Geosynthetics, J. Kuwano & J. Koseki (eds)
© 2006 Millpress, Rotterdam, ISBN 90 5966 044 7

A new theoretical method to evaluate the peak and the residual pullout resistance of extruded geogrids embedded in granular soils

Cardile, G., Gioffrè, D. & Moraci, N.
Università Mediterranea di Reggio Calabria, Dip. MECMAT, Reggio Calabria, Italy

Keywords: soil dilatancy, reinforcement extensibility, pullout resistance, skin friction, bearing

ABSTRACT: Several experimental studies showed the influence of different parameters (reinforcement stiffness, geometry and length, applied vertical effective stress, and geotechnical properties of soil) on the peak and on residual pullout resistance.

In the present paper a new theoretical method was developed to determine the peak and the residual pullout resistance of extruded geogrids embedded in compacted granular soils. The method is capable of evaluating both the bearing and the frictional components of pullout resistance, taking into account the reinforcement extensibility and geometry as well as the non linearity of the failure envelope of backfill soil. The comparison between theoretical and experimental results was favourable, thus confirming the suitability of the proposed approach.

1 INTRODUCTION

The pullout resistance of a geogrid may be evaluated (Jewell, 1996) using the following equation:

$$P_R = 2\alpha_S L_R \sigma'_n \tan\delta + \left(\frac{L_R}{S}\right)\alpha_B B \sigma'_b = 2 f_b L_R \sigma'_n \tan\varphi' \qquad (1)$$

where:

- P_R = Pullout resistance;
- α_S = fraction of geogrid surface area that is solid;
- L_R = specimen length;
- σ'_n = normal effective stress;
- δ = skin friction angle between soil and geogrid;
- S = spacing between geogrid bearing members;
- (L_R/S) = number of geogrid bearing members;
- α_B = fraction of total frontal area of geogrid available for bearing;
- B = bearing member thickness;
- σ'_n = normal effective stress;
- σ'_b = effective bearing stress on the geogrid bearing members;
- f_b = soil-geosynthetic pullout interaction coefficient;
- φ' = soil shear strength angle.

The limits of theoretical expression used to evaluate the soil-geosynthetic pullout interaction coefficient, f_b, have been investigated by different researchers. In particular, previous experimental studies (Moraci and Montanelli, 2000) have shown that the values of f_b are largely influenced by the reinforcement geometry, extensibility and soil dilatancy.

In the present paper a new theoretical method was developed to evaluate the pullout resistance of extruded geogrids embedded in compacted granular soils.

2 THE METHOD

Test results obtained by Moraci and Recalcati (2005) showed that the dilatancy of soil at the interface is the phenomenon that most influences the pullout resistance. Experimental results also showed that the reinforcement extensibility influences the peak pullout resistance. In particular, extensibility effects were more evident in long reinforcements at high vertical confining stresses. In residual conditions, the extensibility effects were negligible. The decrease of the pullout resistance after the peak is related to both reinforcement length and confining stress.

In the case of long reinforcements at high vertical stresses, reinforcement extensibility induces a progressive mobilization of the elementary interaction mechanisms. Vice versa, for short reinforcements and for long reinforcements at low vertical effective stresses the longitudinal strains are small. In such cases, the reinforcement behaves as a rigid material and the interaction mechanisms are activated at the same time. Moreover, different experimental studies

(Matsui et al. 1996, and Palmeira 2004) showed that, the bearing stress, after the displacement corresponding to the maximum value, remains almost constant with any increase in displacement. In order to validate the previous findings the following approach was used:

1. the use of a simple equation (2) for the determination of the pullout resistance P_R in geogrids and soils for which the scale effects are negligible (i.e. S/B larger than 40 and S/D_{50} larger than 1000):

$$P_R = 2C_{\alpha S}\alpha_S L_R \sigma'_n \tan\delta + n_t n_{tb} A_b \sigma'_b \qquad (2)$$

where the new symbols mean:

