Pullout bearing failure mechanism of the anchored geogrid system

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ABSTRACT: The pullout resistance has a significant importance in the secure design of mechanically stabilized earth (MSE) walls. One of the most relevant reinforcements used in such structures is the grogrid. In this reinforcement, the main factor affecting on the pullout resistance is the bearing resistance which is mobilized against geogrid transversal bars. However, due to the limited thickness of these members in the geogrid; the pullout resistance of the reinforcement in some circumstances; cannot satisfy the internal stability of MSE walls. Thus, in this research, a new reinforcement system which is able to increase the passive resistance and therefore pullout resistance - which is fabricated by adding transverse members (a set of steel equal angles) to the traditional geogrid, by means of bolts and nuts- is introduced and called "anchored geogrid" (AG). The pullout behavior of the AG system is experimentally evaluated. The results of the large-scale pullout tests show that the aforementioned system can increase the pullout resistance around three times compared with the traditional geogrid systems. In addition, the bearing failure mechanism of the AG system with a single transversal member in sandy soil with small particles- based on the relations suggested by various scholars regarding pullout failure mechanisms is the general shear failure.

Keywords: Geogrid, Anchored Geogrid, Pullout Resistance, Large-scale.

1 Introduction

Among the various forms of retaining walls, mechanically stabilized earth (MSE) walls have numerous advantages compared to the traditional concrete gravity and cantilever retaining walls—such as lower costs and ease of construction — which have resulted in an increase in the use of this kind of retaining wall around the world (Yu et al., 2015). When geogrids are utilized as reinforcements in MSE walls, the internal stability of the wall can become at risk if the load transmitted to the geogrid is more than the tensile strength of the reinforcement (i.e., failure by tension). The same is true if the shear strength at the soil-geogrid interfaces, along with the passive resistance developed at the front of the transverse elements of the geogrids in order to resist the geogrid sliding from the soil mass, is insufficient (i.e., pullout failure) (Sieira et al., 2009). For the purpose of evaluating the pullout resistance and determining the characteristics of the soil-reinforcement interface, a pullout test based on ASTM D6706 can be used.

During the last few decades, the factors affecting the results of the pullout resistance of the reinforcement have been numerically, analytically and experimentally investigated by many different researchers, some of them utilizing field pullout tests (Palmeira and Milligan, 1989; Raju, 1995; Perkins and Cuelho, 1999; Sugimoto et al., 2001; Palmeira, 2004; Abdi and Zandieh, 2014, Mosallanezhad et al., 2016). These factors include the vertical load application system, the front wall effect, the pullout box dimensions, the specimen geometry and structure, the displacement rate, the clamping system, the friction between sidewall and soil, etc.

In general, the pullout resistance of reinforcement in a pullout experiment can be calculated using the following equation:

$$P=2L\sigma'_n f\tan\varphi \quad (1)$$

where P is the pullout resistance (per unit width); L, the length of the reinforcement that resists the pullout force; σ'_n, the effective normal stress; φ, the soil friction angle; and f, the soil-reinforcement pullout interaction coefficient, which is simply extracted from the large-scale pullout experiment. The f parameter depends on different factors, such as effective vertical stress at the reinforcement level, boundary conditions, and in general the mobilized interaction mechanism along the soil-reinforcement interface during the pullout process. An example of this might be the mobilized interaction mechanism between the soil and the geogrid during the pullout procedure, caused by the skin friction between the soil and the solid surfaces of the geogrid, as well as the bearing resistance produced against the transverse geogrid ribs (Moraci et al., 2014).

By increasing the interaction coefficient between the soil and the reinforcement, the pullout resistance can be improved; therefore, in recent years, various researchers have tried to increase this coefficient by making changes to the soil-reinforcement interface, or to the reinforcement itself. Most of these methods have been applied in order to increase the bearing resistance of the reinforcement and thereby enhance its pullout resistance. When utilizing poor-quality backfill (like clay) in MSE walls, it is possible to apply a thin layer of granular material with high resistance at the soil-reinforcement interface. By using this thin layer of granular soil, as well as increasing the backfill drainage of the materials, the pullout resistance is improved, due to the increase of the soil-reinforcement interaction coefficient (Abdi and Arjomand, 2011; Abdi and Zandieh, 2014). Mosallanezhad et al. (2008) tried to increase the pullout resistance of ordinary geogrids by adding anchors made of high-density polyethylene (HDPE) using industrial strips; they called this system "Grid-Anchor" (G-A). By utilizing this system, the bearing capacity of granular soils located on the reinforced soils increased, due to the increase of pullout resistance of G-A system to the traditional geogrids.

