Interaction behavior of soil and geogrid reinforcement

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ABSTRACT: Geogrid materials are frequently adopted as reinforcement to improve soil properties and geotechnical structural performance. One particular challenge facing engineers when designing soil reinforcement relates to the interface friction that is generated between soil and geogrid material. This aspect is not fully understood and current understanding is based on empirical data from laboratory pull-out interface tests. The objective of this paper is to investigate fundamental aspects of interface mechanics, evaluating the effect of parameters such as confining pressure, stiffness of reinforcement and transverse members of the geogrid stress to enhance design implementation. The research adopts a novel methodology of non-intrusive modelling using transparent soil in conjunction with laser aided imaging to visually observe soil geogrid interaction mechanics in a specially designed pull-out test apparatus.

Keywords: Soil reinforcement, soil-geogrid interaction, transparent soil, pull-out test, laser aided

1 INTRODUCTION

One of the more recent evolutions in the field of geotechnics is the use of geosynthetic materials as reinforcement to improve the shear resistance of soil to economically stabilize earth structures. Their application in engineering earthworks has increased significantly in recent years (Muller and Saathoff, 2015). When designing reinforced earth structures, a vital aspect is to understand the interaction between the reinforcement and the compacted soil as this governs the overall stability. The main function of the reinforcement is to redistribute the stresses within the soil structure in order to enhance the internal stability of the reinforced soil structure. The reinforcement generates tensile strain due to redistribution of internal stresses within the soil-reinforcement composite. The most common example of soil-geogrid interaction research is to investigate pull-out capacity. The uncertainty of interaction mechanics between soil and reinforcement has considerable impact on the ability to implement rigorous analytical solutions, or to assign suitable parameters for interface elements in numerical modelling. By using classical pull-out, previous researchers have indicated that the interface factors vary between 0.6 - 0.8 (FHWA-NHI-00-043, 2001); hence, it is likely that many designs over predict the possible resistance that may be generated. Furthermore, in the absence of field validation, there is considerable debate as to how representative small scale pull-out tests reflect the likely behaviour that would prevail in the prototype structure.

A novel approach described herein uses transparent soil, representative of coarse soil, which allows nonintrusive measurement of soil displacement on a plane highlighted by a sheet of laser light, captured by a digital camera. This enables the measurement of the displacement of the soil on the target plane by using the image process technique “Digital Image Correlation (DIC)’’. This technique allows the observation of the interaction between soil and geogrid, and the shear and pull-out boundary which is mobilised around the geogrid.

1.1 *Research aim*

The principal aim of this research is to investigate the detailed interaction between granular soil and geogrid and to provide a better understanding of the interaction both analytically and numerically. For achieving this aim, this research will adopt physical modelling using non-intrusive modelling techniques of transparent soil coupled with Particle Image Velocimetry (PIV). The purpose of using the transparent soil is to enable direct visualization of interaction mechanics during element pull-out tests between the soil and reinforcement material (Figure 1).

