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Development of a Large-scale Universal Apparatus for Testing Geosynthetic-Soil Systems

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Abstract: In this paper, design and calibration procedures for a new large-scale testing apparatus for testing geosynthetic-soil systems are described. The multiple functionalities of the apparatus are implemented through the use of a single loading frame, driving mechanism, instrumentation, and data acquisition system for three distinct modes of loading: pullout, direct shear, and uniaxial loading. The design is similar to a conventional pullout device, but also includes key modifications and additional modules to adapt it for additional types of experiments. For example, in the uniaxial tension configuration, extension rods are used to transfer the load from the driving mechanism to the mounted specimen. In the direct shear configuration, the bottom half of the shear box is allowed to slide horizontally on low friction roller bearings while connected to the driving mechanism, whereas the top half of the box is fixed. Hydraulic jacks and a steel plate are used to apply the normal pressure in the pullout and direct shear configuration. A series of pullout experiments were performed to validate the functionality of the apparatus and to examine the relationship between the geometry of the geogrid opening and its pullout resistance.

Keywords: geosynthetics, pullout, direct shear, apparatus design.

INTRODUCTION

The response of mechanically stabilized earth (MSE) walls and other reinforced soil structures is mostly dependent on the properties of the reinforcement elements as well as the interaction between these elements and the surrounding soil. In recent years, the use of geogrids as reinforcement elements in MSE structures has gained considerable popularity worldwide due to their low cost, satisfactory performance, and ease of placement during construction. Laboratory tests for determining the mechanical properties of geogrids and geogrid-soil interfaces have emerged and evolved rapidly over the past twenty years or so to keep up with the pace of implementation of geosynthetics in soil reinforcement application. In the United States, the American Society of Testing and Materials (ASTM) has adopted more than 100 standard practices and testing methods related to geosynthetics. In parallel, the need has grown for laboratory equipment capable of performing a wide array of related tests. Among the various standard methods for geosynthetics, three classes of tests are relevant to geogrid and geogrid-soil systems: uniaxial tension, direct shear, and pullout. Specifically, the behavior of geogrids and geogrid-soil systems is addressed in six corresponding ASTM standard methods D 5262-04, D 5321-02, D 6638-01, D 6637-01, D 6706-01, and D 6992-03.A universal large-scale testing apparatus was designed and constructed to conduct a wide array of tests that encompass four of the six geogrid-related standard tests, and can be easily adapted to perform the remaining two. The apparatus was assembled and is housed at the National Research Centre in Cairo, Egypt, where it was calibrated and evaluated through a pilot laboratory testing program. While a number of geosynthetic testing devices have been documented in the literature (e.g., Fannin and Raju 1993; Farrag *et al.,* 1993; Rowe *et al.,* 1989; Wilson-Fahmy *et al.,* 1994), they all serve individual testing functions. To this end, the new apparatus is unique in its universal functionality and modular design, which makes it adaptable to accommodate the various types of experiments.

Review of Earlier Designs:

Various researchers have developed large scale apparatuses to measure soils-geogrid interface properties. Figure (1) illustrates the apparatus located at the University of British Coloumbia, Canada. Fannin and Raju (1993) used this apparatus to perform pullout tests on a uniaxial geogrid embedded in uniformly graded

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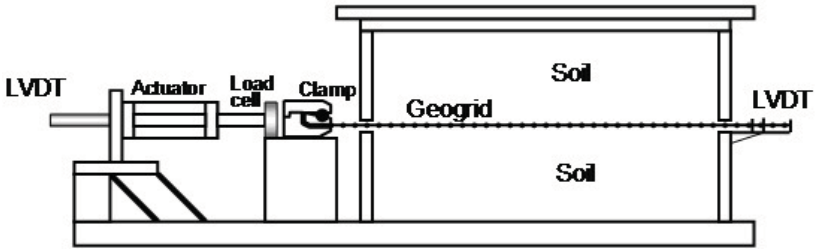


Fig. 1: Schematic illustration of the apparatus located at the University of British Columbia, Canada (after Fannin and Raju, 1993)

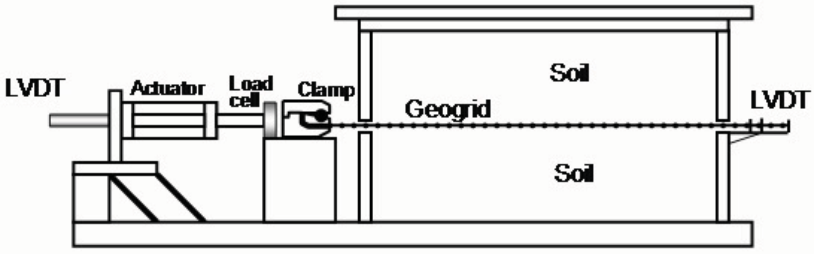


Fig. 2: Schematic illustration of the apparatus located at Kyushu University, Japan (after Ochiai et al 1996)