In this study, the pullout resistance mechanism of an innovative reinforcement system, applied on a large-scale in a granular soil, has been examined experimentally. This efficient and simple system is created by adding rigid bearing transverse elements (a set of steel equal angles) to the ordinary geogrids (extensible reinforcement). This reinforcement system is called "anchored geogrid" (AG) (Fig. 1). It is worth noting that the geogrid utilized in this research is of a uniaxial variety, and made of HDPE. The results of this study indicate a huge increase in the pullout resistance of this system in pullout mechanism compared to that of ordinary geogrids.

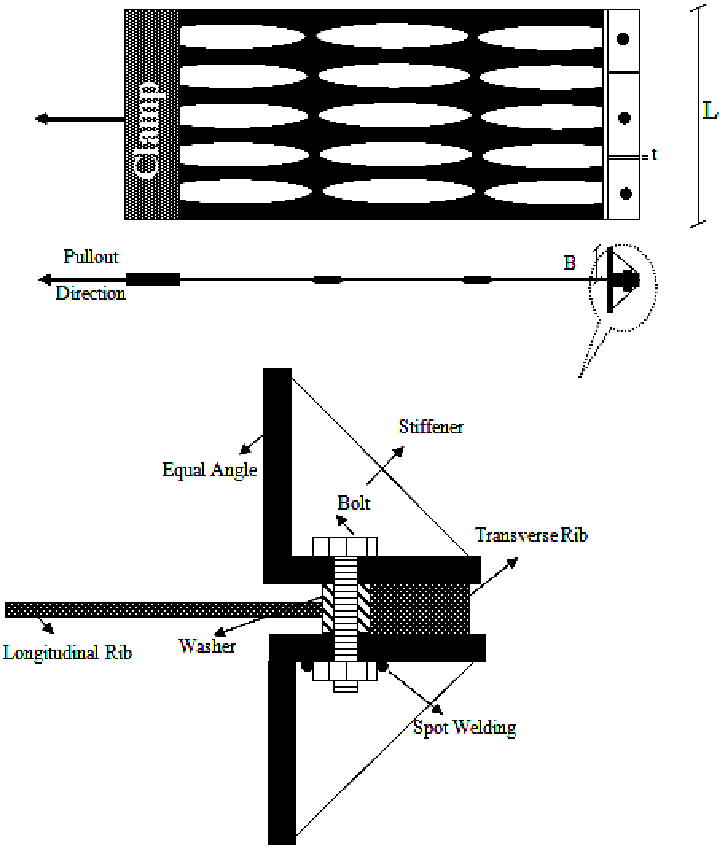

Figure 1. The features of the reinforcement system of anchored geogrid (AG)

2 EXPERIMENTAL RESEARCHS

2.1 *Laboratory pullout tests*

A series of pullout tests was designed in order to evaluate the new AG system's performance in increasing pullout resistance compared to that of ordinary geogrids. A total of 12 pullout tests were conducted, involving large-scale experiments under different overburden pressures of 10, 20 and 30 kPa, and with transverse elements (also called anchorage/bearing elements) with different leg lengths (B) and depths (d=2B). The following depths of the rigid bearing transverse elements in the AG system were tested: 4, 8 and 12 centimeters. It should be noted that in order to check the repeatability of results, all tests were conducted at least twice, and in some cases thrice.

2.2 *Test apparatus*

In this study, a large-scale pullout apparatus was constructed based on ASTM D6706-01 (2013). The experiment apparatus consisted of one rigid pullout box (1200×600×500 mm) containing soil and the experiment specimen, a hydraulic actuator (to apply a pullout force with 50 kN capacity), a hydraulic jack support, a loading clamp assembly, a flexible (airbag) surcharge loading system, and all the instruments needed to record and monitor the required data for analysing the pullout tests (Fig. 2).

