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Investigation of the PVC Geomembrane-Sand Interface Behaviour using the Discrete Element Method (DEM)

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Received: September 13, 2025
Accepted: January 12, 2026
DOI: 10.18466/cbayarfbe.1783279

Abstract

Synthetic polymer-based geosynthetics are widely preferred construction materials in geotechnical engineering for their effectiveness in reinforcing soil structures, controlling erosion, and improving drainage systems. They have many applications, such as landfills, footings, retaining walls, tunnels, and ponds. A detailed examination of their interaction with surrounding surfaces is necessary for geosynthetics to function correctly. This investigation investigates interface shear behaviour between polyvinyl chloride (PVC) geomembrane and granular soil. A 1.5- and 3.0-mm thick PVC geomembrane is tested using a cylindrical direct shear test (DST) via the discrete element method (DEM) using a shear box specimen chamber (radius: 52 mm, height: 75 mm). The experiments were first carried out with only the granular soil type; the soil's shear strength and internal friction angles were obtained. The lower jaw of the shear box was filled with a concrete block, and the geomembrane was then placed on the block surface. By putting soil in the upper jaw of the shear box, the soil–geomembrane contact was defined as the shear surface. The testing program included normal stresses of 12.5, 25, and 50 kPa combined with shear rates of 0.5, 1, and 2 mm/s to evaluate geomembrane behavior. According to DEM simulations, the interface friction angle of PVC–soil with a 1.5 mm thickness is 49%, 53.6%, and 58.2% lower than that of granular soil tested under shear rates of 0.5, 1, and 2 mm/s, respectively. For a thickness of 3.0 mm, the corresponding reductions are 47.7%, 51.2%, and 55.8%. These results, which ranged from one-third to two-thirds of the friction angle, were considered reasonable. Also, the results show that the change in shear rate has a minimal effect on the interface friction angle compared to what is observed in laboratory experiments.

Keywords: Discrete Element Method (DEM), geomembrane, geosynthetic, polyvinyl chloride (PVC), shear behaviour.

1. Introduction

Geosynthetics (GSs) are a diverse group of polymer-based materials engineered to address a variety of complex geotechnical challenges (Wu, Wang, Chen, & Liu, 2020; Shukla, 2021). In geotechnical engineering, geosynthetics are commonly used to significantly improve the strength of weak or problematic soils, facilitate effective drainage, reinforcement, separation, filtration, liquid containment, protection, and moisture barrier, and extend the lifespan and resilience of civil engineering structures. Additionally, geosynthetics are considered Affordable and sustainable, integral to modern construction practices, and commonly used to help improve soil strength, which could be used in subgrade, embankments, slopes, foundations, and earthen dams. Geosynthetics are typically classified into geotextiles, geomembranes, geogrids, geonets, and geocomposites. Geomembranes, in particular, act as impermeable barriers designed to minimize the migration of harmful substances and contaminants into the adjacent environment [3]. Geomembranes also function to prevent fluid seepage, helping to conserve water for drinking and irrigation storage [1]. Additionally, geomembranes and other geosynthetics are employed to regulate and contain fluid flow in applications such as sewage treatment, mining, and canal construction. Polyvinyl chloride (PVC) geomembranes are a key

type of geosynthetic and among the most commonly selected, widely used in projects such as landfill liners and covers. PVC, a synthetic polymer derived from vinyl chloride monomers, is favored in geotechnical engineering due to its flexibility, strong UV radiation resistance, and comparatively low cost [4, 5]. In addition, PVC exhibits excellent chemical resistance, effectively withstanding exposure to acids, alkalis, and oils. PVC geomembranes are impermeable and are manufactured in various thicknesses, typically 0.5-3 mm, depending on the intended use. While thicker membranes offer increased puncture resistance, they are generally less flexible [4]. Investigating interfaces in geotechnical engineering is essential for understanding the interactions between different materials under varying stress conditions, which directly influence the stability and performance of structures. Both the soil-geomembrane and soil-soil interfaces are of crucial importance for load transfer and shear resistance. Characterizing their behavior allows for the design of safer, more efficient structures, optimised use of materials and less chance of failure. Furthermore, insights into the mechanical behavior of interfaces contribute to improving construction techniques and developing advanced geotechnical materials [6, 7]. Several testing methods are available to study interface behavior, including direct shear, simple shear, Vane, triaxial, and ring shear tests. Interface shear resistance is typically characterized by adhesion and the interface friction angle (δ).

The direct shear test (DST) is commonly used in laboratory settings due to its simplicity, cost-effectiveness, and reliability in evaluating soil shear strength. It also enables the measurement of shear resistance at interfaces between various materials under controlled conditions. For instance, Fishman and Pal [8] observed test results on shear strength at the interface of geomembranes and cohesive soils, providing a comprehensive review of the factors influencing measured interface shear strength. Dove and Frost [9] conducted direct shear tests using Ottawa sand (20/30) and HDPE geomembranes, demonstrating that normal stress, particle characters, and material roughness significantly affect the governing shear mechanism. Ling, Pamuk, and colleagues [10] investigated the effect of geomembrane surface roughness by testing PVC geomembrane–cohesive soil interfaces. Their results indicated that textured geomembrane–soil interfaces exhibit higher peak shear strength compared to low-roughness interfaces, although the residual shear strengths were similar.