- $C_{\alpha S}$ = reduction coefficient of geogrid area where skin friction develops;
- n_t = number of geogrid bearing members;
- n_{tb} = number of nodes in a transversal element;
- $A_b = A_t + A_r$ = area of each rib element where the bearing resistance can be mobilized;

Where the bearing stress σ'_b was evaluated (Matsui et al. 1996) by the following equation:

$$\frac{\sigma'_b}{\sigma'_n} = e^{\pi\tan\varphi}\tan\left(\frac{\pi}{4}+\frac{\varphi'}{2}\right) \times \left[\cos\left(\frac{\pi}{4}-\frac{\varphi'}{2}\right) + (1-\sin\varphi)\sin\left(\frac{\pi}{4}-\frac{\varphi'}{2}\right)\right] \qquad (3)$$

where the symbols mean:

- σ'_n = normal effective stress;
- φ'= soil shear strength angle.

2. the use of a particular procedure to take into account the particular structure of the elements on which the bearing resistance mobilizes, the soil dilatancy effects (non linearity of the failure envelope of back fill soil) and the geogrid extensibility.

The method was applied to pullout tests performed (Moraci and Recalcati, 2005) on three different HDPE extruded mono-oriented geogrids (described as GG1, GG2 and GG3 respectively). The geogrids showed similar geometrical characteristics when viewed in plan. They had the same number of tensile elements per unit width and longitudinal rib pitch, and similar elliptical aperture shape.

On the contrary, the geogrids had a different cross sectional shape with major differences in rib and bar thickness (Fig. 1 and Table 1).

The complex geometry of the transverse bars, including the areas A_b in the same transverse element was assumed to be equivalent to that of a strip of uniform thickness, B_{eq} (Fig. 1).

An uniform medium sand was used in the tests ($U = D_{60}/D_{10} = 1.5$ and $D_{50} = 0.22$ mm). Compaction tests provided a $\gamma_{d\max} = 16.24$ kN/m^3 at $w_{\text{opt}} = 13.5\%$. Direct shear tests yielded high single values of the peak shear strength angle ϕ'_p, in the range 48° (for $\sigma'_v = 10$ kPa) to 42° (for $\sigma'_v = 100$ kPa). The shear strength angle at constant volume, σ'_{cv}, was 34°.

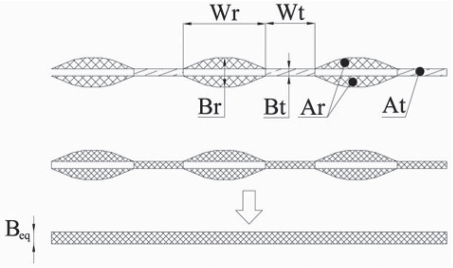

Figure 1. Schematic cross section A-A of the geogrid bar.

Table 1. Structural characteristics of the different geogrids.

Geogrid	W_r (mm)	W_t (mm)	B_r (mm)	B_t (mm)	A_b (mm^2)
GG 1	11.26	6.6	3.80	3.57	66.35
GG 2	11.86	6.0	4.65	4.48	82.03
GG 3	12.36	5.5	5.16	4.85	90.45

The soil shear strength angle δ used to determine of the skin friction component of the pullout resistance based on previous experimental researches on smooth HDPE geomembranes was assumed equal to 1/3 ϕ'.

In order to take into account the reinforcement extensibility, the following assumptions were made:

1. for “long” reinforcements (L_R = 0.9-1.15 m) at high effective vertical stresses, the reinforcement extensibility induces a progressive mobilization of the elementary interaction mechanisms. Under these conditions, the skin friction was evaluated using an average value of the shear strength angle between the peak and the constant volume values, assuming a non linear failure envelope for the backfill soil.
2. for “short” reinforcements (L_R = 0.4 m) and for “long” reinforcements (at low vertical effective stresses) the longitudinal strain is small. In such cases, the reinforcement behaves as a rigid material and the interaction mechanisms are activated simultaneously along the whole reinforcement. Under these conditions, the peak shear strength angle can be used to evaluate both components of the pullout resistance, assuming a non linear failure envelope for the backfill soil and a suitable stress level.

