Strain and stress controlled geosynthetic interface testing

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ABSTRACT: Depending on the frequency, type and number of cycles of the loads emanating from earthquakes, machine foundations or ocean waves, special testing devices capable of controlling stress or strain are needed for the determination of relevant engineering parameters at the geosynthetic interface for design. A multipurpose large size direct shear test device has been developed capable of applying monotonic and cyclic loads both with stress and strain control. An upper box of 300 mm width and 300 mm length slides over the lower box with 900 mm length. The normal stress on the upper box is applied by pneumatic rubber muscle actuators attached to sliding cars moving on rails placed parallel to the bottom box. This way the normality of the force is always sustained even under large horizontal displacements. Strain control is provided by a linear actuator driven by a step motor. The stress control is achieved by antagonistic pneumatic rubber muscle actuators which can apply monotonic and cyclic stress at the interface. The interface behavior of crushed stone and a smooth and a textured geomembrane is investigated under low normal stress and large horizontal displacement. The large dimensions of the box allowed testing of the crushed stone with its actual size which is very critical for the stress concentrations. A special film was used to map the stress distribution at the the interface of crushed stone and the two membranes. At large horizontal displacements, the interface shear strength of the smooth geomembrane increased slightly.

Keywords: geosynthetic interface, cyclic load, residual strength, large horizontal displacement

1 INTRODUCTION

Interface shear strength properties are important design considerations for economic and safe design of nearly all of the projects involving geosynthetics. Realistic values can only be obtained from appropriate laboratory tests or field model tests. Large size aggregates, large displacements, cyclic loads as well as monotonic, loading rate etc. makes the problem even more complex. Several different laboratory equipment may be required to measure all of the above mentioned properties. Developing an equipment capable of achieving multi tasks related to interface property measurement of geosynthetics was the main objective of the research conducted at Boğazici University. Large size direct/interface shear equipment development studies date back to more than twenty years at Bogazici University (Baykal, 2015). A large size dual purpose direct shear test device, a cylindrical interface test device for geosynthetics and finally a large displacement constant area multipurpose direct shear test device are developed.

1.1 Large size direct shear and pull out testing device

The large size direct shear testing device is capable of conducting shear tests, interface tests and pullout tests with changing the front wall of the lower box (Baykal and Doven 2000), (Doven 1996). The dimensions of the box are 0.30 x 0.30 x 0.30 m. The normal load is applied by using an airbag placed on top of the upper box. The horizontal displacement is applied via an electric motor, reduction gear and electronic speed control and the bottom box is pulled and a load cell is attached to the drive shaft. The large size direct shear test device is shown in Figure 1.

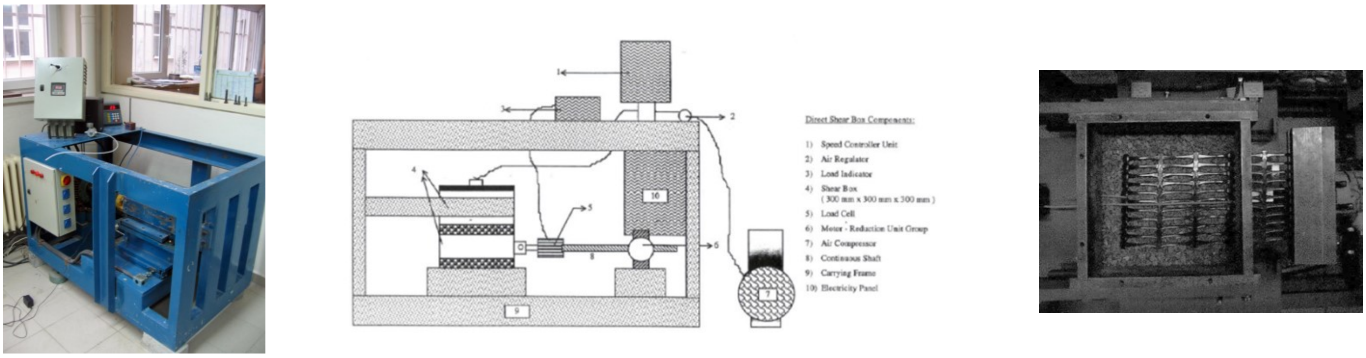

Figure 1. Large size direct shear and pullout testing device (pullout setup at the right).

