Development of a geosynthetic pullout test apparatus with transparent granular soil

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ABSTRACT
The paper describes the development of a transparent granular soil, pullout box apparatus and test methodology that can be used to investigate soil-geosynthetic interaction during pullout. The transparent soil is made of fused quartz particles in combination with a transparent fluid with the same refractive index. The pullout box has a glass bottom and the transparent granular soil allows photographs of the embedded geosynthetic specimen to be taken during the test. In this paper, image analysis is then performed on the photographs using the particle imaging velocimetry (PIV) technique. Axial displacements and strains are computed at locations along the length of a geogrid pullout specimen. These measurements are shown to provide quantitative insight into reinforcement-soil load transfer.

RÉSUMÉ
Cet article décrit le développement d'un sol granulaire transparent, d'un appareil d'essai d'arrachement et d'une méthodologie d'essai qui peut être utilisé pour l'étude de l'interaction sol-géosynthétique lors de l'arrachement. Le sol transparent est composé de particules de quartz fondu combiné à un liquide transparent ayant le même indice de réfraction. La boite d'arrachement est munie d'un fond en verre et le sol transparent permet la prise de photos du géosynthétique encastré durant l'essai à travers le fond du banc d'essai. L'analyse d'image est réalisée sur une séquence de photos avec la technique de vélocimétrie d'imagerie des particules. Dans cet article, la méthodologie est démontrée en calculant les déplacements axiaux et les déformations à certains endroits le long d'un échantillon de géogrille soumis à l'arrachement. On montre que ces mesures portent un éclairage quantitatif sur le transfert de charge entre le sol et la géogrille.

1 INTRODUCTION

Geosynthetic reinforced soil walls, slopes and embankments are now mature applications in geotechnical engineering. Nevertheless, the mechanisms of soil-geosynthetic interaction are not fully understood for polymeric (geosynthetic) soil reinforcement products such as geogrids and geotextiles. The most familiar example of soil-reinforcement interaction is the design for adequate pullout capacity in the anchorage zone of a reinforced soil wall structure. This lack of knowledge is particularly pressing for accurate numerical modelling of the interaction between polymeric (extensible) soil reinforcement products and the surrounding soil in which these materials are placed. In most cases modellers have assumed a perfect bond between the reinforcement and confining soil in numerical simulations of reinforced soil walls, slopes and embankments (e.g. Huang et al. 2009). This approach offers simplicity but there is evidence that load transfer is highly non-linear with tensile load level, confining pressure and location along the length of the reinforcement (Huang and Bathurst 2009).

A common approach to quantify soil-geosynthetic anchorage capacity is to use a pullout box apparatus. The design and operation of these devices is now standardized in methods of test such as ASTM D 6706 (2007). However, a limitation of this type of equipment is the incomplete measurement of the in-situ displacement and strain response of the extensible polymeric reinforcement products (e.g. geogrids) while embedded in soil. Detailed displacement measurements are necessary to understand soil-geogrid interaction mechanisms and as a precursor to the development of advanced interface models. Typically, a limited number of extensometer points are attached to the reinforcement specimen and the extensometer wires taken out the back of the pullout box to displacement measuring devices. The extensometer points may distort the displacements that develop in-situ and give only limited information on displacement and strain distributions along the length of the reinforcement, particularly for extensible geosynthetic materials (e.g. geogrids). In some cases strain gauges have been bonded directly to the geosynthetic reinforcement. However, these devices typically create a hard spot that requires special calibration to convert measured strains to global axial strains in the reinforcement (Bathurst et al. 2002).

A strategy to overcome the problems identified above is to use a pullout box with a transparent Plexiglas bottom and a transparent soil. Transparent soils for laboratory geotechnical testing are not new (e.g. Iskander 2010; Sadek et al. 2002). Early attempts at transparent soils used crushed glass or glass beads in combination with a matching fluid with the same refractive index. However, porous media using glass beads are translucent rather than transparent and they do not represent the geotechnical properties of natural granular soil. Better success has been achieved by matching transparent solid silica powder or a silica gel medium with a colourless pore fluid having the same refractive index. The use of precipitated and flumed silica powder and silica gel beads to manufacture transparent model clay and sand has also been described in the literature. However, transparent silica gel beads can deform

plastically under low confining pressure, are difficult to de-air due to internal particle voids, and can become coloured with time.

