A STUDY ON THE BOX SIZE AND ORIENTATION EFFECTS ON DIRECT AND INTERFACE SHEAR TESTS

by

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B.S., Civil Engineering, Istanbul Bilgi University, 2018

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Civil Engineering
Boğaziçi University
2021

ACKNOWLEDGEMENTS

I would like to express my gratitude to my thesis advisor Professor Gökhan Baykal for his precious mentoring during our work. His innovative ideas, different approaches to the problems added so much value to our study. Most importantly I have learned so many things from my professor and I will continue to my future career confidently thanks to him.

I would like to present my appreciation to the thesis committee members, Prof. Ayşe Edinçliler and Asst. Prof. Tanay Karademir for their valuable guidance and support.

I owe special thanks to my dear professor Tanay Karademir. He always supported me no matter what it was and encouraged me to continue my career in Geotechnical Engineering. There is no way that I can thank him enough.

Furthermore, I am very grateful to our teaching assistant Uğurcan Erginağ and my laboratory buddy Sercan Akbaşak. They were always on my side. They shared their friendship and knowledge with me all the time we worked together. Additionally, I am thankful to our laboratory technicians and my classmates for their contributions to this master thesis.

Special thanks to the Scientific Research Projects Programme. The test device that was used in this study was manufactured as a part of BAP 5580 scientific project.

Finally, I have to present my best feelings to my beloved family. They are the reasons for who I am. I couldn't be able to reach these days without them. They encouraged and supported me countless times during my education. I don't need anything to achieve what I want in this world but my family.

ABSTRACT

A STUDY ON THE BOX SIZE AND ORIENTATION EFFECTS ON DIRECT AND INTERFACE SHEAR TESTS

The large size large displacement shearing device has been under development nearly for the last decade at Bogazici University. Upper box movement, three times larger lower shear box size and pneumatic muscles sliding on rails for normal loading are the unique parts of the device. Upper box movement is essential for multipurpose use: model pile tests, inclined plane tests, residual shear strength tests. The movement of the upper box caused soil loss at large displacements, during direct shear testing, resulting of very low internal friction angles. The objective of this study was to solve this problem using different methodologies. First set of experiments resulted much lower ϕ values than those reported in the literature. Besides these low values, normal stress loss, loading platen rotation and a dilation in front of the upper shear box were observed. The second set of experiments was performed after the partitioning of the lower shear box into three equal compartments. However the obtained measurements were still inconclusive. The third set of experiments was performed by partioning the lower box with one metal platen and a wooden wedge to increase the rigidty of the system. The obtained results were consistent with the direct shear test and the values reported in the literature. The interface shear strength experiments did not show any problem. The size effect between the devices were observed. The solution of the problem related to upper box movement ensured the versatility of the testing system. The planned experimental program could not be finished due to the pandemic restrictions.

ÖZET

DİREKT VE ARAYÜZ KESME TESTLERİNDE KUTU BOYUTU VE ORYANTASYON ETKİLERİ ÜZERİNE BİR ÇALIŞMA

Büyük boyutlu büyük deplasmanlı kesme cihazı yaklaşık on yıldır Boğaziçi Üniversitesi'nde geliştirilmektedir. Üst kutu hareketi, üç kat daha büyük alt kesme kutusu ve normal yükler için raylar üzerinde kayan pnömatik kaslar cihazın özgün kısımlarıdır. Üst kutu hareketi çok işlevli kullanım için gereklidir: model kazık tesleri, eğik düzlem testleri, rezidüel kesme dayanım testleri. Üst kutu hareketi yüksek deplasmanlardaki kesme deneylerinde düşük içsel sürtünme açılarıyla sonuçlanan toprak kaybına sebebiyet vermiştir. Bu çalışmanın konusu karşılaşılmış olan bu problemi farklı metodolojiler kullanarak çözümlemektir. İlk set deneyler literatürde raporlandığından çok daha düşük ϕ değerleri ile sonuçlanmıştır. Düşük değerlerin yanı sıra, normal stres kaybı, yük plakası rotasyonu ve üst kutu önünde bir kabarma davranışı gözlenmiştir. İkinci set deneyler alt kutunun üç eşit kompartımana bölünmesi ile gerçekleştirilmiştir. Lakin, elde edilen ölçümler hala neticesizdi. Üçüncü set deneyler alt kutuyu daha sağlam yapabilmek adına bir metal plaka ve ahşap takoz ile bölümlendirilerek yapılmıştır. Elde edilen sonuçlar direkt kesme deneylerinden ve literatürden alınan sonuçlarla tutarlıydı. Arayüz kesme deneyleri herhangi bir problem gözlenmemiştir. Cihazlar arasında boyut etkisi gözlemlenmiştir. Üst kutu hareketine bağlı problemin çözümü test edilen sistemin çok yönlülüğünü kanıtlamıştır. Planlanan deneysel program pandemi kısıtlamaları nedeniyle tamamlanamamıştır.

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c	Cohesion
c'	Effective Cohesion
cm	Centimeters
$^{\circ}C$	Celsius Degree
C_c	Consolidation Coefficient
C_u	Uniformity Coefficient
D_{50}	Grain Size at Fifty Percent Finer
D_{max}	Maximum Particle Size
D_r	Relative Density
e_{max}	Maximum Void Ratio
e_{min}	Minimum Void Ratio
g	Grams
G_s	Specific Gravity
kg	Kilogram
kN	Kilonewton
kPa	Kilopascals
lbs	Pounds
m	Meters
mm	Milimeters
min	Minute
N	Newton
sec	Second
α	Adhesion
δ	Interface Friction Angle
δ_p	Peak Interface Friction Angle
δ_r	Residual Interface Friction Angle
σ_n	Normal Stress

σ'_n	Effective Normal Stress
τ	Shear Stress
$\varnothing$	Diameter
$\varnothing_{in}$	Inner Diameter
$\varnothing_{out}$	Outer Diameter
ϕ	Internal Friction Angle
ϕ'	Effective Internal Friction Angle
γ	Unit Weight
γ_d	Dry Unit Weight

LIST OF ACRONYMS/ABBREVIATIONS

ASTM	American Society for Testing and Materials
DEM	Discrete Element Method
DIDS	Double Interface Direct Shear
DS	Direct Shear
EN ISO	European Union International Organization for Standardization
EPS	Expanded Polystrene
GCL	Geosynthetic Clay Liner
GICT	Geotextile Soil Interface Cylindrical Test
GM	Geomembrane
GTX	Geotextile
HDPE	High Density Polyethylene
LSDS	Large Size Direct Shear
LVDT	Linear Variable Differential Transformer
MSDS	Medium Size Direct Shear
MSW	Municipality Solid Waste
NW	Non Woven
NWNP	Non Woven Needle Punched
PP	Polypropylene
PVC	Poly Vinyl Chloride
RSD	Ring Shear Device
SMDS	Semi Medium Direct Shear
Tilting T.	Tilting Table
Triaxial C.	Triaxial Compression
VFPE	Very Flexible Polyethylene
XPS	Extruded Polystrene

1. INTRODUCTION

Shearing devices, interfaces and the production of alternative construction materials have always been great concerns at Bogaziçi University. Baykal and Döven [48] designed a special large-scale shearing device which applied normal loads by an airbag to evaluate the engineering performances of fly ash pelletizations in the geotechnical engineering. The movement of the lower box which resulted soil loss from the upper box is solved by adding a plate to the back of the lower box to hold the soil. Since the geosynthetics are often used in geotechnical applications, Baykal and Akkol [41] designed a new interface testing device which was called Geotextile-Soil Interface Cylindrical Test (GICT). The device consisted of a cylinder wrapped by geosynthetic and surrounded soil. This equipment allowed continuous shearing at geosynthetic soil interface to obtain residual shear parameters. Followingly, Baykal and Dadasbilge [47] used the large size direct shear device and conducted pull-out tests. The large size-large displacement equipment was manufactured and tested by Baykal [49] in 2013. Later on, Elmas [36] continued to work on the improved version of Baykal's study in 2019. He conducted both internal and interface shear strength tests to work on waste fill cover soil stability problems.

The large size large displacement direct and interface shear test device has been under development nearly for the last decade at Bogazici University. The top shear box is moving instead of the bottom as used in the conventional test devices. The bottom box is three times longer than the top one to ensure a constant area during shear. A unique normal load application system utilizes pneumatic muscles travelling on sliders so that the normality of the vertical load is sustained even at large displacements up to two times the size of the upper box. The movement of the top box allows testing model piles under active and passive loads. The developed testing system can also be used as an inclined plane with the advantage of normal load application. The interface testing can be carried on even with large size grains like crushed stone. Cyclic load can also be applied with stress and strain control in the horizontal direction and with stress control in the normal load direction.

The multifunctional utilization potential of the developed equipment is great with one drawback observed during direct shear testing. The movement of the upper box caused soil loss at large displacements resulting measurement of very low internal friction angles. Besides these low internal friction values, normal stress loss, loading platen rotation and a dilation in front of the upper shear box were observed. The objective of this study was to solve this problem using different methodologies.

2. LITERATURE REVIEW

This chapter consists of the broad exploration of the literature in terms of internal shear strengths of sand, interface experiments of geosynthetics and shearing device effects. Detailed tables show the main points of the studies in the literature. Furthermore, more detailed summaries of the papers are presented at the end of the tables.

2.1. Review of Large Displacement Shear Strength Studies in Literature

Table 2.1 shows the large-scale shear device usage in literature. Since there is no standard device for the large-scale shearing device, researchers mostly presented their own devices in the literature.

Table 2.2 shows the significant parameters of the explored studies in the literature. In this point of view, the table includes normal stresses, rate of displacements, amount of horizontal displacements, type of soils and the geosynthetics.

Table 2.3 summarizes the studies for the large-scale shear device usage, internal shear strength of sand and the shear strengths of the geosynthetics. Papers were chosen mostly according to their similarity to the present study. Main objectives and results were summarized to be helpful for the researchers. Furthermore, more detailed versions of the studies were written each by each in the following pages. Detailed explanations also included the supporting graphs and images for better contribution to this study.

Table 2.1. Test Types and Box Dimensions in Literature.

Reference	**Test Type**	**Box Dimensions(mm)** (width*length*height)
[4]	-DS	60*60*-
		100*120*-
	-LSDS	200*100*-
[5]	-DS	DS-60*60*20
		Proposed Apparatus-60*60*20
[6]	-LSDS	1000*1000*1000
[7]	-DS	60*60*32
	-MSDS	152*252*152
	-LSDS	1000*1000*1000
[8]	-DS	60*60*26.4
	-MSDS	101.6*101.6*40.64
	-LSDS	304.8*304.8*177.8
[9]	-DS	$\varnothing$60 H=20; 40*40*20
	-SMDS	120*120*120
	-MSDS	300*300*300
	-LSDS	500*800*600
[10]	-DS	64*64*31
	-LSDS	305*305*152
	-Triaxial C.	$\varnothing$74 H=147
[11]	-LSDS	152*254*150
[12]	-DS	$\varnothing$60 H=20
	-RSD	$\varnothing_{in}$=30, $\varnothing_{out}$=50 H=20

Table 2.1. Test Types and Box Dimensions in Literature. (cont.)

Reference	**Test Type**	**Box Dimensions(mm)** (width*length*height)
[13]	-RSD	$\varnothing_{in}=60$, $\varnothing_{out}=100$ H=?
[14]	-LSDS	250*250*250
[15]	-LSDS	300*300*-
[16]	-RSD -Triaxial C.	$\varnothing_{in}=203$, $\varnothing_{out}=269$ H=26
[17]	-DS	100*100*-
[18]	-Triaxial C.	$\varnothing_{in}=50$ H=100mm
[19]	-DS	60*60*20
[20]	-LSDS -RSD	305*406*- $\varnothing_{in}=70$, $\varnothing_{out}=100$ H=?
[21]	-RSD	$\varnothing_{in}=40$, $\varnothing_{out}=100$ H=10mm
[22]	-DISD	100*100*25 (upper) 180*300*25 (lower)
[23]	-LSDS	360*360*180 $\varnothing_{in}=300$
[24]	-RDS	$\varnothing_{in}=89$, $\varnothing_{out}=140$ H=30
[25]	-Tilting T. -DS -LSDS	490*600*25 60*60*- 300*300*-
[26]	-LSDS	300*300*-
[27]	-LSDS	400*600*-
[28]	-DS	$\varnothing=60$

Table 2.1. Test Types and Box Dimensions in Literature. (cont.)

Reference	**Test Type**	**Box Dimensions(mm)** (width*length*height)
[29]	-RDS -LSDS	$\varnothing_{in}$=40, $\varnothing_{out}$=100 H=? 305*305*- (upper) 305*356*- (lower)
[30]	-LSDS	400*600*-
[31]	-RDS	$\varnothing_{in}$=70, $\varnothing_{out}$=100, H=?
[32]	-LSDS	102*102*51
[33]	-DS -Pull Out	71.12*71.12*- 254*431.8*254
[36]	-LSDS	300*300*200 (upper) 300*900*400 (lower)
[40]	-LSDS	300*300*205 (upper) 300*900*205 (lower)
[41]	-DS -GICT	100*100*- $\varnothing$=100 H=266
[42]	-LSDS	300*300*200 (upper) 300*900*(200,400) (lower)
[2]	-LSDS	300*300*200 (upper) 300*900*(200,400) (lower)
[43]	-LSDS	300*300*-(upper) 300*900*-(lower)
[48]	-LSDS	300*300*300
[47]	-Pull Out	300*300*300
[49]	-LSDS	300*300*200 (upper) 300*900*400 (lower)

Table 2.2. Essential Parameters of Studies in Literature.

Reference	Normal Stress (kPa)	Rate of Shearing (mm/min)	Horizontal Disp. (mm)	Geosynthetic Used	Soil Used
[4]	1.5 - 9.8	-	-	-	Crushed Quartz Ottawa Sand
[5]	10 lbs ≈ 12.3kPa 400lbs ≈ 490.5kPa	-	-	-	Plasticine
[6]	30	0.5	60	Grid Georid Geotextile Metal Strip	Leighton Buzzard sand 14/25
[7]	30	0.5	Small≈7 Medium≈14 Large≈60	-	Leighton Buzzard sand 14/25
[8]	38, 68, 95, 122, 150 69, 103, 138, 172, 207	0.25	-	-	Brown Mortar Winter Sand Ottawa Morie Sand Gravel Pack #3

Table 2.2. Essential Parameters of Studies in Literature. (cont.)

Reference	**Normal Stress** (kPa)	**Rate of Shearing** (mm/min)	**Horizontal Disp.** (mm)	**Geosynthetic Used**	**Soil Used**
[9]	50	0.5	5	-	Toyoura Sand
		0.31	10		
		0.75	45		Sandy Gravel
		0.26	90		
[10]	26-184	0.24	7	-	30 different sands
	26-184	0.24	38	-	
	21-83 (Triaxial)	0.11	-	-	
[11]	90.8	0.028	20	-	Leighton Sand Gravel
[12]	30-150	0.01	5	-	Tuffaceous Clay Mudstone Alluvial loess Siltstone Malan loess
[13]	30-300	0.01	95-265	-	Xuechengzhen
	50-400	0.01	975-2307	-	Kamenose

Table 2.2. Essential Parameters of Studies in Literature. (cont.)

Reference	**Normal Stress** (kPa)	**Rate of Shearing** (mm/min)	**Horizontal Disp.** (mm)	**Geosynthetic Used**	**Soil Used**
[14]	5-20	0.5	60	-	Coarse Sand
[15]	147.1, 294.2, 441.3	-	12% (Shear Strain)	-	Babolsar Sand
[16]	- 20	186(Ring Shear) 1.27(Triaxial)	1m to 10m 25% (Axial Strain)	- -	Mississippi River Sand
[17]	25-252	1.2	12	-	Leighton Buzzard Sand 14/25
[18]	100, 200, 500	0.5%/min	15% (Axial Strain)	-	Ottawa Sand Limestone
[19]	25, 50, 100, 200	$2.5*10^{-5}$ mm/per calculation	10	-	Leighton Buzzard Sand
[20]	25, 50, 100, 200 27, 52, 102, 201	3 3	100(LSDS) 3m(RSD)	-Textured&Smooth Geomembrane -Geotextile	Gravel Crushed Stone Sand

Table 2.2. Essential Parameters of Studies in Literature. (cont.)

Reference	**Normal Stress** (kPa)	**Rate of Shearing** (mm/min)	**Horizontal Disp.** (mm)	**Geosynthetic Used**	**Soil Used**
[21]	24 to 480	0.37	50-1500	-Smooth & Textured Geomembrane -Geotextile -Geocomposite	-
[22]	7.5 to 49.5	0.9, 1.1, 1.5	25	-Smooth & Textured Geomembrane - Geotextile	-
[23]	50 to 200	1	20	-Smooth & Textured Geomembrane -Geotextile	Fine Sand Sandy Gravel Ordinary Concrete No-fines Concrete
[24]	50 to 1000	-	250	Geomembrane Geotextile	Ottawa Sand Concrete Sand Gravel

Table 2.2. Essential Parameters of Studies in Literature. (cont.)

Reference	**Normal Stress** (kPa)	**Rate of Shearing** (mm/min)	**Horizontal Disp.** (mm)	**Geosynthetic Used**	**Soil Used**
[25]	5 to 50 (Tilting T.) 25 to 300 (DS) 110-400 (LSDS)	3 1.8 1.8	- - -	-Smooth and Rough HDPE Geomembrane -PVC Geomembrane -Geotextile	- - - -
[26]	25 to 450	5	50	-3 NW Geotextiles -5 Geomembranes	-
[27]	20 to 300	1	40	-Textured Geomembrane -Geotextile	Silty Clay with Silty Sand
[28]	16 to 690	-	140	-Coextruded&Laminated HDPE Geomembrane -2 Geotextiles	-
[29]	17 to 400	0.015 and 0.37	1000 to 1050 (RSD) 100(LSDS)	-PVC Geomembrane -T&S HDPE GM -T & S VFPE GEM	-

Table 2.2. Essential Parameters of Studies in Literature. (cont.)

Reference	**Normal Stress** (kPa)	**Rate of Shearing** (mm/min)	**Horizontal Disp.** (mm)	**Geosynthetic Used**	**Soil Used**
cont...				-Drainage Composite -Geonet -Unreinforced GCL -5 Geotextiles	
[30]	50-300	1	40	-Textured Geomembrane -Geotextile	Clay
[31]	48 to 480	44 (Clay/GM) 10 (GTX/GM)	120	-Geomembrane -Geotextile -Geonet	Clay
[32]	10 to 400	1	80	-S&T Geomembrane -4 Geotextiles	-
[33]	158, 316, 478.8	0.127 to 1.27 (DS) 3.81 (Pull Out)	6.35 (DS) 60 (Pull Out)	-S. Geomembrane -Geotextile -Geonet	Clay

Table 2.2. Essential Parameters of Studies in Literature. (cont.)

Reference	**Normal Stress** (kPa)	**Rate of Shearing** (mm/min)	**Horizontal Disp.** (mm)	**Geosynthetic Used**	**Soil Used**
[36]	6, 16, 26	1	Up to 230	-NWNP Geotextile -Smooth & Textured HDPE Geomembrane	Crushed Stone
[41]	20, 40, 50	-	-	-4 types Geotextiles	Ottawa Sand Brown Sand
[2]	7.5	-	Up to 150	-Rough & Smooth Geomembrane	Crushed Stone
[43]	7	1	Up to 150	-Textured & Smooth Geomembrane	Crushed Stone
[48]	-	-	-	-	Fly Ash Pellets
[47]	50, 100, 150	1-5	-	-Uniaxial Polypropylene Geogrid	Crushed Stone

Table 2.3. Results & Objectives of The Studies Reviewed.

Reference	**Results and Objectives**
[4] Parsons	Three different sizes of shear boxes were used to investigate the scale effect on direct shear testing. Crushed Quartz and Ottawa Sand were used for shearing. Results showed that ϕ' decreases when size increases.
[5] Roscoe *et.al.*	Shear failure doesn't occur at every point of the shearing plane at the same time in the direct shear test. In fact, failure starts from two edges of the shear box and progresses through the center of the specimen. This fact causes lower friction angles than the real values. To overcome this problem a new apparatus was proposed which can allow the volume changes during the shear test with moveable rubber parts.
[6] Palmeira and Milligan	Detailed behaviors of reinforced soils could not be observed properly in small size shearing device. A large size direct shear device was produced to overcome this lack of proper information. The main purpose of the study was to find the effects of different reinforcements on the shearing failures in the sand. Test results articulated that the addition of reinforcements with an inclined way inside the soil increases the shear strength.
[7] Palmeira and Milligan	Scale effect of direct shear boxes were investigated on Leighton sand 14/25. Small, medium and large size direct shear boxes were used for the study. In contrast to small and medium-size boxes, a large size box was produced by the researcher. Results showed that the size effect didn't cause remarkable differences in terms of internal friction angles. However, shear zone thickness and post-peak behavior of sand were affected by the box sizes.

