting items to study.

3 NUMERICAL ANALYSES

In order to define the failure envelopes for unreinforced and reinforced foundations, a series of two-dimensional numerical analyses on a prototype strip footing has been performed, making use of the finite element software package PLAXIS V8 (Plaxis BV 2004).

3.1 *Strip foundation on unreinforced soil*

The numerical model consists of a stiff strip footing, (having width B=1 m), subjected to an inclined force.

The inclination α of the applied force with respect to the vertical direction varies from 0° to 23°.

The foundation was treated as an elastic plate with significant flexural rigidity (EI=3.02 e+5 kNm) and axial stiffness (EA=1.45 e+7 kN/m).

A rectangular cluster (dimensions 20B×8B) composed by triangular elements is used to schematize the foundation soil, assumed to be a dry and homogeneous sandy deposit. The simple Mohr-Coulomb model has been considered for these preliminary analyses, whose main object was to investigate failure conditions.

A medium dense sand is considered, having unit weight γ =15.16 kN/m^3. The peak friction angle ϕ' and dilatancy angle ψ are respectively 41° and 10°. The soil stiffness is described by the Poisson's ratio ν=0.2 and Young's modulus E=2.8·e+4 kN/m^2.

The soil parameters have been chosen and calibrated on the basis of experimental and numerically simulated triaxial tests, performed on dry silica sand (Ticino Sand). The interaction soil-footing is characterized by an interface reduction factor R_{int} equal to 0.48 (=0.55ϕ'). Further details on the numerical test program are reported in Bovolenta et al. (2006).

Figure 1 reports the values of the horizontal H and vertical V components of the inclined failure load, both normalised by the vertical failure load for unreinforced soil $V_{M,UR}$. The set of failure values allows one to define the foundation failure envelope.

According to well established literature results (e.g. Nova & Montrasio 1991; Gottardi & Butterfield 1993) the failure envelope in the plane (V-H) can be expressed by simple analytical relationships, such as a symmetrical parabola, intersecting the V axis at the origin and at $V_{M,UR}$

$$H / V_{M,UR} = \mu_h \cdot \left(V / V_{M,UR}\right) \cdot \left[1 - \left(V / V_{M,UR}\right)\right]$$

where the initial slope μ_h represents the simple sliding condition ($\mu_h \cong 0.42$). Figure 1 illustrates the satisfactory agreement between numerical results and what predicted by the reported relationship. As expected, the maximum value of the ratio $H/V_{M,UR} \cong 0.1$ is obtained for $V/V_{M,UR}$=0.5.

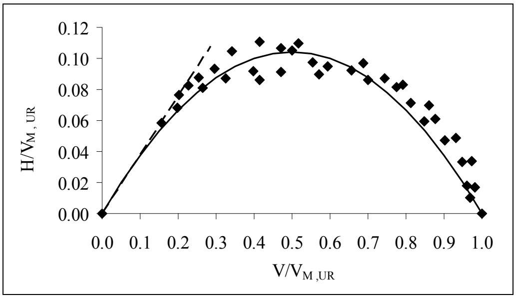

Figure 1. Failure envelope of unreinforced footing

3.2 *Strip foundation on reinforced soil*

As suggested by many authors the foundation failure value and how it is achieved depend on the reinforcement own properties (geometrical and mechanical) and its arrangement within the soil (number of layers, placement depth, spacing, length, etc.).

Usually, the reinforcement is designed taking into account the following specifications: (i) the first reinforcement layer should be located close to the bottom of the footing at an optimum depth, u, of 0.2B to 0.5B (B is the footing width), (ii) the optimum vertical spacing, h, of reinforcement was found to vary from 0.2B to 0.5B, (iii) the number of georeinforcement layers, N, is usually in the range 2 to 4; (iv) the effective length, L, of the reinforcement should be not greater than 5B and not less than 2B.

In addition, it has been recognized that geogrids are more effective than geotextiles and that high stiffness geogrids perform better than geogrids with lower tensile modulus.

The already described model and soil parameters have been adopted in the numerical analyses in order to evaluate the reinforcement effect. The analyses are devoted to investigate:

1. the influence of the number of geogrid layers;
2. the influence of geogrid length;
3. the influence of geogrid mechanical characteristics (strength and stiffness).

The paper reports some of the gained results as far as the first two items are concerned.

Beneath the strip footing different arrangements have been modelled, considering as reinforcement element a typical bi-axial polypropylene geogrid (aperture size about 40x40 mm). Its main mechanical characteristics are indicated in Table 1.

In accordance with the above indications, the following reinforcement features have been adopted in the numerical analyses:

- u=0.35B
- h=0.25B
- N=1; 2; 3
- L=2B; 3B; 4B

The geogrid axial stiffness is EA=550 kN/m, an average value assumed considering soil reinforcement strain compatibility.

Since the performance of reinforced soil foundation depends not only on soil and reinforcement properties but also on the interaction mechanism, interface elements have been adopted, which allow the specification of a reduced friction angle δ to be compared with soil friction angle. On account of the geogrid geometrical characteristics, a ratio $R_{int} = \tan\delta/\tan\phi' = 0.86$ has been adopted (Jewell 1996).