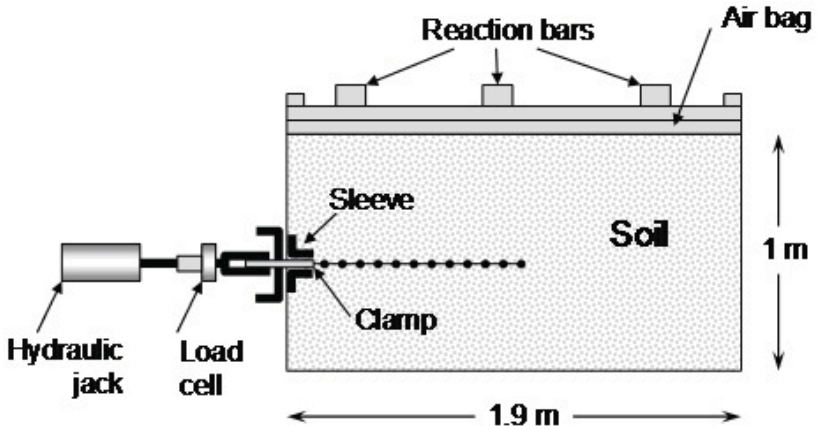


Fig. 3: Schematic illustration of the apparatus located at Drexel University (after Wilson-Fahmy et al 1994)

coarse grained angular sand. The apparatus has internal dimensions of 1.30m×0.64m×0.60m for length, width, and depth, respectively. The clamping system is comprised of three parts - a lower jaw, an upper jaw, and a central insert connected to the actuator by a swivel connector. The normal stresses are applied using a flexible water bag, while the pullout force is applied using a hydraulic system consisting of a pump, several pressure valves, and a double acting actuator. The pullout force is measured using a load cell, and the surcharge pressure is measured using a water pressure transducer. The displacements of the free and clamped ends of the sheet are measured using two displacement transducers. The strains along the specimen are measured using five strain gauges mounted along the centerline of the specimen.

Figure 2 shows the pullout test located at Kyushu University, Japan (Ochiai *et al.,* 1996). The pullout box is smaller than that shown in Fig. 1, with internal dimensions of 0.60m×0.40m×0.40m for length, width, and height, respectively. Unlike the apparatus described by Fannin and Raju (1993), the normal stress is applied here using an air pressure bag at the top of the box, whereas the pullout force is applied using a screw jack with a constant speed of 1.0 mm/min. A load cell attached to the clamping system is used to measure the pullout load. Displacements along the geogrid were measured using stainless-steel wires (telltales) attached to the grid junctions and connected to dial gages secured outside of the pullout box. The apparatus located at

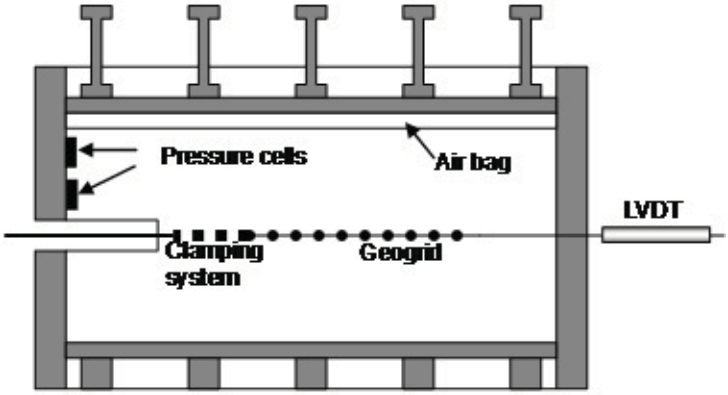


Fig. 4: Schematic illustration of the apparatus located GERL, Louisiana (after Farrag *et al* 1993)

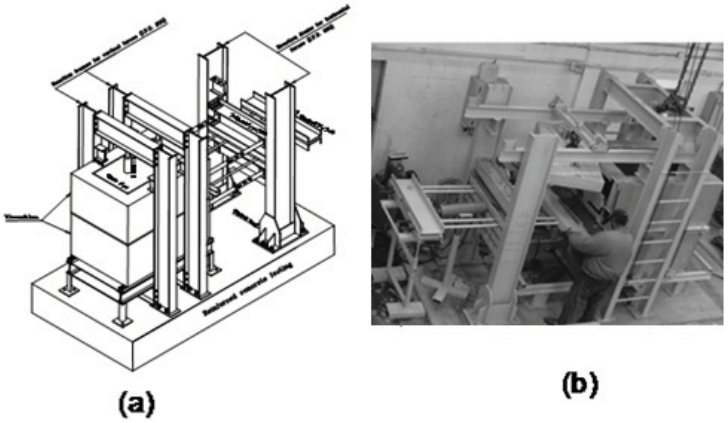


Fig. 5: (a) Isometric view of the back, and (b) photograph showing the front of the new universal NRC apparatus.

Drexel University in Philadelphia (Wilson-Fahmy *et al.,* 1994) is larger in size, with internal dimensions of 1.90m×0.91m×1.10m (Fig. 3). The normal stress is applied using an air pressure bag, and the pullout forced is applied using a manually operated hydraulic jack of 110kN maximum capacity. The pullout force is measured using a load cell 45kN in capacity, attached to a readout unit, while the displacements were tracked via dial gauges and steel wires shielded in copper tubing, attached at the geogrid junctions.

Farrag *et al.,* (1993) presented results from pullout tests conducted on the apparatus located at the Geosynthetics Engineering Research Laboratory (GERL), in Louisiana. The inner dimensions of the box are 1.52m×0.90m×0.76m, as shown in Fig. 4. The method of application of the normal stress and pullout force are the same as those of the Drexel apparatus. Among the unique features of the GERL apparatus is that the tests can be performed under either displacement or load control modes. In contrast to other devices, the clamping system in this apparatus extends inside the soil in order to minimize the potential for extension and failure of the unconfined geogrid near the clamps outside the box. The pullout force is measured using a load cell attached to the clamping system, while the displacement of the clamping system at the front of the geogrid are measured using LVDT's. The displacements along the geogrid are measured using five telltales connected to LVDT's placed at the rear of the box. In addition, pressure transducers are placed on the inside of the front wall to measure the lateral earth pressure exerted on the wall.

