Use of geogrid as a reinforcing element for shallow foundations

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ABSTRACT
In general, work carried out on low bearing capacity or high deformability soils engages complex solutions. A modern solution to this geotechnical problem is the use of special techniques to improve the mass foundation's performance. Against this background geosynthetics - or more specifically geogrids - have been playing a leading role in replacing and enhancing traditional reinforcement solutions in order to reduce cost. Some research particularly developed based on experimental tests and/or numerical analyses shows parametrically variation in the bearing capacity of shallow foundations caused by the presence of geogrid reinforcements. The main parameters studied include: depth of the first reinforcement layer, width of the geogrid, the amount of reinforcement, spacing between layers and total reinforcement thickness. Therefore, this paper aims to present critical analyses of the state of the art on use geogrid as a reinforcing element for shallow foundations. Using that material improves bearing capacity of soil and reduces the settlement, thus it is possible to execute shallow foundation and reduce costs compared to conventional designs. This paper is justified mainly because of the lack of understanding interaction mechanisms between the geosynthetic, the soil and the foundation structure, which restricts the development of design methodologies and the prediction of the behavior of the reinforcement in the long term.

1. INTRODUCTION

Nowadays, population growth and intense urban expansion in large cities are leading to a growing demand to build on poorly supported soils. In general, this less competent massif with high deformability develop significant deformations upon request, which in many cases makes difficult the execution and functionality of the work. A modern way to solve this geotechnical problem is to use special techniques to improve the foundation mass performance.

In this context, in order to reduce costs, geosynthetics, in particular geogrid, have been playing a prominent role in replacing and enhacing the traditional reinforcement solutions. Geosynthetic soil reinforcement is a versatile technique that has advantages such as cost effectiveness, simplicity of construction process and the wide variety of available materials (Pinto, 2013).

Alston *et al.* (2015) reported the application of geogrid reinforcement in the construction of two storage liquid tanks with 31 m diameter in Canada's coastal region (Figure 1). The adoption of the technique allowed savings of approximately US$ 300.000,00 compared to the estimated initial costs of US$ 500.000,00 for the solution with piles or gravel columns. Post construction stress monitoring showed that the reinforced tank foundation performed within tolerable limits.

a) Geogrid reinforcement on excavation base b) Tank built on geogrid-reinforced ground mass

Figure 1. Reinforced ground mass tank construction (Alston *et al.,* 2015)

In the interaction mechanism of soil-structure-geosynthetic, the synthetic material, which deforms according to the structure's request, adds a portion of the tensile strength to the soil due to the developed friction. Particularly, in the case of shallow foundations laid on low bearing and high compressibility massifs, the introduction of geosynthetic provides increased carrying capacity and a significant reduction in settlements.

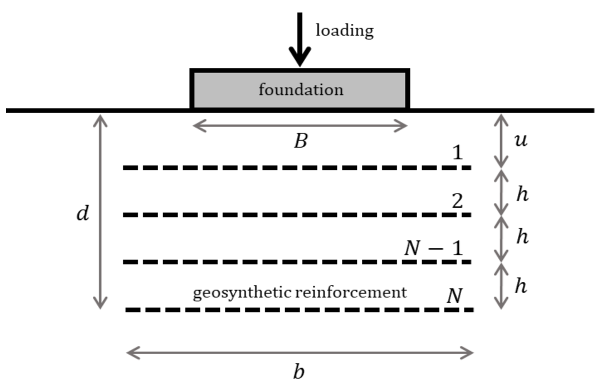
Although most of the research has shown positive results, the use of geosynthetic to reinforce shallow foundations in engineering practice is still very limited, especially in Brazil. This is mainly due to the lack of understanding of the interaction mechanisms between geosynthetic, soil and foundation structure, which restricts the development of design methodologies, even at the international level.

Thus, this paper aims to present the state of the art of the use of geogrid as a reinforcement element of superficial foundations. This work aims to contribute to a better understanding of soil-structure-geosynthetic interaction mechanisms, which can enable and expand the use of this reinforcement technique in engineering practice.