This paper describes the successful development of a novel pullout box apparatus that is used in conjunction with a transparent granular soil. The paper describes the silica sand (fused quartz) material that was found to have sufficient hardness and chemical durability to simulate the properties of typical sand. A specially formulated transparent fluid was developed that has the same refractive index as the fused quartz particles but at the same time is not volatile or pose a potential health hazard in the laboratory. The resulting soil-fluid mixture is transparent. When placed in the pullout box with an embedded geogrid specimen, the geogrid is visible through the transparent bottom of the box. The displacements of a geogrid placed in the transparent soil are computed from sequential digital images taken by a row of synchronized cameras located below the pullout box. Digital processing is carried out using PIV software. This is the first time that this experimental approach has been reported in the literature for sand-geogrid systems. The paper describes the transparent soil, pullout box, image capture and processing, and illustrates the experimental approach with example data.

2 TRANSPARENT SOIL

2.1 Materials

The granular particle constituent of the transparent soil is a commercially available crushed fused quartz which is a non-crystalline (glass) form of silicon dioxide (SiO_2) quartz sand. The material is manufactured by melting natural quartz crystals present in quartzite sand at approximately 2000°C, and then cooling. Heating causes the crystals within the quartz to become fused together and to be non-porous. The fused quartz particles are impermeable and non-absorbing to most fluids. They are angular, hard and fracture resistant, chemically resistant and have good optical transmission. The material used in this investigation is equivalent to a coarse poorly graded sand designated as SP according to the Unified Soil Classification System (D_{50} = 1.68 mm, C_c = 0.68 and C_u = 2.04).

The transparent fluid was prepared by mixing two clear mineral oil fluids together. One of the oil fluids has a refractive index greater than the fused quartz and the other a refractive index value which is less. By adjusting the mix the resulting fluid can be designed to have the same refractive index as the quartz (1.4586 at 22 ^{o}C). The mineral oils are the principle ingredients used in baby oil and similar pharmaceutical products. The resulting mixture is non-toxic, non-volatile, colourless, stable and odourless. The final mixture of oil has a viscosity of 10 centistokes which means that this fluid is 10 times more viscous than water.

Figure 1 shows the granular particles in a dry (opaque state) and transparent after inundation with the matching mineral oil fluid. The background pattern at the left of the photograph is an image representing a geogrid at a distance of 50 mm behind the front wall of the Plexiglas container.

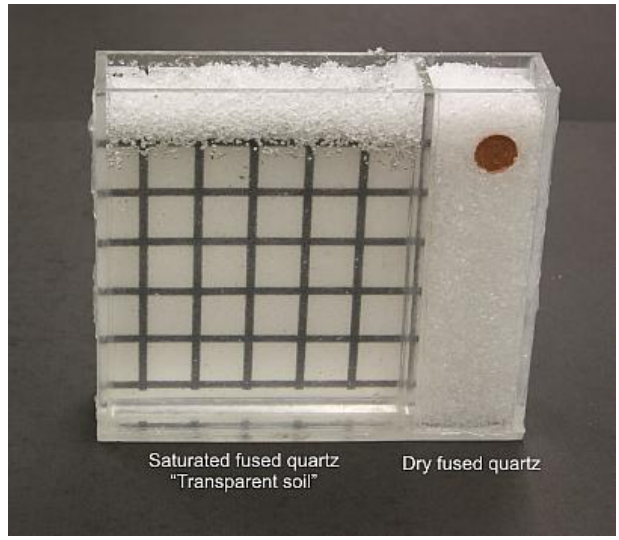


Figure 1. Photograph showing fused quartz in dry state (right) and inundated with mineral oil with matching refractive index (left). Note copper coin for scale