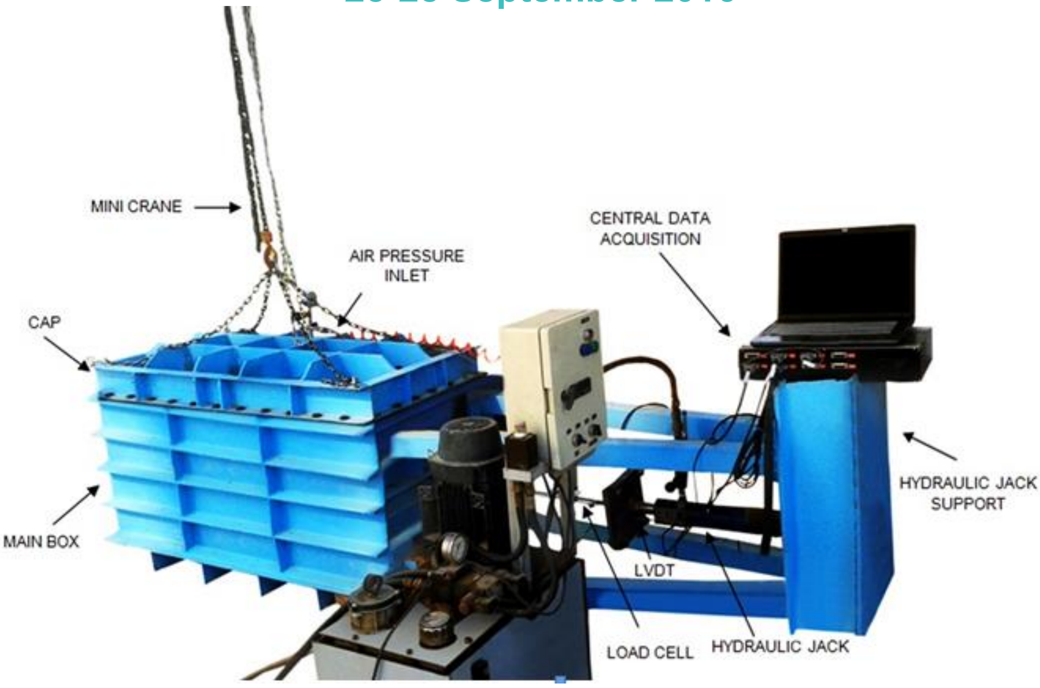

Figure 2. Large-scale pullout apparatus.

2.3 *Test materials*

2.3.1 *Geogrid reinforcement*

In this research one HDPE-extruded uniaxial geogrid was used as the base geogrid. In Table 1, the physical and mechanical characteristics of the geogrid, as provided by the manufacturing company, are shown.

Table 1. Geogrid material characteristics

Geogrids	
Aperture size MD*, longitudinal (mm)	220
Aperture size TD**, transverse (mm)	13/20
Tensile strength at 2% strain (kN/m)	17
Peak tensile strength (kN/m)	60
Yield point elongation (%)	13

*MD: machine direction (longitudinal to the roll)
**TD: transverse direction (across roll width)

Table 2. Soil properties used for sample preparation

2.3.2 *Granular soil*

The soil used in this experiment was sandy soil, which was classified as poorly graded sand (SP), based on the Unified Soil Classification System (USCS). Properties of this soil were determined based on the appropriate ASTM standards, which are shown in Table 2.

2.3.3 *Anchorage elements*

Steel equal angles were used as transverse elements (anchorage members), the thickness of all of which was 5 mm. The length of the different transverse elements was chosen in accordance with the geogrid's width (about 300 mm). In addition, in the transverse elements with leg lengths of 40 and 60 mm, stiffeners were used to increase their rigidity.

2.4. Sample preparation and test procedure

Soil was loaded in three layers of about 80 mm into the lower half of the experiment box, and compacted. After the soil was compacted and reached a level of 250 mm (underside of reinforcement), the reinforcement connected to the clamp (ordinary geogrid or AG system) was positioned at this level (Fig. 3).

For the next stage, sand was loaded in three layers of about 80 mm onto the reinforcement and compressed, until the upper half of the experiment box was also full. It is worth noting that, to reach uniform compaction, the sand layers were compacted by three strokes of a steel hammer of about 10 kg, with a steel surface of 300×300 mm and thickness of 50 mm. The height of the hammer fall was around 250 mm, meaning the energy transmitted to the soil through this compression method was about 10,200 Nm/m^3. The relative density of the sand was around 65% and the unit weight of the soil was 16.3 kN/m^3.

For the next stage, an airbag was placed over the soil and the top lid was closed using bolts. The airbag was filled up to the desired overburden pressure (i.e., 10, 20 and 30 kPa). After completing all the above-mentioned tasks, the pullout force could be applied, following ASTM D6706-01, in the form of either a constant rate of displacement (1 mm/min ± 10%) or a controlled stress rate method (uniform rate of load application; not exceeding 2 kN/m/min). In this study, the second method (controlled stress rate method) was used to apply the pullout force.