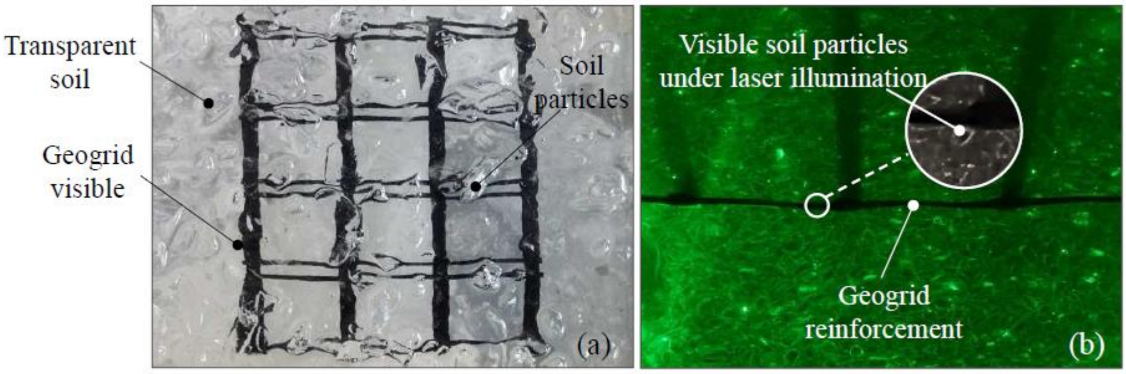


Figure 1. Photograph showing geogrid in transparent soil; (a) under natural light (plan view), (b) under laser illumination (side view).

2 PHYSICAL MODELLING

Interaction between soil and reinforcement can be evaluated using a pull-out box. British Standard and American Society for Testing Materials codes of practice outline such experiments (configuration and geometry) and note that these are influenced by the particle size of soil and side wall friction characteristics. While these classical testing methods offer the opportunity to evaluate ultimate pull-out capacity and determine an estimate of likely interface friction, they fail to offer any conclusive evidence as to the localised mechanics, zone of influence or interactions that govern the global response. For this reason a modified pull-out test system has been devised to enable internal visualisation of the soil and reinforcement.

Ezzein and Bathurst (2014) performed pull-out tests on transparent granular soils to quantify the interaction between soil and geogrid by using the non-contact measurement technology. In that research, the tracking process was achieved by painting fused quartz particles and embedding these particles in a single layer immediately above and below the geogrid specimen. High contrast marker indicators were also used along the geogrid to monitor progressive strain within the reinforcement during pull out. Ferreira and Zornberg (2015) presented a newly developed transparent pull-out test for evaluation of local soil-geogrid interaction under small displacement and strain using the procedures of Ezzein and Bathurst (2014). The current research adopts a similar methodology but extends this technique by introducing laser aided imaging to illuminate a cross section vertical plan within the soil, which reveals the outline of individual soil particles so that the soil-reinforcement interaction mechanics can be quantified. This technique gives an opportunity to visualise the movement of transparent soil particles at higher resolution over the whole cross sectional plane of interest and is not limited to only tracking individual soil particles as in previous studies.

2.1 *Test system development*

The test pull-out box with internal visualisation capabilities was designed in SolidWorks 3D to ensure full integration of components prior to fabrication. This paper presents a summary of this system and full details are presented in Tatari 2016 (Thesis). Each plate was constructed from 20 mm thick aluminium which was sufficiently stiff to minimise deflections/strain of the boundary under the proposed working stresses. The chamber was mounted on a base plate 730 mm in length and 300 mm in width. Vertical plates bolted to the base formed the box sides producing an internal sample dimension of the 500 mm (L) × 200 mm (W) × 200 mm (H). Each plate was anodised black to minimise laser light reflection. To observe the interaction performance of the soil and reinforcement during a pull-out event it was necessary to incorporate several Perspex windows into the box design. A viewing window 440 mm long × 140 mm high was incorporated into the front plate to enable visual observation of the exposed internal soil plane within the model. A strip window 440 mm long × 50 mm wide was incorporated into the base plate to enable the introduction of the laser illumination from (Figure 2). Fluid lines were also located on the base plate to enable filling of the test box from a header tank.