Other designs of apparatuses for measuring the geosynthetic-soil interface properties have been reported in the literature. For instance, Lopes and Ladeira (1996a; 1996b) described the design of a pullout apparatus similar to those described earlier, and used it to study the effect of boundary and initial conditions on the interface properties. Kharchafi and Dysli (1993) described a simple apparatus, which was used to study the interaction and failure mechanisms along the soil-geosynthetic interface via X-ray imaging. Fox *et al.,* (1997) designed and evaluated a large scale device capable of measuring interface properties in a pullout-double shear

mode. By and large, all these apparatuses were designed to operate in a single mode of loading, whether it be pullout or direct shear.

Description of the New Universal Apparatus:

The design of the new apparatus supersedes earlier designs in its adaptability to various loading and boundary conditions, thereby eliminating the need for multiple equipment, driving mechanisms, and data acquisition systems. The apparatus is configurable both in terms of hardware and software to allow the performance of geosynthetic pullout tests, soil-geosynthetic direct shear tests, and uniaxial tension tests. In addition, the apparatus can be configured to serve as a large-scale direct shear apparatus for testing the shear strength of gravel, stone, and municipal solid waste. The apparatus is currently assembled and operates at the Pilot Plant Laboratory of the National Research Centre (NRC) in Cairo, Egypt. A rigid reinforced concrete footing, 4.2m long, 2.0m wide, and 0.5m deep, was built to support the apparatus. The backbone of the NRC apparatus is comprised of five main components:

- A steel box-frame, herein called the *main box*, split horizontally along the middle, in which the soil is compacted and the geosynthetic sheet are placed
- A overhead reaction frame to enable the application of vertical forces and normal stresses
- An upright reaction frame for applying horizontal pullout and uniaxial tension forces
- An overhead crane system to handle the top-loading of the materials and to assist in the apparatus assembly, and
- A rail system at the bottom to enable the bottom half of the main box to slide horizontally in the direct shear mode.
- Each of the components is fully described next, and detailed drawings are presented to assist with the description. Figures 5a and 5b show an isometric view for the new universal NRC apparatus.

Main Box:

The main box, in which the soil and geosynthetic specimens are placed, has inner dimensions of 1.20m×0.70m×1.16m for length, width, and height, respectively. It is split horizontally, at its mid-height, into two halves – upper and lower. The walls of the lower half consist of a grid of 200mm I-beams (IPN No. 200) capped at their top level by IPN-200 channels to create a flat horizontal surface (Fig. 6). The inner surface of the box is created by lining the I-beam and channels with steel plates of 6mm thick, while the outer surface of the box is covered with galvanized steel plates 2mm thick. The inner dimensions of the lower half are 1.20m×0.70m×0.48m in length, width, and height, respectively. Similarly, the walls of the upper half of the main box are constructed of a grid of I-beams and channels lined with steel plates on both the inside and outside. The inner dimensions of the upper half are 1.20m×0.70m×0.63m.The upper half of the box can slide relative to the lower half by virtue of six low friction roller bearings – three on either side – equally spaced along the side walls of the box (Fig 7a). The roller bearings, 140mm in diameter, are mounted on smooth axles onto the bottom half of the main box, and are embedded into grooves on the top half to guide the movement of the box during shear. In its assembled configuration, a vertical gap of 40mm is maintained between the top and bottom halves of the box, but the gap can be readjusted by changing the diameter of the roller bearings. This assembly of rollers and grooves is herein called *the intermediate bearing system*. A similar system, attached at the bottom level of the lower half of the box and mounted on steel rails, is referred to as *the lower bearing system*. The role of the intermediate and lower bearing systems is to allow the bottom half of the main box to slide relative to the top during direct shear testing. Alternatively, the top and bottom halves of the main box can be rigidly interconnected using bolts distributed along the sides as shown in Fig. 7a.

Reaction Frame for the Vertical Forces:

Two adjacent reaction frames (Fig 5a) are designed to resist the reaction from the vertical hydraulic jacks, which are used to apply vertical forces or normal pressures on the soil. This normal pressure is transferred to the soil by means of a rigid steel plate, herein called the *top plate*, which is placed on the soil surface prior to loading. The advantages and limitations of using such a rigid plate as opposed to an air bag are discussed later. Each frame consists of two columns bolted to the foundations and braced together using four IPN-200 beams. Forty-eight high strength steel bolts, 16mm in diameter, are used to assemble the two frames. The vertical reaction frames are designed to resist a vertical force of 200 kN, equally divided among each frame. Two IPN-200 brackets, each 300mm in length, are welded to the frames for the crane serviceability.

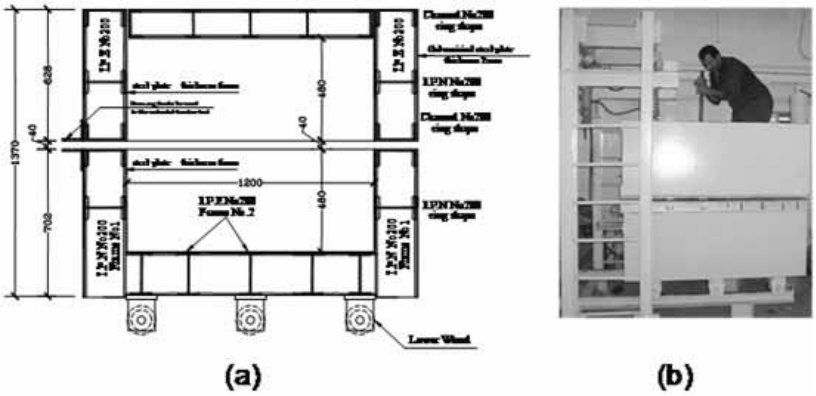


Fig. 6: (a) Elevation cross section, and (b) photograph showing the elevation view of the new universal NRC apparatus.