The maximum horizontal displacement used for this equipment is 60 mm corresponding to 20 per cent of the length of the sample. Residual tests may be conducted only by moving the box back and forth till the residual interface shear values are reached. The test system has been successfully used for several commercial projects as well as research (Baykal&Danyıldız, 2009; Baykal & Dadasbilge, 2008; Dadasbilge 1999).

1.2 Geosynthetic soil cylindrical test device

A cylindrical interface testing device is developed for geosynthetics interface testing (GICT) (Baykal, 1997; Akkol, 1997; Akkol and Baykal, 2001). The geosynthetic to be tested is wrapped over a kestamide cylinder with three boundary conditions; free, one end fixed and two ends fixed. The typical testing set up is given in Figure 2. The cylinder which is wrapped with goesynthetic is placed in the special container and the soil is filled around it at the target relative density. The normal force on the cylinder is applied by a special rubber airbag wrapping the sand at the periphery. By applying air pressure to the peripheral airbag the required normal load is applied to the geosynthetic. The cylinder is rotated by an electric motor with a reduction gear. A torque transducer is placed between the kestamide block holding the geosynthetic and the drive shaft of the motor. This way it is possible to measure the torque applied on the interface of geosynthetic and the sand at specified relative density. Using the measured torque value, the interface shear stress is calculated.

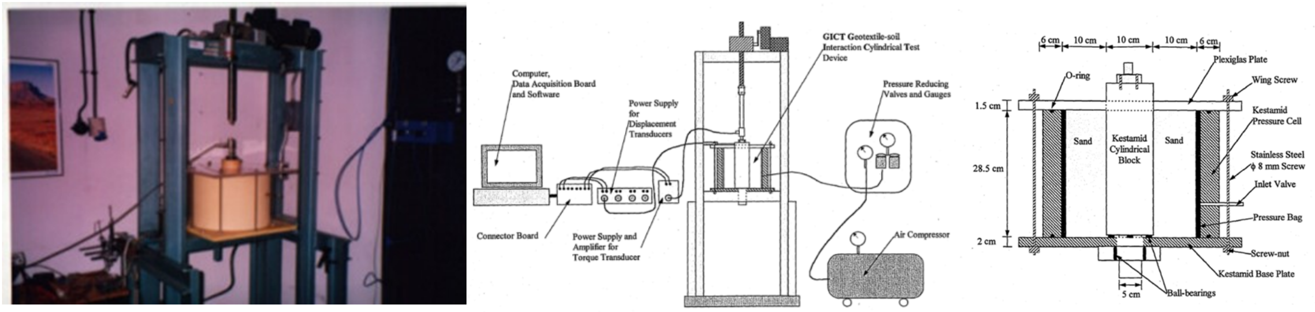

Figure 2. Geosynthetic Cylindrical Interface Test Device.

2 LOADING CONDITIONS

To be able to design geotechnical structures safely and economically, there is a need to determine the corresponding engineering properties under the expected loading conditions. Monotonic and cyclic loads act on geotechnical structures. Under the effects of earthquakes, machine foundations, or ocean waves, the geotechnical structures are subjected to cyclic loads with different type, frequency, and duration. Appropriate testing equipment with loading mechanisms simulating the in situ loads is needed. The typical loading conditions encountered in soil structure interaction problems and the corresponding test loading types may be summarized as; strain control: earthquakes (Short duration low number of cycles); stress control: machine foundations(high frequency, long duration, large number of cycles, harmonic) and ocean waves (low frequency, large number of cycles, harmonic). For different loading conditions both stress and strain control are needed. To fullfill all of the testing requirements, a versatile testing equipment both stress and strain control capability is needed. Controlling stress or strain may be simple or very complicated depending on the type of loading mechanism selected. For example, if stress control is required, the use of pneumatic loading systems become very simple due to simplicity of controlling the air pressure delivered into the cylinder. In addition to its simplicity it is also accurate. Stress control test with other conventional mechanical systems will require close loop control system with high cost. The accuracy obtained will be also limited when compared to that of a pneumatic system.