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
[8] Cerato and Lutenegger	The main purpose of the study was to explore scale and specimen size effects on shear strength tests. Shear tests were performed using five different types of sands at different states. Three different size shear boxes were used for scale effect evaluation. Wide ranges of normal stresses were applied on specimens. Results showed that there is an obvious scale effect on friction angle values. Friction angle values decreased when box size increased.
[9] Wu *et.al.*	Size effect, specimen effect and box shape effect on direct shear tests were investigated by using two different soil specimens. Six different types of direct shear apparatuses were used. Direct shear apparatuses were taken from other studies in the literature. Results showed that shear strength of soil differs in size and the shape of the box. Furthermore, there was no obvious specimen effect in Toyoura sand.
[10] Bareither *et.al.*	30 different sands were used to investigate shearing behavior of sands at different gravel contents aim to use as backfill materials. DS, LSDS and Triaxial Compression tests were performed at large displacements for comparison. Results showed that there was no significant difference between shear boxes when gravel content is less than 30%

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
[11] Simoni and Houlsby	The main purpose of the study was to find fraction effects of gravel inside the sand at different percentages and D_{max} values. The large size direct shear device was used to perform tests. Relatively low normal stresses were applied to avoid the crushing effect. Results showed that even a small amount of gravel ingredient increases the peak strength values of tested specimens at the same relative densities.
[12] Vithana *et.al.*	The main purpose of the study was to find a correlation between DS and RSD by using five different landslide soils from the real landslide fields. The reason for seeking correlation was the result of differences between DS and RSD at large displacements. $\Phi_r = 1.0852\Phi - 6.0247$ correlation proposed by the researchers.
[13] Gibo *et.al.*	Two types of soils were taken from real landslides from China and Japan were used to explore the reactivation of residual soils by using a ring shear device. Xuechengzhen soil has more sand and silt content than Kamenose soil. It was observed that reactivation of soils is possible, not as the initial state, under low normal stress values. Additionally, Xuechengzhen soil showed more reactivation than Kamenose, so sand and silt content caused positive effects on the tests.

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
[14] Fannin *et.al.*	The main objective of the study was to characterize friction angles and effective vertical stresses for proper stability analysis. Four different soils were tested in the field. Furthermore, a reconstituted soil sample was prepared and tested as well for shallow slips. Results revealed that normal stress values and grain size distributions directly affect the results. Likewise, if these parameters simulate correctly then reconstituted soils will give similar results.
[15] Yazdanjou *et.al.*	Gravel content effect, as well as the relative density effect, were investigated by using a large size direct shear device in this study. Findings showed that as relative density increases shear strength also increases. Also, gravel content causes an increment in shear strength of the sand more than relative density increment.
[16] Sadrekarimi and Olson	There are three common devices that are used for shearing experiments. Large displacements are very important to understand the behavior of soils. Ring Shear Device seems to be the most appropriate for large displacements. However, it has some drawbacks as well. A new ring shear device was proposed. Triaxial and Ring Shear tests were performed for comparison. Similar results were achieved for constant volume & drained tests from the ring shear device as well as drained & undrained tests from the triaxial device.

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
[17] Lings and Dietz	100mm square direct shear apparatus was modified to eliminate the existing disadvantages of DSA. Wings attached ball races were added to the DSA for reduction of upper box rotation as well as free dilation capability. This sudden softening capability made it possible to observe accurate results at large displacements. Upper shear box rotation did not fully overcome with these modifications. However, the results were not affected drastically by the upper box rotation.
[18] Guo and Su	Two different types of soils were used to investigate the angularity effect of soil particles into the shear strength and dilation. Ottawa sand and crushed limestone were used for exploration. Triaxial compression tests were performed under different normal loads at medium dense state. Findings showed that angularity of soil causes interlocking and dilation which leads to higher strength. Interlocking effect is mostly seen in peak stress ratio rather than the critical state.
[19] Ni *et.al.*	The significance of micro properties on shear strength of granular materials was studied by using the Discrete Element Method computer program. Different particle numbers, sizes, shapes were tested and compared with Leighton Buzzard Sand. According to the results, bulk friction angle was affected from particle size to shear box size ratio up to a level. Friction angle and dilation increase with less spherical particle shapes and interparticle friction angle.

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
[20] Jones and Dixon	This study explores the geomembrane-geotextile interface shear strengths with some additional factors. Textured GM-GTX interface shear strength was found obviously higher than the smooth GM-GTX. Smooth PP geomembranes showed better resistance than HDPE geomembranes. The type of soils above the geotextiles used for the demonstration affected the results. The type of textured geomembrane and cover soil both affected the results. RSD tests showed lower strength values than LSDS due to the lack of cover soils during tests.
[21] Stark *et.al.*	Smooth & textured geomembrane-non woven geotextile, textured geomembrane-drainage geocomposite interface shear strength tests were accomplished in this study for better slope stability designs using geosynthetics. Textured geomembrane interfaces showed 200-300% better peak strengths than smooth geomembranes. Mass per unit area, polymer composition, fiber type and fabric style are important parameters for geotextile in terms of peak strength values rather than residual. Lower mass per unit area geotextiles showed better performances than those higher ones when normal stress was higher than 100kPa. Geocomposite did not affect the interface shear strength remarkably.

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
[22] Akpinar and Benson	The effect of temperature on interface shear strengths was investigated by using smooth & textured geomembranes and non-woven needle-punched geotextile. A special double interface shear device and a specially produced chamber for keeping the temperature as required were used to perform tests. According to the results, both peak and post interface friction angles increased with increasing temperature. However, changing of shear rate did not affect the results noticeably.
[23] Cen *et.al.*	A large size direct shear device was proposed to evaluate interface shear strengths of several soils and geosynthetics. Although the shear boxes were square, they used cylindrical inner frames to avoid normal load concentrations. After monotonic interface experiments the following conclusions were made: GM-Soil tests showed that there is a significant effect of texturing about 12-15% in friction angles. GM(t)-GT results were higher than the GM(s)-GT about 6°-8°. GM-OC experiments did not show remarkable differences with texturing.
[24]	In this study, HDPE geomembrane interface tests were performed to investigate whether field designs are too conservative or not. cont...

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
Negussey *et.al.*	Non-woven geotextile and cohesionless soils were used to find peak and residual interface friction angles at large displacements in the ring shear device. Interface tests showed that angularity at interfaces increased the peak friction angles. No peak behavior was observed in geomembrane-geotextile interface experiments. Finally, it was claimed that RSD considers kinetic frictions which can be less than real static frictions when testing. So, real peaks actually be less than test results and it leads to more conservative designs.
[25] Wasti and Özdüzgün	Interface experiments were conducted at a tilting table, large-scale direct shear and small direct shear devices by using different types of geomembranes and non-woven geotextile. Objectives were to investigate size effect, device effect and normal stress effects on the interface shear strength. Size effect was found as negligible. The tilting table showed a few degrees lower results than the direct shear device on rough HDPE. On the other hand, smooth HDPE results were similar for both shearing devices. A significant strength drop was detected under low normal stress levels when normal stress increased.
[26] Bacas *et.al.*	Interface experiments of five types geomembranes and three types geotextiles were performed to explore effects of roughness pattern, asperity height, fiber length and GTX manufacture. cont...

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
	Results showed that interface strength changes with normal stresses. Lower normal stresses cause superficial friction, whereas high normal stresses cause matrix level friction which is greater. Non-woven monofilament GTX is more appropriate for irregular textured and dense geomembranes. Needle-punched non-woven GTX is more appropriate for evenly spread regular textured geomembranes. Finally, the distance between the asperities is important. Closer means higher friction, however too close acts as a flat surface and causes loss of friction.
[27] Feng and Cheng	Co-textured geomembrane, geotextile and silty clay were used to perform shear strength experiments to see the peak and residual behaviors. The main point of the study was to see the shear behaviors under increased normal stresses and large displacements. Results consistently showed that the peak and residual values are always higher at their first shearing.
[28] Li and Gilbert	Post strength reduction was investigated by using two types of textured geomembranes and two types of non-woven geotextiles at a direct shear device. Tests were proceeded by changing the interface materials one by one. Results revealed that the post strength loss was mostly caused by geomembranes rather than geotextiles. Most severe strength losses were observed when specimens were under high normal stresses.

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
[29] Hillman and Stark	RSD and LSDS shearing experiments were performed to see the effects of different types of geomembranes and geosynthetics on interface shear strength. Tests confirmed that RSD revealed similar results with LSDS under the same conditions. The faille side of PVC GM showed fewer shear resistances than the smooth side of the PVC GM. Post peak strength losses were remarkably less in PVC GM compared with textured HDPE and VFPE GMs. Staple fibers showed better shear resistances than continuous single fibers in NW GTX/ PVC GM. Less mass per unit area geotextiles showed better results in PVC geomembrane experiments. Calendered geotextiles showed better results in faille PVC geomembrane-geotextile tests. Drainage composites without geotextile decreased the friction angles of the interfaces. PVC geomembrane-drainage composite results were similar to textured HDPE-geotextile results.
[30] Feng and Lu	Textured HDPE GM, non-woven geotextile and clay were used to perform interface shear strength experiments. The main point of the study was to compare shear strength results under constant normal stresses and increasing normal stresses. Peak and residual strength values decreased with increased shearing time in both GT/GM and Clay/GM. Around 5°of decrement was observed in repeated shear strength experiments.

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
[31] Stark and Poeppel	Large displacement shearing experiments were performed by using torsional ring shear apparatus. Materials were selected properly for the Kettleman Hills composite liners. RSD showed perfectly consistent results when compared with Kettleman Hills case history direct shear results. Critical interfaces changed according to normal stress values. Geosynthetic interfaces might be more important than clay interfaces depending on the normal stresses, water contents and ingredients of clay.
[32] Kim and Frost	Constraint effect on interfaces was studied by using smooth and textured geomembranes as well as four types of NW geotextiles. Unconstrained NW geotextile-smooth geomembrane interfaces showed lower strength values than constrained conditions. The strength losses were 26% for peak and 33% for residual states. Textured geomembrane-NW geotextile interface results were lower in the unconstrained setup. The strength losses were 38% for peak and 44% for residual states. Finally, glue usage for fixing geotextiles for interface experiments was unrecommended.
[33]	Series of interface experiments were conducted for exploring Kettleman City waste fill facility failure. Smooth GM, geonet, geotextile and compacted clay liner interfaces were tested for their shear strengths.

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
Mitchell *et.al.*	Direct shear device and pull out box test results showed similar residual interface friction angle values. Residual interface friction angles were considered in all judgements. Amount of strength loss between peaks and residuals were quite small for all interface tests. GM/Geonet, GM/Clay and GM/GTX interfaces showed similar results, therefore the starting point of failure was uncertain.
[36] Elmas	Internal and interface shear strength tests were performed in a specially designed large scale shearing device. The aim was to explore the performance of landfill cover materials at large horizontal displacements. A newly designed large scale large displacement shearing device was used to reach large horizontal displacements without area correction. Crushed stone shear strength results were found lower than the literature. All interface results, however, showed higher shear strength values, even at large displacements, than the literature.
[40] Yıldız	A large scale device was proposed with pneumatic artificial muscles. Artificial muscles were used to apply normal forces and shear forces during shearing. Application of loading was realised by filling the muscles with air. The use of artificial muscles in geotechnical engineering was recommended.

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
[41] Baykal and Akkol	A new interface device was proposed under the name of GICT. A cylindrical block was covered with geotextile and planted inside the sand storage. Results were compared with 100mm-100mm direct shear device. According to the promising results, GICT was reflected as a convenient apparatus for soil geotextile interfaces.
[42] Baykal	An alternative normal loading element was presented to be used in the direct shear experiment. Artificial pneumatic muscles were offered as a loading element rather than pneumatic cylinders. Contraction due to its structural type makes it possible to apply normal and cyclic loads. The capacities are quite high and the application is also really simple. As a result, this artificial muscles could be used widely in geotechnical engineering.
[2] Baykal	A new large scale large displacement shearing device was presented. Several modifications were conducted to eliminate existent limitations like area correction. Crushed stone versus rough&smooth geomembranes were used for confirmative interface experiments. Results indicated that smooth GM versus crushed stone mobilized instantly and continued that way. Rough GM versus crushed stone showed a peak at 50mm displacement and then strength loss was observed.
[43]	Series of shear and interface tests were conducted using smooth&textured geomembrane and crushed stone. The aim was to observe the crushed stone effect on geomembrane.

Table 2.3. Results & Objectives of The Studies Reviewed. (cont.)

Reference	**Results and Objectives**
Baykal *et.al.*	Peak internal friction angle of crushed stone was found as 37.6°. Interface friction angle of textured geomembrane was found as 45°.
[48] Baykal and Döven	According to the statistics, only a small portion of the fly ashes is regained and used in construction industry. This small portion is mostly used in concrete production. So, the use in terms of geotechnics is negligible. This study presents the production of fly ash pelletization for landfill usages. Various tests were performed to evaluate their features. Internal friction angles of the specified pellets were found between 29°- 45°. It was concluded that the fly ash pellets could be used in geotechnical engineering projects.
[47] Baykal and Dadasbilge	A pull-out device was manufactured by modifying a LSDS. Crushed stone and uniaxial polypropylene geogrid were used in pull-out tests. Results showed that the device should be improved for better outcomes. However, the general behavior of the product could be obtained by using the presented device.
[49] Baykal *et.al.*	A unique multipurpose large scale shear device was designed and manufactured in the scope of BAP 5580 project. The device has a unique system. Normal loads and cyclic loads are applied with pneumatic artificial muscles. The top box is used for lateral loading instead of lower. The lower box is three times larger than the upper box.

One of the earliest studies was performed by Parsons [4]. Three different size direct shear boxes were used to investigate whether there was a size effect or not. Quartz sand and Ottawa sand were used in shearing experiments. Dimensions of the boxes were 60mm-60mm for small size, 100mm-120mm for medium size, 120mm-200mm for large size. Also, 120mm sides were used in the shearing directions. All specimens were at loose state. Results showed that Quartz Sand ϕ's were between 30.7° - 31.5° and Ottawa Sand ϕ's were 28.5° - 31.0°. Finally, it was concluded that internal friction angles decreased slightly when the shear box sizes were increased.

Shearing failure starts simultaneously at every point of the shearing plane in real cases. On the other hand, during the laboratory testing, shearing failure starts at the two edges of the shearing box and progresses through the center of the shearing plane. This unrealistic behavior causes low internal friction angles according to the Roscoe *et.al.* [5]. To overcome this problem, a new shearing box was manufactured which could allow volume changes during shearing. Moveable rubber parts were added to the direction of movement for achieve volume changes. Plasticine was used as a specimen. Plasticine samples were cut with cheese wire at one-centimeter intervals after placement of the specimen in the shear box. The reason behind cutting the samples and create stripes was to observe the deformations after shearing. The shear box should be designed in such a way that it could be removed part by part and be inspected, without distortion. Two different normal loads were applied during the tests which were 10 lbs and 400 lbs to observe what happened under low and high normal stress values. Results showed that the specimen which was inside the normal shear box was deformed more than the proposed shear box.

"Observing the effect of the reinforcement inside the soil using the conventional shear boxes is not reliable" said Palmeira *et.al.* Therefore, reinforcement tests should be performed in a large size shearing device [6]. A large size direct shear device that had 1m*1m*1m dimensions was manufactured to perform reinforced sand shearing experiments. The normal stress value was 30kPa, the rate of shear displacement was

0.5mm/min and horizontal displacement was 60mm for all tests. Internal friction angle of sand was found as 49.4° without any reinforcement. Galvanised metal grid, polymeric geogrid, woven geotextile from polyester, smooth & rough metal strip were used as reinforcement materials. Reinforcements were placed at 30° inclination. Results revealed that reinforcement inside the soil increased the shear strength. High normal stresses were excluded, 30kPa in this study, by bond failures. The effect of reinforcement deformation, for example bending, was found as insignificant. Finally, the limit equilibrium method that uses peak conditions for failure analysis was considered improper to estimate the results.

Leighton Buzzard sand was used to explore the size effect of different size shear boxes in direct shear testing by Palmeira *et.al.* [7]. The sand was chosen because the same sand was already used by some other researchers and it would be appropriate to use the same soil to compare the results. Three sizes of shear boxes were used in the tests which were small size (60mm*60mm*32mm), medium size (252mm*152mm*152mm) and specially manufactured 1000mm*1000mm*1000mm shear boxes. 30kPa normal stress was applied in all tests. After the shearing tests, the internal friction angles of Leighton Buzzard sand were found as follows; small (50.1°), medium(50.2°), and large(49.4°). Despite common shear stress vs. horizontal displacement graphs, shear stress normalized with vertical stress versus horizontal displacement normalized with shear zone thickness graphs were used to interpret the behavior of the sand at different sizes of shear boxes. According to the results, the size difference of the shear boxes did not change the internal friction angle values significantly. However, the shear zone thickness and the post-peak behavior of sand remarkably changed when different size shear boxes were used. Even after the critical state was reached in the small box, the sand continued to dilate in the large size shearing box.

The scale and specimen size effects in shear strength experiments were studied by Cerato *et.al.* [8]. Five different sand at wide range of normal stresses were tested to be sure of the sample behaviors. Each sand was prepared at three different states which were loose, medium dense and dense. Each test was repeated five times for accuracy. Three different specimen preparation techniques were used on sands. The moist compacted technique was used on Winter sand and Brown Mortar; Ottawa and Morie sand samples were prepared by using dry pluviation technique and Gravel Pack samples were prepared by spooning & tamping. The reason behind the use of different preparation techniques for sampling was to compare with existing studies in the literature. Generally, results showed that peak friction angles decreased when the box size increased, nevertheless it was not possible to observe peak behavior in each test, hence, constant volume friction angles were used for evaluation. One final point was that Ottawa sand was found to be the least affected soil in terms of the specimen size. The effect considered as negligible.

The scale, shape and specimen type effect of shear strength tests were performed by Wu *et.al.* [9] with using different direct shear apparatuses. Poorly graded Toyoura Sand and well-graded sandy gravel were chosen for testing. Six different kinds of direct shear devices were used. All of them were taken from other studies in the literature and were discussed in detail. According to the results, the shape effect exists in direct shear tests. Disk shape shear box gave more progressive results than the rectangular shape shear box. Consequently, use of rectangular shear boxes were advised. Followingly, the scale effect existence pointed out. Thus, shear strength decreased when box size increased. Finally, no specimen effect was observed in Toyoura sand which was a uniform rounded type of sand.

30 different sands were chosen to be used as backfill materials for MSW walls [10]. The main idea was to add gravel (0% - 30%) inside the sand and observe the shear behavior differences. Also, the behaviors of different shear apparatuses at large displacements were investigated. That's why small size and large size direct shear boxes as well as triaxial compression devices were used in the shear strength experiments

with sand. Results showed that friction angle differences between SSDS and LSDS test results were less than 4°(less than 2°most of the cases). According to the researchers, if gravel content was less than 30%, the results would be similar to those obtained from the large size direct shear devices and SSDS could be used in such specimens. Furthermore, the repeatability of the tests in three test devices was highly possible. Finally, some of the LSDS tests showed gradual stress increments at large displacements and this effect was caused due to the force concentrations by particle movements at the front side of the upper box and the backside of the lower box.

The gravel effect of sand in terms of friction angle and dilatancy was studied by Simoni *et.al.* [11]. A large size direct shear device was used to perform the tests. Eightyseven tests were performed at different relative densities in total. Leighton Buzzard Sand was used as the main soil. Gravels had 6mm and 20mm D_{max} values. 90.8kPa was applied to prevent grains from crushing effects. Results revealed that peak strengths at the same densities increased with gravel fractions even the amount of fraction was low (0.1-0.2). Finally, further studies and experiments were advised to explore the effects of mineralogy, grain shape and confining pressure of gravels that were used in the experiments.

The ring shear device and the direct shear device test results at large displacements were significantly different than each other according to the Vithana *et.al.* [12]. Observations showed that direct shear device achieved large displacements with reversal movements and this could not simulate the field conditions properly. Oppositely, the ring shear device appropriately simulated the field conditions and could be used to achieve very large displacements. However, due to the easy establishment and cost-effectiveness, the DS device is still a commonly used device in the literature. Thus, a correlation could be a good solution to achieve accurate results from tests. To achieve that shearing tests were performed by using five different landslide soil specimens at direct shear and ring shear devices.