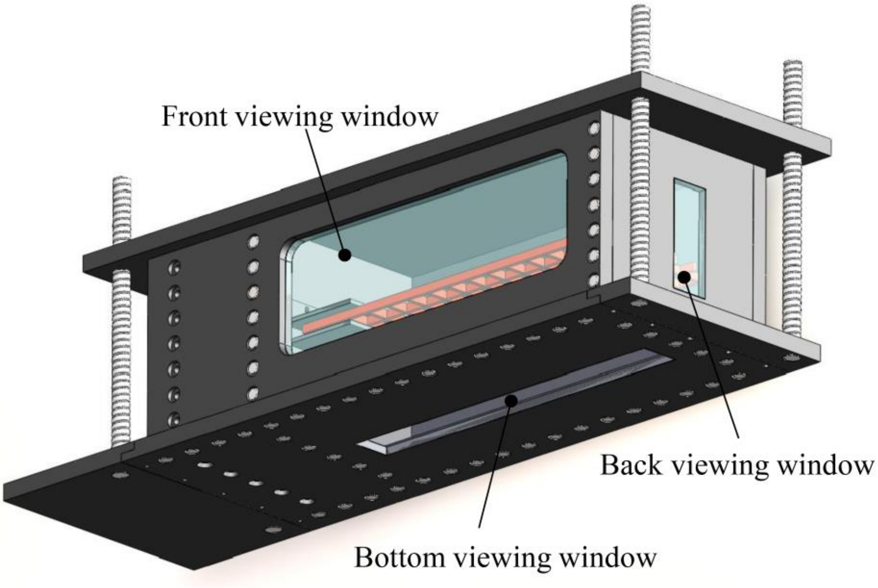


Figure 2. Location of three viewing windows in pull-out box

To simulate difference stress conditions at the soil-reinforcement interface it was necessary to apply vertical confining stress. After some consideration it was decided to apply the vertical stress via a flexible rubber membrane rather than a rigid plate, in accordance with recommendations by Palmeira and Milligan (1989). This would ensure that the applied stress was more uniform across the width of the sample and also prevent detrimental interaction effects with the chamber walls which would be more pronounced for a rigid boundary. To restrain the air bag a 20 mm thick aluminium plate was bolted to the top of the box so that it could be pressurised. The geogrid is placed in the mid-height of the box between the friction sleeves and secured using a clamping system. This clamping system was crucial to ensure that it was able to transfer the necessary pull-out force from the actuator to the reinforcement uniformly without local rupturing.

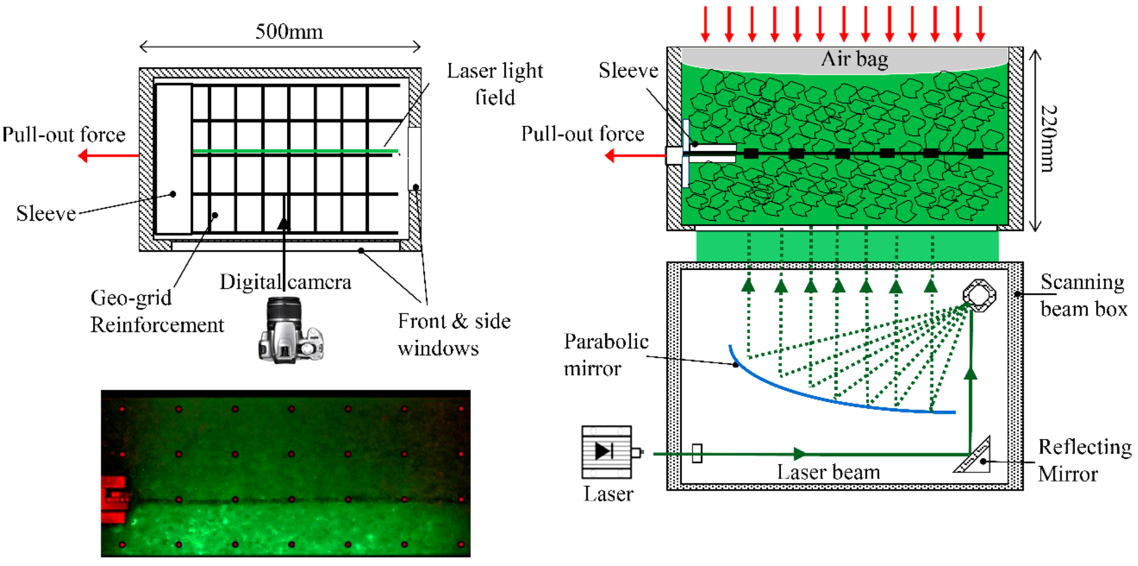
2.1.1 *Test methodology*

To investigate soil-reinforcement interaction mechanics laser aided imaging was used to illuminate a plane of interest within the soil volume. A digital camera captured images throughout the pull-out event from which the soil particle movement and hence interaction mechanics was derived. The test methodology illustrates in Figure 3.