On the otherhand when strain controlled testing is required it is nearly impossible to do the precise position control using pneumatics. For strain controlled testing linear actuators driven by step or servo motors with gear reduction system will be the simplest to control and accurate load application system.

3 PNEUMATIC MUSCLE ACTUATORS

Stress control of the testing system developed is done by the help of rubber muscle actuators. The rubber muscle is called as; pneumatic artificial muscle, pneumatic muscle actuator, fluidic muscle, biometic muscle. Pneumatic muscle actuators are known for their high force to size ratio. A 40 mm rubber muscle can generate up to 6500 N of tension at 600 kPa air pressure. The rubber muscle is woven with a network of steel wires which contract with the application of air pressure causing the muscle to pull up.

The rubber muscles are composed of three sections; 1) airtight inflatable membrane in the inner section, 2) a structural web surrounding the inner membrane, 3) an upper and lower connector where both the membrane and the web are fixed (Figure 3 left). Upon application of the air pressure, the inner membrane is inflated causing stresses in the structural web tendons. This way the contraction of the membrane and the web pulls the upper and lower connectors creating a tension force. The comparison of the forces developed by the same size conventional pneumatic cylinder and fluidic muscle (artificial muscle actuator) is given in middle Figure 3. For the same diameter, the force exerted by the fluidic muscle is much larger than that of the conventional pneumatic cylinder. This property allows the use of much smaller diameters for the fluidic muscle making it practical. The force output obtained for increasing air pressure at contraction levels 5, 10, 15 and 20 per cent are presented in Figure 3 (right). In summary keeping the contraction level at 5 per cent, a 4 cm diameter muscle sustains 4500 N pulling force which can only be achieved by a huge diameter air cylinder (Yıldız,2010).

In the loading mechanism developed, the bottom connector is attached to a car moving on a rail fixed along the side of the bottom shear box. The top connector is attached to a loading beam in direct contact with the sample enclosed in the upper shear box. Adjusting the air pressure, gives the desired normal force acting on the sample.

For robotic control there are typical problems related with precise force control and precise position control. Due to high rigidity of most of the systems, most of the times it is easy to precisely control the position rather than the force. In geotechnical applications the application of normal loads in desired magnitudes is a must to be able to conduct the test in a correct manner. With artificial muscles controlling the force is a simple and easy process because of the simplicity of the system. The flexibility of the system is also another advantage for the transfer of the load to the soil. Because of the above mentioned problems and advantages, two different loading systems are incorporated to the developed testing system. While the normal load is applied through artificial muscle, the horizontal displacement is controlled by a step motor controlled linear actuator.

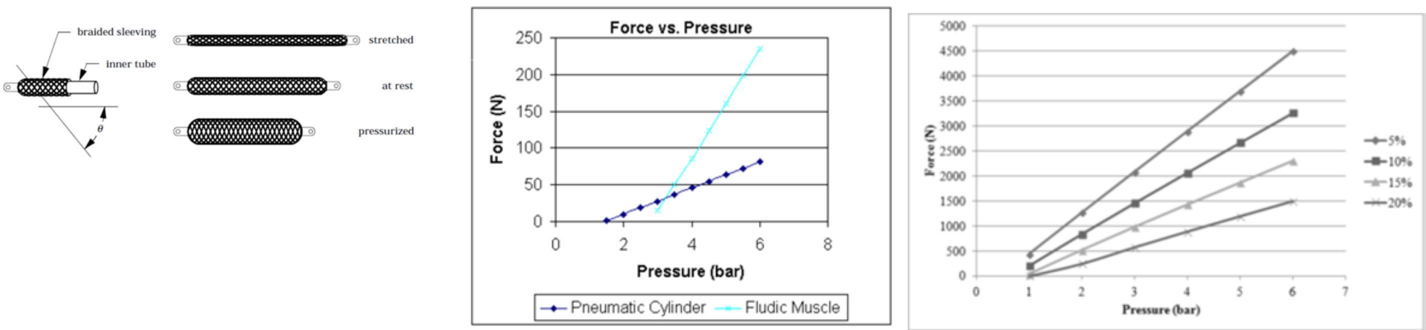

Figure 3. Components of a fludic muscle (left); force vs pressure values for pneumatic cylinder and fludic muscle (middle); force development at various contraction values for 40 mm artificial muscle (right).