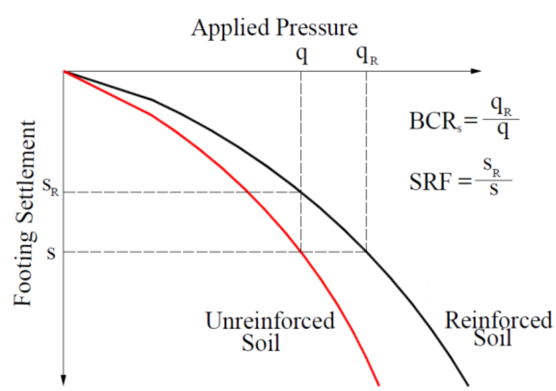
2. GEOGRID FOUNDATION REINFORCEMENT

The concept of soil reinforcement was first published by Vidal (1969) and was consolidated in Binquet e Lee (1975a, 1975b) pioneering work with an evaluation of the behavior of the sand-reinforced sandy massif. Over time, with new demands and technologies regarding material, shape and size, the material strips were replaced by geotextiles, geocells and geogrid.

Since then, researchs based on experimental tests, numerical and analytical analyzes has sought to investigate reinforced soil performance as well as the effects of different parameters on repression load behavior. The main parameters studied include: depth of the first reinforcement layer (u), geosynthetic width (b), number of reinforcements (N), spacing between layers (h) and overall thickness of the reinforcement (d). The works developed shows that the use of reinforcements can significantly increase the carrying capacity and reduce the settlement in shallow foundations. The Figure 2 shows the configuration of a geosynthetic reinforced foundation and the typical load-settlement behavior of a reinforced foundation and without the inclusion of the reinforcement.



a) Geometric parameters of reinforced foundations



b) Load-settlement behavior of reinforced foundations (Chen, 2007)

Figure 2. Configuration of a geosynthetic reinforced and the load-settlement behavior of reinforced foundations

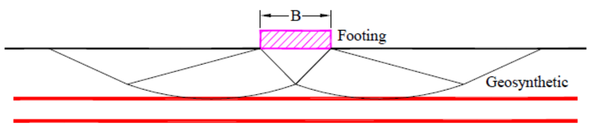
In this sense, two terms are used to evaluate the benefits of geosynthetic reinforcement: BCR (bearing capacity ratio) and SRF (settlement reduction factor). BCR is defined as the ratio between the stress in the reinforced mass and the stress of the unreinforced foundation for the same settlement, whereas SRF is the ratio between the reinforcement massifs settlement and the settlement without the introduction of the reinforcement for the same tension level.

3. REINFORCEMENT MECHANISMS

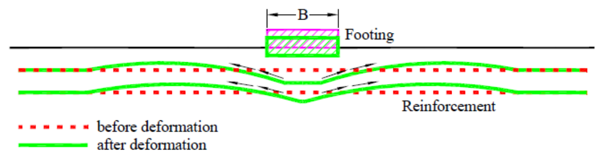
The reinforcement mechanisms proposed in the literature are divides into three categories (Figure 3):

- Rigid boundary: when the depth of the first reinforcement layer (u) is greater than a certain value, the reinforcement acts as a hard limit and the failure occurs above the first reinforcement layer;

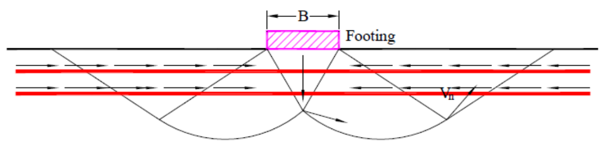
- Membrane effect: With the load applied the foundation and the soil move down, deforming and tensioning the reinforcement. Due to this rigidity, the synthetic material develops a tensile force that contributes to an increase in the carrying capacity of the massif. In this sense, for this mechanism to occur, a certain amount of settlement is necessary and, consequently, the geosynthetic must have length and rigidity to resist the stressing forces;
- Confinement or lateral constraint effect: due to the relative displacement between ground and reinforcement, a frictional force is induced at the soil-reinforcement interface. In this way, na interlock can be returned by the interaction between the soil and the synthetic material and the lateral deformation is restricted. As the behavior of most soils depends on the stress state, lateral confinement tends to increase compressive strength and decrease lateral deformation.