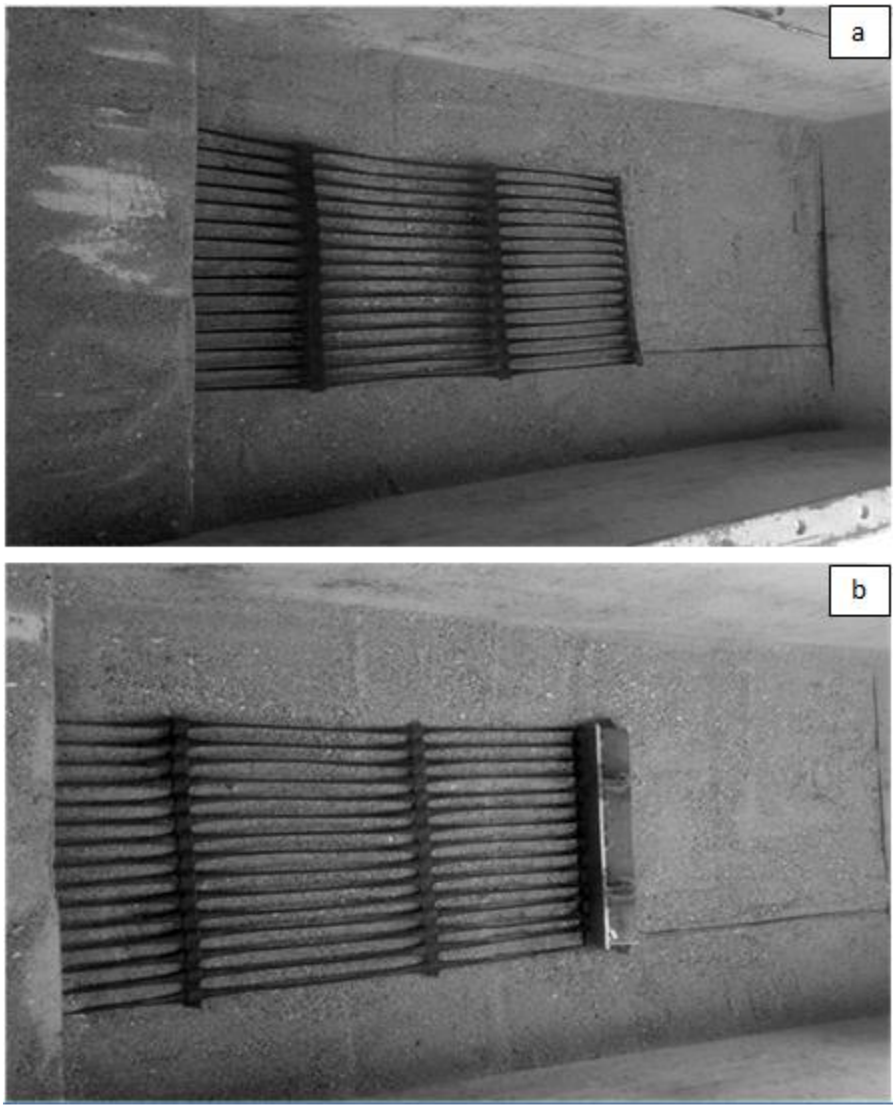

Figure 3. (a) Ordinary geogrid system; (b) anchored geogrid system

3. RESULTS AND DISCUSSION

What follows next is the results obtained from the large-scale pullout tests, and the parameters influencing them, for the two reinforcement systems investigated in this research.

3.*1 Conventional geogrid*

One can determine the pullout reinforcement resistance per unit width (P) using the results of the pullout tests. On the whole, a pullout test is terminated when geosynthetic rupture occurs, or when the frontal displacement of the reinforcement reaches 90 mm (Abdi and Zandieh, 2014).

In Figure 4, the results obtained from the pullout test for an ordinary geogrid system are demonstrated. As the figure shows, with the increase in the overburden pressure, the amount of corresponding pullout resistance and displacement also increased, as was expected. As mentioned before, the pullout resistance of geogrid results from the friction between its solid surfaces and the soil, as well as the passive resistance developed against its transverse ribs. Both these mechanisms are mobilized as a result of elongation. In general, friction between the soil and the solid surface of the geogrid is noticeable at the early stages of the pullout test and in small displacements (Sieira et al., 2009). On the whole, the share of skin friction in the production of peak pullout resistance,