4 STRESS MAPPING AT THE INTERFACE

Sensitive films, a dedicated scanner, calibration sheet and special software is used to map the stress variation between crushed rock aggregates, crushed rock and smooth geomembrane interface and crushed rock and textured geomembrane interface. The sensitive film roll, film cross section and color intensity chart versus stress correlation chart are presented in Figure 4. An application for geogrid-concrete interface is presented in the same Figure (Baykal,2014).

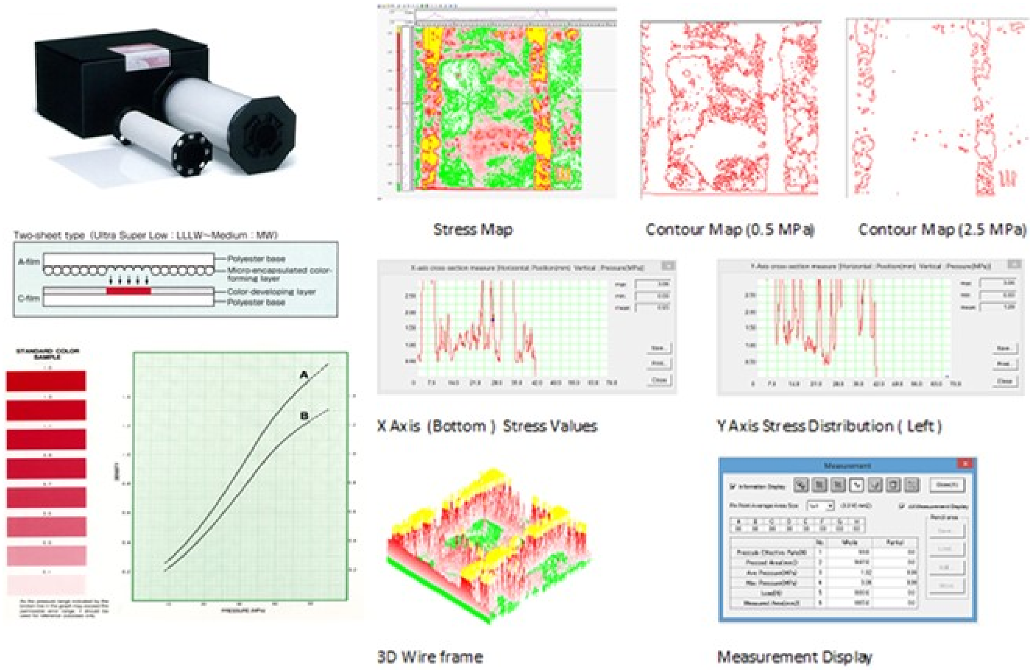

Figure 4. Sensitive film roll, film crossection, color intensity-stress chart and geogrid interface application.

Special indicator films are composed of micro paint capsules. Upon application of stress at the interface, the paint in these micro capsules explode and the color intensity changes corresponding to the magnitude of the contact stress applied. The color is fixed on the developer film. Indicator films are commercially available for stresses ranging from extreme low pressure 50 kPa to super low pressure 2500 kPa for low range stress measurements. The pressure limit for low pressure films is 10000 kPa. The loaded film is scanned through a dedicated scanner. The scanner has a special cover and is calibrated using a calibration sheet before each use. The scanned file is input to the special software. Humidity and temperature corrections are conducted by the software and the stress map is developed.

5 LARGE DISPLACEMENT DIRECT SHEAR TEST DEVICE

The main idea behind the development of the hybrid testing system both with stress control and strain control is to use the simplest, economic and accurate loading system to fulfil the testing requirements. With the developed testing system both stress and strain control systems are used separately for precise control. The first module is the stress control module with antagonistic system. The second module is the main direct shear module with normal load application system with artificial muscle actuators which is also stress controlled. The third module is the step motor driven linear actuator which is strain controlled. The antagonistic load application system and the normal load application system use pneumatic muscle actuators eliminating the need for huge reaction frames. Being commercially available off the shelf makes the use of pneumatic muscle actuators implementable in geotechnical engineering laboratories where air supply is always available.