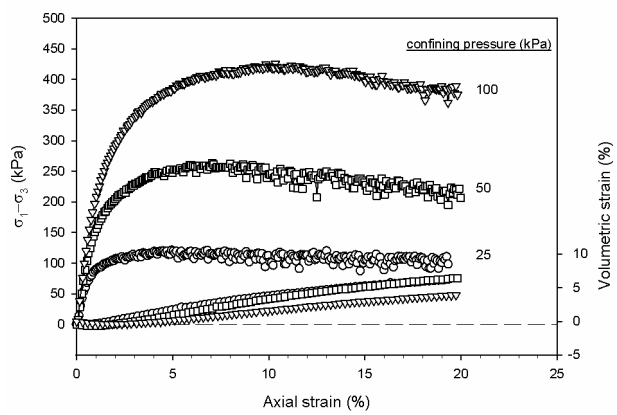


Figure 2. Stress-strain plots from triaxial compression testing of fused quartz-mineral oil mixture prepared to 95% relative compaction

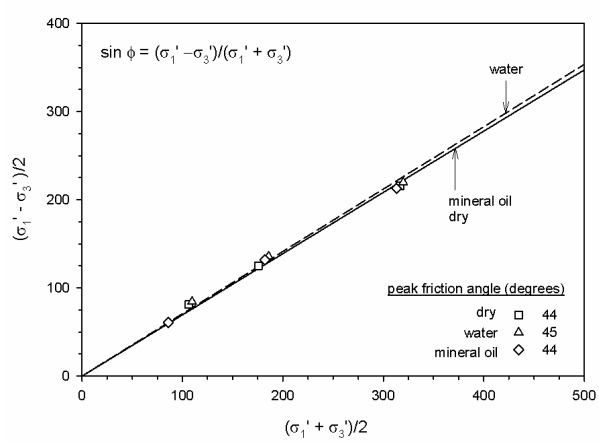


Figure 3. Strength envelopes from triaxial compression testing of coarse fused quartz in dry state and with different pore fluids

2.2 Geotechnical properties

A program of laboratory testing was carried out to quantify the geotechnical properties of the transparent soil and to compare these properties with natural sand materials (Ezzein and Bathurst 2011). The tests included particle size analysis, compaction testing, direct shear box testing, triaxial compression testing and one-dimensional compression tests. Due to space constraints only selected test results are reported here.

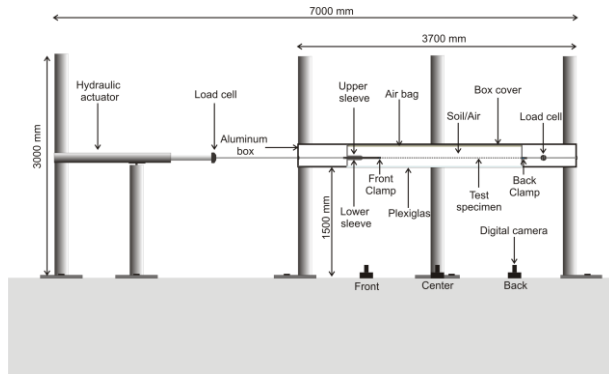
Proctor compaction tests performed on this narrow-graded material showed that it has a flat compaction curve. This is an advantage since it means that density control of the as-placed material is not an issue. Figure 2 shows the results of conventional triaxial compression testing carried out on specimens of coarse fused quartz fully saturated with mineral oil. The qualitative trends and quantitative values for stress-strain and volumetric strain versus axial strain plots are judged to be typical of dense sands. Triaxial compression tests were also carried out at axial displacement rates of 0.5 to 5% strain/min to detect (if any) the influence of mineral pore fluid viscosity on stress-strain response. The differences were insignificant. Hence, for the very low rates of axial loading used in the pullout test program described later, the influence of oil pore fluid viscosity on test results is judged to be negligible. Linear strength envelopes fitted to results of conventional triaxial tests on fused quartz specimens in a dry state and with mineral oil and water pore fluid are summarized in Figure 3. This figure shows that there is no practical difference in the effective shear strength of the soil based on pore content. Direct shear box tests also demonstrated that regardless of pore volume type (air or fluid), the material behaved as a dilatant granular material with post-peak strain softening. One-dimensional compression tests were carried out on fused quartz specimens and these confirmed that the 1-D compression modulus of the material was typical of natural sand and that particle breakage was negligible for the sand in both a dry state and fully saturated with mineral oil.