The box was filled with crushed fused silica in 50mm layers from constant height with light compaction up to the mid-plane level where the geogrid was located. At this time the geogrid was prepared attaching it within the specially designed clamp system and inserted in the test chamber. The load ram was fixed, geogrid laid out along the soil surface and pulled taught to ensure a horizontal interface. Additional soil particles were placed and compacted to fill the upper portion of the chamber. The air-bag was located and the aluminum plate attached to seal the chamber. A crucial aspect when modelling with transparent soil is to ensure that the material is fully saturated as entrapped air diminishes optical transmission. To aid this process a vacuum was applied to the test chamber and optically matched pore fluid drawn into the chamber.

2.2 *Transparent soil material*

The transparent soil consists of fused silica aggregate which is mixed with two type of mineral oil, technical white oil (Foodlink 15 supplied by Lincol oil) and Paraffin (N-Paraffin C10 − C13 supplied by Aztec Oil) that are mixed at 80 : 20 ratio by volume, which have the same reflective index with fused silica. The fused silica is produced from high purity Quartz Sand was manufactured by Xuzhou New Hitech Silica Materials Co., Ltd in China. The size of soil particles is between 10-15 mm with the mean particle size (D_{50}) of 7.42 mm which is classified as GP according to the unified soil classification system. The coefficient of uniformity, C_u is 1.342 and the coefficient of curvature, C_c is 1.009. The aggregate has a shear friction angle of 47°. The dry unit weight of fused silica specimens is 12kN/m^3.



Plan view

Cross sectional view

Figure 3. Schematic pull-out test set up (after Tatari, 2014)

2.3 *Geogrid reinforcement*

The geogrid used in this research was selected in consideration of the nominal average particle size of the soil that could be sourced. Reflecting on literature (Lopes and Lopes, 1999) the geogrid aperture size needs to be considerably larger than the soil particles to allow the particles to embed in between the apertures to mobilise the passive resistance in the bearing members. The biaxial geogrid used in this research is identified as Fortrac® R150/30-30 which is manufactured by HUESKER Synthetic GmbH Company. The nominal specifications of the geogrid are presented in Table 1.

Table 1. Geogrid material properties of Fortrac® R150/30-30 (from manufacture's website)

Property		**Type or value**
Raw Material, Coating		PET, Polymer
Coating		Polymer
Weight (EN ISO 9864)		~600g/m^2
Ultimate tensile strength (EN ISO 10.319)		
	Longitudinal	≥150kN/m
	Transversal	≥30kN/m
Strain at nominal tensile strength (EN ISO 10.319)		
	Longitudinal	≤12.5%
Stiffness		~ 1200kN/m
Mesh size		30×30 mm

3 IMAGE PROCESSING

Digital photography and digital image correlation (DIC) methods are used to observe the interaction between soil-reinforcement. White et al. (2003) developed an in-house code for image correlation referred to as "GeoPIV'' based on DIC that utilizes variation in soil texture for tracking soil displacement in geotechnical application. GeoPIV is a MATLAB^{TM} module that implements particle image velocimetry in a manner suited to geotechnical testing (White et al 2003). This method is suitable for measuring planar displacements of any textured plane surface.

Images were captured using a Canon EOS 1100D single lens reflex (SLR) with an 18-55mm lens. During the test, the camera was mounted on a camera bracket at a distance of 1.0 m from the front of the test chamber and was triggered at regular intervals. Image analysis was conducted using GeoPIV (White et al.