The interface shear test device's (Figure 5) upper box is 300 mm by 300 mm, moving on the lower box with 900 mm length and 300 mm width. The height of the top box is 200 mm and the height of the bottom box can be adjusted as 200 mm or 400 mm. ASTM D3080 requires a minimum shear box width larger than10 times the maximum aggregate size. The minimum initial thickness of the sample is given as 6 times the max aggregate diameter. In addition to these two requirements, the standard sets the width to thickness ratio as 2:1. ASTM D5321 is specially developed for geosynthetic interface testing. Minimum width of shear box is given as 15 times D_{85} (grain size corresponding to 85 % passing). This standard sets the depth of each shear container as minimum 6 times the D_{max}. According to the latter criterion the developed shear test device can accommodate max D_{85} 20 mm for width criterion and D_{max} 30 mm for depth of each shear box containing soil criterion. These values are typical for most of the drainage material size used in geotechnical applications.

Figure 5. Large displacement interface test device; antagonistic loading unit (left); shear box (middle); linear actuator unit (right).

The rubber muscle actuators are attached to a rail near the lower box and can travel together with the upper box. The muscles are connected to a beam in twin order on the top box, exerting compression to the soil in the upper box. Up to three beams with six rubber muscles can be attached providing a theoretical total of 39000 N normal force. Calibration tests are conducted using one set of beam applying up to 8000 N normal force. The developed system has many advantages; no reaction frame is needed; the top box is traveling instead of the bottom box which enables testing model piles also; the rubber muscles are commercially available and can be purchased off the shelf; pneumatic control is possible so that cyclic normal loads can be applied. The normal stress is applied by the help of up tp 6 pneumatic artificial muscles, which have a diameter of 40 mm, a nominal length of 250 mm and radial air inlet valves at both end fittings.The bottom part of the muscles, which are connected to rod eyes, are fastened to a linear guide. The top parts, which are connected to rod clevises are fastened to an aluminum beam in order to transmit the tensile load of the muscles to the loading platen. The muscles can operate efficiently up to 25% contraction and the generated force output decreases with increasing contraction ratio. Keeping the contraction at a minimum level, is prefererred to obtain large force output.

Considering the fact that a ten storey high building typically exerts 100 kPa to the underlying soil, for a 0.09 m^2 contact area of the shear box containing soil, the force generated by artifical muscles will be adequate (typical 300 kPa normal stress capacity). 100 kPa normal stress can be achieved even using two 40 mm pneumatic artificial muscles. An antagonistic horizontal cyclic load application system is designed and produced using two opposing pneumatic artificial muscles. One pneumatic muscle applies the tension load, while the opposing muscle is used to bring the actuator muscle to its original position for the second cylic load application. The system is capable of appying a cyclic horizontal load of up to 6000 N. This will correspond to aproximately 50 kPa of horizontal cyclic shear stress on the sample. Considering the fact that the seismic coefficient for 1 st degree earthquake zone is 0.42, for a 10 storey high building 42 kPa horizontal stress will be adequte to simulate the earhquake load. For larger loads a second or third muscle actuator should be added to the setup.

As shown in Figure 5, the small size upper box is pulled or pushed over the fixed larger bottom box. A stepper motor with reduction gear is used to move the linear activator. The step motor is controlled by PLC software by the control box shown towards the right end of the equipment.The capacity of the linear actuator is 15 KN capable of applying upto 170 kPa shear stress for the 0.09 m^2 upper box. The PLC software is capable of applying monotonic and cyclic horizontal loads with strain control. The control unit at the left part of the shear box uses PLC software to control the antagonistic loading system. The antagonistic system is composed of two opposing artificial muscle actuators pulling and pushing against each other to apply cyclic load to the upper box. This provides a stress controlled interface test execution.

6 CASE STUDY

The cover layer of waste disposal sites contain geosynthetic layers where the interface between geosynthetics and the cover soil, drainage layer and waste material is critical due to the steep side slopes and low confinement (7-10 kPa). To demonstrate the capability of the developed direct shear interface test device a smooth and a textured geomembrane's interface behavior with crushed stone is investigated at large horizontal displacement. The model represents typical drainage material underlain by geomembrane on a slope. A small normal stress of 7.5 kPa is used. The sloped interface is typical for final cover layer of a waste disposal site. The number two size crushed stone is standard for concrete applications. The stone diameter is typically between 16 mm and 23 mm range. The grain size distribution parameters of the crushed stone limestone are (Dmax = 30mm , D_{85}=20mm, D_{50}=14mm, G_S=2.97).