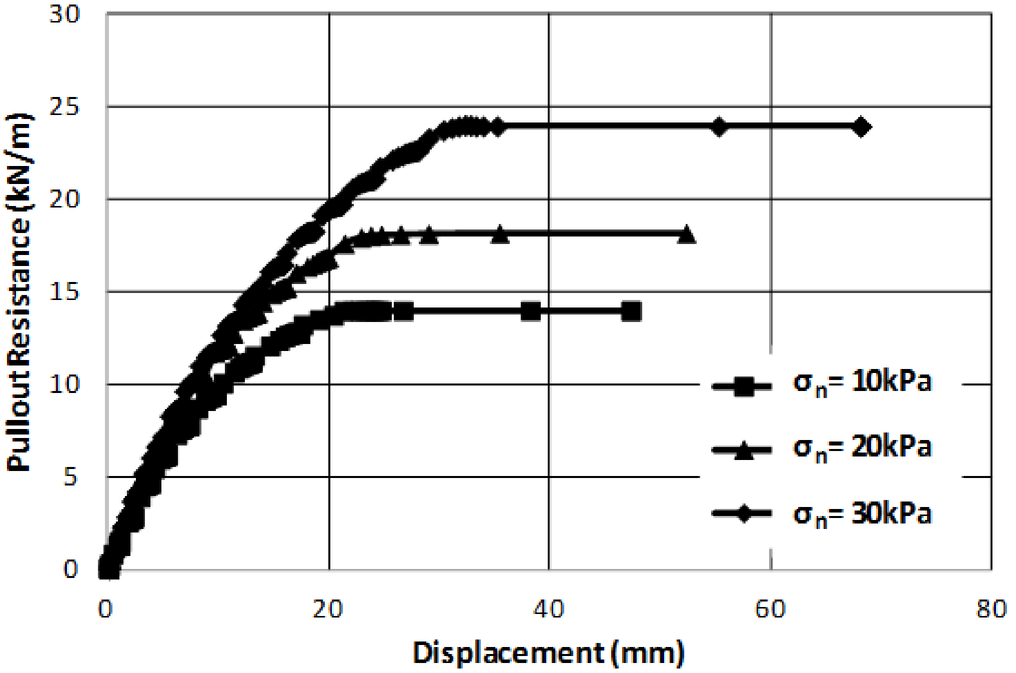

Figure 4. Ordinary geogrid pullout resistance under different overburden pressures

compared to that of bearing resistance, is small (Touahamia et al., 2002; Palmeira, 2009; Abdi and Zandieh, 2014). Thus, with an increase in overburden pressure, the soil compression around the geogrid increases and, as a result, not only raises the skin friction between the soil and the solid surfaces of the geogrid, but also adds it to the amount of passive resistance produced against the transverse ribs (which have a greater contribution to pullout resistance).

3.2 *Anchored geogrid*

3.2.1 *Pullout resistance of a single isolated transverse element*

Figure 5 shows the pullout resistance of an AG system. As shown in Fig. 5a, in the AG system with transverse elements of 40 mm depth (i.e., leg length of 20 mm), the amount of pullout resistance is increased with an increase in the overburden pressure. While under higher overburden pressures (20 and 30 kPa), the difference in amounts of pullout resistance in different displacements is reduced. According to Fig. 5a, the reason for this issue can be explained as follows: under the low overburden pressure (10 kPa), considering the small depth of transverse element (d = 40 mm) and the low overburden pressure, a complete pullout (increase in displacement at a constant rate, under a constant pullout force) has taken place in a displacement of about 60 mm. In other words, with an increase in the pullout force, and as a result of elongation of the geogrid, a state of failure is created against the end transverse member; following this, the AG system is not capable of resisting the pullout force, and consequently a complete pullout takes place. However, under higher overburden pressures, the confining pressures around the reinforcement are increased, the result being an increase in the passive resistance of the AG system. As a result of the increase in the overburden pressures on this system, the shear stress developing at the soil-reinforcement interfaces becomes more non-uniform, and progressive failure develops in the system (i.e., an increase in fluctuations on the pullout chart). As is clearly demonstrated in Fig. 5a, until the desired displacement (about 90 mm), the AG system was still resistant against the pullout force and complete pullout had not yet taken place. In other words, under overburden pressures of 20 and 30 kPa, a state of failure was not achieved against the anchorage element, and consequently the difference in values of pullout resistance was reduced.