According to the results, the following correlation was proposed in this study.

$$\Phi_r = 1.0852\Phi - 6.0247 \tag{2.1}$$

Φ_r represents friction angle from ring shear device and Φ represents friction angle from direct shear device [12].

The reactivation of residual soils was investigated by Gibo *et.al.* [13]. Two types of soils were used to perform large displacement shear tests which were taken from real landslide areas in Japan and China. The Xuechengzhen soil had more sand and silt contents than the Kamenose sand. The ring shear device was chosen to achieve large displacement ratios for the tests. According to the results, reactivation (gaining its strength again) of soils was possible and it gave better results when the sand and silt ratio was higher. Also, reactivation occured more obviously when low normal loads were applied otherwise, there was not a big difference between the residual state and reactive state.

The grain size distribution and vertical effective stress relations were investigated by Fannin *et.al.* [14] to characterize them properly for further studies. Four sand-based soils were tested directly on the field by using a large size direct shear device. All the specimens were belonged to the shallow slip areas. According to the grain size distribution of field specimens, a reconstituted soil was prepared in the laboratory and tested by using the same large size direct shear device. Low effective stresses were applied to simulate field conditions better (5-20kPa). Specimens were sheared 60mm. Test results confirmed that the amount of normal stress and grain size distribution played a vital role in shearing tests. If field conditions were well simulated, reconstituted soils would give similar results with those of real field specimens.

The gravel effect as well as the relative density effect on shear strength were studied by Yazdanjou *et.al.* [15] with using a large size direct shear device. Babolsar sand was used as the main soil which was a uniform soil. Direct shear tests were performed by changing the relative density as well as changing the gravel content. 35% (loose), 60% (medium dense) and 85% (dense) relative densities were used in tests. Gravel contents were 20%, 40% and 60% in tests. Findings revealed that both gravel content and relative density increments showed a positive effect on the shear strength. Additionally, the effect of gravel increment in shear strength was found more than the relative density increment effect.

The importance of knowing the shear behavior of the sands at large displacements for geotechnical designs was marked by Sadrekarimi *et.al.* [16]. Three common shearing devices in the literature were investigated for their large displacement capabilities which were direct shear device, triaxial device and ring shear device. Direct shear devices and triaxial devices were eliminated because of limited displacement capabilities. The ring shear device has the advantage of large-displacement capabilities but it has also disadvantages like nonuniform stress-strain distributions, soil extrusion, complicated undrained testing preparation and wall friction. So, a new ring shear device was designed and produced to eliminate those problems as much as possible. Following modifications were done to overcome the problems,

- Correct ring dimensions were selected for prevention of nonuniform stress-strain distributions.
- Wall friction was measured by auxiliary load and torque cells.
- Quad rings were used to prevent soil extrusion in tests.

Triaxial and ring shear tests were performed for comparison purposes by using the Mississippi River sand which was silty, fine-grained sand. Findings were consistent in terms of friction angles. Results also confirmed that the triaxial device could not reach the desired amount of large displacements.

The disadvantages of commonly used direct shear apparatus were investigated and a modified shear apparatus was proposed which could eliminate those disadvantages [17]. Leighton Buzzard 14/25 sand was used in tests. Most of the tests were performed in the dense state under 25kPa normal stress. The upper box rotation, restricted vertical displacement and the inaccurate horizontal loads caused by friction of O ring seals were tried to be eliminated. The symmetrical approach was followed to eliminate those problems. Wings were attached to prevent load pad jammings and upper box rotations during shearing. After the wing modification, sudden softening behavior was observed as it should be and inaccurate friction angles at large horizontal displacements were also eliminated. The gap size of $5D_{50}$ was applied with rubber edging to avoid false high strength which was a common problem of 0.5mm gap size. The upper box rotation was blocked completely with the symmetrical testing. But, it was revealed that the effect of upper box rotation on the results were not that important.

The angularity effect of particles to the shear strength and the dilation of the soils were investigated by using two types of soils [18]. Ottawa sand and crushed limestone were used as rounded and angular samples respectively. Triaxial compression tests were performed under 100kPa, 200kPa and 500kPa normal stresses at medium dense state. Findings showed that shear strength increased with angularity and certainly affected the dilation. Furthermore, angularity effects were observed more prominently in peak stress ratio rather than the critical state. Also, researchers commented that the internal friction angle at the critical state might differ from reality since the uniform deformation at large displacements was hard to simulate in a triaxial compression test.

The DEM computer program was used by Ni *et.al.* [19] to observe the effects of micro properties of angular materials. Leighton Buzzard sand was used to compare computer results with the real results. Tests were performed by changing the shapes, sizes and the number of particles at large horizontal displacements. The commonly used direct shear box which was 60mm square, 20mm deep was used in both reality and simulations. Simulations showed the following outcomes,

- Mobilised friction angle decreased with normal load increments.
- Less spherical particle shape meant more friction.

- Residual strength and dilation remarkably affected from particle size to shear box size ratio, dilation and residual strength decreased with particle number increments.
- Deformations occurred in the 10mm center zone of the samples for both real and simulation tests.

An extensive study on geotextile geomembrane interfaces was accomplished by Jones *et.al.* [20] using the large scale direct shear apparatus and the torsional ring shear apparatus. Furthermore, some factors were changed to see their influences on the interface shear strength. Three different types of soils were used above the geotextile during the LSDS tests to demonstrate the field conditions. Likewise, smooth, HDPE textured, PP textured geomembranes were used for tests. The non-woven needle-punched geotextile was used in all tests. The whole study was performed under large displacements and a relatively high rate of shearing that was 3mm/min. The results were extensive and remarkable,

- Lower density and thinner geotextiles showed better peak strength values.
- Residual interface strength was independent of the cover soils or nylon block.
- HDPE geomembrane showed better interface shear strength values by using angular cover soils whereas PP geomembrane almost un-affected.
- Smooth geomembrane interfaces reached peak strengths at remarkably lower horizontal displacements than textured geomembrane interfaces.
- Textured geomembrane interfaces had more strain-softening than those performed with smooth geomembranes.
- Nylon block cover was a suitable material for cover soil simulation.
- Due to the lack of cover soils, RSD test results were lower than the LSDS results. Also, complete rotations caused the loss of strength in interfaces as well.

Textured & smooth geomembrane/geotextile and textured geomembrane/drainage geocomposite interface shear strength tests were performed by Stark *et.al.* [21]. The aim was to make better slope stability analyses and designs using geosynthetics. Three different types of textured geomembranes, five different types of non-woven needle-punched geotextiles, one type of smooth geomembrane and one type of drainage geocomposite were used in interface shear strength tests. The torsional ring shear apparatus was chosen because of the unlimited horizontal displacement capacity.

- Textured geomembrane showed 200-300% more peak shear strength values than the smooth geomembrane interfaces. However, the post strength loss was 50-60% higher than the smooth geomembrane interfaces.
- Large denier continuous single polypropylene fiber type showed better results than staple polypropylene and polyester type fibers when there was no other different parameter between geotextiles. Also, it was added that differences in fiber type lost their effect after 900-1000mm horizontal displacement [21].
- Calendering increased the shear strength of geotextile-textured geomembrane interfaces 10-20% at peak, 20-30% at residual states.
- Drainage geocomposite interfaces did not show obvious differences than those non-woven geotextile interfaces under 500kPa normal loads.
- 270 g/m^2 non-woven geotextile showed better peak strengths than 540 g/m^2 non-woven geotextile interface for more than 100kPa normal stresses.

The effect of the temperature on interface friction angles was investigated by Akpinar *et.al.* [22]. HDPE smooth & textured geomembranes, as well as non-woven polypropylene geotextile, were used. A double interface shear device proposed by Gilbert *et.al.* [37] was used in the tests. Also, a specially produced chamber was used to keep the desired temperature when tests proceed. The chamber had dimensions of 500mm length, 550mm depth and 260mm width. Testing temperatures were 0°C, 10°C, 21°C and 31°C. Tests were performed under three rate of displacements which were 0.9, 1.1 and 1.5 mm/min. The amount of horizontal displacement was only 25mm because of the DISD limits. Results showed that both GMS-GTX and GMT-GTX interface friction angles increased with increasing temperatures, 2-3°from 0°C to 33°C to be exact. On the other hand, changes in the rate of displacements did not create a noticeable difference in terms of interface friction angles.

A large size direct shear device was proposed to perform extended interface experiments by using HDPE textured & smooth geomembranes, geotextile, fine sand, sandy gravel, ordinary concrete and no-fines concrete [23]. Although the shear boxes were rectangular, an inner frame that was cylindrical was implanted to perform soil-GM experiments. The reason behind the use of a cylindrical frame was to avoid load concentrations during tests. A trapezoidal-shaped smaller upper box was used for GM-GT interface experiments. A smaller upper box aimed to rule out area corrections. Findings showed that there was a significant texture effect between soils and geomembranes. It changed according to the soil gradation and size as well. The use of textured geomembrane increased internal friction angles about 12-15%. Furthermore, GM-GT interfaces, also, were affected by textured geomembrane usage about 6°-8°. Followingly, ordinary concrete interfaces did not show an obvious texturing effect in contrast with no fine concrete interfaces. All in all, it was claimed that the proposed large size direct shear device confirmed the previous works in the literature and could be used for further studies.

The HDPE geomembrane interfaces were investigated by Negussey *et.al.* [24] using U.B.C. ring shear apparatus which was proposed by Bosdet [38]. Non-woven geotextile, Ottawa sand, concrete sand and angular heap gravel were used for geomembrane interface experiments under 50kPa to 1000kPa normal stresses. Normal stress effect on residual strength was negligible at concrete sand-geomembrane-gravel interfaces. Secondly, the use of thinner geomembrane did not show peak or residual interface angle increments due to the higher dilatancy. Geomembrane-geotextile interfaces did not show peak behavior. So, there was almost no difference between residual and peak interface friction angles. Finally, it was added that using kinetic resistances in tests showed smaller friction angles than using static resistances and this led engineers to make more conservative designs than necessary.

The interface shear strengths by using smooth & rough HDPE geomembranes, PVC geomembrane and non-woven needle-punched geotextile were studied by Wasti and Özdüzgün [25]. Three different shearing devices were used to see the size effect and device effect on the interface shear strength. Also, different amounts of normal stresses were applied to find their effects. Findings of smooth and rough geomembrane interfaces showed that interface size was not obvious or remarkable. Direct shear device results were a few degrees higher than the tilting table results. Differences were obvious, especially in rough geomembrane interfaces. One of the most important findings of the study was sudden strength drops under low normal loads. When normal loads were slightly increased, sudden strength loss was observed. However, these strength drops were only valid for low normal stresses.

The effects of roughness pattern, asperity height, fiber length and geotextile manufacture on interface shear strength was focused by Bacas *et.al.* [26]. For this purpose, three types of non-woven geotextiles were used which were needle-punched monofilaments, needle-punched staple fibers and thermally bonded monofilaments. Also, five types of geomembranes were used which were smooth surface, irregular heavy textured and regular evenly spread asperity. Large scale direct shear device was used in all tests and all tests were performed under 25 to 450 kPa normal stresses. With these extended ranges of normal loads, effects of low and high normal loads were also investigated. After all these experiments, the following outcomes were reached,

- Interface shear strength depends on normal stress levels. Low normal stresses show superficial frictions whereas high normal loads show matrix friction which causes higher interface shear strengths.
- Non-woven monofilament geotextile was recommended to use with the irregular textured dense type of geomembrane.
- Non-woven needle punched filament type geotextile was recommended to use with evenly textured regular geomembranes, especially under high normal stresses (bigger than 100kPa).

- Monofilaments showed better frictions than staple fibers under low normal stresses (smaller than 100kPa).
- Distance between asperities affects strength properties. Less distance means more friction and more shear strength. But it should be included in the calculation that if asperities become so close the system may act like a flat surface which causes loss of friction and shear strength.

The soil/geomembrane and geotextile/geomembrane interfaces were performed by Feng *et.al.* [27]. The co-textured HDPE geomembrane, non-woven geotextile and silty clay with silty sand soil were used to perform experiments at large size direct shear device. The original point of the study was to shear the materials under increased normal stresses and displacements at once. In this way, the real behaviors and friction angles of selected materials could be found. As a conclusion, geomembrane geotextile interfaces reached their peak values around 2mm displacements whereas geomembrane soil interfaces reached 5-10mm displacements. Furthermore, geomembrane geotextile interfaces showed more softening behavior than geomembrane soil interfaces. The percentage of softening behaviors were 20% and 15% respectively. One other important finding was that peak strengths reached higher displacements when they first sheared. Likewise, the peak friction angles were higher when materials first faced with shearing. Finally, the real friction angle was the result of progressive shear strength experiments which were lower than constant normal stress shearing experiments.

Post shear strength loss of interface experiments were studied by Li and Gilbert [28]. Co-extruded, laminated HDPE geomembranes as well as the polyester & polypropylene continuous filament non-woven needle-punched geotextiles were used to perform interface shear experiments. All tests were carried out by using a small direct shear device that had a diameter of 60mm. A lower shear box was replaced with a wooden plate to increase shear displacement without area loss. Additionally, tests were conducted incrementally to reach the desired high shear displacements. Also, the tests were performed in a double interface shear device for comparison purposes. Tests were executed again and again by changing normal stresses, geomembranes and geotextiles.

Results showed that only a small portion of strength loss was recovered by changing the geotextile with a new one before the next increment. However, replacing the geomembrane with a new one was regained its strength more than 70% at high normal stresses even though there was no feasible damage on geomembranes.

Interface experiments were performed using different types of geomembranes and geotextiles to observe their effects [29]. In this way, MSW landfill areas could be designed more effectively. Torsional ring shear apparatus was chosen for the tests, however, a large-scale direct shear device was also used for limited numbers of experiments to prove that RSD shows similar results with LSDS. After the tests following outcomes were reached,

- Limited tests gave similar results between RSD and LSDS under 192 or 200kPA normal stresses.
- Smooth side of the PVC geomembrane showed better friction angle values than the faille side due to the higher flexibility and contact area.
- Post peak strength loss was remarkably less in faille PVC geomembrane-NW geotextile interfaces than textured HDPE and textured VFPE geomembrane-NW geotextile interfaces. The reason behind this fact was texturing demolished the geotextile more than PVC faille geomembrane, during shearing.
- Staple fiber nonwoven geotextile had more strength than continuous single fiber NW geotextiles during shearing. Because continuous single fibers are long and get damaged more severely during shearing.
- 205 g/m^2 mass per unit area NW geotextile showed higher strength values than 540 g/m^2 NW geotextile. The explanation was that number of fibers damaged by shearing was more than lightweight NW geomembranes.
- Since the calendered geotextiles had rougher surfaces, their shear strength values were greater than those that were not calendered.
- Geotextile in drainage composites helped to get higher resistance values than those drainage composites which did not include geotextile but geonet.

Effects of repetitive use and increasing normal loading in interface shear strength were investigated by Feng *et.al.* [30] with using non-woven polypropylene geotextile, textured HDPE geomembrane and clay. A large size direct shear device was chosen as a testing apparatus. The main point of applying increasing normal loads was to simulate the real loading system in MSW structure. The GT/GM interfaces under different constant normal stresses and their repetitions are plotted in the study. An apparent outcome was that peak and residual strength decreased when the same specimen was used again. Furthermore, virgin specimens reached the peak values at larger shear displacements than the used specimens. Increasing normal loading which is more likely to a real case decreases the strength of the interface. Like repetitive usage curves, increasing normal loading during the experiment shortened the distance of reaching peak strength. Finally, the peak and residual interface friction angles decreased with increasing the normal stress during tests rather than keeping them constant.

Interface shear strength experiments of non-woven geotextile, HDPE geomembrane, geonet and clay were performed by Stark and Poeppel [31] with using torsional ring shear device. Interfaces were ordered according to the Kettleman Hills case history. Therefore, secondary clay/secondary geomembrane and geotextile/geomembrane results were compared with each other. First of all, the ring shear device gave perfectly consistent results when compared with the Kettleman Hill case direct shear results. Secondly, the importance of the interfaces changed according to the changing normal loads. Thus, geosynthetic to geosynthetic interfaces were more critical than SC/SG interfaces if the amount of normal stresses was under 280kPa. As expected, if normal stresses were higher than 280kPa, then SC/SG interfaces were more critical than geosynthetic to geosynthetic interfaces. Furthermore, since SC/SG interfaces were functions of water content, normal stress and type of soil, it could be said that geotextile/geomembrane interfaces could be more critical and they should definitely be considered in the design [31].

Constraint effect on interfaces was studied by Kim and Frost [32]. Testing materials were chosen as smooth & textured HDPE geomembrane, as well as four types of non-woven needle-punched geotextiles, due to their widely use in literature. Geotextiles were chosen in a way that mass per unit area, raw material and producer could be compared.

Lower mass per unit area value geotextile showed better strength results both in constrained and unconstrained conditions. Also, it was added that light geotextile needed more shear displacement for reaching peak strength values.
Results showed that unconstrained interfaces had lower strength values at each interface experiments. The amount of strength losses was around 26% and 33% for peak and residual states respectively in NW geotextile-smooth geomembrane. Likewise, strength losses were 38% and 44% for peak and residual states respectively in NW geotextile-textured geomembrane interfaces.
Furthermore, it was found that the most important features of the interfaces in terms of shear resistance were geotextile filament elongation and texture damage in geomembranes. Finally, it was concluded that the unconstrained mechanism showed lower strength results and represented the field conditions better. Thus, glue usage for fixing geotextiles was unrecommended.

A slope failure occurred in Kettleman City in 1988. Lateral displacements of 35ft and vertical displacements of 14ft were observed during failure. The waste facility consisted of multiliner systems. Investigators felt suspicious from these interfaces. Thus, it was needed to be investigated to prevent possible failures in the future. Mitchell *et.al.* [33] performed interface shear experiments to find out that what was the real cause of failure in Kettleman city waste fill structure. For these purposes, smooth HDPE geomembrane, HDPE geonet, geotextile and clay were used. Besides direct shear experiments, pull-out experiments were also performed for confirmation. Findings showed that residual interface friction angles of both devices were similar. Loss of strength between peak and residual values were quite small, therefore residual strengths were used in judgements. Combinations of interface experiments showed similar residual values. Thus, the exact starting point of the failure could not be decided from these tests. But, it was pretty certain that failure started from one of these interfaces.

Internal and interface shear strength experiments were performed by Elmas [36] to explore the landfill cover material performances at large horizontal displacements. For this purpose, a specially designed large scale constant contact area direct shear device was used [49]. The amount of horizontal displacements were up to 230mm. Since the target of the study was landfill covers, the crushed stone which had 19mm Dmax value, non-woven needle-punched geotextile and HDPE smooth&textured geomembranes were used as testing materials. After experiments, the peak internal friction angle of crushed stone was found as 37.6°which was lower than the literature. During all shearing tests bulging occurred in front of the upper box. On the other hand, interface shear strength experiment results were found higher than the literature for both geomembrane types even at the large displacements. Interlocking between the crushed stone and the geotextile might have caused this disfunctioning according to the Elmas [36].

The implementation of artificial pneumatic muscles into geotechnical engineering was studied by Yıldız [40]. Pneumatic muscles were implemented to the shearing device because of their higher power/weight ratio, cost-effectiveness and easy application than its rivals. Additionally, the presented device had a larger lower shear box to avoid area decrements during shearing [49]. Furthermore, the size and the set up were chosen according to the ASTM direct shear and interface shear strength experiment standards.

An alternative apparatus for interfaces called as geotextile soil interface cylindrical test device (GICT) was proposed by Baykal and Akkol [41]. During the preparation, a cylinder block was covered with geotextile by clamping or gluing and then placed into its chamber before the soil implementation. Normal loads were applied with air pressure bags.

Results were determined according to the torque transducer's data. It was observed that the contact efficiencies were lower than the 100mm-100mm direct shear results. Besides that, results were comparable and considered as a promising alternative shearing device.

An alternative element to apply normal and shear forces in the direct shear experiment was presented by Baykal [42]. A pneumatic artificial muscle was advised rather than a pneumatic cylinder, airbag, etc. Also, an artificial muscle that has a 40mm diameter can be loaded up to 6500 N theoretically. But its capacity decreases with loading because of its contracting behavior. Furthermore, a newly developed large size large displacement shearing device was presented. The device had distinct features like smaller upper box, upper box movement and normal loading with artificial pneumatic muscles. Finally, a framed system of large scale direct shear device was eliminated; artificial pneumatic muscles are practical and possible to be used in every geotechnical laboratory; its structure also capable of applying cyclic loads; applying cyclic loads make the device adequate to perform pile tests; it can apply normal loads always at 90°whichever the horizontal displacement is, thanks to its railed system.