a) Rigid boundary



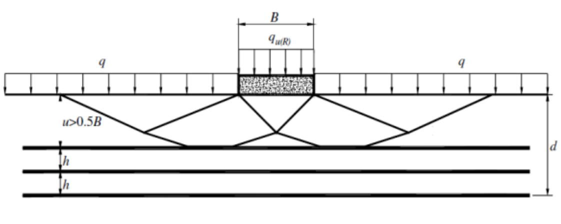
b) Membrane effect



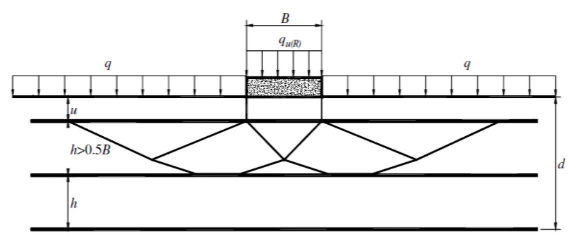
c) Confinement effect

Figure 3. Reinforcement mechanisms (Chen, 2007)

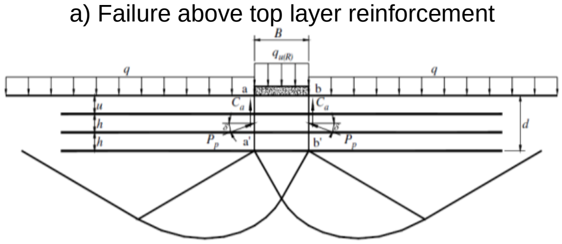
In this context, Sharma *et al.* (2009) reports four types of foundation break in reinforced soil mass: soil break above the first reinforcement layer, break between geosynthetic layers, foundation laid on tough soil layer supported by less competent layers and rupture within the zone reinforced with synthetic material (Figure 4).



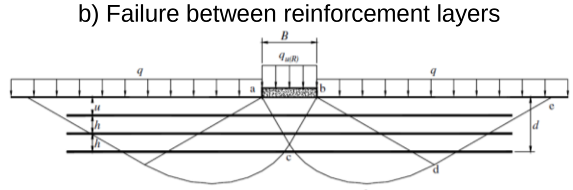
a) Failure above top layer reinforcement



b) Failure between reinforcement layers



c) Failure similar to footings on a two-layer soil system



d) Failure within reinforced zone

Figure 4. Failure modes of reinforced soil foundation. (Sharma *et al.,*2009)

The first two rupture mechanisms, above and between the reinforcement layers, can be avoided by maintaining convenient spacing of the geosynthetic layers. Chen (2007) shows that this spacing must be less than 0,5B to prevent both break modes from occurring. In engineering pratice, this requirement is nor usually difficult to meet. Thus, the studies emphasize foundation rupture in two soils system and rupture within a reinforced zone.

4. EXPERIMENTAL STUDIES

Experimental studies seek to determine parametrically the variations in the carrying capacity of surface foundations caused by the presence of reinforcement. These jobs define optimal settings for width, depth, spacing, and number of reinforcements. Table 1 summarizes the main experimental studies.

Table 1. Summary of experimental studies (1st part)