On the basis of the experimental results obtained by Matsui et al. (1996) and Palmeira (2004) the bearing resistance component of pullout resistance was evaluated using the peak shear strength angles corresponding to the different vertical effective stresses, in order to take into account the non linearity of the failure envelope of the backfill soil.

Equation (2) permits also the evaluation of the residual pullout resistance P_{RR}. In this case in order to evaluate the skin friction component of pullout strength, the soil shear strength angle at constant volume σ'_{cv} was used. In order to evaluate the reduction of the skin friction component induced by the passive failure surfaces developed on bearing members, a reduction coefficient $C_{\alpha S}$ of the geogrid area, where skin friction develops (α_S), was used (Moraci and Gioffrè, 2006). This value, derived from the assumption that the maximum extension of passive failure surfaces are equal to 40 times the thickness of the equivalent bearing members is given by:

$$C_{\alpha S} = \frac{S_{\text{eff}}}{S} = \frac{S - 40 * B_{eq}}{S} \tag{4}$$

- S = spacing between geogrid bearing members;
- B_{eq} = equivalent bearing member thickness (Fig. 1).

This reduction was only applied under residual conditions.

3 EXPERIMENTAL VALIDATION OF PROPOSED METHOD

In order to validate the proposed method, the theoretical values of the peak and residual pullout resistances (P_R^{theor} and P_{RR}^{theor}) obtained using equation (2) were compared with the experimental results (P_R^{exp}, P_{RR}^{exp}) obtained by Moraci and Recalcati (2005) reported in Table 2.

Figures 2.3 show (for the different reinforcement lengths) the comparison between experimental and theoretical values of the peak and residual pullout resistances, evaluated for the different applied vertical effective confining stresses. Moreover, from the method it is possible to observe that the skin friction component of the peak pullout resistance (P_{RS}^{theor}) is small in comparison to the bearing component. The skin friction component of residual pullout resistance (P_{RRS}^{theor}) is also small in comparison to the bearing component. Such small values are due to the reduction of the skin friction component caused by the bearing failure surfaces (interference effects). Figures 2.3 show that the proposed method is in close agreement with the experimental data.

In particular, an under-estimation of the peak pullout resistance was observed. This aspect was more evident for short reinforcements, this could be due to the local increment of the vertical effective stress due to the constrained dilatancy, which is not considered in the simple proposed model (Table 3).

Table 2. Peak (P_R) and residual (P_{RR}) pullout resistance (kN/m) measured in the tests (Moraci and Recalcati, 2005).

Geogrid	Spec. Length (m)	Normal stress σ'_v 10 kPa P_R	10 kPa P_{RR}	25 kPa P_R	25 kPa P_{RR}	50 kPa P_R	50 kPa P_{RR}	100 KPa P_R	100 KPa P_{RR}
GG 1	0.40	9.62	5.63	20.26	13.29	30.95	18.93	39.79	26.43
GG 1	0.90	16.62	12.14	34.55	29.79	52.53	50.34	78.44*	–
GG 1	1.15	20.00	14.76	37.13	34.32	62.79	62.79	72.48*	–
GG 2	0.40	13.42	8.44	24.76	15.43	41.18	24.04	56.59	37.51
GG 2	0.90	21.32	15.43	39.99	32.14	70.07	62.46	103.91	103.91
GG 2	1.15	26.96	19.53	51.43	44.00	75.62	75.62	106.91*	–
GG 3	0.40	12.84	7.36	22.72	13.64	37.68	25.18	58.68	49.04
GG 3	0.90	19.85	15.48	41.80	34.69	72.95	61.27	97.59	97.59
GG3	1.15	24.35	19.61	47.75	43.79	81.77	81.77	115.19	115.19

*Specimen failure

Table 3. Percentage differences between experimental results and theoretical values.