2003) at a 100 pixel patch size that yielded a standard error of 0.001 pixels, which is comparable to the precision quoted by White et al. (2003).

4 RESULTS

The pull-out resistance of a geogrid is a combination of skin friction which is generated by soil passing over soil, and over geogrid members and the bearing resistance of transverse ribs (Jewell, 1996). However, the mechanism of interaction between the soil and geogrid depends on several factors such as soil type and size of soil particles, density of soil, geometry of geogrid, strength, stiffness and surface roughness of the geogrid (Palmeira, 2009). This paper introduces a novel test methodology suitable to evaluate the interaction behavior between soil and geogrid that may provide new understanding to enrich our understanding. Results presented herein are to demonstrate the capability of the new test facility and offer some preliminary insight of the additional understanding that can be generated. Three trial pull out tests were conducted at three confining pressures of 12.5 kPa, 25 kPa and 50 kPa, mobilized up to 40mm applied displacement. The load-displacement response of the geogrid are presented in Figure 4.

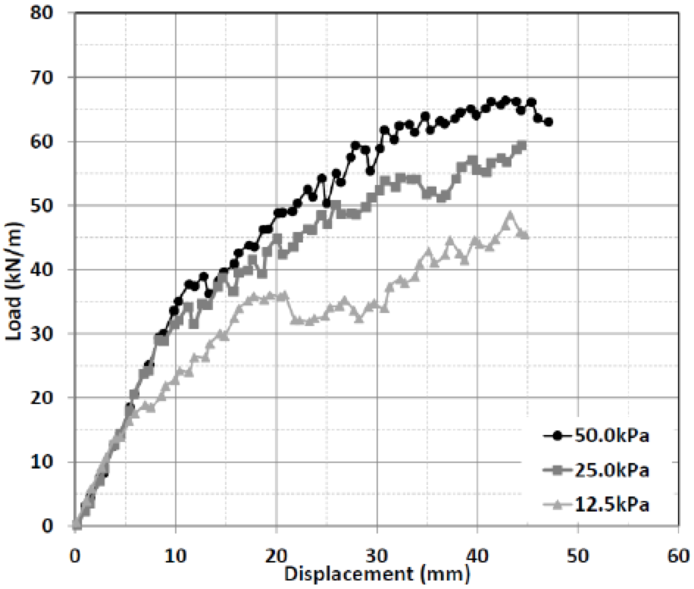


Figure 4. Load-displacement plots of geogrid specimen

The results of the tests are presented in Figure 4 which reflect the traditional load-displacement information that can be gained from pull out tests. An initial elastic region up to 5mm displacement is observed beyond which variable pullout capacities are recorded. As with many pull out test scenarios, the reinforcement was not anchored; hence the early behaviour observed reflects pre-tensioning of the reinforcement before mobilization of interface resistances. Images captured confirmed this pre-straining of the reinforcement prior to soil pull out. As expected increased confinement yielded increased pull out capacity, and it is on this basis that interaction coefficients are derived; without any other validation of the test performance. In the revised test system, the images of real time visualization of the interface have been analyzed to reveal horizontal displacement of soil particles at each aperture location from the clamp system along the length of the geogrid as showed in Figure 5. The results show that a large horizontal displacement of soil particles is consistently apparent adjacent to the geogrid location with the largest displacement along the horizontal line of pull out of the geogrid, diminishing with distance away from the reinforcement. On this basis a zone of influence can be defined as 4 to 5.5 times the D_{50} of the soil. Maximum soil displacement was observed to correspond to the transverse rib positions which confirms the frictional interaction. The magnitude of the horizontal displacement of the soil particles has an inverse relation to the amount of confining pressure. By increasing the confining pressure the interlock between soil particles is increased so that the movement of soil particles by sliding, shearing or rotation is restricted more than at lower confinement.