Fig. 7: (a) Intermediate bearing system with the bolts rigidly connecting the top and bottom halves of the main box, and (b) the lower bearing system.

Reaction Frame for the Horizontal Forces:

A reaction frame is designed to resist a 250-kN horizontal force exerted from a horizontal jack. It consists of two IPN-320 columns fixed at the base bolted to the foundation and braced laterally by three beams. Two of the bracing beams – the intermediate and lower – are fabricated of a built-up section, each consisting of two IPN-260 channels back to back with a gap of 40mm. The third (upper) bracing beam is made of a built-up section of two IPN-200 channels back to back. The purpose of the upper and lower beams is to provide a fixing support and a horizontal reaction for the upper and lower halves of the main box during uniaxial tension and pullout tests. Four steel pipes, each with an outer diameter of 70mm and a thickness of 10mm, are used to support the top and bottom halves of the box during uniaxial tension and pullout tests. The pipes are connected at one end to the main box and at the other end to the reaction frame. The purpose of the middle beam, located between the two columns, is to resist the reaction from the horizontal jack during application of the horizontal force in pullout tests. Both the lower, and the middle beams are connected to the steel columns using eight 16-mm bolts at both ends. Two IPN-200 brackets, 300mm in length each, are welded to the reaction frame for crane serviceability.

The Crane System:

The purpose of the crane system is multifold. First, it serves as a hoisting mechanism for the top plate while the sample is being prepared (see Fig. 8). Second, it is used to lift the top half of the main box during maintenance of the intermediate rolling system. Third, it can be used to lift large quantities of soil during sample preparation and dismantling. The crane system has the ability to move along the apparatus on an elevated steel rail, and provides a maximum lifting capacity of 10 kN.

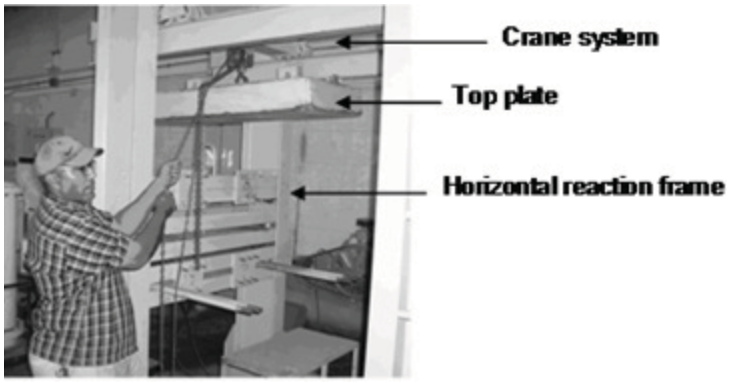


Fig. 8: The crane system, in use by a lab technician, for lifting the top plate.

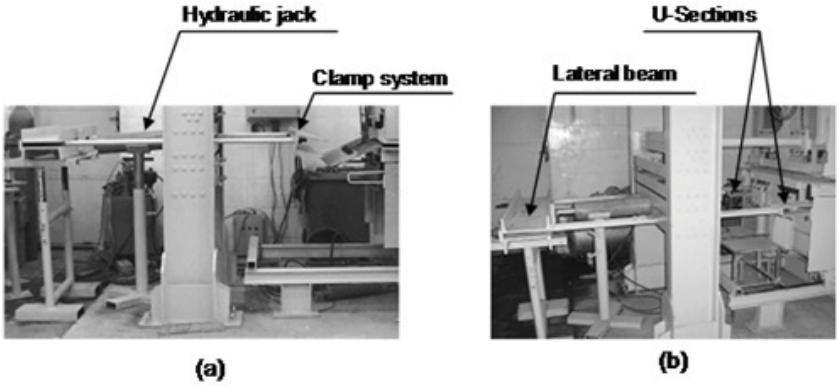


Fig. 9: Photographs showing the horizontal loading system during (a) pullout testing and (b) direct shear testing.

Loading System of the Universal Apparatus:

Loading in the new apparatus is applied via a hydraulic pump attached to hydraulic jacks. The hydraulic system is capable of applying a normal stress of 230 kPa, which simulates an overburden pressure roughly equivalent to an embankment/wall height of 12 m. The maximum horizontal force is 250 kN, which, based on the dimensions of the apparatus and the maximum normal stress, corresponds to a friction angle close to 55° in the direct shear test mode.

The Vertical Loading System:

To achieve the required normal stress on the soil, two hydraulic jacks, each 100 kN in capacity, are used. Each jack reacts against the reaction frame and transfers the load to the soil through the rigid top plate. The plate consists of a grid of IPN-140 I-beams capped at the top and the bottom by two steel plates 6mm thick. The rigidity of the upper plate was designed to ensure transfer of the two concentrated loads from the hydraulic jacks into a distributed normal stress on the soil. A pressure valve is used to control the pressure supplied to the jacks from the hydraulic pump.