L_R (m)	σ'_v (kPa)	GG1 $\frac{P_R^{\text{theor}} - P_R^{\text{exp}}}{P_R^{\text{exp}}}$ (%)	GG1 $\frac{P_{RR}^{\text{theor}} - P_{RR}^{\text{exp}}}{P_{RR}^{\text{exp}}}$ (%)	GG2 $\frac{P_R^{\text{theor}} - P_R^{\text{exp}}}{P_R^{\text{exp}}}$ (%)	GG2 $\frac{P_{RR}^{\text{theor}} - P_{RR}^{\text{exp}}}{P_{RR}^{\text{exp}}}$ (%)	GG3 $\frac{P_R^{\text{theor}} - P_R^{\text{exp}}}{P_R^{\text{exp}}}$ (%)	GG3 $\frac{P_{RR}^{\text{theor}} - P_{RR}^{\text{exp}}}{P_{RR}^{\text{exp}}}$ (%)
0.40	10	24%	17%	32%	3%	24%	22%
0.40	25	29%	5%	28%	1%	16%	25%
0.40	50	26%	3%	31%	1%	20%	5%
0.40	100	7%	17%	18%	2%	17%	15%
0.90	10	10%	9%	13%	6%	0%	16%
0.90	25	16%	15%	9%	3%	8%	1%
0.90	50	13%	22%	19%	22%	17%	13%
0.90	100	*	*	11%	26%	0%	14%
1.15	10	7%	12%	14%	5%	2%	15%
1.15	25	2%	8%	12%	11%	1%	2%
1.15	50	9%	22%	6%	19%	8%	19%
1.15	100	*	*	*	*	6%	9%

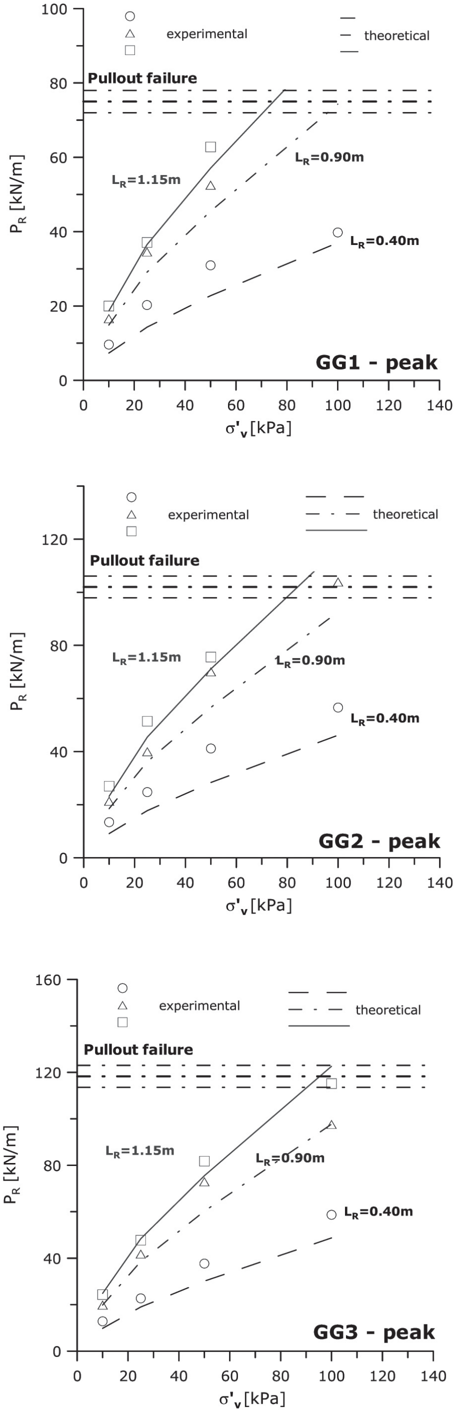

Figure 2. Comparison between experimental and theoretical values of peak pullout resistance.