In summary, the transparent soil described here is a satisfactory analogue to natural angular sand soils prepared in dry or water saturated conditions.

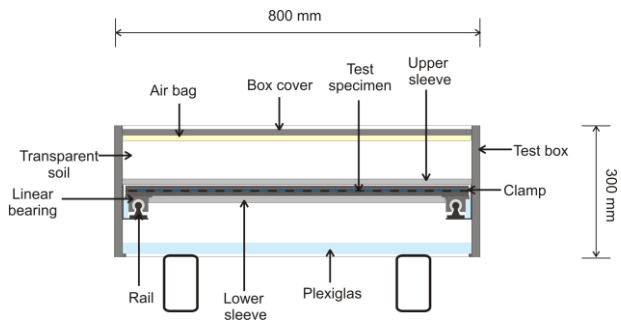
3 PULLOUT BOX APPARATUS AND ANCILLARY EQUIPMENT

3.1 General

The general arrangement of the pullout box test apparatus is illustrated in Figure 4. A photograph of the pullout box and ancillary equipment is shown in the photograph in Figure 5. The pullout box is 3700 mm in length, by 800 mm wide by 300 mm high. The box is made of 13 mm-thick aluminum plate with a central 2400 mm long viewing area in the bottom made of 25 mm-thick clear Plexiglas. The box is supported by a stiff steel frame and elevated 1500 mm above the floor to provide working space below the apparatus and adequate field of view for the cameras. The steel frame is bolted to the laboratory strong floor and was designed to be very stiff to prevent



a) cross-section view



b) front view

Figure 4. General arrangement of pullout box

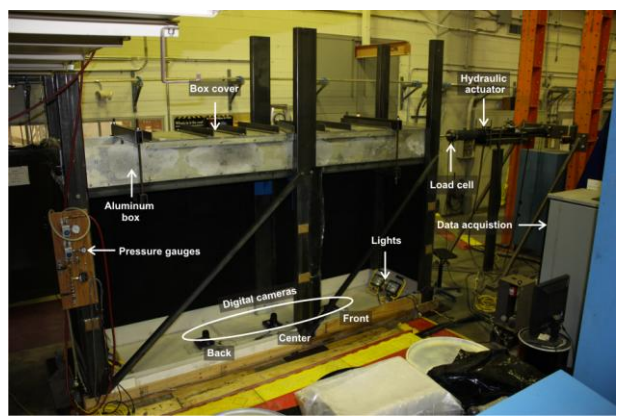


Figure 5. Photograph of pullout box test facility

longitudinal deformations of the box during axial loading of the test specimen.

The test specimen (e.g. geogrid) is located at about mid-depth in the box and clamped at both ends. The specimen can be loaded in tension while in air or embedded in (transparent) soil. The front clamp is attached to a rod which in turn is connected to a hydraulic actuator. The computer-controlled MTS hydraulic actuator includes a 50 kN-capacity load cell that is used to record axial load at the front end of the geosynthetic test specimen and an internal linear-variable differential transformer (LVDT) to monitor axial displacement. The opposite end of the test specimen is attached to a fixed (back) clamp attached to a rod connected to a load cell.

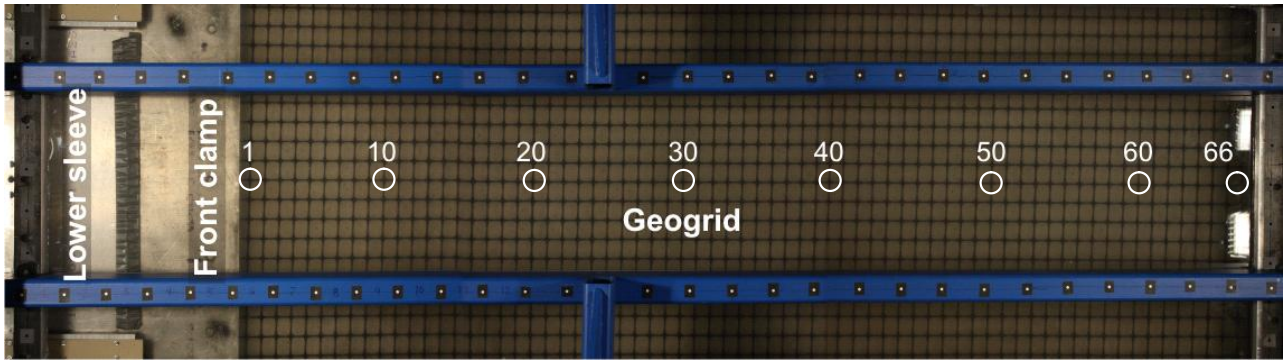


Figure 6. Image of geogrid test specimen and example PIV targets taken through the transparent soil from below the pullout box