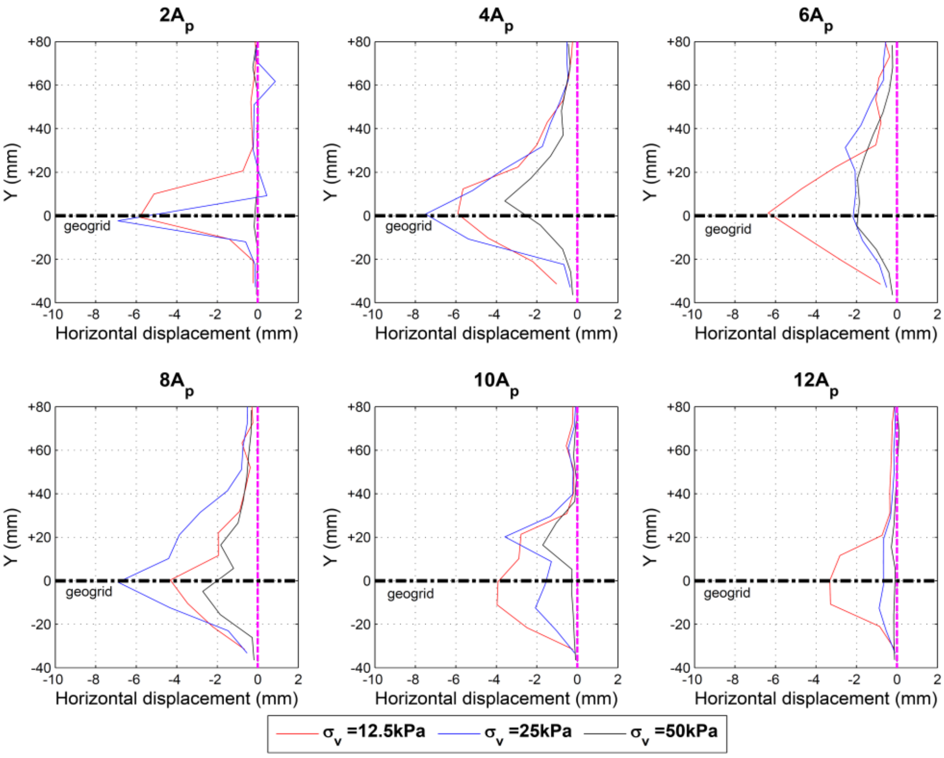


Figure 5. Comparison of the horizontal displacement of soil particles at end of the test under different confining pressures for different distances from the clamp (A_p: aperture size of geogrid)

Figure 5 also provides preliminary insight as to the mobilization of resistance along the reinforcement whereby it is clearly observed that the level of soil movement reduces with distance from the clamp position where the pull out force is applied. This observation confirms that different levels of strain occur across the geogrid and that some areas may be near rupture, however additional resistance is not utilized. Due to these observations, additional work is underway to investigate the influence of pre-tensioning and the uniformity of resistance mobilized in the reinforcement.

5 CONCLUSION

- A novel new test system has been established, enabling internal observation of soil-reinforcement interaction that will enable transformative insight of interaction mechanics.
- Larger horizontal displacement of soil particles is consistently apparent adjacent to the geogrid location with the largest displacement concentrated near the rib positions.
- The magnitude of dilation is greater near to the goegried. As the interlock between soil particles and the geogrid’s apertures is greater, but the soil particles beyond the shear bond have a lower interlock so particles simply shear over each other.
- The results show the boundary of the zone of influence of the geogrid was observed to be at a distance from the interface of 4 to 5.5 times the D_{50} of the soil. The soil particles beyond the zone of influence has less than %5 of the movement of the soil which happens adjacent to the geogrid.

ACKNOWLEDGEMENTS

The work reported herein was conducted at the University of Sheffield. Support from the technical staff in the Department of Civil and Structural Engineering to develop the test system is gratefully acknowledged. The authors wish to acknowledge the support of HUESKER Synthetic GmbH Company who provided the geogrid material for this research.

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