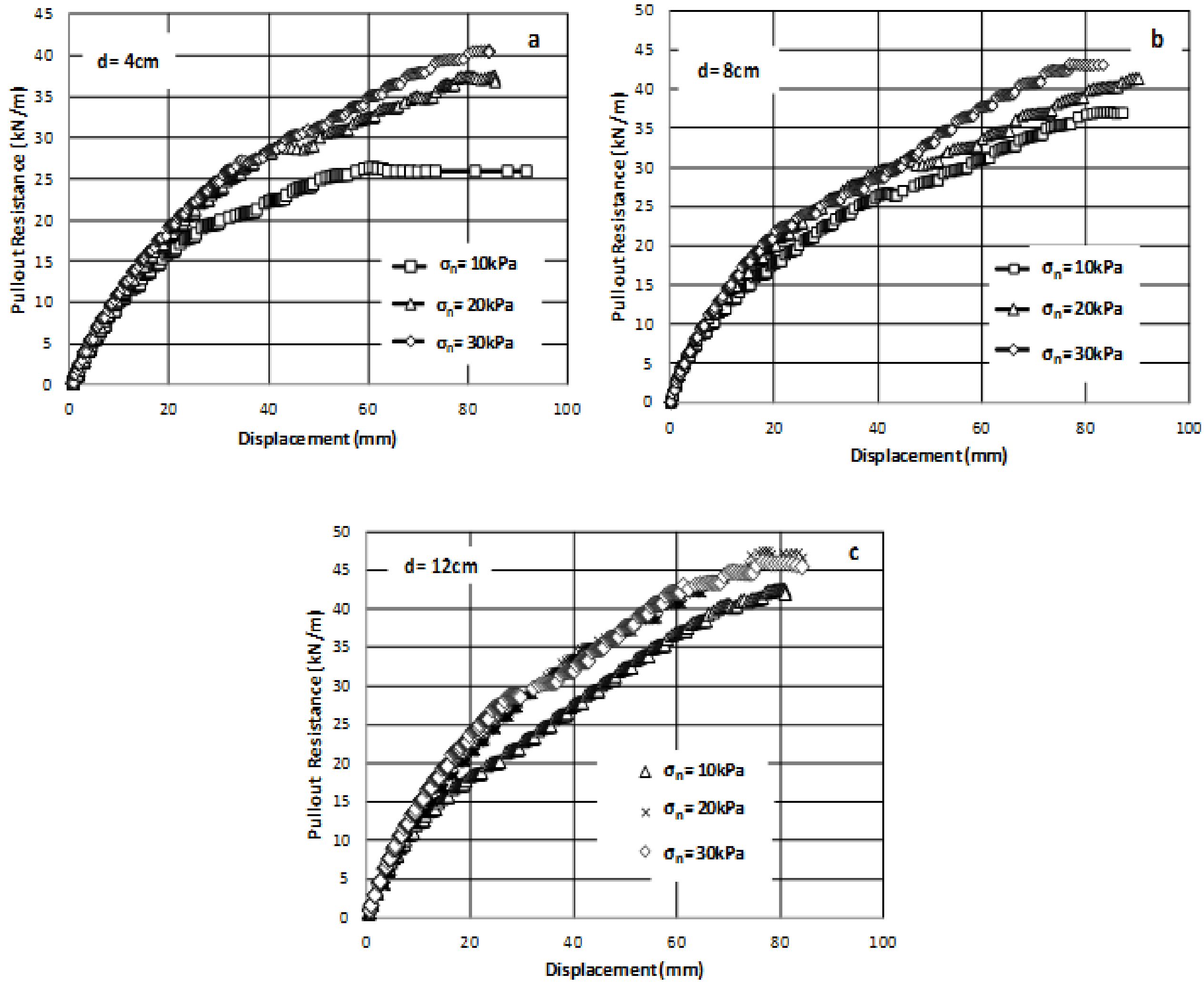

Figure 5. The pullout resistance of anchored geogrid systems with one anchorage member of different depths under different overburden pressures: (a) d = 4 cm; (b) d = 8 cm; (c) d = 12cm.

In Fig. 5b, the pullout resistance vs. displacement of the AG system with transverse elements of 80mm depth (i.e., leg length of 40 mm), under various overburden pressures, is illustrated. As can be observed in the figure, as a result of the doubling in depth of the transverse element (d) and the consequent increase in its bearing area (L×d), the passive resistance of the system is increased. On the other hand, following the increase in the bearing area of the anchorage element, the passive pressure resulting from the steel transverse element on the soil against it is reduced under equal pullout forces, when compared to that of transverse elements with a smaller bearing area. Thus, in equal conditions, if transverse elements are used with a greater bearing area, greater pullout forces will be needed to produce the state of failure against these elements.

As is clearly shown in Fig. 5b, an increase in overburden pressure has little effect on the pullout resistance, up until the predetermined displacement of 90 mm. This issue results from the fact that, as in the previous situation (transverse elements with a depth of 40 mm), even though complete pullout takes place only under the lowest overburden pressure (10 kPa), the increase in the depth of the transverse elements has caused that almost by the end of the experiment (displacement of about 80 mm), complete pullout has occurred. Moreover, with an increase in the overburden pressure (20 and 30 kPa), a state of failure is not created against the transverse elements until the end of the experiment (displacement of about 90 mm). Thus, the pullout resistance of the AG system with transverse elements of 80 mm depth was not significantly different under different overburden pressures.

By increasing the depth of the steel transverse elements to 120 mm (i.e., leg length of 60 mm), there was no complete pullout even under the lowest overburden pressure (10 kPa), and with an increase in the amount of overburden pressure in practice, no big change took place in the final pullout resistance. Under these conditions, the steel transverse element mounted on the last transversal rib of the geogrid anchored the end of the base geogrid in the soil. In this state, an increase in the overburden pressure merely causes greater non-uniformity of the shear stress mobilized on the soil-reinforcement interfaces during the pullout process (Fig. 5c).