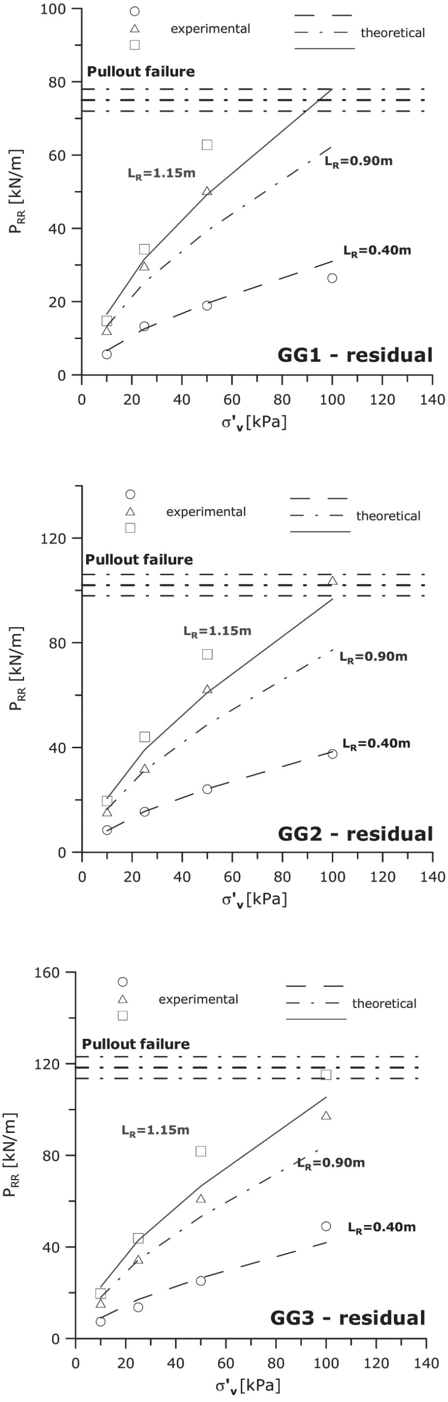

Figure 3. Comparison between experimental and theoretical values of residual pullout resistance.

4 CONCLUSIONS

Comparison between the theoretical and experimental results permits the following conclusions to be drawn:

- The proposed method predicts the experimental data well especially for extensible reinforcements.
- The skin friction components of the peak and of residual pullout resistance are small in comparison to the bearing component.
- The proposed method can be used also to evaluate the combination of σ'_v and L_R relating to the confined reinforcement pullout failure.

REFERENCES

Jewell, R.A. (1996). "Soil reinforcement with geotextiles." CIRIA Special Publication 123, Thomas Telford ISBN 0 7277 2502 5.

Matsui, T., San, K.C., Nabesahirna, Y. and Arnii, U.N. (1996). "Bearing mechanism of steel reinforcement in pull-out test." Proceedings of the International Symposium: Earth Reinforcement, pp. 101-105. Fukuoka, Kyushu, Japan.

Moraci, N. and Montanelli, F. (2000). "Analisi di prove di sfilamento di geogriglie estruse installate in terreno granulare compattato." Rivista Italiana di Geotecnica N. 4/2000, pp. 5- 21.

Moraci N. and Recalcati P.G. (2005). "Factors affecting the pullout behaviour of extruded geogrids embedded in a compacted granular soil." Geotextiles and Geomembranes (submitted for publication).

Moraci N. and Gioffrè D. (2006). "A simple method to evaluate the pullout resistance of extruded geogrids embedded in a compacted granular soil." Geotextiles and Geomembranes (in press).

Palmeira, E.M. (2004). "Bearing force mobilitation in pull-out tests on geogrids." Geotextiles and Geomembranes Vol. 22, pp. 481-509.