The opposite end of the load cell is attached to a rod which is bolted to the end of the pullout box. This arrangement can provide some of the axial reaction to the test specimen as it is pulled forward at the actuator end.

For tests carried out with transparent soil the entire 3700 mm length of the box is flooded with mineral oil.

The transparent soil can be surcharged by an airbag placed on the top surface of the soil and reacting against a 13 mm-thick aluminum cover plate. The bag is inflated pneumatically to simulate overburden pressures as great as 100 kPa. The box cover plate is secured by a system of angle bars and threaded rods that are self-reacting with the pullout box.

The Plexiglas plate at the bottom of the box is supported by a pair of 51 by 102 mm hollow rectangular steel sections running the length of the apparatus (Figure 4b).

3.2 Front clamp

The front clamp is 500 mm in length and 750 mm wide and is made up of two 13 mm-thick aluminum plates that are bolted together. The inside surfaces of the plates have a matching pair of 50 mm-wide bevelled grooves to receive the end of the test specimen which is cast into a strip of resin. The clamp is supported by a pair of frictionless linear bearings to maintain clamp alignment (Figure 4b). A 19 mm-diameter stainless steel rod connects the clamp to the load cell at the front end of the hydraulic actuator. The rod passes through a fluid-tight bushing at the front end of the pullout box to prevent escape of mineral oil.

To minimize the effect of soil and front wall interactions on test results, the front clamp passes between two 13 mm-thick aluminum plates forming a sleeve with bevelled front ends as recommended by ASTM D 6706 (2007). The sleeves extend 200 mm into the soil zone and are rigidly bolted to the pullout box prior to testing. At the start of a test with soil, the front clamp extends 200 mm past the sleeve into the soil volume. A 2 mm-gap between the clamp and the sleeve allows for free movement of the clamp within the sleeves. Soft rubber strips are secured permanently over the ends of the sleeves to prevent sand particles from becoming jammed in the space between the front clamp and the sleeves.

3.3 Image capture, calibration and data acquisition

Three digital cameras are located below the Plexiglas viewing window and along the longitudinal centerline of the pullout box (Figure 4a, 5). The cameras are CANON EOS Digital REBEL XSi single-lens reflex (SLR) model type. During a test the cameras are synchronized to capture images of the test specimen at intervals during a pullout test. Figure 6 shows the three images spliced together to capture the entire length of the test specimen between the front and end clamps. By using three cameras rather than one camera (with a longer focal length and greater field of view), the resolution of each single image is greater.

Image calibration using a calibration sheet is required first in order to associate image coordinates with a set of physical co-ordinates using a scale factor. The calibration sheet is made of 0.1 mm-thick white adhesive vinyl glued to a 19 mm-thick clear Plexiglas plate. The vinyl sheet was printed with a high-precision square grid of 5 mm-diameter black dots on 50 mm centers.

A commercial software package called PIVview 2C (PIVView; PivTec GmbH, Gottingen, Germany) was used to perform the image analysis which involved tracking groups of pixels at target locations on the geogrid and then converting these movements to displacements.

4 TEST METHODOLOGY

In this paper the test methodology is demonstrated by describing a typical pullout test on a specimen of punched drawn biaxial polypropylene (PP) geogrid. The specimen is 2100 mm long by 750 mm wide.

4.1 Test preparation

The first step in the experimental method is to prepare the two ends of the geogrid at the front and end clamps. The geogrid ends are slotted into the grooved openings mentioned earlier. The ends are sealed and the clamps used as a form into which a two-part resin is poured. The cured resin provides a continuous hardened bar to uniformly transfer tensile load from the specimen to the end clamps.