The Horizontal Loading System:

To apply the horizontal force, a 250 kN horizontal jack is used. In the pullout and uniaxial loading modes, the force is transferred to the geogrid through four steel rods, each 25-mm in diameter, attached to the horizontal jack using a lateral beam. The four steel rods are connected to the geogrid clamping system on the other end.The same technique is used to transfer the horizontal force to the lower half of the main box during direct shear testing, but in this case the horizontal jack and the front beam are transferred to the lower beam of the reaction frame prior to testing. The front clamping system of the sample is replaced by two U-sections attached to the lower half of the main box at its mid height by eight 20-mm bolts. The steel rods are then

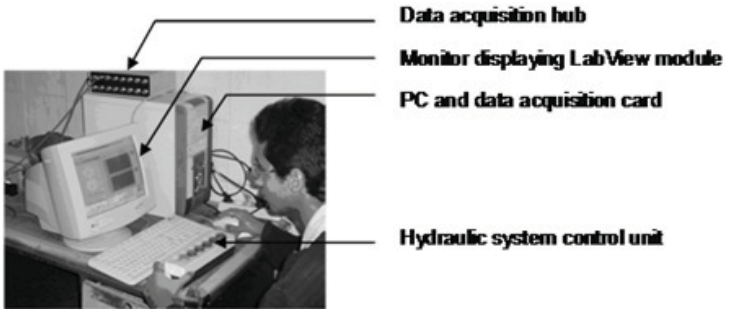


Fig. 10: Data acquisition and control system.

fixed to the two U-sections to transfer the load from the hydraulic jack to the lower half of the main box.The horizontal displacement rate of the horizontal hydraulic jack is between 10 and 60 mm/min and can be changed by adjusting the pressure valve. Figure 9 shows an elevation view of the horizontal loading system during pullout and direct shear.

The Clamping Systems:

For pullout tests, the geogrid sample is attached at the front end to a clamping system that is referred to herein as the *front clamping system*. In the case of uniaxial tension tests, in addition to the front clamping system, the geogrid is attached to the back of the main box using the *rear clamping system*.

The Front Clamping Sytem:

The front clamping system consists of two steel plates, each 6mm thick, sandwiching the geogrid sample via eighty-four bolts, each 4mm in diameter, to prevent slippage of the sample. In addition, both steel plates have rough inner surfaces to increase the interface friction between the sample and the steel plates and to reduce stress concentrations. The two steel plates are attached to a U-section through six 20mm bolts. The load is transmitted to this clamping system via the four 25mm diameter steel rods, as explained earlier.

The Rear Clamping System:

The rear clamping system consists of a fixed clamp, to be used only during uniaxial tension tests. It consists of two steel plates with inner rough surfaces attached to the sample in a manner similar to the front clamps, and bolted to two steel angles fixed on the inside of the main box via six 20mm bolts.

Instrumentation and Data Acquisition:

Two pressure sensors, one attached to the vertical loading system and the other to the horizontal loading system, are used to measure the pressure in the vertical and the horizontal jacks. Two displacement transducers (LVDTs) are used to measure the displacement at two different positions on the tested specimen. The LVDTs are connected to the specimen using telltale wires which are encased in small-diameter steel pipes, which act as protective sleeves to allow the wires to move freely without interference with the surrounding soil during the tests. The pressure sensors and the LVDTs are attached to an electronic data acquisition system consisting of a National Instruments^{TM} data acquisition card, a personal computer, and a customized LabView^{TM} software module, as shown in Fig. 10. The current apparatus configuration does not yet al.,low electronic control of the hydraulic pressure from the personal computer. Instead, control of the loads applied by the hydraulic jacks is achieved through a manual control unit (Fig. 10). An upgrade to the apparatus is currently underway for full automation of the system controls through the PC interface.

Tests Configurations:

The apparatus can be configured to perform three types of tests: uniaxial tension, pullout, and direct shear. Each test mode is performed with slight modifications in the apparatus setup. In this section, detailed descriptions of the steps required to perform each test are presented.

Uniaxial Tension Test:

Uniaxial tension tests are performed on geosynthetic specimens to measure their maximum tensile strength and elongation, in addition to other mechanical properties such as yield stress and creep behavior. Figure 11

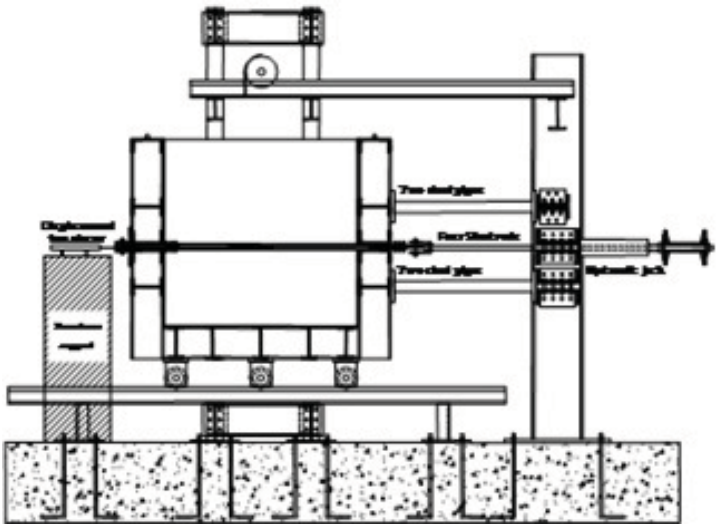


Fig. 11: Schematic of the apparatus during uniaxial tension.