Reference	Geogrid reinforcement			Shallow foundation			Tank			Optimal parameters			
	Polymer	Tensile strength (kN/m)	Aperture size (mm)	Type	B(cm)	L/B	B_t/B	L_t/B	Z_t/B	u/B	b/B	h/B	N
Guido *et al.* (1986)	Polypropylene	20	38 x 28	Square	31,0	1,0	3,9	3,9	3,0	0,25	3	0,25	3
Mandal and Sah (1992)	-	8	-	Square	10,0	1,0	4,6	4,6	4,6	0,175	-	0,20	-
Khing *et al.* (1993)	Polypropylene	-	25 x 33	Strip	10,0	3,0	11,0	3,0	9,0	0,25 - 0,40	11	0,40	6
Omar *et al.* (1993a)	Polypropylene - high-density polyethylene copolymer	-	25 x 33	Square	7,5	1,0	14,7	4,0	12,0	1,00	4 - 8	0,33	3
				Strip	7,5	4,0	14,7	4,0	12,0				
Omar *et al.* (1993b)	Polypropylene - high-density polyethylene copolymer	-	25 x 33	Square	7,5	1,0	14,7	4,0	12,0	0,33	8	0,33	6 - 7
				Rectangular	7,5	2,0							
				Strip	7,5	4,0							
Das and Omar (1994)	Polypropylene - high-density polyethylene copolymer	-	25 x 33	Strip	5,0	6,0	39,2	6,0	18,0	0,33	8	0,33	-
					7,5	4,0	26,1	4,0	12,0				
					10,0	3,0	19,6	3,0	9,0				
					12,5	2,4	15,7	2,4	7,2				
					15,0	2,0	13,1	2,0	6,0				
					17,5	1,7	11,2	1,7	5,1				
Khing *et al.* (1994)	Polypropylene	11	25 x 33	Strip	7,5	2,0	12,3	2,0	12,2	0,67	6	0,67	-
	Polypropylene - high-density polyethylene copolymer	9	25 x 33										
Yetimoglu *et al.* (1994)	Polypropylene	29	80 x 14	Rectangular	10,0	1,3	7,0	7,0	10,0	0,25	4,5	0,20	-
Adams and Collin (1997)	Polypropylene	34	25 x 30	Square	30,0	1,0	Field test			0,48	-	0,25 - 1,50	3
					45,0	1,0							
					60,0	1,0							
					90,0	1,0							

Table 1. Summary of experimental studies (2nd part)

Reference	Geogrid reinforcement			Shallow foundation			Tank			Optimal parameters			
	Polymer	Tensile strength (kN/m)	Aperture size (mm)	Type	B(cm)	L/B	B_t/B	L_t/B	Z_t/B	u/B	b/B	h/B	N
Alawaji (2001)	High density polyethylene	12	20 x 20	Circular	10,0	-	4,5	-	3,5	0,10	4	0,10	
Boushehrian (2003)	Polyethylene	28	5 x 5	Circular	15,0	-	6,7	-	6,7	0,47	-	0,20	3
Sitharam and Sireesh (2004)	Polypropylene	20	31 x 41	Circular	15,0	-	6,0	6,0	4,0	0,30	6	0,40	6
Chen *et al.* (2004)	Polyester Polypropylene Polypropylene	-	25 x 25 33 x 33 33 x 33	Square	15,0	1,0	10,0	6,0	6,0	0,33	6	0,33	5
Dash *et al.* (2004)	Polypropylene	20	35 x 35	Strip	10,0	3,3	12,0	3,3	7,0	0,30	8	0,30	6
Patra *et al.* (2005)	-	60	94 x 42	Strip	8,0	4,5	10,0	4,5	8,8	0,35	5	0,25	4
Boushehrian and Hataf (2008)	Polyethylene	8	3 x 3	Circular	15,0	-	6,7	-	6,7	0,20	-	0,20	3
Alamshahi and Hataf (2009)	High density polyethylene	6	27 x 27	Strip	10,0	5,0	13,0	5,0	6,0	0,75	-	0,75	-
Latha and Somwanshi (2009)	-	20 40 40	35 x 35 30 x 30 220 x 17	Square	15,0	1,0	6,0	6,0	4,0	0,10	5 - 6	0,50	4
El Sawwaf and Nazir (2010)	High density polyethylene	45	20 x 220	Rectangular	8,0	1,5	7,5	10,0	7,5	0,30	5	0,60	3
Tafreshi *et al.* (2011)	Polyethylene	6	27 x 27	Strip	10,0	2,2	10,0	2,2	10,0	0,35	4 - 5	0,35	5
El Sawwaf and Nazir (2012)	Polypropylene	14	42 x 50	Strip	8,0	6,3	12,5	6,3	6,3	-	-	0,50	3
Demir *et al.* (2013a)	Polypropylene	60	30 x 30	Circular	30,0	-	Field test			0,10 - 0,50	-	0,15 - 0,30	-
Demir *et al.* (2013b)	Polypropylene	60	30 x 30	Circular	30,0 45,0 60,0 90,0		Field test			-	-	-	-