A newly designed large-scale shearing device was explained by Baykal [2]. The device was designed to eliminate some common DS device limitations like area correction, unwanted upper box movements and limited horizontal displacements. The apparent differences were upper box movement instead of the lower box; three times larger lower shear box than upper box; pneumatic artificial muscles for normal loading; lateral artificial muscles for cyclic loading. After the design and production, some interface experiments were performed to see the device's performance in practice. To do that, rough&smooth geomembranes and crushed stone which had Dmax values between 16mm to 23mm were used in interface experiments. According to the results, smooth geomembrane crushed stone interfaces showed an instant mobilization and then kept their strength till even at large displacements. On the other hand, the rough geomembrane crushed stone interface experiment showed two peak attempts at 50mm and 60mm. After that sudden loss of strength was observed.

The effects of crushed stone over geomembranes as an illustration of waste landfill cover was studied by Baykal *et.al.* [43]. Series of internal and interface shear strength experiments were performed using a large-scale shearing device. Using a large size of materials and constant contact area led researchers to use this mentioned shearing device. All tests were applied under large horizontal displacements. Peak internal friction angle of crushed stone was found as 37.6°, also a bulging behavior in front of the upper shear box was observed. Besides that, the residual friction angle was found as 58°. Furthermore, the interface friction angle of textured geomembrane versus crushed stone was found as 45°. Finally, unexpected deformations in the geomembranes were observed despite very low normal stresses.

Fly ash pellets were used in wide geotechnical tests for its geotechnical applications [48]. Since the negligible portion of the fly ash pellets were used in geotechnical projects, possible application areas of the fly ash pellets were explored. In this point of view, one of the tests was the direct shear test for landfill purposes. The size of the pellets was near to the gravels and that's why a large-scale device was manufactured for testing. Internal friction angles of the different groups of pellets were found between 29°-45°. After all test results, it was concluded that fly ash pellets could be produce according to the needs and could be definitely used in geotechnical projects.

A new pull out setup was presented by Baykal *et.al.* [47] using a multipurpose large-scale shearing device. The device was modified for pull-out testing of crushed stone and uniaxial polypropylene geogrid according to the ASTM standards. Tests were performed under 50kPa, 100kPa and 150kPa normal stresses. Rate of displacements was between 1-5 mm/min. Main parameters of the tests were normal pressure, displacement rate and specimen width. Other parameters were not included in calculations because of the device limitations. Findings showed that device needed futher improvement for detailed testing outcomes. However it could be used for basic inferences.

A multipurpose large size large displacement shear device was designed and manufactured by Baykal [49]. The device was manufactured as a part of BAP 5580 Scientific Research Programme. The device is unique on several points. Pneumatic artificial muscles were used to apply normal and cyclic loads. PLC controlled step motor was used to apply horizontal loads. Difference size shear boxes were used. The lower shear box was produced three times longer than the upper shear box. Area decrements during shear were eliminated with this approach. Also, the device is capable of horizontal displacement capacity up to 600 mm theoretically. Upper box movement during shear made it possible to conduct several types of experiments: pile testing, pull out tests, cyclic loading with stress control, interfaces and direct shear testing. Finally, the device was found as a valuable tool for geotechnical laboratories.

3. METHODOLOGY

Two different kinds of direct shear devices were used to evaluate the shear strength behaviors of sand and interface shear behavior of geotextile and geomembrane. First one was the traditional direct shear device which is the most common device for determining the shear strength of soils. Second one was the large size large displacement shearing device [2]. All tests were performed according to ASTM 3080 [34] and ASTM 5321 [35] standards.

Following sections describe testing apparatuses, testing materials and testing conditions.

3.1. Testing Apparatuses

Two types of shearing devices were used to evaluate the shear strenghts of soils. First one was traditional direct shear apparatus and the second one was specially designed large size and large displacement shearing device.

3.1.1. Traditional Direct Shear Apparatus

Traditional direct shear device was used to perform shear and interface shear experiments. The tests were performed to evaluate the shear strength parameters. Test results were compared with the large size large displacement shear device and the literature.

Figure 3.1. Traditional Direct Shear Device.

Figure 3.2 shows 60mm-60mm shear box which was used in this study. 25kPa, 50kPa and 75kPa normal stresses were applied to the specimens to evaluate the shear strength behavior of the target specimen which was Akpınar sand. Further information about soil is provided under the testing materials section.

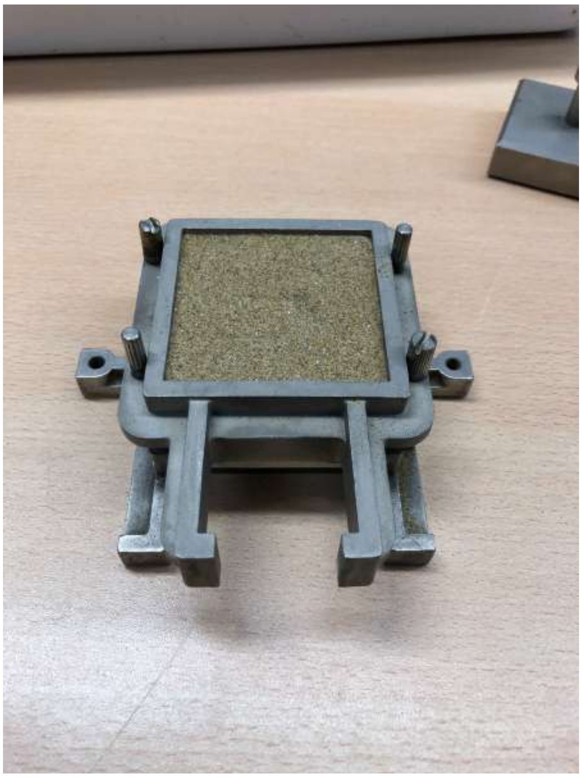

Figure 3.2. Shear Box 60mm-60mm.

3.1.2. Large Size and Large Displacement Direct Shear Device

In this thesis, the large size and large displacement direct shear device was used to perform shear strength experiments on sand, geomembrane and geotextile. Figure 3.3 shows the general view of the device. The device is one of the innovative apparatuses which have been designed and produced over the years in Geotechnical Laboratory at Bogazici University [44].

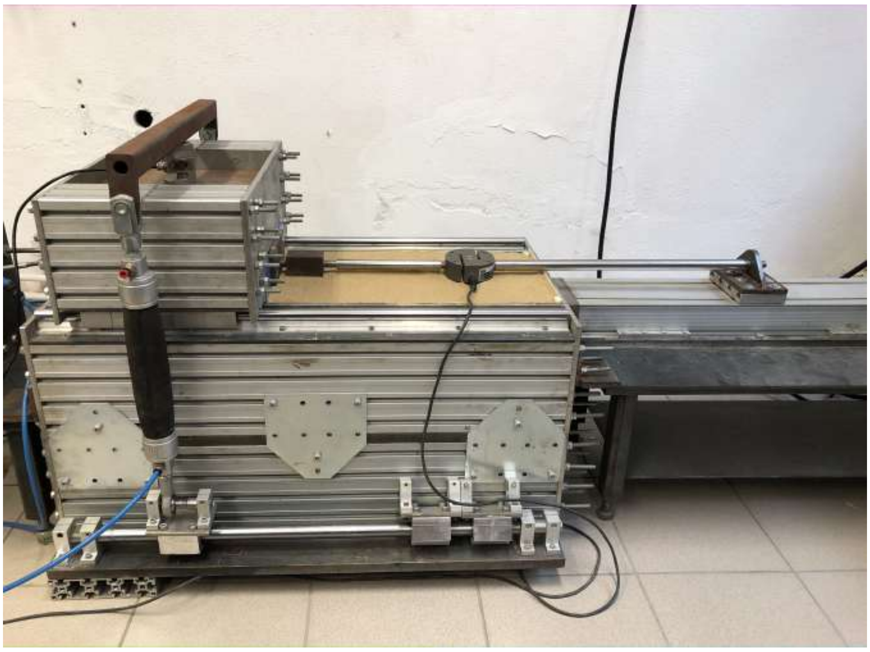

Figure 3.3. Large Size and Large Displacement Shearing Device.

The device consists of a large lower box, upper box and stepper motor linear actuator system which is located at the right side of the device. Lower box has 300mm width, 900mm length and 400mm depth. Additionally, lower box depth can be adjusted in two different combinations. It can be arranged as 400mm depth or 200mm depth. Further depth requirements can be achieved by using rigid materials. Wooden plates were used for this purpose in this study. Upper box has 300mm width, 300mm length and 200mm depth. On the contrary to traditional shearing devices, upper shear box moves in this device. Lower box was designed three times longer than the upper box to achieve large amount of displacements without area corrections. This device can perform a shear test more than 300mm horizontal displacement. Higher amount of horizontal displacements can be achieved by simple modifications.

The device uses two to six, pneumatic artificial muscles for normal loading. Muscles were produced by Festo. Specifically, DMSP-40-250N- RM-RM model was used in this device. Muscles have 40mm-250mm dimensions, diameter and length respectively. Additionally, it has 6500 N maximum capacity and it can contract 25 percent of its length. Thus, 13000 N normal load can be applied in the current state. If the number of muscles are increased (ex.6 muscles) this capacity can reach up to 39000 N.

The pneumatic muscles are attached to the rails which are located bottom two sides of the lower shear box. Muscles can move on these rails with the upper shear box. Followingly, normal loads are applied always perpendicular to the shearing plane. The muscles are attached to a metal beam on top of the upper shear box. This metal beam is used to transfer loads to the soil. Upper side of the muscles are attached to the beam with rod clevises. Lower side of the muscles are attached to the rails with rod eyes.

Finally, a stepper motor linear actuator system is assembled on the right side of the device. This system controls the horizontal displacements. The initial point of the movement and the current location of the system with real time data could be observed. Rate of displacements and movement directions can be modified according to the desired test conditions. 1mm/min displacement rate was used in this study.

3.2. Testing Materials

Main concern of this thesis is to perform shear strength experiments on both direct shear and large size, large displacement direct shear device. In this perspective sand was used for internal shear strength; two types of geomembranes and non-woven needle punched geotextile were chosen for interface testing.

3.2.1. Sand

In order to perform internal shear strength experiments, Akpınar sand was used.

Akpınar sand was chosen for two main reasons;

- To simulate Ottawa 14/25 sand. The sand is suitable for testing on both shear devices.
- Ottawa sand was used widely in the literature. Detailed investigation is possible.

Table 3.1. Sieve Analysis.

Sieve No.	**Sieve Size (mm)**	**Passing (%)**
4	4.75	100
10	2	100
16	1.18	100
20	0.85	99.9
40	0.425	98.7
60	0.25	1.6
140	0.106	0.4
200	0.075	0.2

Table 3.1 shows the grain size distribution of Akpınar sand.

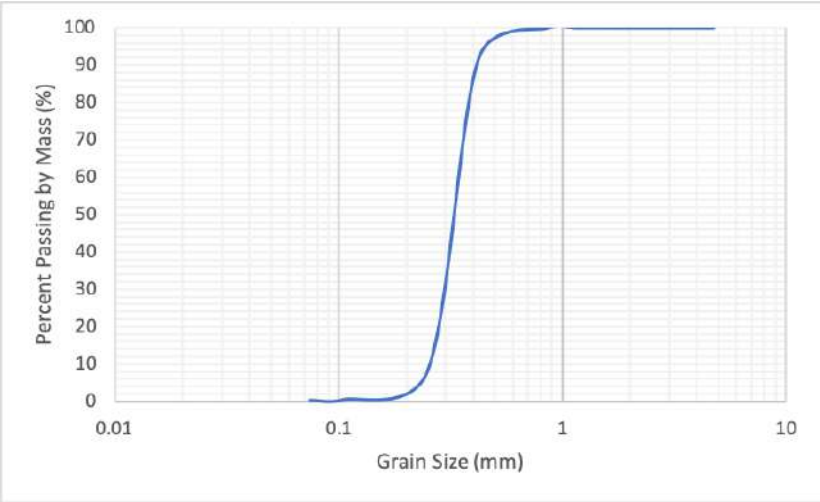

Figure 3.4. Grain Size Distribution.

Figure 3.5. Akpınar Sand.

Table 3.2. Properties of Akpınar Sand.

Gs	**e max**	**e min**	**Cc**	**Cu**	**Dr(Loose)**	**Dr(M. Dense)**	**Dr(Dense)**
2.63	0.68	0.47	1.15	1.22	20%	50%	70%

3.2.2. Geomembrane

Textured and smooth HDPE geomembranes were used for interface testing. The geomembranes were placed in lower shear box.Dimensions of the geomembranes were 295mm width and 895mm length for large scale shear device. The shearing area was $90000 mm^2$.

Table 3.3. Geomembrane Properties [36].

Test	**Standard**	**GMs**	**GMt**
Geomembrane Surface	Type	Smooth	Textured
Material Type	Type	HDPE	HDPE
Density, g/cm^3(min.)	ASTM D1505	0.94	0.94
Thickness (mm)	ASTM D5199/ ASTM5994	2	2
Asperity height (mm)	GM12	-	0.25
Yield Strength (kN/m)	ASTM D6693 (type 4)	35	33
Break Strength (kN/m)	ASTM D6693(type 4)	54	50
Yield elongation (%)	ASTM D6693 (type 4)	12	12
Break elongation (%)	ASTM D6693 (type 4)	750	750
Tear Resistance (N)	ASTM D1004	270	270
Puncture Resistance (N)	ASTM D4883	690	690

3.2.3. Geotextile

The non-woven needle punched geotextile was used for interface testing. The material was chosen to its wide use with geomembranes in the literature. The test specimens that were used in this study had 297mm lenght and 297mm width for large scale shear device. The geotextile was placed in the upper shear box. All interface tests were performed when geotextile was on top of the geomembrane. Shearing area was 90000mm^2. Since the large scale shear device has larger lower shear box, shearing area is kept constant.

Table 3.4. Geotextile Properties [36].

Test	**Standard**	**Unit**	**Values**
Density	EN ISO 9864	g/m^2	500
Thickness (at 2kPa)	EN ISO 9863-1	mm	3.5
Tensile Strength (Longitudinal-Transversal)	EN ISO 10319	kN/m	18/20
Break Strength (longitudinal-Transversal)	EN ISO 10319	%	min.50
Static Puncture	EN ISO 12236	N	3800
Dynamic Puncture	EN ISO 13433	mm	9
Water Flow Rate, V_{H50}	EN ISO 11058	1/sec*m^2	40
Size of Opening, O_{90}	EN ISO 12956	mm	0.0071

3.3. Test Conditions

Shear strength and interface shear strength experiments were performed to calibrate and eliminate drawbacks of the multipurpose shearing device. In order to perform tests, ASTM 3080 [34] and ASTM 5321 [35] standards were followed. Further two subsections summarize these standards in detail.

3.3.1. Shear Strength Test Conditions

ASTM 3080 [34] states that:

- The minimum specimen width should be 50mm and greater than 10 times of the maximum particle size diameter.
- The minimum specimen thickness should be 13mm and greater than 6 times of the maximum particle size diameter.
- Minimum width to thickness ratio should be 2:1.
- Rate of displacement should be slow enough to allow dissipation of water inside the specimen during shearing.
- Gap size between the upper and lower shearing boxes should not be greater than the maximum particle size diameter.

Since, both small and large scale direct shear devices were used to perform shear strength tests, it would be appropriate to give measurements for both devices.

3.3.1.1. Traditional Direct Shear Device.

- 60mm-60mm direct shear box was used.
- Specimen thickness was around 28mm.
- Width to thickness ratio was 60:28.
- Rate of displacement was chosen as 1mm/min. All tests were performed under dry conditions.
- Gap size was less than 1.2mm which was the maximum particle size diameter of Akpınar Sand.

3.3.1.2. Large Size Large Displacement Direct Shear Device.

- The upper box has 300mm-300mm dimensions and the lower box has 300mm-900mm dimensions.
- Specimen thickness was 150mm.
- Width to thickness ratio was 300mm:150mm.
- Rate of displacement was chosen as 1mm/min. All tests were performed under dry conditions.
- Gap size was less than 1.2mm which was the maximum particle size diameter of Akpınar Sand.

In terms of normal stresses: 25kPa, 50kPa and 75 kPa normal stresses were applied to all specimens during shear tests.

3.3.2. Interface Shear Strength Test Conditions

ASTM 5321 [35] describes the standards for geosynthetic to geosynthetic and soil to geosynthetic interface experiments:

- Minimum dimesion of geosynthetic should be 5 times of maximum opening size.
- Depths of containers which have soils in it, should be at least 50mm and 6 times the maximum particle diameter.
- Normal load applying device should have a ±2% accuracy during shearing.
- Rate of displacement should be between 6.35mm/min to 0.025mm/min.
- Geosynthetic should be fixed on a solid block and it has to be placed flatly. To fix geosynthetics clamps or glues can be used.

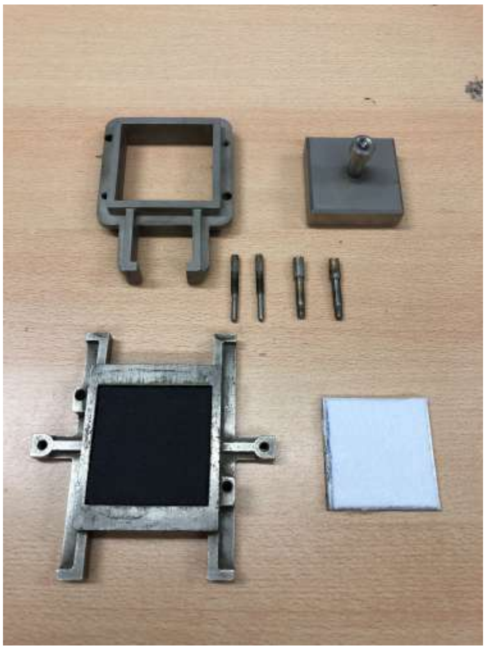

Figure 3.6. 60mm-60mm Geomembrane-Geotextile.

All geosynthetics and geomembranes were glued on wooden rigid blocks. Additionally, screws were used in the lower box of the large size direct shear device. Screws were never placed in the shearing surfaces.
Figure 3.6 shows the small size direct shear box which was used in smooth geomembrane and geotextile interface experiments. Both geomembrane and geotextile were levelled exactly to the shearing surfaces. Otherwise results would be inconclusive.

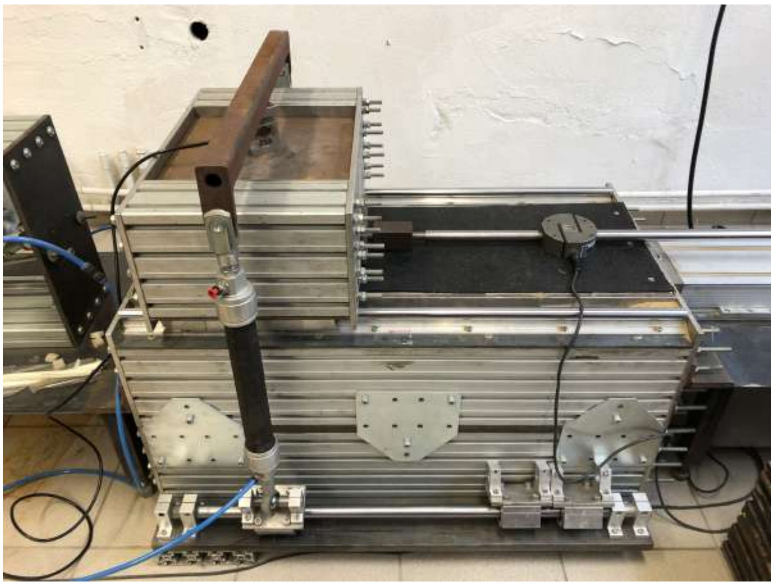

Figure 3.7. Textured Geomembrane and Geotextile Interface in Large Size Direct Shear Device.

Figure 3.7 shows the interface experiment of textured geomembrane and non-woven needle punched geotextile in large size direct shear device. Geomembrane was levelled perfectly to the shearing plane. Geomembrane was both glued and screwed on top of the rigid wooden block.

Figure 3.8. 300mm-300mm Geotextile for Interface Experiments.

Figure 3.8 shows the 300mm-300mm non-wowen needle punched geotextile which was glued on top of the wooden block for large size shearing device interface experiment.