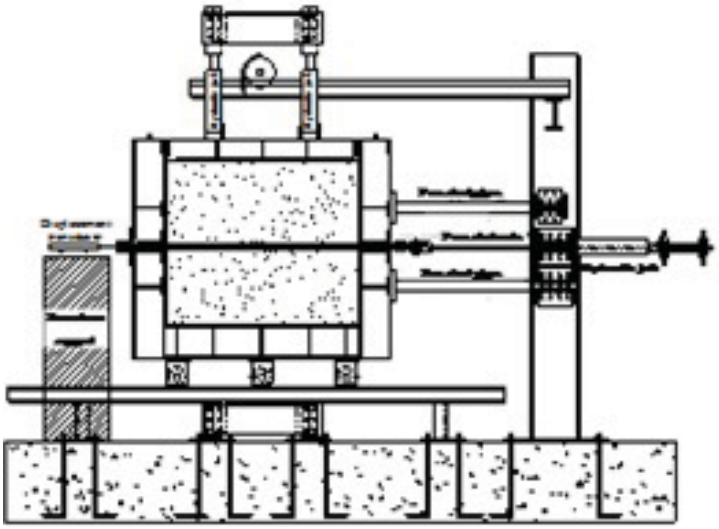


Fig. 12: Schematic of the apparatus during pullout testing.

shows a schematic of the apparatus during a uniaxial tension test. The steps required to perform the test are as follows:

- A sample of the tested geogrid (geosynthetic) sheet is prepared to the required dimensions.
- The sample in fixed onto both the front and the rear clamping plates. These plates have inner rough surfaces to prevent slippage of the tested specimen.
- The upper half of the main box is lifted using the crane system, and the lower half is pulled from underneath the reaction frame along the lower bearing system.
- The sample is secured in place using the front and rear clamping systems.
- The LVDT and telltales are attached at the required positions onto the geosynthetic specimen.
- The horizontal jack is attached to the middle horizontal beam of the reaction frame.
- The lower half of the main box is returned to its initial position underneath the reaction frame. The upper half of the main box may also be lowered onto the lower half.
- The four steel pipes are bolted to the main box to prevent any movement during application of the horizontal load.

- The four steel rods are bolted to the front clamp system (U-section) and the front beam.
- The pressure transducers and the LVDTs are connected to the data acquisition system and the test is initiated by applying uniaxial tension to the geosynthetic through the hydraulic jack.

Pullout Test:

In this configuration, the geosynthetic specimen – typically a geogrid – is embedded in soil and pulled while subjected to a normal stress. The measured pullout force is used to determine the soils/geogrid interface shear parameters. Figure 12 shows the final setup of the apparatus during the pullout test. The steps required to perform the test are as follows:

- The geogrid sample is prepared to the required dimensions (1.0m long × 0.6m wide is recommended for this apparatus). Telltale wires are connected to the geogrid at the specified locations.
- The sample is fixed to the roughened sides of the front clamping steel plates.
- The upper half of the main box is lifted using the crane system and the lower half is moved outward on the lower bearing system.
- The soil is compacted into the bottom half of the main box in two layers, each 0.25m thick. Quality control of the density can be performed using one of two methods: i) a predetermined weight of dry soil is compacted to the specified height, thus achieving the required density, or ii) nondestructive density tests are performed on each compacted layer to measure the actual density in place.
- The geogrid sample is placed on top of the soil filling the bottom half of the main box.
- Telltales attached to the geogrid are slipped into the protecting sleeves and connected to the corresponding LVDTs.
- The lower part of the main box is moved back to its initial position on the bottom steel rails. The upper half of the main box is lowered to its original position, that is, resting on the lower half and separated from it by the intermediate bearing system.
- The top and bottom halves of the main box are bolted together to prevent relative sliding.
- The soil is filled up and compacted in two layers, 0.25m each, onto the top half of the main box. The top plate is lowered on top of the soil using the crane system.
- The horizontal jack is placed along the middle horizontal beam in the reaction frame, and the vertical jacks are placed in their respective locations on the top plate.
- The four steel pipes are bolted in place to prevent the main box (both parts) from moving during application of the horizontal pullout load.
- The four steel rods are connected to the front clamping system and the front beam which is, in turn, attached to the hydraulic jack.
- The pressure transducers and the LVDTs are connected to the data acquisition system and the test is initiated by applying the normal stress to the top of the soil via the vertical hydraulic jacks. The pullout load is then applied through the horizontal loading system.

Direct Shear Test:

This test configuration can be implemented either on a soil-geosynthetic interface subjected to a normal stress to determine interface shear parameters, or in a soil-only setting as in a conventional direct shear test on soil. The soil-only setting has been very useful in testing large-diameter soils including well-graded sandy gravel. Figure 13 illustrates the final setup of the apparatus for direct shear testing. The steps required to perform a direct shear test are described next:

- The upper half of the main box is lifted using the crane system. The lower half is moved outward on the lower bearing system.
- Depending on the type of direct shear test, one of two possible scenarios is followed:
- For direct shear testing on soil only, the soil is compacted in two layers, each 0.25m thick, using the same procedure described above for pullout testing.
- For direct shear testing on soil-geosynthetic interface, a geosynthetic sample is glued or stretched onto a 1.19m × 0.69m wooden or steel board. The dimensions of the geosynthetic sample must be larger than the board in order to fold around the edges of the board. A series of spacers are placed in the bottom half of the box, and the board is placed on top so that it is flush in level with the edge of the bottom half of the main box. The board onto which the geosynthetic fits snuggly into the main box, and can be locked into the bottom half of the box using a special steel angle mechanism.