The entire box is flooded with mineral oil in depth increments of 25 mm. The fused quartz is pluviated into each layer of mineral oil over the inside of the pullout box above the viewing area. Air bubbles are allowed to rise out of the oil prior to placement of the next layer to ensure that the granular soil is 100% saturated. Each layer is hand tamped using a steel plate. After 100 mm of soil has been placed, the surface of the granular soil is carefully levelled and the calibration sheet is placed at the same location (elevation) as the test specimen. Calibration images are taken and the calibration sheet is then removed. The test specimen with the two end clamps attached is then placed over the granular surface and the top front sleeve secured in place. A small axial preload is put on the specimen to remove any warps in the specimen prior to placing the soil cover. The incremental flooding and pluviation of the granular soil is then continued in 25 mm lifts until there is about 150 mm of transparent soil cover above the geogrid specimen.

Once all the transparent soil is in place a lubricated polyethylene sheet is placed over the granular soil surface followed by a nonwoven geotextile and the airbag described earlier. The sheet and geotextile are used as a friction-reducing liner at the top boundary of the soil-geogrid system. Finally, the restrained self-reacting top cover of the pullout box is secured in place.

4.2 Test procedure

The airbag located at the top surface of the soil is inflated to a pressure corresponding to a target depth of soil cover. The data acquisition system used to record load cells and LVDT readings is turned on and the front clamp is advanced at a constant rate of displacement (e.g. 1 mm/minute matching the recommended rate according to the ASTM D 6706 (2007) method of test). The three cameras below the pullout box are triggered simultaneously with the data acquisition readings. This ensures that data taken from image processing are synchronized with test specimen boundary loads and displacements. The rate of data capture in the example test was once every 15 seconds but much higher rates are possible with the cameras and data acquisition equipment.

5 RESULTS

In the example test described here the airbag was not pressurized. Hence, the overburden pressure was due only to the thin 150 mm depth of soil placed over the geogrid specimen. The tensile loads measured at the front and back clamps versus displacement at the front clamp are shown in Figure 7. The plot shows that there is a difference of 3.2 kN in axial load recorded at the ends of the specimen which means that there is load transfer between the geogrid and the surrounding soil. To extract displacement data corresponding to locations between the clamps (i.e. in the soil) PIV image analysis was performed on sequential images from each camera and then the displacement values from each camera field of view concatenated together. The displacements are obtained by tracking square patches made up of 32 x 32 pixels. At the focal length used to capture these images

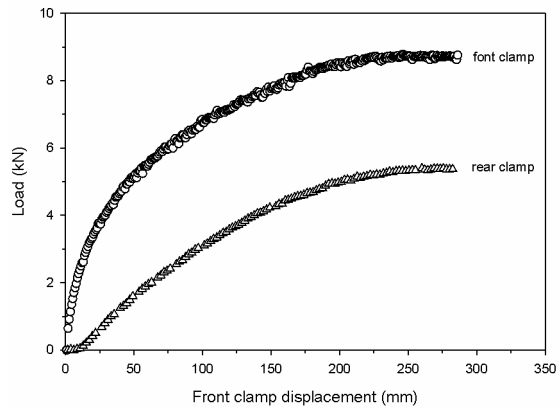


Figure 7. Tensile load at front and back clamps versus displacement measured at the front clamp