4. PULLOUT BEARING FAILURE MECHANISMS

Different researchers have proposed various relationships in order to evaluate the pullout bearing failure mechanisms on the basis of plane strain conditions. These mechanisms include general shear failure (Peterson and Anderson, 1980); punching failure (Jewell et al., 1984); and modified punching failure (Chai, 1992; Bergado et al., 1996; Horpibulsuk and Niramitkornburee, 2010). In granular soils, the maximum bearing resistance of a single isolated transverse element is σ_{bmax}, which can be displayed as shown below:

$$\sigma_{bmax} = N_q \sigma_n \quad (2)$$

In the above equation, σ_n is the normal pressure and N_q is the bearing capacity factor, which depends on the pullout mechanism. The Nq parameter for the different mechanisms in relation to the soil friction angle (φ) can be obtained as below:

$$N_q = \exp[\pi \tan\varphi] \tan^2(\pi/4 + \varphi/2) \quad \text{for general shear failure} \quad (3)$$

$$N_q = \exp[(\pi/2 + \varphi) \tan\varphi] \tan(\pi/4 + \varphi/2) \quad \text{for punching shear failure} \quad (4)$$

$$N_q = (1/\cos\varphi) \exp[\pi \tan\varphi] \tan(\pi/4 + \varphi/2) \quad \text{for modified punching shear failure} \quad (5)$$

In order to evaluate the mechanism governing the AG system's pullout, graphs of N_q against φ, based on equations 2–5, were drawn and compared with the measured amounts of N_q obtained from the results of the large-scale pullout tests, which were determined as follows: σ_{bmax} / σ_n. It should be noted that the amount of the ultimate bearing resistance of (σ_{bmax}) can be obtained as the ratio of the pure ultimate pullout force applied on the anchorage element to the area of the transverse elements (L×d) (Horpibulsuk and Niramitkornburee, 2010).

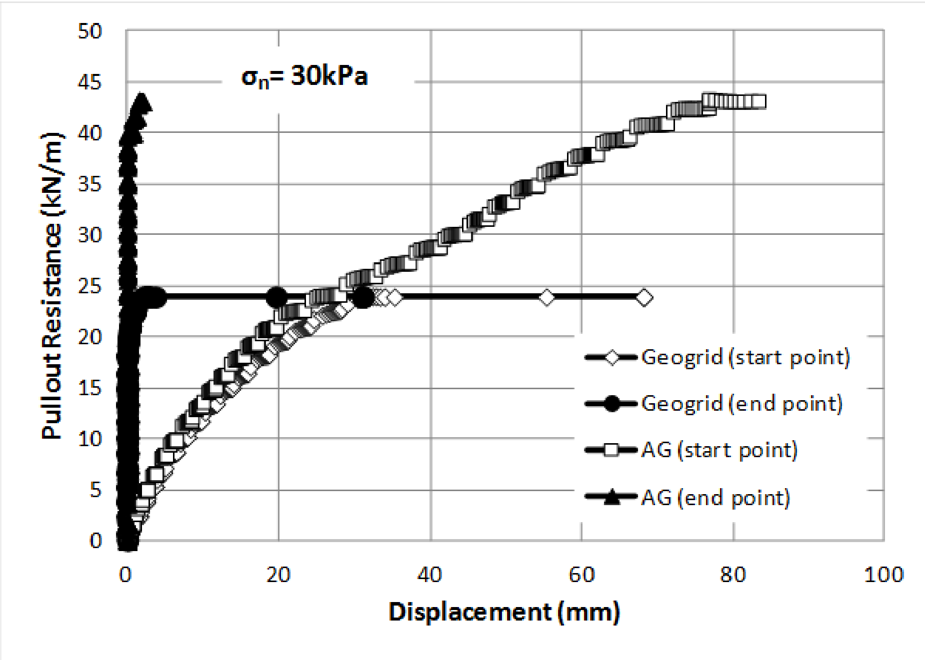

Figure 6. Comparing the beginning and end displacements of the ordinary geogrid system and the anchored geogrid system employing one transverse element (d = 8 cm), under an overburden pressure of 30 kPa