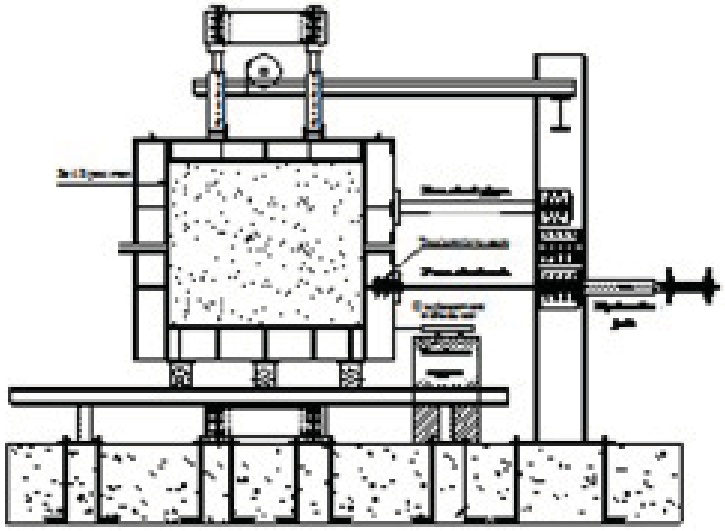


Fig. 13: Schematic of the apparatus during direct shear testing.

- The lower half of the main box is returned back to its initial position. The top half of the main box is lowered back on top of the bottom half, separated only by the intermediate bearing system. The two halves of the main box are temporarily bolted to prevent relative sliding during soil compaction.
- Compaction of the soil is continued in two layers, each 0.25m thick, and the top plate is lowered in place using the crane system.
- The horizontal jack is attached along the lower horizontal beam of the reaction frame, and the vertical jacks are placed into position on the top plate.
- The two upper steel pipes are bolted onto the top half of the main box and the reaction frame to prevent lateral movement of the top plate during testing. The two lower steel pipes are not connected to the bottom half of the box in this configuration.
- The four steel rods are connected to the clamping system (U-sections) attached to the lower part of the main box.
- The LVDTs are connected to the front of the lower part of the main box. The pressure transducers and the LVDTs are connected to the data acquisition system and the test is initiated by applying the normal stress to the top of the soil via the vertical hydraulic jacks. Direct shear loading is then applied through the horizontal loading system.

Calibration, Maintenance and Performance Evaluation:

A calibration was performed on the apparatus to measure the influence of the friction in the intermediate and lower bearing systems on the applied force. It is worth noting that during apparatus assembly and initial operation, with the two boxes full of soil, one person could easily push the boxes on the bottom bearing system. However, to accurately determine the effect of friction of the rolling system on the results, direct shear test was conducted, with no soil in the boxes. The normal stress on the rolling systems was simulated by the weight of the boxes, and the horizontal force was applied using the horizontal hydraulic jack. Based on several trials, the friction in the rolling systems was found to be a maximum of 3% of the normal stress. This implies that the rolling systems consumes no more than 3% of the pulling force during the direct shear tests. This percentage should be reduced from the measured pulling force to accurately determine the shear stress acting on the soils. In the case of uniaxial testing and pullout this reduction does not apply since no rolling occurs.

Calibration of the LVDTs, pressure sensors, and hydraulic system was also performed using manufacturer recommended procedures. The calibration constants were incorporated into the data acquisition software. Regular apparatus maintenance is essential for data accuracy and reproducibility. The most important maintenance components are:

- thorough cleaning of the apparatus after each test using water in order to remove soil residues
- Periodic lubrication of roller bearings using a special grease and viscous oil. This maintenance item is performed before each test.

Table 1: Geometry of HDPE geogrids used in this study.

Sample	Opening width (*b*)mm	Opening length (*h*)mm	Rib width (*w*)mm
A	100	100	30
B	60	60	25
C	50	100	25
D	30	100	20
E	45	45	17

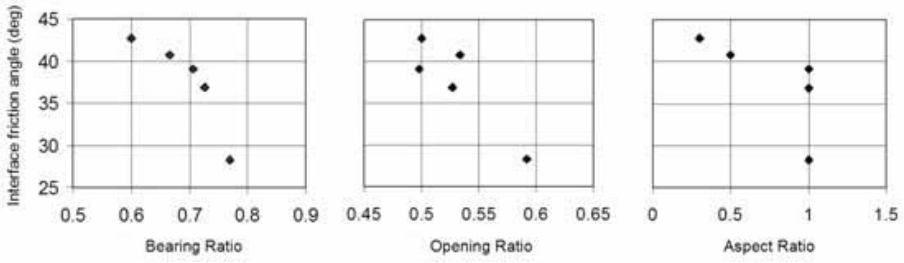


Fig. 14: Relationship between the interface friction angle and various geometric descriptors.

- Periodic maintenance of the hydraulic pumps and jacks as recommended by the manufacturers
- Periodic checking of the main box and other apparatus components for misalignments, bends, and cracks that could affect the accuracy of the results.

To verify the operability of the apparatus, a number of pullout tests and direct shear tests were conducted to evaluate the operability of the apparatus. Uniaxial tension tests were also performed using the new apparatus and confirmed the operability of the apparatus. Results were verified against manufacturer published data as well as typical values published in the literature. With the help of two trained technicians, the typical sample preparation time for direct shear and pullout tests is currently less than three hours.The top plate was designed as a grid of steel beams, with high rigidity, to ensure a uniform distribution of vertical displacement. This is unlike the majority of earlier apparatus designs, where an air bag is used to apply the normal pressure. The use of an air bag ensures uniform distribution of stresses on the surface of the soil as long as the walls of the box are covered with a lubricant prior to compacting the soil. The new apparatus design can accommodate an air bag underneath the top plate, with the top plate bolted to the box. The use of an air bag can limit tilting of the top plate, which was observed during some of the tests. Such tilting can also be minimized by using four hydraulic jacks evenly distributed over the top plate.