Moreover, around the reinforcements a refined mesh was adopted to minimize the effect of mesh dependency on the numerical modelling, especially for cases involving changes in geogrid number and length. The same refinement has been adopted beneath the plate.

Table 1. Geogrid mechanical parameters

T_{ult}	strain at T_{ult}	T at 2% strain	T at 5% strain
(kN/m)	(%)	(kN/m)	(kN/m)
30	10	11	22

3.2.1 *The effect of number of geogrid layers*

In order to investigate the failure envelope dependence on the number of geogrids, different reinforcement arrangements have been modelled.

The analyses have been performed varying the inclination of the applied force and evaluating the components H and V of the collapse load for N=1 to 3 and L/B= 2 to 4.

As illustrated in Figure 2 (referred to the case L=2B), the collapse loads have been normalised by the maximum vertical failure value for the unreinforced footing $V_{M,UR}$. The envelope for unreinforced soil is the same already showed in Figure 1.

Notwithstanding a certain scattering in the failure values, the following remarks can be drawn:

- the shape of the failure envelopes obtained from the numerical analysis results (dotted lines) is similar to the one of the unreinforced foundation;
- the remarkable increment in size clearly indicates the reinforcement contribution on both load components (it is worth pointing out that for H=0 the failure envelopes intersect the V axis at BCR values);
- sliding condition prevails increasing the inclination of the applied load. In these cases the presence of several reinforcement layers is not particularly significant as demonstrated by the coincidence among the different failure envelopes for $V/V_{M,UR} < 1$ (angle $\alpha > 20°$);
- since Figure 2 is referred to short geogrids (L/B=2), the results seem to indicate that in this particular arrangement the reinforcement are more effective as to the vertical load component than to the horizontal one;
- increasing the number of layers the envelope size significantly increases, improving the vertical load carrying capacity.

3.2.2 *The effect of geogrid length*

The results of the analyses performed varying the reinforcement length (L/B=2 to 4) are illustrated in Figure 3 (referred to the only case N=1). Notwithstanding an expected scattering in the collapse values, purely indicative failure envelopes can be identified as well.

Analogously to the previous analyses it is possible to observe that:

- the shape of the envelopes is similar to that of the unreinforced case;

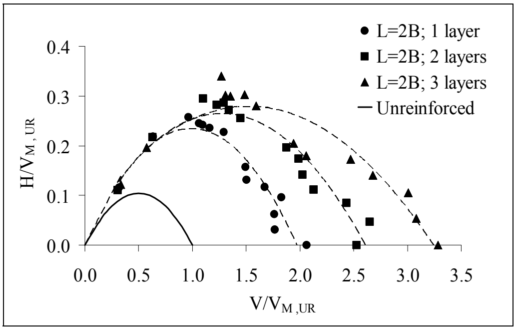

Figure 2. Failure envelopes of unreinforced and reinforced footing (L=2B; N=1 to 3)

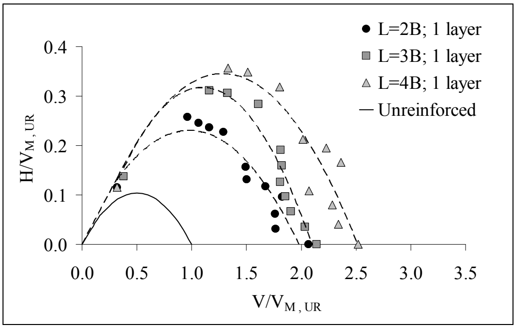

Figure 3. Failure envelopes of unreinforced and reinforced footing (L=2B to 4B; N=1)

- the size indicates that increasing the geogrid length, the footing can bear higher horizontal loads (note that comparing with Figure 2, the BCR values, on the V axis for H=0, are lower being N=1);
- the relative increment in maximum H values tends to decrease when the geogrid length increases (a significant reinforcement contribution is appreciable for L/B= 2 or 3, while the maximum H values almost coincide for L/B= 3 and 4). It seems ineffectual to extend excessively the geogrid length over footing edges, when the failure is clearly located within the reinforced soil, as in the case of only one reinforcement layer. In fact, the resistant shear stresses are mobilized along geogrid sides, over the failure zone located next to the plate.

4 FINAL REMARKS

A study was undertaken in order to investigate the failure conditions of a shallow strip footing subjected to an inclined load. The results gained in numerical analyses have shown that, also in the case of geosynthetic reinforced soil foundation, it is useful to resort to the “failure envelope” approach in order to obtain collapse load values and indications about failure mechanisms.

The soil reinforcement by geogrids remarkably increases the size of the failure envelopes, whose shape is similar to the unreinforced foundation one. As previously described, it can be observed that:

- the envelope size significantly increases, improving the vertical load carrying capacity, when increasing the number of layers;
- on the contrary, the number of reinforcement layers do not contribute significantly to the foundation bearing capacity in occurrence of very inclined loads;
- short reinforcement ($L/B \leq 2$) are almost ineffective as far as the increase of footing bearing capacity under very inclined load is concerned;
- moreover, it seems ineffectual to extend excessively the geogrid length over the footing edges.

Further analyses and comparisons with available experimental measures and analytical solutions are scheduled, in order to better understand failure mechanisms, the role played by geogrid mechanical properties and possible non linear phenomena.

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