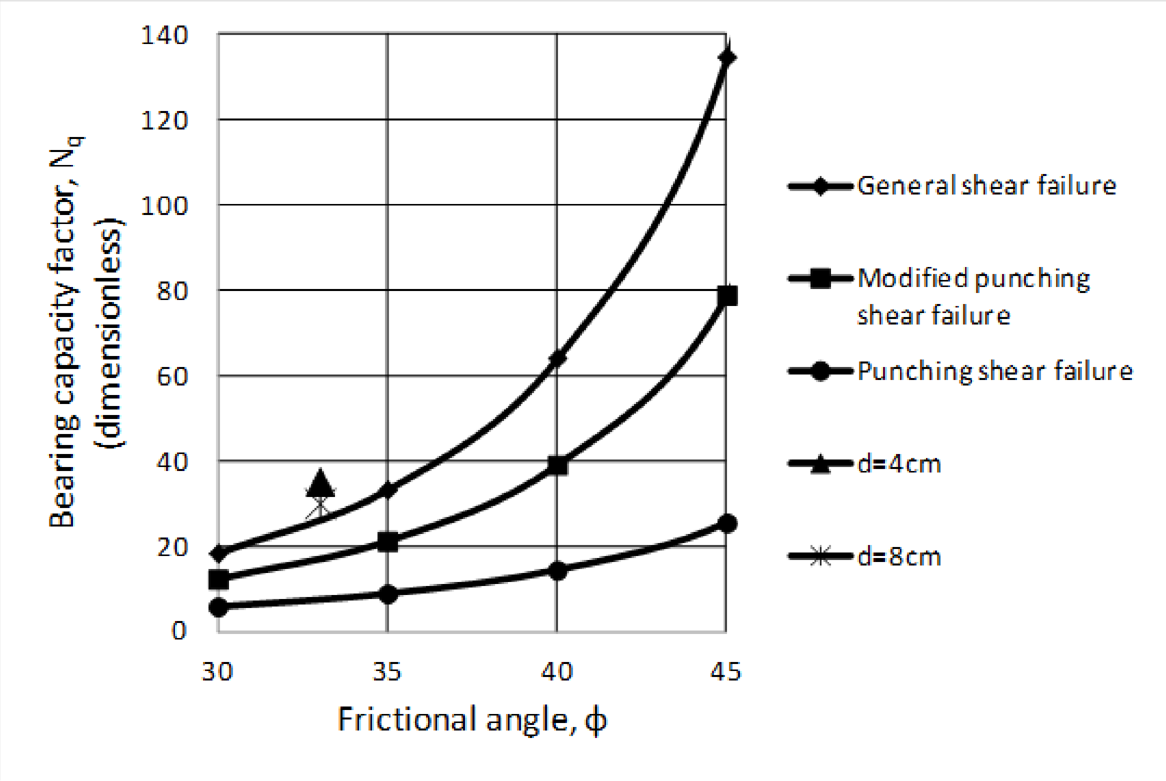

Figure 7. Comparison between measured and predicted bearing capacity factors (N_q)

The issue should be taken into account that, in the large-scale tests conducted on the AG system, complete pullout took place only under low overburden pressures (10 kPa) and when using transverse elements with depths of 40 or 80 mm. In other words, a pullout failure mechanism was formed against the transverse elements; thus, only in the above-mentioned measured amounts did it compare with the predicted amounts. To clarify, as can be seen in Fig. 6, the front and back ends displacements of both the ordinary geogrid and the AG system employing one transverse element of 80 mm depth, under an overburden pressure of 30 kPa. This figure shows that, by the end of the experiment on the ordinary geogrid system, the front and back ends of the geogrid showed displacements of 31 and 68 mm, respectively. Meanwhile, under equal circumstances, the beginning of the AG system reinforcement experienced about 90 mm of displacement, and the end was displaced only by 2 mm (almost negligible).

According to Fig. 7, a comparison of the results shows that the pullout failure mechanism governing the AG system embedded in poorly graded sand has an appropriate accordance with general shear failure. In general, although the displacement around the bearing elements of the AG system during the pullout process is three-dimensional, by using equation (3) — which is obtained based on the plane strain failure model — the effect of the three-dimensional process in this system can be indirectly taken into consideration. Thus, the equation for general shear failure can be used to predict the maximum bearing stress (σ_{bmax}) in compacted granular soil with small particles.

It should be noted that in order to evaluate σ_{bmax} took into account only the bearing resistance, and contribution of skin friction was ignored.

5. CONCLUSIONS

In this study, the performance of an innovative reinforcement system (AG) in the pullout mechanism was evaluated in relation to that of the ordinary geogrid system, using large-scale pullout tests. In addition, the pullout failure mechanism of this system, were evaluated, with results as follows:

- In general, due to the presence of rigid transverse elements, the anchored geogrid (AG) system has numerous advantages when compared to the traditional geogrid system, such as the increase in flexural rigidity and bearing resistance. The presence of the above-mentioned factors greatly improves the performance of the AG system in comparison to the ordinary geogrid system in the pullout mechanism.
- If in the AG system the depth of transverse elements and the overburden pressure are such that complete pullout takes place, the amount of soil dilation in this system compared to that of an ordinary geogrid system also increases, which in turn causes an increase in the interaction between the soil and the reinforcement, and consequently, the pullout resistance.
- If an AG system is made using even a single transverse element of the appropriate depth (d), this system will be capable of completely anchoring the end of the base geogrid in the soil in the pullout mechanism, until the predetermined displacement. In sum, in conditions where the internal stability of MSE walls with traditional geogrid is not satisfactory, with the use of an AG system, it would be possible to guarantee the internal stability of such walls under equal circumstances.
- Under low overburden pressure (10 kPa), the AG system is capable of increasing the ultimate pullout resistance to three times that of the ordinary geogrid system; by increasing the overburden pressure to 20 and 30 kPa, this amount will be reduced to 2.6 and 2, respectively.
- The comparison of the results showed that, in sandy soils with small particles, the maximum bearing stress (σ_{bmax}) of a single isolated transverse element could be predicted with suitable accuracy using the general shear failure equation.

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