Geotextile and textured-smooth geomembrane interface experiments were performed with both shearing devices. Every test was repeated three times. Tests were performed under 25kPa, 50kPa and 75kPa normal stresses.

4. RESULTS AND DISCUSSION

In this study, three different shear box orientations were investigated. Traditional direct shear device and large scale shear device [49] were used in shear experiments. Akpınar sand was used to simulate Ottawa 14/25 sand. HDPE Geomembrane and non-woven needle punched geotextile were used for interface testing. All tests were performed under 25kPa, 50kPa and 75kPa normal stresses. Following sections present the results of all the tests and the discussion.

4.1. Shear Strength Test Results

Shear strength tests were performed by using Akpınar sand. Akpınar sand was chosen to simulate Ottawa 14/25 sand. Ottawa sand was chosen to its wide use in the literature. Additionally, the soil is proper to use in both small and large size shearing devices. ASTM 3080 [34] standards were followed in all shear experiments.

4.1.1. Traditional Direct Shear Test Results of Sand

Direct shear tests of sand were performed for three different states which were loose, medium dense and dense. 25kPa, 50kPa and 75kPa normal stresses were applied during shearing. Relative densities were 20% for loose, 50% for medium dense and 70% for dense sample. Horizontal displacements were 10% of the original specimen width. Rate of displacement was 1mm/min. A total of 27 direct shear tests were conducted. Figure 4.3 shows the normal stress versus shear stress peak values of sand for all three states. Normal stress values are different than 25kPa, 50kPa and 75kPa because of the area corrections.

Table 4.1 shows the internal friction angles of Akpınar Sand for three states that were found in traditional direct shear device.

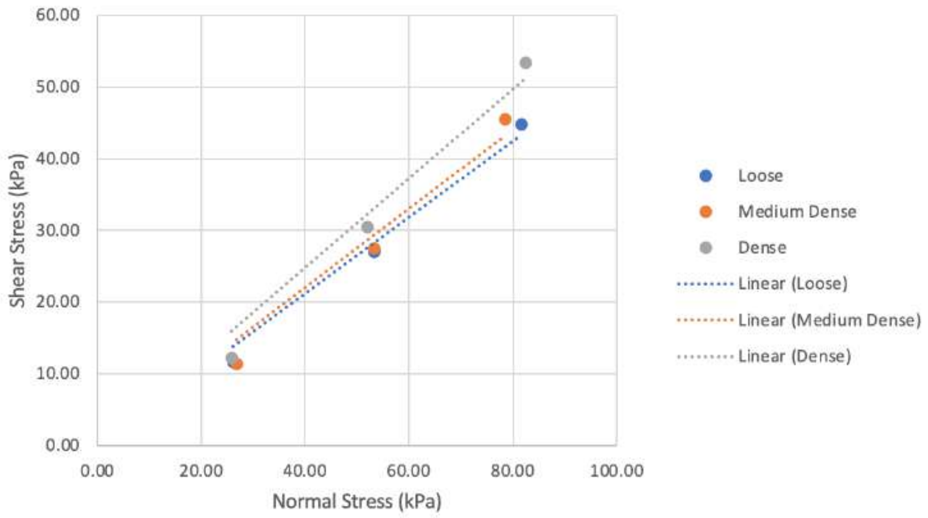

Figure 4.1. 1st Set Normal Stress vs. Shear Stress Akpınar Sand (small size).

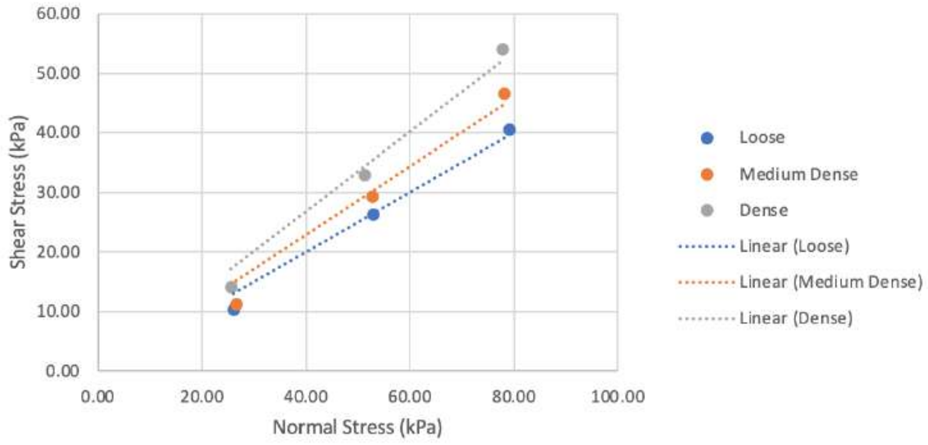

Figure 4.2. 2nd Set Normal Stress vs. Shear Stress Akpınar Sand (small size).

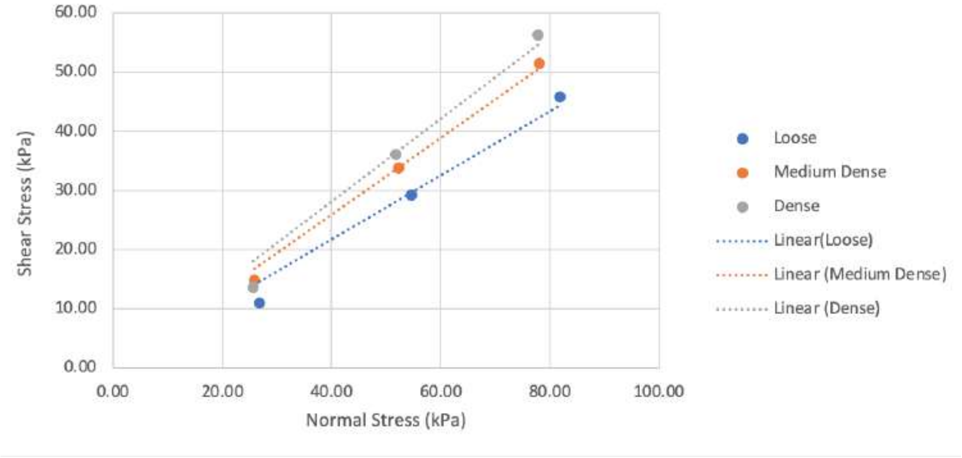

Figure 4.3. 3rd Set Normal Stress vs. Shear Stress Akpınar Sand (small size).

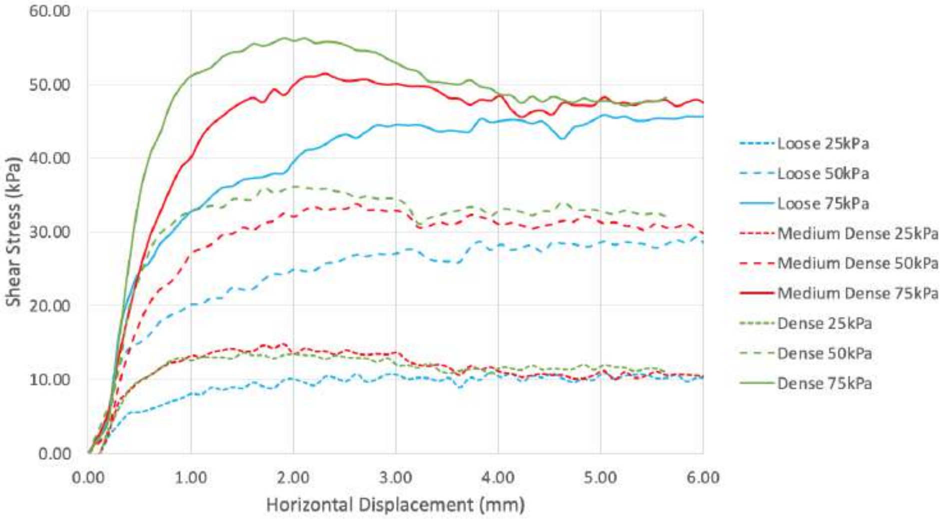

Figure 4.4. Horizontal Displacement vs. Shear Stress for Akpınar Sand.

Figure 4.4 shows the shear stress vs. horizontal displacement curves for three different states. Amount of horizontal displacement was 6mm which was equal to 10% of the original specimen width.

Table 4.1. Internal Friction Angles of Akpınar Sand.

		Loose	**Medium Dense**	**Dense**
Peak	ϕ	29.70°	33.65°	36.41°
Residual	ϕ	29.02°	30.05°	30.97°

Dilation is another important parameter for cohesionless soils under shearing. Since Akpınar Sand was a type of cohesionless soil, it was appropriate to observe its behaviors. Dilation and contraction were, basically, determined according to the loading plate movements. All measurements were taken with a LVDT sensor.

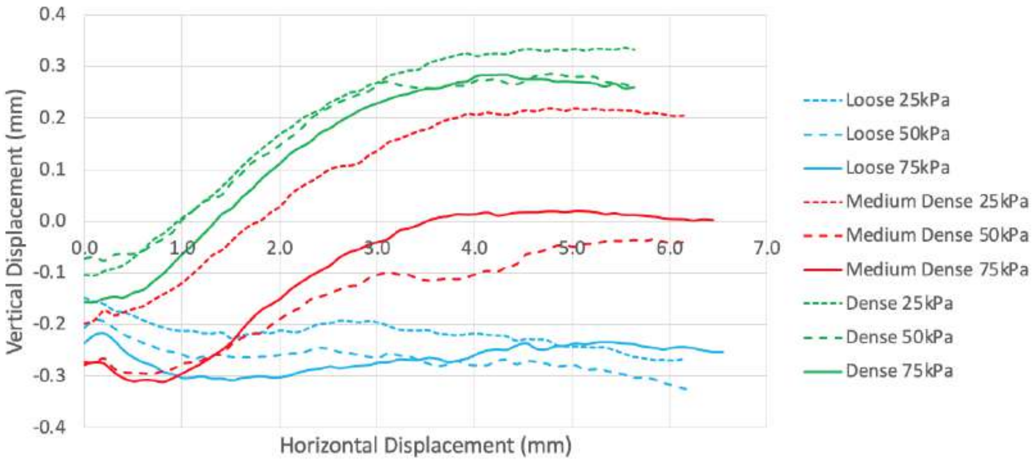

Figure 4.5. Vertical Displacement vs. Horizontal Displacement of Sand.

Table 4.2. Dilation Angles of Akpınar Sand.

	Loose	**Medium Dense**	**Dense**
Dilation Angle	-0.30°	3.65°	6.41°

Figure 4.11 shows the dilation and contraction behaviors of Akpınar Sand under different loads and relative densities. Table 4.2 shows the dilation angles of Akpınar sand. Results showed that loose samples tended to contract whereas dense samples tended to dilate after rapid contraction as expected. Also, the amount of normal load played an important role in terms of vertical movements. Dilation and contraction amounts increased when normal loads increased. The peak stress values were reached at approximately 2mm horizontal displacement. Residual stresses were observed at approximately 5mm horizontal displacement. Peaks were observed clearly. 16% post peak stress loss was observed for dense state. 9% post peak stress loss was observed for medium dense state. Maximum amount of vertical displacement was observed in dense 75kPa specimen. It was measured as 0.45mm.

4.1.2. Large Size and Large Displacement Direct Shear Device Test Results of Sand

Normal stresses were 25kPa, 50kPa and 75kPa at all shearing tests. Rate of displacement was 1mm/min. Amount of horizontal displacement was 10% of the specimen width which was 30mm.

First set of experiments were performed by filling the shear boxes with sand at different soil states.

Figure 4.6 shows the empty shear box before testing. The lower box was sealed to keep all the sand inside the box during the tests. Also, geomembrane was placed on top of the sealing for preventing seals from sand punctures under loaded test conditions.

Figure 4.6. 1st Type Orientation (Empty).

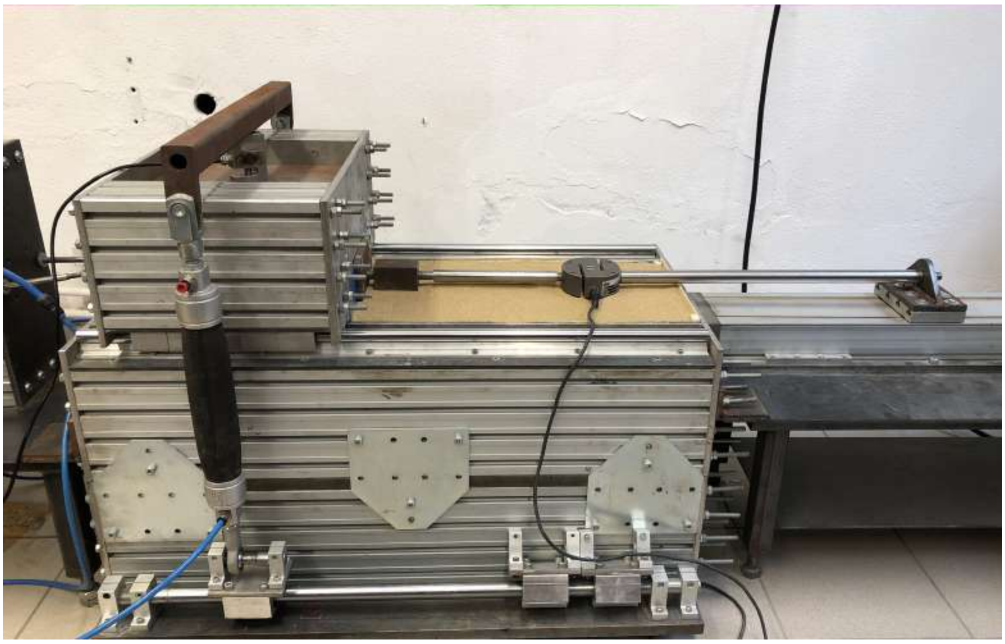

Figure 4.7. 1st Type Orientation (Filled).

Figure 4.7 shows the filled shear box. Normal load was measured with a load cell just under the metal rod and shear forces were recorded with the horizontal load cell. Metal plate tilted towards the direction of movement during the shearing and an undesired dilation in front of the upper shear box was observed.

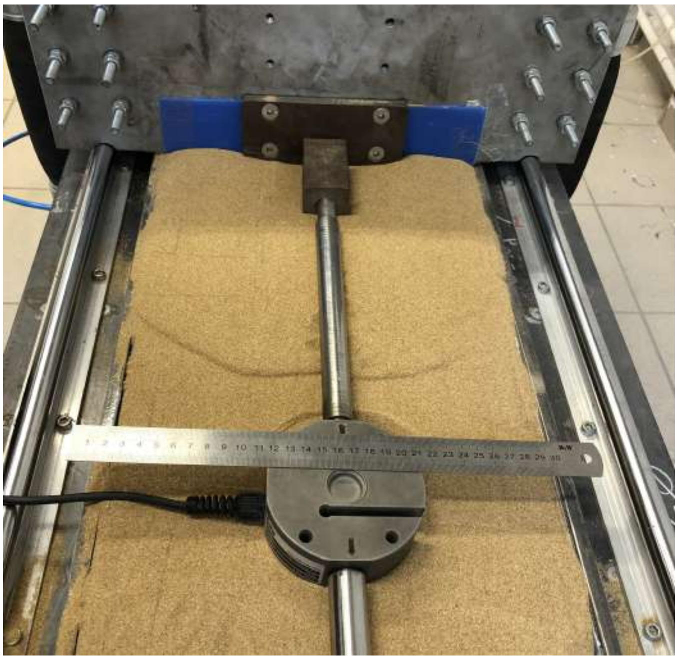

Figure 4.8. Dilation behavior after 1st Type of Orientation tests.

Figure 4.8 shows the dilation in front of the upper box after the tests were performed. Dilation occurred towards the direction of movement. Normal load values were unstable during the test and it was consistently tending to decrease. Normal loads were tried to be stabilized by the operator regularly. This loss of normal load and the unexpected dilation were related with each other. Normal load was decreasing because of the high settlements and sand particles were moving towards the unloaded section of the lower shear box. This partical movements were causing dilation in front of the upper shear box and extreme settlements.

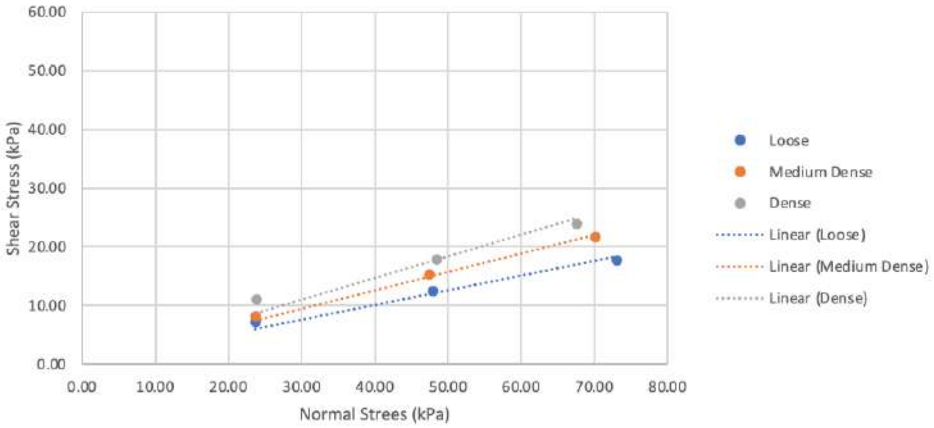

Figure 4.9. Shear Stress vs. Normal Stress after 1st Type of Orientation.

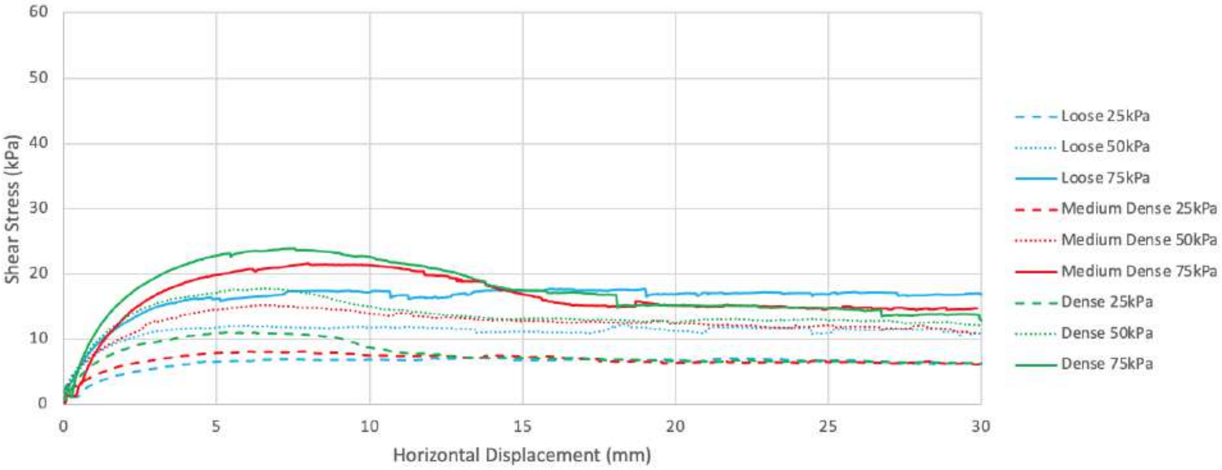

Figure 4.10. Shear Stress vs. Horizontal Displacement after 1st Type of Orientation.

Figure 4.9 and 4.10 show the results of shear strength for sand in large-scale shear device. The peaks were observed at around 7mm horizontal displacement. The residual state was reached at around 20mm horizontal displacement. 40% post peak stress loss was observed at 75kPa dense sample. 32% post peak stress loss was observed at 75kPa medium dense sample.

Table 4.3. Internal Friction Angles of Sand after 1st Type of Orientation.