Table 1. Summary of experimental studies (3rd part)

Reference	Geogrid reinforcement			Shallow foundation			Tank			Optimal parameters			
	Polymer	Tensile strength (kN/m)	Aperture size (mm)	Type	B(cm)	L/B	B_t/B	L_t/B	Z_t/B	u/B	b/B	h/B	N
Abu-Farsakh *et al.* (2013)	Polyethylene		25 x 25	Square	15,0	1,0							
	Polypropylene	-	33 x 33				10,0	6,0	6,0	0,33	6	0,33	3
	Polyethylene		22 x 25	Rectangular	15,0	1,7							
Cicek *et al.* (2015)	Polyester	35	20 x 20										
	Polyester	55	40 x 40	Strip	10,0	5,0	10,0	5,0	10,0	-	5	-	-
	Polypropylene	45	14 x 70										
Biwas *et al.* (2015)	-	20	-	Circular	15,0	-	6,7	6,7	6,7	-	6	-	-
Prasad *et al.* (2016)	-	40	30 x 30	Square	20,0	1,0	5,0	5,0	5,0	0,30 - 0,45	5	-	-
Roy and Deb (2017)				Square	7,5	1,0							
				Rectangular	7,5	1,5	12,0	12,0	8,0				
	-	-	1,5 x 1,5	Rectangular	7,5	2,0				-	4 - 5	-	-
				Rectangular	10,0	1,5	9,0	9,0	6,0				
				Square	15,0	1,0	6,0	6,0	4,0				
Suku *et al.* (2017)	Polypropylene	20	30 x 30	Circular	15,0	-	10,0	10,0	6,7	0,33	3	-	-
El-Soud and Belal (2018)					7,5	5,1	16,0	5,3	16,0				
	High density polyethylene	45	20 x 220	Strip	10,0	3,8	12,0	4,0	12,0	0,25	7,5	-	-
					12,0	3,2	10,0	3,3	10,0				
Elsheseny *et al.* (2019)	Polypropylene	20	39 x 39	Strip	20,0	5,0	7,5	5,0	5,0	0,35	5	0,35	
Lopes (2019)	Polyester	12	4 x 4	Strip	2,0	2,4	10,0	2,5	10,0	0,4	5	-	-

Note: B is width or diameter of the shallow foundation, L is length, of the shallow foundation, B_t, L_t e Z_t are, respectively, the width, length and depth of the test tank, u is the depth of the first layer of reinforcement, b is length of reinforcement, h is the vertical distance between the layers and N is the number of reinforcement layers.

Such studies, mostly of small-scale physical models, indicate an increase in the carrying capacity of a shallow foundation and a reduction in settlement with the introduction of reinforcement. Due to the particularities of each work, some differences in the optimal parameter values of the reinforcement configuration are found. However, some general conclusions and observations can be made:

- The optimum depth of the first reinforcement layer is between $0.15B$ and $0.40B$;
- Placing the first reinforcement layer deeper than the width of the foundation does not cause a significant increase in load capacity;
- The optimal width of geosynthetic reinforcement ranges from $4B$ to $6B$;
- The optimum reinforcement spacing, as well as the optimal depth of the first layer, is between $0.15B$ and $0.40B$;
- The optimal total vertical depth of the reinforcement layer ranges from $1.3B$ to $2B$;
- Increasing the number of reinforcement layers beyond a specific number of 3 to 5 layers does not produce a significant increase in load capacity;
- Bearing capacity ratio (BCR) improvement values become more expressive at higher settlement;
- The lower the resistance of the foundation soil, the higher the BCR value, suggesting that the reinforcement is more effective in low bearing mass.

5. LAWS OF SIMILARITY AND SCALE EFFECT

An essential requirement in physical modeling studies is the similarity between prototype and experimental model parameters. To get the representative in the modeling, it is necessary to guarantee a geometric, dynamic and kinematic similarity:

- Geometric similarity: Model dimensions should be related to prototype counterparts by a constant scale effect;
- Dynamic similarity: the forces in the model and prototype must be related by a constant scale effect at corresponding points;
- Kinematic similarity: The velocities at the corresponding points of the model and prototype must be in the same direction and their magnitudes differ from the scale effect. Basically, if the conditions of geometric and dynamic similarity are met, kinematic similarity is automatically found.