The two geomembranes used (smooth, textured) in this study are from the same company. Both of them are 2 mm thick with close physical properties except the 0.25 mm asperity size of the textured geomembrane. The properties of the geomembranes are given in Table 1.

The lower box (900 mm by 300 mm) is filled with wood beams, and the geomembrane is fixed on the wood beams so that it is flush with the upper side of the lower box. The stress indicator film is cut to fit to the bottom of the upper box. Crushed stone is carefully placed on top of the indicator film to the target relative density of 50 percent. The weight of the crushed stone placed into the upper shear box is measured. Wood beams are placed on top of the crushed stone. Steel weights are added to reach 7.5 kPa normal stress to simulate the confinement from cover soil and crushed stone for the case of sloped cover of a waste disposal site.

Table 1. Properties of geomembranes tested.

Geomembrane surface	Smooth	Textured
Material	HDPE	HDPE
Density g/cm^3	0.540	0.540
Thickness mm	2	2
Texture height mm	0	0.25
Yield strength kN/m	35	33
Break strength kN/m	54	50
Yield elongation %	12	12
Break elongation %	750	750

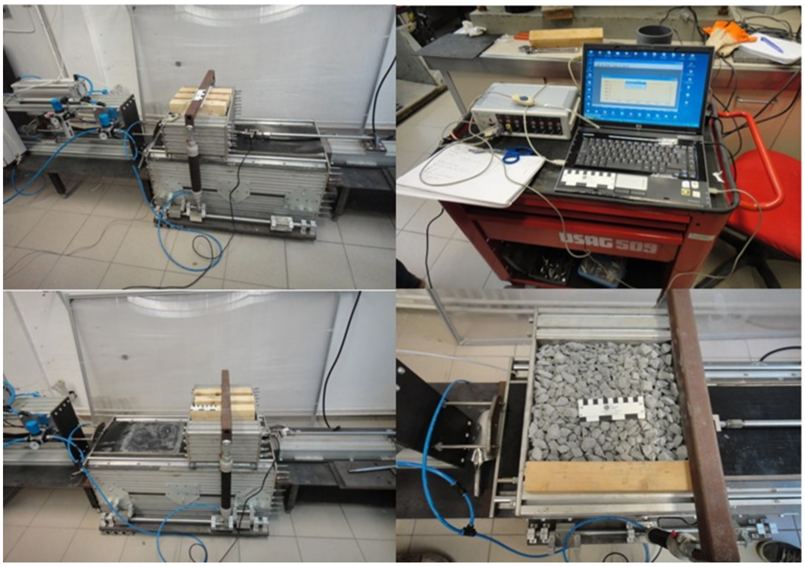

Figure 6. Scenes from beginning (left up) and end (left down) of the test.

The test setup is shown in Figure 6. Notice the position of the upper box at upper left side of the figure. At the end the box has traveled more than 300 mm over the geomembrane and the pneumatic muscle actuators sustained their normality throughout the test. They travel over the rail cars together with the upper box. This picture is from calibration tests. In this demonstration study the very low normal load is applied by adding a couple of steel weights on the crushed stone. In the full set up there are three sets of pneumatic muscle actuators which makes the system capable of applying up to 300 kPa normal stress (for most of the tests the typical normal stress applications are 50 kPa, 100 kPa and 150 kPa for a test set). The rate of horizontal displacement used was 1 mm/ minute. The PLC software of the strain control unit (step motor driven linear actuator) allows cyclic load application also.