		Loose	**Medium Dense**	**Dense**
Peak	ϕ	13.47°	17.11°	19.12°
Residual	ϕ	12.52°	12.14°	12.93°

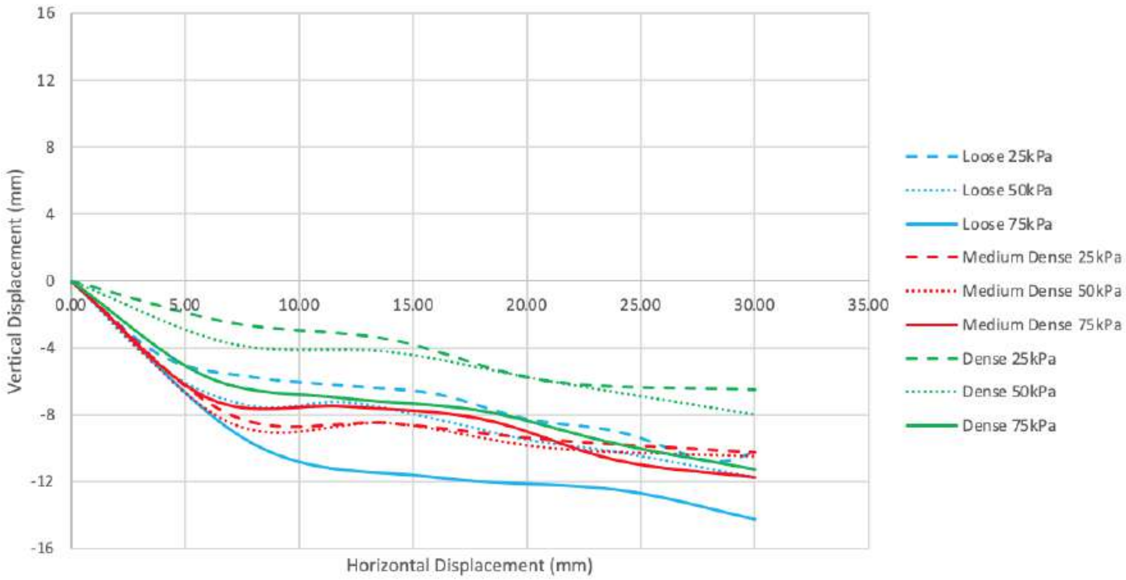

Figure 4.11. Vertical Displacement vs. Horizontal Displacement after 1st Type of Orientation.

Table 4.3 shows the internal friction angles of Akpınar Sand. Figure 4.11 shows the vertical displacement versus horizontal displacement graph after 1st type of orientation. The general contraction behavior was observed in all specimens. Dilation behavior was observed between 10mm and 15mm horizontal displacements. However, the dilations were not high enough to stop the contraction. Additionally, dilation behavior was observed after peaks were reached. Medium dense specimens showed higher dilation amounts than the other two states. Medium dense 75kPa specimen showed the highest dilation. This contradiction needs repetition and further investigation. Furthermore, it was clear that some parameters were affected by the system and showed consistent contraction behavior even though small dilation behaviors were observed.

Second methodology was to separate lower box into three sections by using metal blocks. With this way, stress losses and undesired particle movements (towards unloaded sections) during shearing could be prevented.

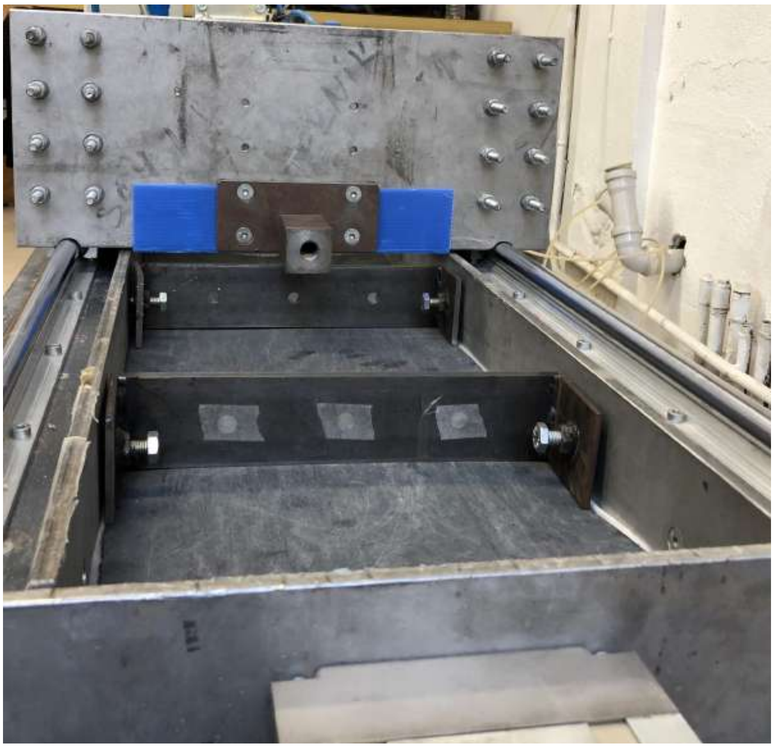

Figure 4.12. 2nd Type Orientation (Empty).

Figure 4.12 shows the empty shear box after metal blocks were assembled. Metal block dimensions were 297mm length, 60mm height and 10mm width. Metal blocks were fixed to both sides of the shear box with screws. Tightening the screws increased the friction between the screw and the box wall.

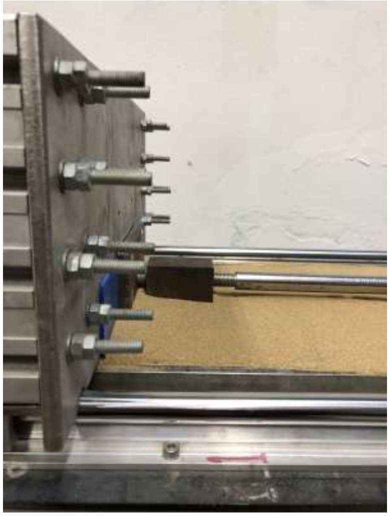

Figure 4.13. Dilation behavior after 2nd Type of Orientation tests (Side view).

Figure 4.14. Dilation behavior after 2nd Type of Orientation tests (Top view).

Figure 4.13 and 4.14 show the dilations in front of the upper shear box. Amount of dilations was remarkably decreased after metal blocks were assembled. Normal load loss and loading platen movements were also decreased but could not eliminated totally.

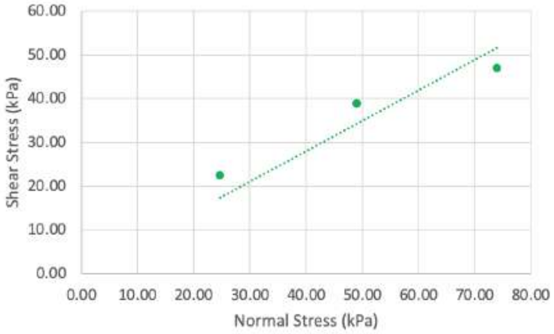

Figure 4.15. Shear Stress vs. Normal Stress at 2nd Type of Orientation tests.

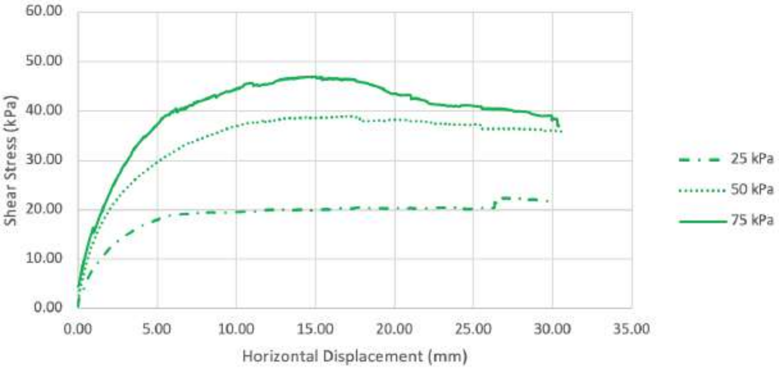

Figure 4.16. Shear Stress vs. Horizontal Displacement at 2nd Type of Orientation.

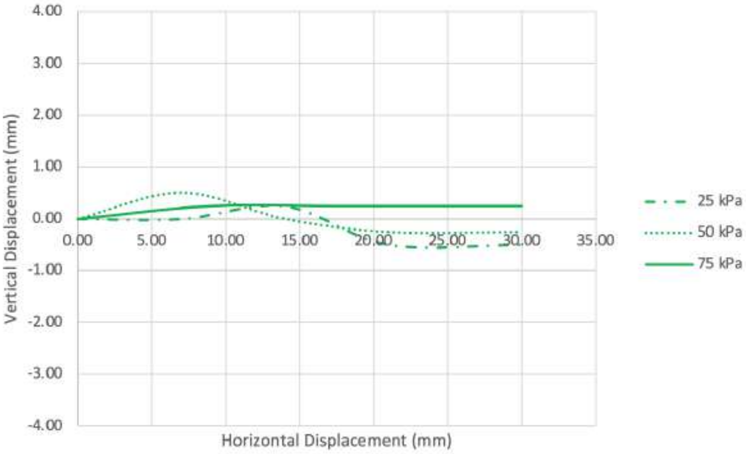

Figure 4.17. Vertical Disp. vs. Horizontal Disp. at 2nd Type of Orientation.

Figure 4.15, 4.16 and 4.17 show the behavior of sand after assembly of metal blocks. However, the results were still inconclusive. Graphs show the dense sample results and according to these data, peak internal friction angle was found as 32.6°which was lower than both the traditional DS results and the literature. Besides that, additional test attempts were failed each time and very diverse results were found.

This problem was caused by two main reasons according to observations. First one was, metal blocks did not fully prevent the normal load loss, since blocks were 60mm high, on the other hand, sample height was 75mm. Therefore, dilation in front of the shear box was observed again. Second one was, rails of the upper shear box started to make some noises. It was really hard to push the upper box even when it was empty. Thus, rails were affected by something else but not the sand.

Then, it was figured out that metal block screws expanded the lower box about 1 mm and this caused the rails not to function properly. Also, there was a slight movement in the metal block which could also affect the normal load loss during shear experiment. Further experiments were not conducted due to the disfunction.

For this purpose, again same metal block was used. But this time one of them was used not two. The metal block was 60mm high and the soil sample height was 75mm. This height difference was causing soil movement that was observed in the previous cases. Therefore, a wooden wedge was fixed on the metal block which had dimensions of 297mm length, 15mm height and 10mm width. The previous case showed an expansion when the screws tightened firmly to prevent movements of the metal block. A wooden wedge which had dimensions of 587mm length, 50mm height and 50mm width, was placed perpendicularly to the metal block to overcome the expansion problem. Since the important part of the shearing was the first 300-350mm part, one rigid wood wedge was used. Second metal block was removed from the system.

Figure 4.18. 3rd Type Orientation (Empty-Side View).

Figure 4.18 and 4.19 show the empty shear box after levelled metal block and wood wedge assembled.

Figure 4.19. 3rd Type of Orientation (Empty-Top View).

After this modification in the device, no dilation was observed at the end of the tests. Likewise, the normal loads stayed still during the tests and shear stresses reached expected levels.

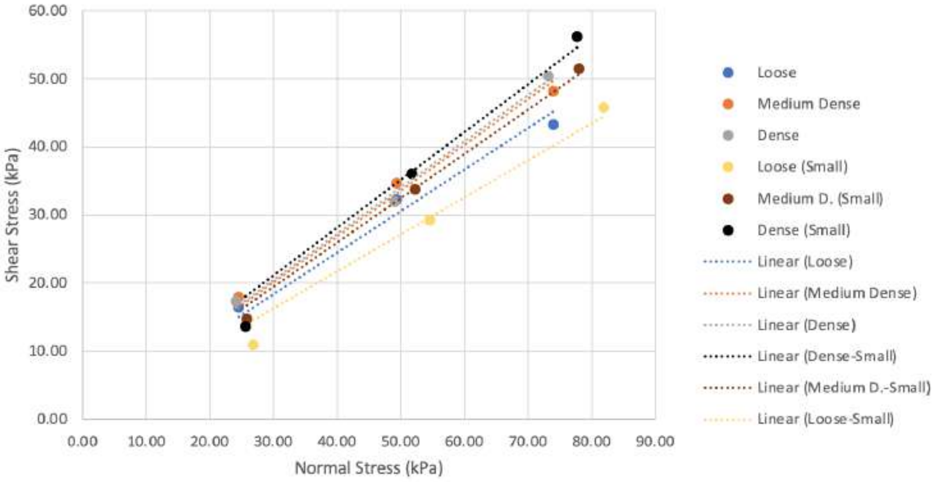

Figure 4.20. Shear Stress vs. Normal Stress 3rd Type of Orientation.

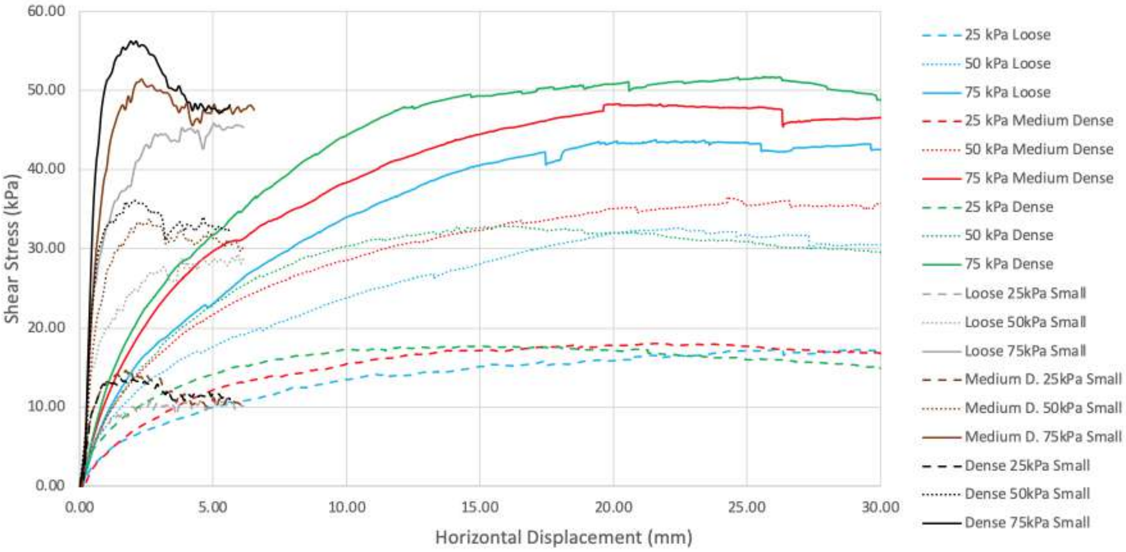

Figure 4.21. Shear Stress vs. Horizontal Displacement 3rd Type of Orientation.

Figure 4.20 shows the normal vs. shear diagram of sand after final adjustments which were levelled metal block and wood wedge. Likewise, Figure 4.21 shows the shear stress vs. horizontal displacement curves. The graph includes the curves of the traditional direct shear device.

According to the results, peak behaviors were observed at approximately 25mm horizontal displacements. On the other hand, the peaks were observed at approximately 2mm horizontal displacements in traditional shear device. The results were consistent in terms of peak shear stresses. However, the peaks were reached at larger amount of displacements after each orientation. Table 4.4 shows the internal friction angles of sand at different states in large size large displacement direct shear device.

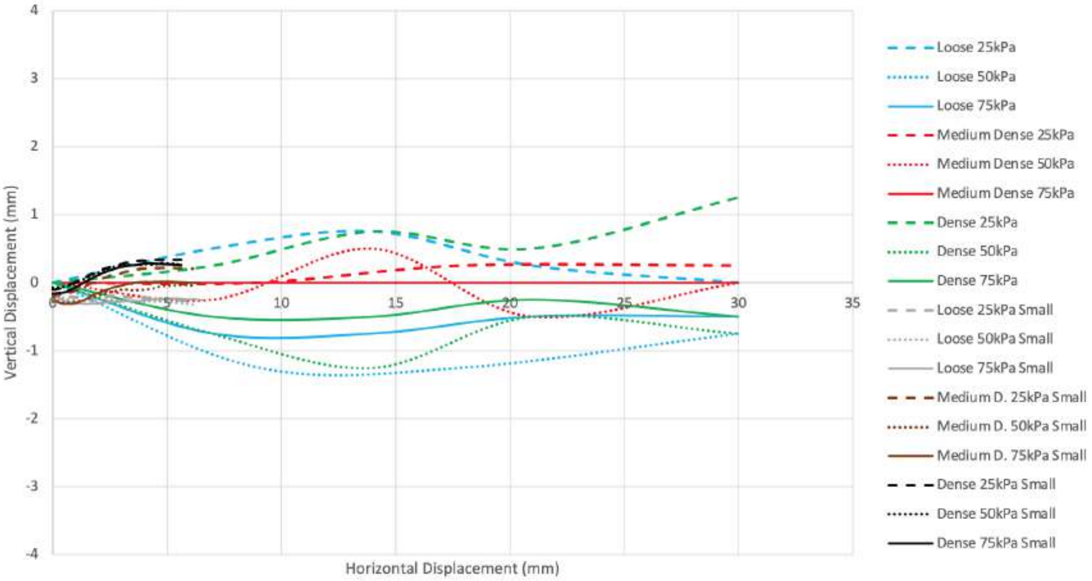

Figure 4.22. Vertical Displacement vs. Horizontal Displacement of Sand-3.

Figure 4.22 shows the vertical displacements under different loads and relative densities. Figure also shows the small scale device results. Inconsistent contraction and dilation behaviors were observed. Loose 25kPa showed an instant dilation which was not expected. This can be explained by the amount of data taken from the plate during tests. The tests need further investigation and repetition.

Table 4.4. Internal Friction Angles of Sand after 3rd Type of Orientation.

		Loose	**Medium Dense**	**Dense**
Peak	ϕ	30.58°	33.15°	34.14°

The peak internal friction angles were found 1-2°lower than the traditional direct shear results. Those differences are supported the size effect investigations in the literature. Residual values could not be found because peaks were reached at higher horizontal displacements in large scale device. Dilation angles could not be found due to the inconsistent vertical displacements. Only one set of experiments were performed for each type of orientation because of the corona virus restrictions.

Table 4.5. Internal Friction Angles from Literature.

Reference	**Soil Type**	**Box Size**	ϕ
[4]	Ottawa Sand	Small to Large	31°- 28.5°(Loose)
[8]	Ottawa Sand	Small to Large	30.7°-30.3°(Loose) 35.6°-35°(Medium Dense) 39°-36°(Dense)
[9]	Toyoura Sand	Small to Large	42.6°- 37°(Dense)
[10]	P1-S2	Small to Large	32.9°- 31.7°(Dense)
	P1-S6	Small to Large	32.5°- 31.8°(Dense)
	P1-S7	Small to Large	38°- 34.8°(Dense)
	P3-S6	Small to Large	34.5°- 35.2°(Dense)
[11]	Leighton Buzzard Sand	Large	31.66° (Loose to Dense)
[19]	Leighton Buzzard Sand	Small	37.4° (Dense)

Table 4.5 shows the internal friction angles of similar sands in the literature. Akpınar sand was sieved to simulate Ottawa sand in terms of specific gravity, e_{max}, e_{min} and max. particle size. The results were consistent with the literature for both small and large size shear devices. Also, size effect was observed between small and large size shear devices like in the literature. It can be said that developed large scale direct shear device gives consistent results in terms of peak internal friction angles. Further comment and critisms have been dealt within the Discussion section.

4.2. Interface Shear Strength Test Results

Interface shear strength experiments were performed both in traditional direct shear device and the large size large displacement shear device. Smooth, textured geomembranes and non-woven needle punched geotextile were used to perform interface shear strength experiments for calibration and further experimental studies. All experiments were performed according to the ASTM 5321 [35] standards. All tests were performed under 25kPa, 50kPa and 75kPa normal stresses. Rate of displacement was chosen as 1mm/min. Amount of horizontal displacement was chosen as 10% of the specimen width. 6mm horizontal displacement for traditional shearing device and 30mm horizontal displacement for the large size shearing device. Totally, 18 tests were performed in traditional direct shear device and six tests were performed in the large-scale shear device. Due to the pandemic, number of tests in large-scale device were limited.

4.2.1. Smooth Geomembrane - Geotextile Interface Test Results

Smooth Geomembrane and non-woven needle punched geotextile interface experiments were performed in both traditional shearing device and large size shearing device. Twelve tests were performed in total.

The geotextile was placed on top of the geomembrane in all tests. Shearing area was $3600mm^2$ in traditional device, $90000mm^2$ in large scale device. Interface materials were levelled perfectly to avoid any kind of additional friction between the surfaces and shearing boxes. Geomembrane and geotextile were fixed on metal blocks to prevent foldings and movements during shearing. Normally, standards advise to use clamping technique for fixing purpose and add that interface materials should not move at all during the tests. Clamping consists of screws and those screws should be placed in such a way that the effect on the test results is minimized. In other words screws should not be placed on interface planes. Traditional direct shear device is not appropriate to use screws for fixing purposes. A strong multipurpose glue was used to fix the interface materials to the metal blocks.