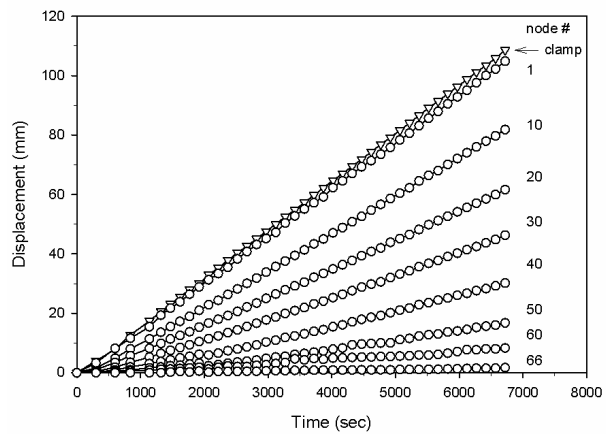


Figure 8. Longitudinal displacements of example nodes during pullout

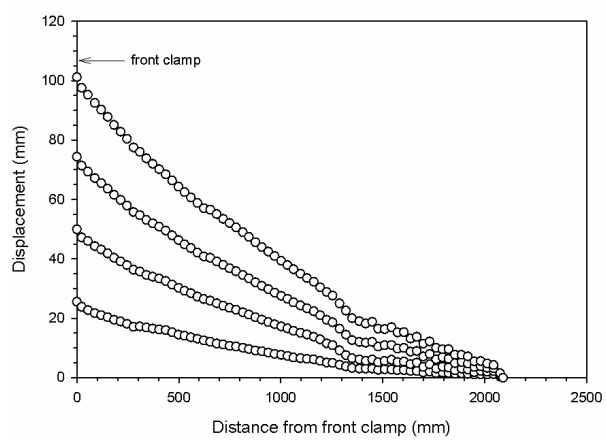


Figure 9. Displacement profiles along length of geogrid reinforcement specimen

the size of a pixel corresponds to 0.26 mm in object space.

Patch tracking was carried out at locations along selected longitudinal member junctions. Example patch numbers are illustrated in Figure 6. The displacements recorded at each of these locations with time are plotted in Figure 8. The data plots show that the extensible geogrid does not move as a uniform sheet. The same data can be re-plotted in the form of displacement profiles as presented in Figure 9 and strains in Figure 10. The non-linear curves in these last two figures illustrate that the magnitudes of longitudinal displacements and strains vary with distance from the front of the clamp. This is consistent with the load transfer to the surrounding granular soil deduced from Figure 7.

6 CONCLUSIONS

This paper describes a novel transparent granular soil and its use to quantify soil-geogrid interaction using the non-contact PIV technique.

The transparent sand soil described in this paper has advantages over other analogue granular soils reported in the literature, particularly sands manufactured with silica gel beads. Some of the major advantages include:

a) Particles are hard with negligible breakage in oil and do not deform plastically under loading.
b) Particles do not contain internal air voids that can make de-airing difficult.
c) Particles do not react chemically with or absorb the oil pore fluid.
d) The refractive index and transparency of the colorless oil is stable with time.
e) The oil fluid is odourless, non-toxic, has low volatility and high ignition temperature which make it an ideal pore fluid in a laboratory environment.
f) Clear visible depth of 120 mm (coarse fused quartz) when placed in a container made of 25 mm-thick Plexiglas.
g) The fused quartz material and mineral oils are inexpensive.

The transparent soil described in this study offers a wide range of opportunities as an artificial soil in geotechnical laboratory testing focused on granular soil-structure interaction problems and fluid flow in porous media. An example of the use of this material to study infiltration of surface fluid into a column of soil has been reported by co-workers at RMC (Siemens et al. 2010).

To the best of knowledge of the writers this is the first time that this material has been used in combination with a large pullout box to capture soil-geogrid interaction in plan view. The pullout box apparatus and experimental technique described in this paper is now being used to study the soil-structure interaction of a wide range of polymeric and metallic grid materials during pullout.

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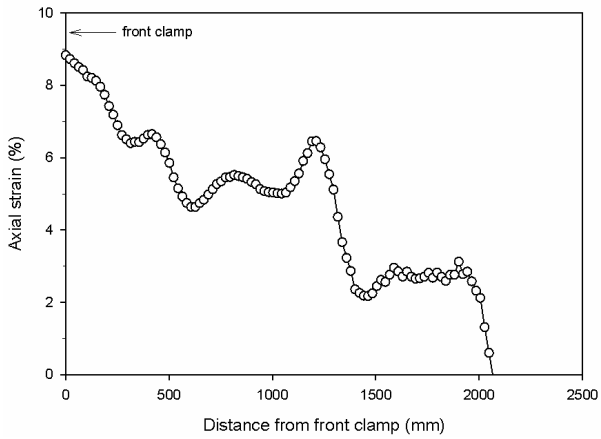

Figure 10. Tensile strain versus distance from the front clamp

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