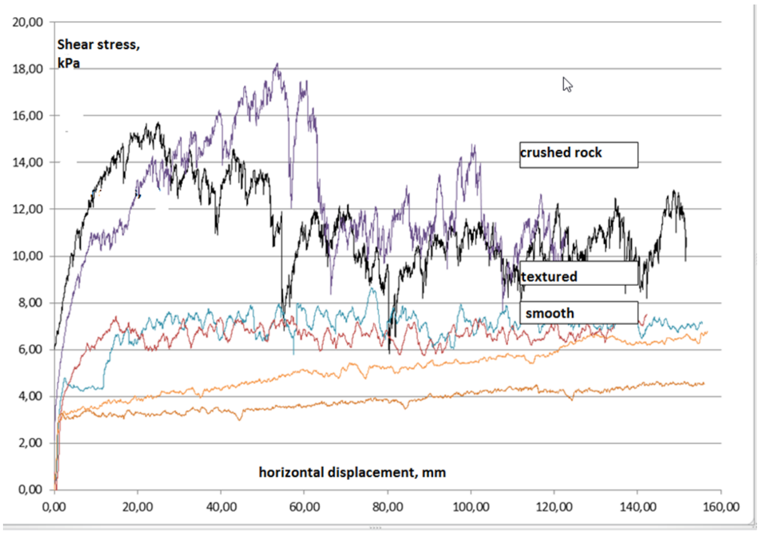

Figure 7. Shear stress vs horizontal displacement variatoion for crushed stone (top 2), crushed stone-textured geomembrane (middle 2) and crushed stone- smooth geomembrane.

The variation of shear stress with horizontal displacement is presented in Figure 7. For crushed stone test the shear stress reaches its peak level and is reduced to residual values. In this case the bottom box is also filled with crushed stone. The width to thickness ratio of the sheared crushed stone was 1:1 which violated ASTM D3080 s 2:1 ratio. At large displacements dilation of crushed stone in front of the shear box is observed. This should be considered in evaluation of the stress reduction at large displacement. For geomembrane interface tests no such problem has been enountered. The geomembrnes were perfectly fixed and stay fixed throughout the test. The smooth geomembrane interface test showed the smallest interface shear stress values. An interesting observation is slight increase in stress levels at larger horizontal displacements. The crushed rock edges marked the geomembrane surface deeply. The textured geomembrane improved the interface shear stress level and sustained this level even at high displacements. The discussion of the results will be given in other publications. This study is presented here for showing the functionality of the developed equipment.

The interface stress maps are obtained by the indicator films placed at shear plane.The results are striking (Figure 8). The yellow color shows stress levels larger than the measuring range of the indicator film (50- 250 kPa range film is used). Green color indicates contact stresses lower than the range of the film. The distribution and shape of stress concentrations illustrate interlocking between crushed stone. The middle figure lacks these interlocking stress concentrations for the smooth geomembrane. The sliding of crushed stone over smooth geomembrane is visible through longer footprints of sliding stone. The accumulation of stress concentrations to the front wall of the shear box may be the explanation of gradual increase in shear stress at large dislplacements. The right figure demonstrates contact stress distribution identical to that of crushed stone stating that the asperities push the shear inteface into the stones.

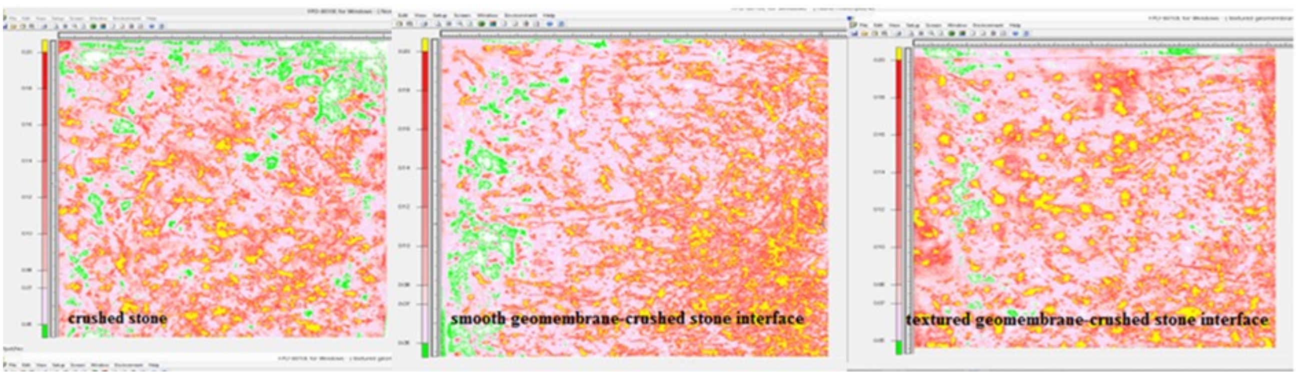

Figure 8. Stress maps; crushed stone (left); smooth geomembrane and crushed stone (middle) and textured geomembrane ad crushed stone (right).