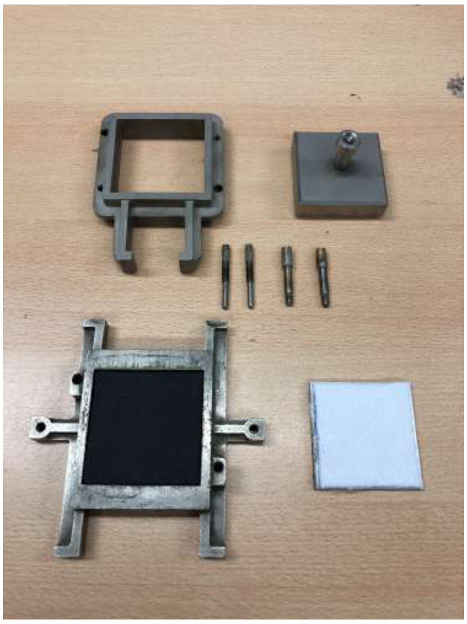

Figure 4.23. 60mm-60mm Geomembrane(S)-Geotextile.

Figure 4.23 shows the levelled smooth geomembrane and geotextile before testing in the traditional shear device. Geomembrane was placed into the lower box. Specimen dimensions were adjusted to fit exactly in the shear boxes. Lower box was moving during the shear experiments. Geomembrane was the material that was moved. Tests were performed in three sets. Each set included three tests at different normal stresses which were 25kPa, 50kPa and 75kPa. Finally, 9 tests were performed in traditional direct shear device.

Three tests were performed in large size direct shear device.
290mm-890mm wooden blocks were cut to be used in interface experiments. This time both screws and strong multipurpose glue were used to fix the interface materials to the wooden surface. Screws were placed to lower shear box but upper shear box interface material was fixed only by glue. The difference between the upper and lower shear box was the size. Since, lower box was three times longer than the upper box, screws could be used in a way that will not affect the test results.

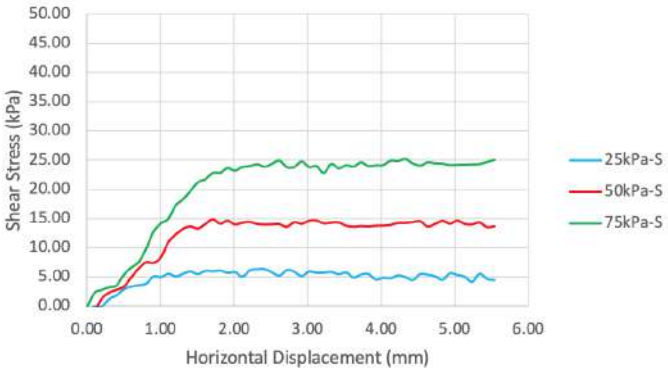

Figure 4.24. GM(S)-GT Traditional Shearing Device.

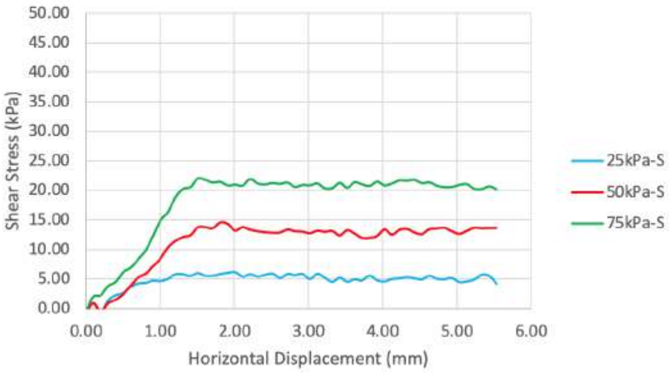

Figure 4.25. GM(S)-GT Traditional Shearing Device-2.

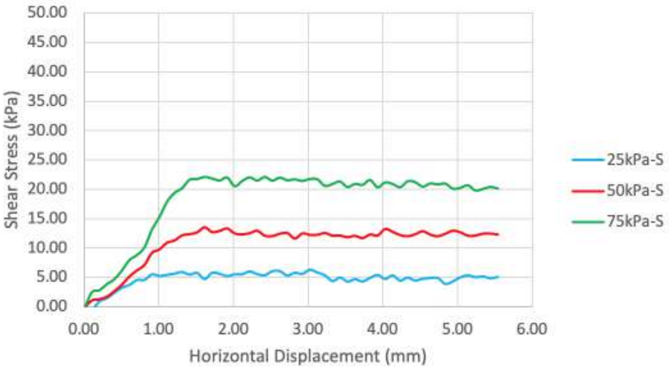

Figure 4.26. GM(S)-GT Traditional Shearing Device-3.

Figure 4.24, 4.25 and 4.26 show the shear stress versus horizontal displacement graphs of smooth geomembrane and geotextile interface in 60mm-60mm traditional direct shear device.

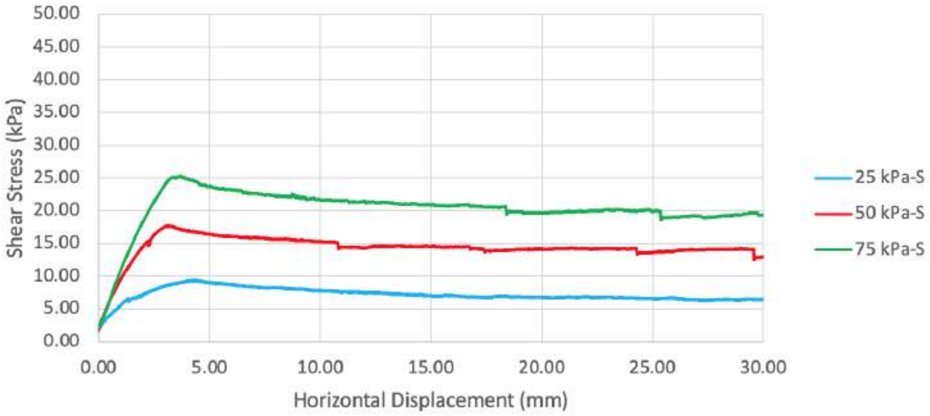

Figure 4.27. GM(S)-GT Large Size Shearing Device.

Figure 4.27 shows the shear stress versus horizontal displacement graph of smooth geomembrane and geotextile in large size direct shear device.

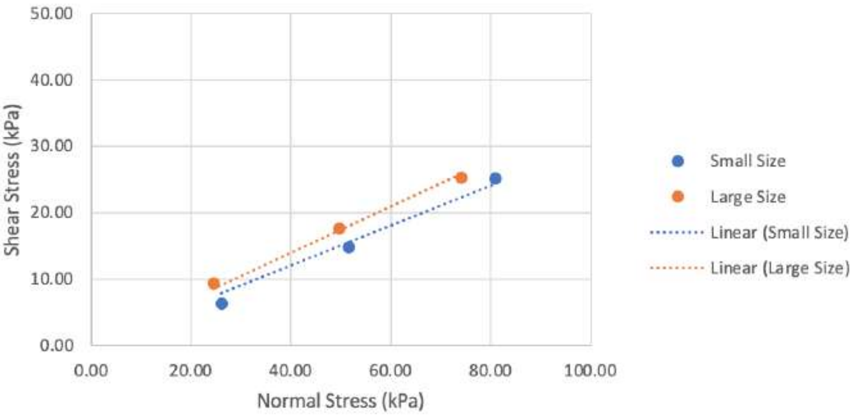

Figure 4.28. GM(S)-GT Shear Stress vs. Normal Stress.

Figure 4.28 shows the shear stress versus normal stress values of smooth geomembrane and geotextile in small and large size shearing devices.

Table 4.6. Interface Friction Angles of GM(S)-GT.

		Small Size	**Large Size**
(Peak)	δ	17.43°	18.83°
(Residual)	δ	17°	13.51°

Table 4.6 shows the interface friction angles of smooth geomembrane and geotextile interfaces in both large and small size shearing devices. Three sets of experiments were performed in traditional direct shear device. One set of experiments were conducted in large size large displacement shear device. Although there is a difference around 1-2°, graphs and table show that two devices confirm each other in terms of interface peak friction angles.

Small size shearing device results did not show peak behaviors due to limited horizontal displacement whereas large size shearing device did. The peaks were reached at 1-2mm horizontal displacements in small scale device. The peaks were reached at 3-5mm horizontal displacements in large scale device. Post peak strength loss was observed only in large scale device and it was 20% for 75kPa normal stress. Another difference was gradually sudden decrements were observed in large size shearing device results at 50kPa and 75kPa. These behaviors might be affected by the compressor power which was used to fill air inside the muscles and apply normal load on target specimens. The compressor consistently starts up when air pressure drops. Normally, there is no need to start up when less amount of normal stresses, such as 25kPa, are applied. However, when high normal lstresses, such as 50kPa and 75kPa, are applied, the compressor needs to start up to fill the lost pressure. Thus, it may cause sudden fluctuations at the results inevitably.

4.2.2. Textured Geomembrane - Geotextile Interface Test Results

Textured geomembrane & non-woven needle punched geotextile were used for interface experiments of this study. Traditional direct shear device and large size large displacement shear device were used in interface experiments. Horizontal displacement amounts were 6mm for traditional direct shear device and 30mm for large-scale shear device. 25kPa, 50kPa and 75kPa normal stresses were applied in all tests. Rate of displacement was $1mm/min$. Multipurpose glue was used for fixing the interface materials. Screws were used in only large scale device. Geotextile was placed on top of the geomembrane in all tests. Shearing areas were $3600mm^2$ for traditional shear device and $90000mm^2$ for large-scale shear device. Shearing area was decreased in small scale device due to the use of same size shear boxes. The shearing area was kept constant in large-scale device due to the three times longer lower shear box. Twelve experiments were performed in total where nine of them in small size shearing device and three of them in the large size shearing device. Repetition experiments of the large-scale device could not be performed due to the corona virus restrictions.

(a) Geotextile (b) Geomembrane(T)

Figure 4.29. GM(T)-GT specimens for 60mm-60mm shear box.

Figure 4.29 shows the geotextile and textured geomembrane specimens which were fixed on metal blocks by using strong multipurpose glue.

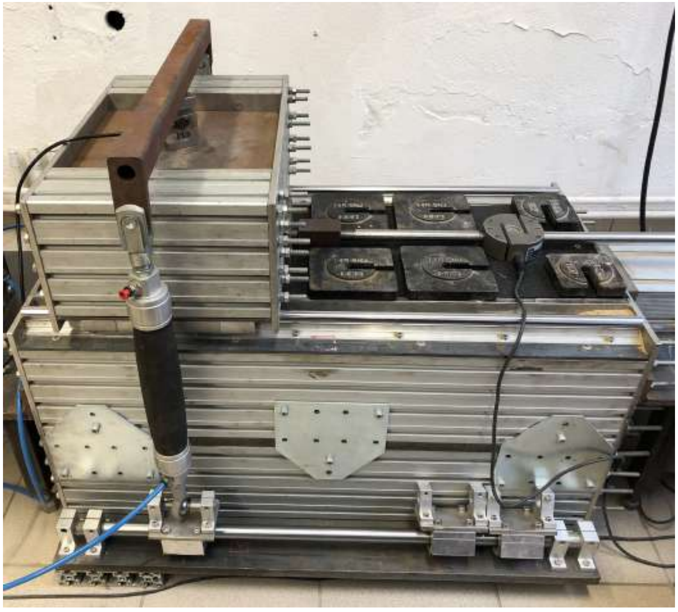

Figure 4.30. GM(T)-GT at Large Size Shearing Device.

Figure 4.30 shows the set up of textured geomembrane and geotextile for shearing at large size shearing device.

Additional weights were placed on top of the geomembrane during the test for just to be sure that there is no expansion and folding at the geomembrane. Weights were placed in such a way that they did not need to be moved during the tests. Finally, precautions worked well and no folding, expansion or any kind of movement that could affect the test was observed. Upper box was moving in large-scale device. Lower box was moving for shearing in small scale device.

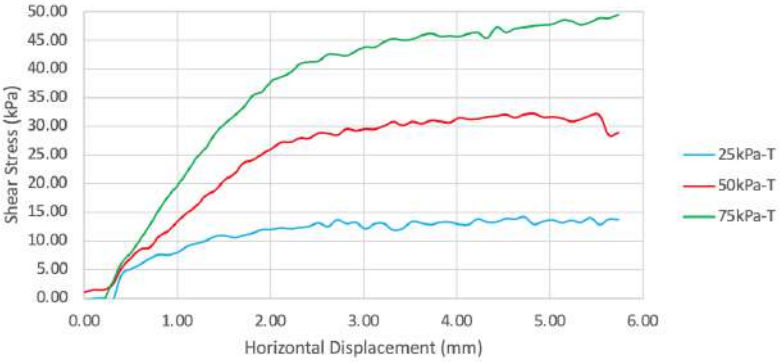

Figure 4.31. GM(T)-GT Traditional Shearing Device.

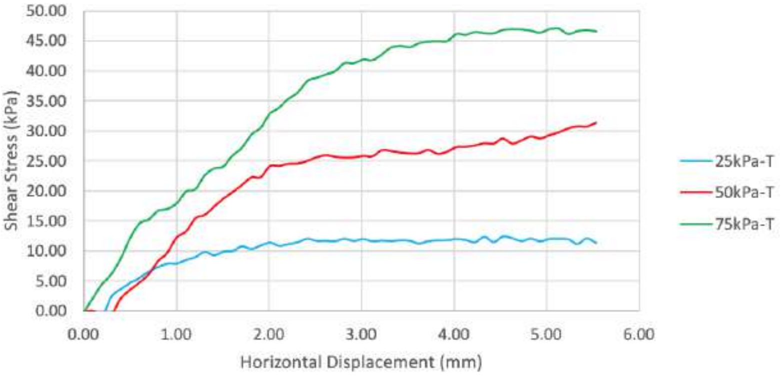

Figure 4.32. GM(T)-GT Traditional Shearing Device-2.

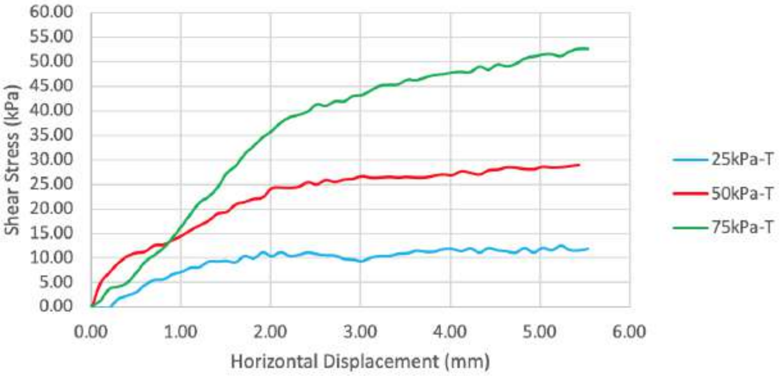

Figure 4.33. GM(T)-GT Traditional Shearing Device-3.

Figure 4.31, 4.32 and 4.33 show the shear stress versus horizontal displacement graphs of textured geomembrane & geotextile interface experiments at traditional shearing device.

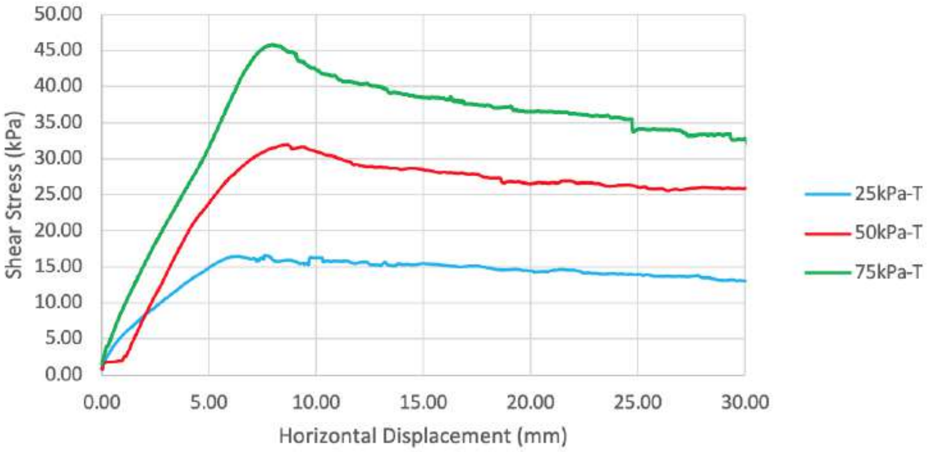

Figure 4.34. GM(T)-GT Large Size Shearing Device.

Figure 4.34 shows the shear stress versus horizontal displacement results of textured geomembrane and geotextile at large size shearing device.

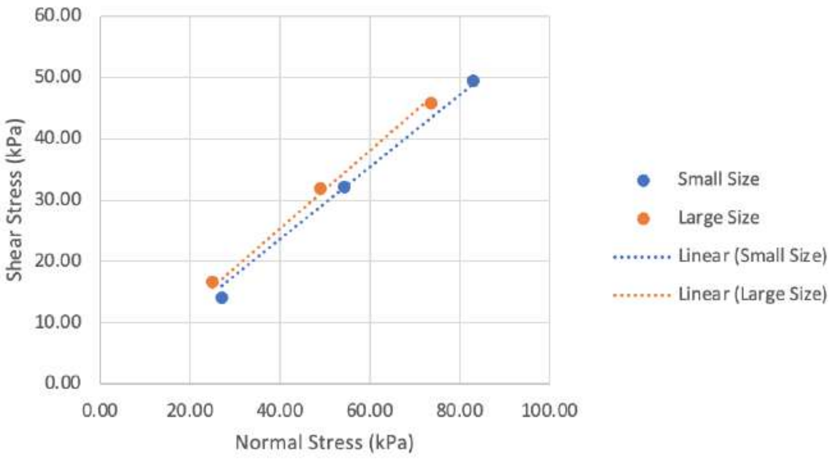

Figure 4.35. GM(T)-GT Shear Stress vs. Normal Stress.

Figure 4.35 shows the shear stress versus normal stress results of chosen specimens at both of the shear devices.

Table 4.7. Interface Friction Angles of GM(T)-GT.

		Small Size	**Large Size**
(Peak)	δ	31.07°	31.95°
(Residual)	δ	30.58°	23.59°

Table 4.7 shows the interface friction angles of textured geomembrane & geotextile at small and large size direct shear devices. Only one set of experiments was performed in large-scale device. Results confirmed that the developed large size, large displacement shearing device also worked for interface experiments. Post peak stress loss was only observed in large-scale device. Peaks were reached at approximately 5mm horizontal displacement in traditional direct shear device. Peaks were reached at approximately 7mm horizontal displacement in large-scale shear device. Less than 1% difference was observed between devices in terms of peak values. Like all other experiments, this difference was caused by, most probably, size effect and operator sensitivity. Furthermore, temperature and humidity can cause differences at results.

One other important thing was material status after experiments. Smooth geomembrane & geotextile interface experiments showed no visible deformations at both interface materials. Oppositely, pilling deformation was observed after textured geomembrane & geotextile experiments were performed. Furthermore, most apparent pilling deformation was observed in large size shearing device. This behavior was, most probably, caused by large shearing area and large amount of horizontal displacement when compared with small size shearing device. Likewise, more shear strength loss was expected when deformations increased. Finally, no visible deformations were observed in both textured and smooth geomembranes after interface experiments were performed.

Figure 4.36 and Figure 4.37 show the shear stress versus horizontal displacement of smooth/textured geomembrane and geotextile interface results at both shearing devices. Although results were similar in terms of peak interface friction angles, graphs were different from each other. Peak behaviors of interface materials were observed in large size shearing experiments whereas small size shearing device interface results did not show peaks due to the limited horizontal displacement. Loss of strength after peak strength was reached, is logical and it is a material fact that engineers would expect and consider it in their designs. More detailed material behaviors were observed in large-scale shear device than the traditional direct shear device.

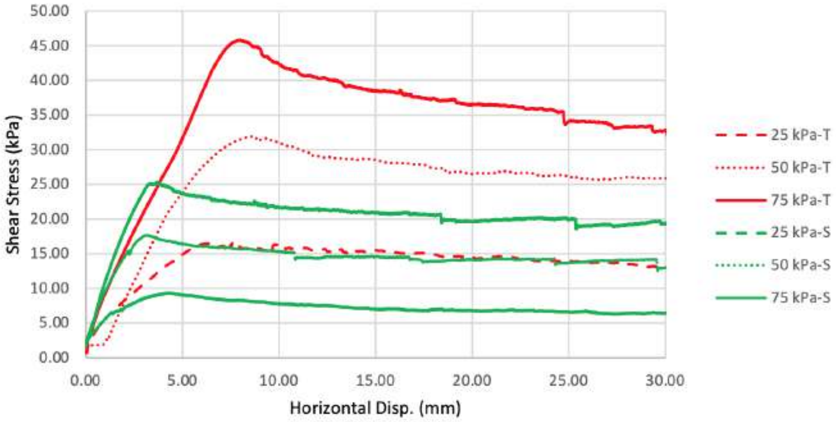

Figure 4.36. GM(S) vs. GM(T) in Large Size Shearing Device.