Experimental Program and Results:

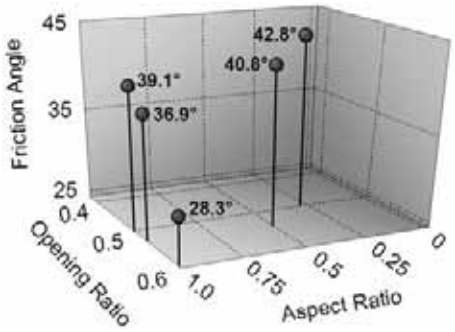
A series of pullout tests were conducted to examine the relationship between the geometry of the geogrid opening and the ultimate resistance to pullout. To ensure consistency among the geogrid materials, a 2-mm thick (t=2 mm) HDPE geomembrane was punctured using precision tools to create several grid patterns, which were then used as samples for the testing program. Table 1 lists the various opening widths (b), opening lengths (h), and rib width (w). The values selected for this study are consistent with typical opening geometries and rib width of commercially-available geogrids. The soil was classified as medium to fine siliceous sand, with an average grain size, D_{50}=0.60 mm, a coefficient of uniformity, C_u=2.8, and a coefficient of curvature, C_c=1.03. All tests were performed under a relatively low normal stress of 0.8 t/m^2, and the corresponding angle of interface friction was calculated by assuming a cohesion intercept of zero.

In general, the soil-geogrid interface resistance is governed by numerous factors, including the thickness of the geogrid, the grain size distribution of the sand, the geometry of the geogrid openings, the extensibility of the geogrid, and the rigidity of the longitudinal and transverse ribs. It is well documented in the literature that the principal interaction mechanism during pullout is that of passive resistance or bearing along the geogrid's transverse ribs (e.g., Jewell et al., 1984, Farrag et al., 1993).In this study, with all other factors being constant, only the influence of the geometry of the geogrid opening on the pullout resistance was examined. As such, the relationships were plotted between the soil-geogrid interface friction angle and the following various geogrid geometry descriptors:

- the bearing ratio, defined as the ratio between the opening width, b, and the total width, [b+w]; the opening width, b, also represents the spacing between the longitudinal ribs
- the opening ratio, defined as the ratio between the opening area, $b \times h$, and the total area, [b+w]/[h+w]
- the aspect ratio, defined as the ratio between the opening width, b, and the opening length, h; the opening length, h, can also be defined as the spacing between the transverse ribs.

The results plotted in Fig. 14 indicate that a strong relationship exists between the interface friction angle and the bearing ratio. Because the interaction mechanism is one of passive resistance or bearing along the transverse ribs, the resistance mobilized along a particular transverse rib depends on its flexural rigidity; as the ratio *b/w* increases, the flexural rigidity decreases, and so does the passive bearing resistance. However, one should expect that such a relationship is not universal, as the magnitude of bearing resistance developing along the whole surface area of the geogrid depends also on the spacing, *h*, between the transverse ribs. If the distance *h* is too large, less bearing would be mobilized along the total surface, and the equivalent interface friction angle would decrease. Conversely, for very small values of *h*, the passive resistance developing at each transverse rib would interfere with adjacent ribs. However, the results presented in Fig. 14 indicate that, within the range of grid geometries studied here, the relationship between the interface friction angle and the bearing ratio is independent of the actual values of *b* and *h*. In addition, it is expected that for very small bearing ratios, the fraction of area available for bearing along the longitudinal ribs as a function of the total cross sectional area of the geogrid would decrease, and so would the equivalent friction angle. The results presented in Fig. 14 evidently do not cover such a small range of bearing ratios.

Fig. 14 also suggests that no unique relation can be identified between the interface friction angle and either the opening ratio or the aspect ratio independently. However, it can be hypothesized that the interface friction angle varies as a function of both the opening ratio and the aspect ratio, interdependently. In other words, the friction angle decreases as the opening ratio increases, provided that the aspect ratio is constant. Similarly, for a constant opening ratio, the interface friction angle decreases as a function of increasing aspect ratio. To verify this hypothesis, the data was presented in a three-dimensional graph (Fig. 15), where the interface friction angle was plotted as a function of both the opening ratio and the aspect ratio. It can be inferred from the figure that a unique surface exists which defines the relationship between interface friction angle, opening ratio, and aspect ratio. This conclusion supports the hypothesis that the interface friction angle varies as a function of both the opening ratio and the aspect ratio.



Conclusions

Design and calibration procedures for a new large-scale testing apparatus for testing geosynthetic-soil systems were presented. The apparatus, which is housed at the National Research Centre in Cairo, Egypt, featured multiple functionalities by using of a single loading frame, driving mechanism, instrumentation, and data acquisition system, together with detachable components and modules to allow three modes of loading: pullout, direct shear, and uniaxial loading. Calibration and testing were conducted on the apparatus to verify its operability. The pilot experimental program indicates that the new apparatus is capable of performing a wide range of tests pertinent to soil-geosynthetic systems, including direct shear testing on gravel. An experimental program was conducted using the new apparatus to verify the dependence of the pullout soil-geogrid friction angle and various geometric descriptors of the geogrid openings. Additional modifications are currently being introduced to fully automate the system and to allow for dynamic loading capabilities.

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