7 CONCLUSIONS

The developed large size large displacement multipurpose direct shear testing system successfully utilized pneumatic muscle actuators where stress control is needed. The stress control is simple, economic and accurate with pneumatic control. The comparatively large capacity of pneumatic muscle actuators decreases the need for massive reaction frames with an innovative sliding normal load mechanism. For accurate position control linear actuator is the optimal solution and its performance was validated with the developed equipment. The antagonistic system for the application of cyclic load is also simple and accurate. The flexible nature of the muscle also is preferable to rigid systems for transfer of the cyclic load to the interface. The case study with smooth and textured geomembrane and crushed stone demonstrated the capacity and implementability of the developed equipment. For geosynthetics interface studies, the developed interface equipment will be a useful tool to extent present state of the art knowledge for large horizontal displacements and behavior under cyclic loading. Stress mapping methodology clearly identified the actual contact areas and it revealed important information about the interface behavior. The interface stress map obtained from the textured geomembrane was similar to the stress map obtained from crushed rock interface. The developed equipment will help to understand the interface and shear behavior at large displacements in detail.

ACKNOWLEDGEMENTS

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REFERENCES

Akkol,O. 1997. A new test device and method; geosynthetic-soil interface cylindrical test GICT). PhD dissertation, Bogazici University, Istanbul.

Akkol, O. and G.Baykal, 2001. A new test device and method: geotextile-soil interface cylindrical test (GICT)", Proceedings of the Fifteenth Conference on Soil Mechanics and Geotechnical Engineering, Istanbul-Turkey, Vol 2, pp-1547-1550.

ASTM D 3080. 2011. Standard test method for direct shear test of soils under consolidated drained conditions.

ASTM D 5321. 2017. Standard test method for determining the shear strength of soil-geosynthetic and geosynthetic-geosynthetic interfaces by direct shear test.

Baykal,G., Keklik, A. and Elmas B. 2017. The behavior of smooth and textured geomembranes under low confinement at large horizontal displacement (in Turkish). G7 National Geosynthetics Conference. 11-12 May 2017, Istanbul.

Baykal, G. 2016. Implementation of pneumatic muscles in geotechnical laboratory equipment development. 4th International conference on new developments in soil mechanics and geotechnical engineering, 2-4 June 2016, Near East University, Nicosia.

Baykal, G. 2016. Contact stress mapping in geotechnical 4th International conference on new developments in soil mechanics and geotechnical engineering, 2-4 June 2016, Near East University, Nicosia.

Baykal, G. 2015. Development of Soil-structure interface testing system using pneumatic muscles. BAP 5580 project. Bogazici University, Istanbul.

Baykal, G. 2015. Interface interaction. XVII ECSMGE Conference, Edinburg.

Baykal, G. 2014. Pressure mapping system for geosynthetic interfaces. IGS World conference, Berlin.

Baykal, G. and Danyıldız E. 2009. Geocomposite-geomembrane interface parameter investigation, Bogazici University Rolling Fund Project. Istanbul.

Baykal, G. and Dadasbilge. O.2008. Experimental investigation of pull-out resistance of uniaxial geogrids. Proceedings of the 4th regional conference on geosynthetics in Shangai, p 174-178, Shangai

Baykal, G. and A. G. Doven. 2000. Utilization of fly ash by pelletization process:theory, application areas and research results", Resources, Conservation and Recycling, Vol. 30, pp. 59-77.

Baykal, G. 1996. Development a new testing equipment and method for geosynthetic soil interface. Bogazici University scientific project. BAP 1284, Bogazici University, Istanbul.

Dadaşbilge O. 1999. Experimental investigation of the pullout resistance of uniaxial grids. MSc Thesis, Bogazici University, Istanbul.

Yıldız,A. 2010. Utilization of pneumatic artificial muscles on a direct shear test setup. MSc Thesis, Bogazici University, Istanbul.