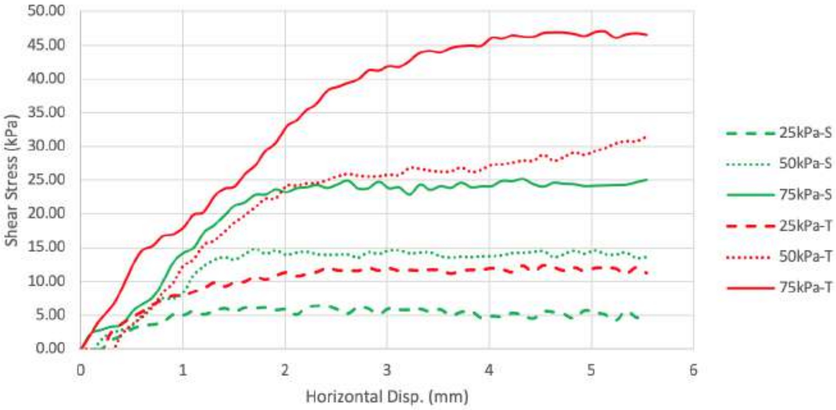

Figure 4.37. GM(S) vs. GM(T) in Small Size Shearing Device.

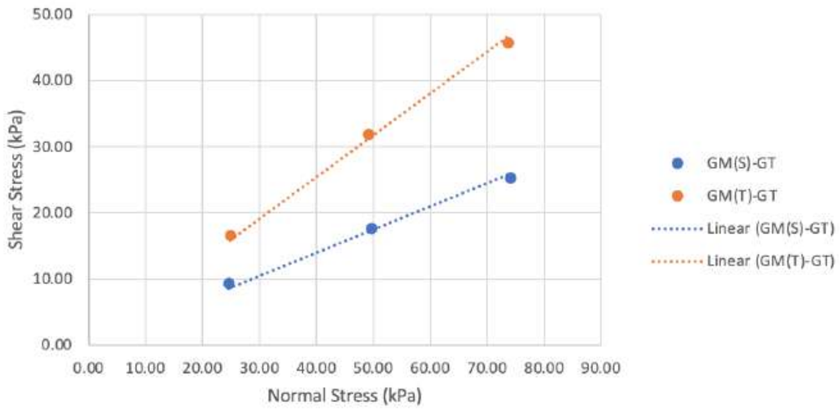

Figure 4.38. GM-GT Shear Stress vs. Normal Stress in Large Size Device.

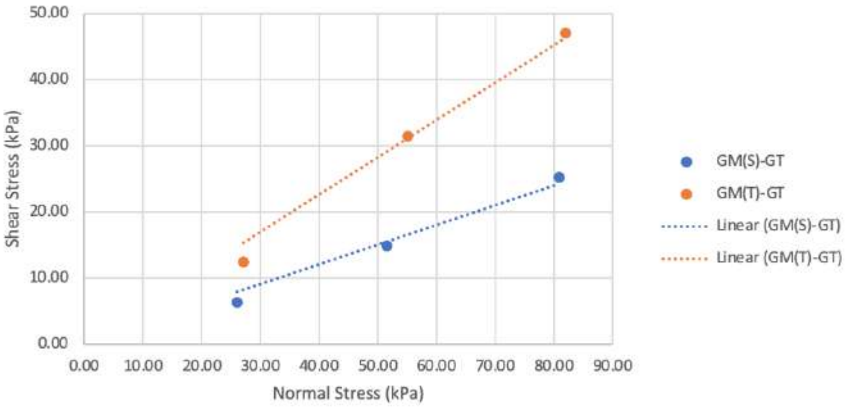

Figure 4.39. GM-GT Shear Stress vs. Normal Stress in Small Size Device.

Table 4.8. Interface Friction Angles of GM & GT.

		Small Size	**Large Size**	**GM Type**
(Peak)	δ	17.43°	18.83°	**Smooth**
(Peak)	δ	31.07°	31.95°	**Textured**
(Residual)	δ	17°	13.51°	**Smooth**
(Residual)	δ	30.58°	23.59°	**Textured**

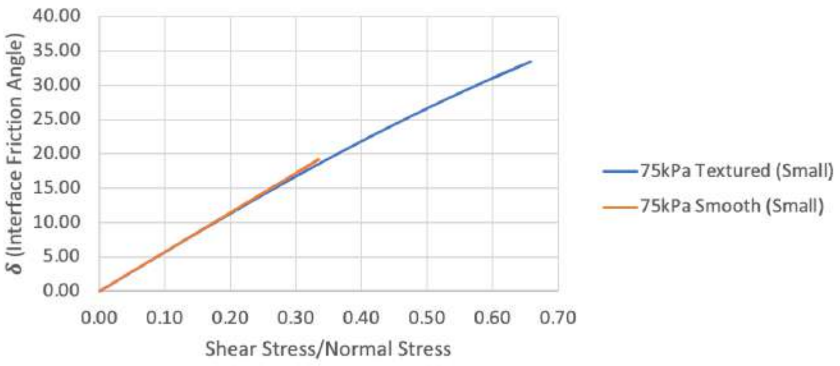

Figure 4.40. GM(T)-GT and GM(S)-GT Normalised Version-Small Size.

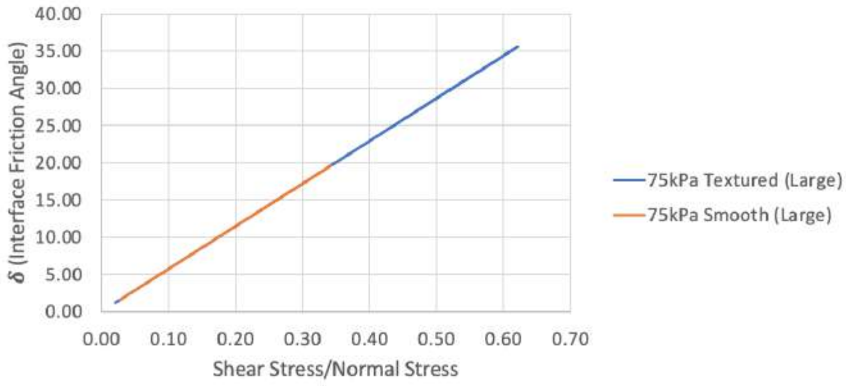

Figure 4.41. GM(T)-GT and GM(S)-GT Normalised Version-Large Size.

Table 4.8 shows the interface friction angle values. Figure 4.40 and figure 4.41 show the normalised version of interface results under 75kPa normal stress in both shear devices. Size effect was observed. Interface friction angles decreased when the shear box size increased. The textured geomembrane was found much stronger than the smooth geomembrane interfaces.

Table 4.9. Interface Friction Angles in Literature.

Reference	**Geosynthetic Type**	**Box Size**	δ
[20]	S&T HDPE Geomembranes PP and HDPE Geotextiles	Large	6.1°- 6.5°(Smooth) 14.2°- 17°(Textured)
[21]	3 Textured HDPE Geomembranes Smooth HDPE Geomembrane 3 NWNP Geotextiles	Large RSD	9°- 15°(Smooth) 26°- 31°(Textured)
[22]	S&T HDPE Geomembranes NWNP PP Geotextile	Small	11.6°- 14.5°(Smooth) 25.4°- 27.7°(Textured)
[23]	S&T HDPE Geomembranes Geotextile	Large	11.61°(Smooth) 20.88°(Textured)
[24]	HDPE Geomembrane NW Geotextile	Small RSD	6.5°(Smooth) (Residual)
[25]	S&T HDPE Geomembranes NWNP Geotextile	Small Large	12.3°- 14.19°(Smooth) 28.1°- 30.34°(Textured) 12.28°(Smooth) 27°(Textured)
[26]	5 Geomembranes 3 NW Geotextiles	Large	24°(Textured)
[28]	Textured Geomembrane NW Geotextile	Small	24°- 28°(Textured)
[29]	Textured Geomembrane NW Geotextile	Small RSD	9°- 11°(Smooth) 31°- 39°(Textured)
[30]	Textured Geomembrane Geotextile	Large	21.1°- 22.8°(Textured)

Table 4.9 shows the interface peak friction angles that were taken from the literature. Various experiments were performed by many researchers in the literature. Every one of them tried to investigate different aspects of interfaces like moisture effect, size effect, fiber type effect, temperature effect, texture effect (etc.). Most common interface materials, HDPE geomembranes and geotextiles, were used by the researchers for effective comparison. The same approach was followed in this study as well. Differences of results were observed due to the different aspects of the studies, various types of geomembranes and geotextiles as well as different shearing devices. In this study, the measured smooth geomembrane/geotextile interface friction angles were higher than those reported in literature for both shear apparatusses. On the contrary, textured geomembrane/geotextile interface friction angles were similar to those reported in the literature. Further comments and critisms can be found in the Discussion section.

4.3. Discussion

4.3.1. Discussion of Shear Strength Experiments

Shear strength experiments of soils are one of the most common applications in geotechnical engineering. Although there are several devices which are used in shear strength experiments, most common device is the direct shear device. The reasons of common usage are cost effectiveness and easy sample installation. That is why direct shear device was chosen for conducting experiments in this study as well.

The large scale shear device that was used in this study was designed and manufactured in Bogazici University [2,40,42,44,49]. The device was produced with some unique features like pneumatic artificial muscles for normal load application, upper box movement and constant contact area(even at large displacements).

Pneumatic artificial muscles were used in the shearing device because of their high loading capacities and easy to buy&find in the market. The large-scale device was manufactured with the contributions of Scientific Research Projects Programme (BAP 5580). Detailed information about the muscles and the large size large displacement device can be found in the study of Baykal [49].

One of the remarkable differences between the conventional direct shear device and the large scale device is upper box movement during shearing. Normally, lower box moves during shearing to keep the normal load perpendicular to the shearing plane. However, due to nonuniform upper box movements, additional moments and frictions occur. That is why a new shearing device with upper box movement during shearing was proposed by Qui *et.al.* [45]. Wu *et.al.* [9] and Baykal [2,49] performed their experiments with upper shear box moving devices. No negative comments were made due to this mechanical change.

Area correction is a necessity in direct shear devices because of their same size upper and lower shear boxes. This mechanical feature limits the amount of horizontal displacement. Liu *et.al.* [39] used a larger lower shear box like in this study and shared his experiences. The use of a larger lower shear box caused normal stress loss and defected shear zone. Because of such problems, shear strength of the selected specimen was found lower than the reality.

The Ring Shear Device device was widely used because of its unlimited horizontal shear capacity. But, since the device shears the same area again and again its reliability is questionable. Unlike the RSD, the developed shear device shears the specimen progressively and horizontally like in the real cases. Thus, the way that it works is closer to the real field conditions and has the potential of showing more reliable soil behavior than the RSD.

Akpınar Sand was used to simulate the Ottawa sand. The behaviors and the friction angle values of Akpınar Sand in both shear devices were consistent with each other and the literature. Parsons [4] and Cerato *et al.* [8] both used Ottawa sand to investigate scale effect on shearing. The results of Akpınar Sand were consistent with both of the studies.

One of the earliest studies of scale effect on shearing was presented by Parsons [4]. The internal friction angle of Ottawa Sand decreased about 2-3°when large scale device was used. In 1989 Palmeira and Milligan [7] also performed direct shear experiments at different size shear boxes and found no remarkable differences between results. However, further studies showed that there was an obvious scale effect between devices. Parsons, Cerato *et al.*, Wu *et al.* and Bareither *et al.* [4, 8–10] indicated that shear strength of soils decreased with large shear boxes. Results of Akpınar sand also confirmed these friction angle decrements when larger size shear box is used.

Dilation in front of the upper shearing box was observed during the shearing experiments with using sand. These soil movements caused normal stress loss and therefore lower shear strength values. Elmas [36] faced with the same problem when he performed shear strength experiments with crushed stone. Even though crushed stone had angularities and sharp edges, still the internal friction angles were found lower than the expectations and the reality. Liu *et al.* [39] also performed shearing experiments by using different shear boxes. Their results indicated that size difference between upper and lower shear boxes caused normal load loss and particle movements during shearing. That's why equal size shear box usage was recommended in the literature. However, modifications that were done in this study also gave promising results and made it possible to reach higher displacement values without strength losses and area corrections.

Large scale shear device that was used in this study, showed similar shear stress versus horizontal displacement graphs without any modification. However, internal friction angle values were so smaller than it should be. A couple of modifications were accomplished to avoid loss of normal loads and soil movements. Peak internal friction angles following modifications were so similar to those in the literature. Residual internal friction angles could not be found after modifications were done because there were no obvious shear strength loss at the range of the selected horizontal displacements.

Soil particle movements during shearing cause loading plate movements. These particle movements are called as dilation and contraction. Generally, loose specimens tend to contract because of the voids between the particles whereas dense specimens tend to dilate after an instant contraction behavior due to the normal loading. These behaviors are generally observed in vertical displacement versus horizontal displacement graphs. Traditional direct shear device results were consistent with the literature in terms of loading plate movements. But, the results from the large scale device, without modifications, showed that every single specimen tried to contract independent of its state which did not reflect the reality. These results also proved that there were normal load and soil loss during shearing, that's why all specimens tended to contract independent of relative densities. The results of this study showed major improvements after lower box modifications. Specimens started to behave according to their states.

The behaviors of the large size large displacement shear device on soil was investigated by only Akpınar sand. Different mechanical device behaviors could be observed when different soils are used. Also, the modifications that are accomplished in this study was to test this particular soil. Different soils might need different approaches and further alternative modifications.

4.3.2. Discussion of Interface Shear Strength Experiments

During all interface experiments, geotextiles were placed on top of the geomembranes to simulate the real field conditions as much as possible. ASTM 5321 [35] suggests to use clamping technique to secure interface materials to prevent movements during shearing. However, it was hard to achieve such systems in traditional direct shear device. So, this study focused on the main mechanism which recommended no movements at interface materials. That's why a multipurpose glue was used to fix the interface materials. Glue was the only fixing material in small scale shear device, on the other hand metal screws and glue were both used to fix interface materials at large scale shear device.

Jones & Dixon and Akpınar & Benson [20, 22] both used clamps for fixing of interface materials in their studies. Feng [27] used glue to fix geomembranes on the lower box and used clamps to fix geotextile under the upper shear box. Furthermore, Cen *et al.* and Stark *et al.* [21,23] both used glue to fix their interface materials. Beside these studies Akkol and Baykal [46] studied on interfaces at different constraint levels and found that friction angles increased with constraints. claimed that The use of glue or clamp constrained the materials and led to higher shear strength values than reality was found by Kim and Frost [32]. The use of unconstraint conditions in interface experiments were highly recommended. Therefore there is no strict rule of clamp use in the literature.

Elmas [36] performed interface shear strength experiments by using textured&smooth geomembranes, non-woven needle punched geotextiles and crushed stone. The elongation of geotextile due to shearing was observed more in smooth geomembrane tests. He found slightly higher friction values and added that this set up needed further explorations. On the other hand, Baykal *et.al.* [43] performed interface experiments using textured&smooth geomembranes and crushed stone under low normal stress (7kPa). High friction angle values and dramatic geomembrane damages were found following the tests. Thus, geotextile plays a vital role in interfaces and requires further research.

It was observed that the graphs of geomembrane/geotextile interfaces showed peak behaviors. Furthermore, post peak stress reduction was observed in both smooth & textured geomembrane interfaces with geotextiles [26–28, 32]. In this study, large scale interface experiments showed similar behaviors with the literature. However, small scale experiment results showed no obvious peak and post peak stress reduction behaviors like in the literature. The peak values are not present due to the limited horizontal displacement in small shear device.

Results were affected by the upper box movement and the area of shear. The constant and larger shear area resulted in more detailed material behaviors. Upper box movement eliminated the undesired vertical displacements and extra moments. Furthermore, the upper box movement affected the sheared material. Geomembrane was the sheared material in the small-scale device whereas geotextile was the interface material that sheared first. The large-scale device simulates the real cases better than the small-scale device.

Small Size Shear Device shear stress vs. horizontal displacement graphs showed fluctuations during shearing. On the other hand these sudden and continuous fluctuations were not observed in Large Size Direct Shear Device.

Smooth geomembrane/geotextile interface peak friction angles were found 2-3°higher than the literature in this study [20, 21]. Type of fiber, rate of displacement, moisture content, mass per unit area etc. could be the cause of these differences between this study and the literature. Also, the smooth geomembrane properties could have caused these differences because Li & Gilbert [28] claimed that post peak stress reductions predominantly depended on geomembranes than geotextiles. This reveals the importance of geomembrane as well. Besides all that, textured geomembrane/geotextile test results were found highly consistent with the results of this study.

Deformations of materials play a vital role for the designing stage. The experiments showed that no visible deformations occured between smooth geomembrane/geotextile interfaces. On the other hand, pilling of geotextile was observed after textured geomembrane/geotextile experiments. Li and Gilbert's [28] study showed that geomembrane was deformed remarkably and caused loss of strength between interfaces more than geotextiles. They did not mention visible deformations on geomembranes following experiments. So, its exploration obviously requires more detailed observations, use of microscopes and further researches.

5. CONCLUSIONS AND RECOMMENDATIONS

The large size large displacement direct and interface shear test device has been under development nearly for the last decade at Bogazici University. The top shear box is moving instead of the bottom opposed to the method used in the conventional test devices. The bottom box is three times longer than the top one to ensure a constant area during shear. The movement of the upper box caused soil loss at large displacements resulting measurement of very low internal friction angles. The objective of this study was to solve this problem. Calibration experiments of the multipurpose large scale large displacement shearing device were accomplished by testing materials, confirming results with Direct shear test device (60mm60mm shear box) and comparing with the literature. Due to the pandemic, the planned experimental programme could not be completed. The results presented are limited. For shear strength experiments Akpınar Sand was used to simulate Ottawa sand. For interface experiments HDPE Geomembranes (textured & smooth) and Non-woven Needle Punched Geotextile were used. All internal and interface shear experiments were subjected to 25kPa, 50kPa and 75kPa normal stresses.

Filling the upper box to full depth of the box resulted in very low internal friction angle values for large size direct shear test device. Dilation in front of the upper box, unstable normal loads and exaggerated vertical displacement values were observed.

To overcome the problems related to the movement of the upper box, the lower box was partitioned into three compartments with the same dimensions of the upper box. This way the soil loss from the upper box during shear was minimized. One upper box moving on practically three lower boxes minimized the vertical flow of the sand into monolithic lower box. In addition the height of the soil in the upper and lower boxes were limited to the recommendation given in ASTM recommendations. The box walls had to be supported with a wood wedge and metal plate configuration to make the walls more rigid. This way the internal friction angle values obtained were slightly lower (1-2 degrees) than those obtained from conventional direct shear test device. The dilation of sand in front of the upper box was also minimized. The internal friction angle difference between the small and the large-scale shear device supported that size effect exists. The use of larger shear boxes are resulted with lower internal friction angles.

The use of different size upper and lower shear boxes are not recommended in the literature. Also, the number of studies that used different size shear boxes are very limited. This study contributes to the literature and indicates that after necessary modifications are done, the use of different size shear boxes are possible. This possibility brings the advantages of high horizontal displacements without area corrections. The modifications could be changed according to the desired test specimens and conditions.

More than twenty interface tests were conducted for smooth geomembrane-geotextile interface and textured geomembrane-geotextile interface both in conventional direct interface shear device and large size large displacement interface shear test device. All results were in good agreement.

Large size direct shear test devices are hard to find in most of the geotechnical engineering laboratories. Moving the top box and having a large bottom box makes the equipment a versatile multipurpose test device.

As for recommendations, two large and square metal platen could be assembled perpendicularly into the lower shear box instead of one small metal platen and a wooden wedge. In this way, the device would be more practical and versatile.

The higher amount of displacements (at least 60mm) should be achieved to observe more detailed material behaviors.

Repetitions and the configurations of the tests should be increased to have solid scientific outcomes.

More sensors and cameras could be planted to the device to have more detailed data and real-time material behaviors. Additionally, interface materials should be checked with a microscope before and after interface experiments.

The inner walls of the shear boxes could be sealed with low friction materials so that the effects of the wall frictions are eliminated.

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