In the case of geogrid-reinforced surface foundations, when performing a small-scale model test, it is necessary to consider the scale effects to properly simulate the reinforcement configuration and the properties of the soil and synthetic material. According to Fahker and Jones (1996), the interpretation of reduced model tests without taking into account the scale effect overestimates the reinforcement effect.

The scale effect of the model is obtained through a dimensional analysis, being object of several studies of the bibliography (Love, 1984; Fahker and Jones, 1996; Viswanadham and Konig, 2004; Sireesh *et al.*, 2009; Tafreshi *et al.*, 2011; Hong *et al.,* 2016; Mehrjardi and Khazaei, 2017). Thus, dimensional similarity analysis provides dimensionless parameters, known as π_i, numbers, that convert variables between a physical model and its prototype.

The Table 2 presents the scale factor of the various parameters of a reduced geosynthetic reinforced foundation model. Thus, to achieve similarity between the experimental test conditions and the full-scale situation, it is necessary that the dimensionless parameters, the numbers π_i, have the same values for the model and prototype.

6. CONCLUSION

The article discussed the use of geogrid as a reinforcement element for shallow foundations, with emphasis on reinforcement mechanisms, experimental studies and laws of similarity and scale factor. The work is especially justified by the potential application of the geogrid reinforcement technique and the limited knowledge of the combined performance of the synthetic material, the soil and the foundation structure.

The three types of reinforcement mechanisms proposed in the literature were presented: rigid boundary, membrane effect and confinement effect and the four types of rupture: soil rupture above the first reinforcement layer, geosynthetic layer rupture, foundation rupture laid on resistant soil layer supported by less competent layer and rupture within the zone reinforced with synthetic material.

Experimental studies, mostly of small-scale physical models, define optimal settings for width, depth, spacing, and number of reinforcements. Studies suggest that reinforcement is most effective in low bearing mass. In small scale model tests, it is necessary to consider the laws of similarity to adequately represent the behavior of geosynthetic reinforcement.

The behavior of the geogrid reinforced foundation depends on the geometry of the reinforcement, the properties of the synthetic material and the foundation mass. However, limited knowledge of the interaction between the elements makes it difficult to develop sizing methodologies and predict long-term reinforcement behavior. Stands out, based on a better understanding of the soil-structure-geosynthetic mechanism, the technique can be applied in engineering practice with greater safety and economy.

Table 2. Characteristic values used for model to prototype scaling.

Dimensionless factor		Characteristic	Scaling factor (prototype/model)
Test geometry	$\pi_1 = s/B$	s	λ
	$\pi_2 = u/B$	u	λ
	$\pi_3 = h/B$	h	λ
	$\pi_4 = b/B$	b	λ
	$\pi_5 = d/B$	d	λ
Properties of soil	$\pi_6 = D_{50}/B$	D_{50}	λ
	$\pi_7 = G/B\,\gamma$	G	λ
	$\pi_8 = \varphi$	φ	1
	$\pi_9 = Dr$	Dr	1
Properties of geogrid	$\pi_{10} = J_t\,\gamma/G^2$	J_t	λ^2
	$\pi_{11} = a_t/B$	a_t	λ
	$\pi_{12} = b_t/B$	b_t	λ
Applied pressure	$\pi_{13} = B\,J_t/s^2\,q$	q	λ

Note: B is the width of the foundation, s is the settlement, u is depth of the first reinforcement layer, h is the spacing between reinforcement layers, b is length of reinforcement, d is the total thickness of the reinforcement, D_{50} is the diameter. average soil grain size, γ is the specific soil weight, G is the shear deformation modulus of the soil, φ is the friction angle Dr is the relative density, J_t is the geosynthetic stiffness modulus, a_t is the aperture size, b_t is the geogrid filament thickness, q is the applied pressure and λ s the scale factor of the model.

ACKNOWLEDGEMENTS

The authors thank CAPES, UENF and Huesker Brazil support of this research.

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