Despite these studies, limitations in existing laboratory apparatus and methods make it hard to examine the micro mechanical interactions between geomembranes and soil directly. The discrete element method (DEM) provides an operative alternative for this purpose and has been widely used to study geosynthetic and soil interactions. For example, Lai et al. [11] examine the soil-arching impact within geogrid-reinforced, pile-supported embankments; Wang and Alonso-Marroquín [12] investigated load transfer behavior between geogrids and sand; Kostkanová and Herle [13] examined the interface behavior of coal-fouled ballast reinforced with geogrids under direct shear; and Cheng, Yamamoto, and Thoeni [14] studied the stresses and fabric anisotropies of soils in geotextile containers.

To study the effects of geomembrane thickness on the shear behaviour of the geomembrane-sand interface using the Discrete Element Method (DEM), a detailed 3D direct shear model was designed using the Altair software [15]. This model facilitated a comprehensive analysis of the micro-mechanical interactions between soil and geomembrane. The shear strength behaviour of both soil-soil and soil-geomembrane interfaces was thoroughly examined. Two different geomembrane thicknesses were used, and the tests were conducted under varying normal stresses and shear rates to capture their influence on interface performance.

Furthermore, the DEM model developed in this study provide an innovative and realistic representation of the direct shear test (DST), facilitating simulation of soil–geomembrane interaction that closely replicates laboratory behavior. Unlike previous DEM studies that often utilized simplified or non-representative material properties, the parameters in this model, including particle size distribution and membrane stiffness, were chosen to reflect actual soil and PVC geomembrane conditions accurately. This methodology enhances the model's accuracy, improves the reliability of the micro-mechanical results, and provides a more practical contribution to understanding geomembrane–sand interface behavior.

2. The Discrete Element Method (DEM)

The DEM simulates the mechanical behaviour of granular material by applying Newton's motion laws to individual particles [16]. During the simulation cycle, forces generated from particle-particle and particle-geomembrane interactions are calculated. In each cycle, Newton's laws are repeatedly applied to determine the acceleration, velocity, and displacement of a single particle. The updated displacement is then used to compute the contact forces and torques from particle interactions at their new positions [17]. This process is iterated multiple times to simulate the behaviour of the bulk material [18]. DEM is particularly well-suited for analysing the unique behaviour and motion of granular materials [18] or investigating the effects of interface behaviour [19]. The DEM's Direct Shear Test (DST) model was developed innovatively to mimic the intricacies of the actual direct shear test process. The model consists of a cylindrical box with a radius of 52 mm and a height of 75 mm. The shear box was designed to remain undeformed under the applied normal and shear stresses. The lower cylinder is free to move beneath the fixed upper cylinder. In this setup, a dead-weight sphere positioned atop the upper cylinder provides and allows the sample to experience a constant normal load The horizontal loading system applies a shear force at a constant displacement rate in a direction parallel to the lower cylinder's movement. Furthermore,

Celal Bayar University Journal of Science
Volume 22, Issue 1, 2026, p 154-162
Doi: 10.18466/cbayarfbe.1783279

the model's material properties were adjusted to match those of steel, in accordance with the American Society for Testing and Materials standards [20]. The trial-and-error method was used to determine the DEM parameters, as shown in Table 1, to ensure the simulation results were acceptable as outlined in Table 1. The various components of the model are shown in Figure 1.

The reason for choosing DEM in this study rather than another method is that it simulates soil as individual particles and allows for direct simulation of contact, friction, and interlocking—all essential phenomena in the behavior of the sand–geomembrane interface. The finite element method (FEM), on the other hand, uses compatibility equations and constitutive models to handle soil as a continuum. This dependence may make it more difficult for FEM to represent discontinuous and nonlinear particle interactions. DEM is more appropriate and effective for examining interlocking, particle rotation, and interface shear behavior because it offers grain-level micromechanical knowledge.

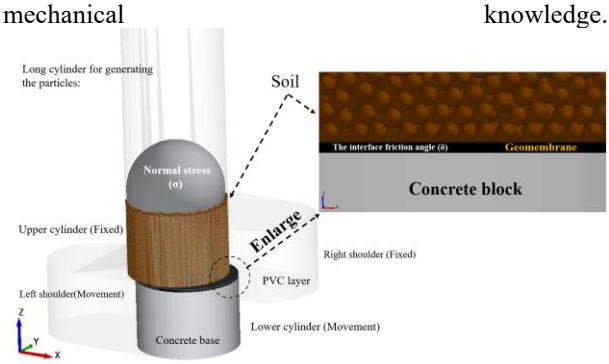


Figure 1. The elements of the DST model

Granular materials were prepared in a cylindrical cell using spherical beads with a radius of 1.5 mm. These particles filled the shear cylinder and were compacted under normal forces (gravity forces) for all samples. To ensure operative comparison between samples, the simulations were conducted in three stages. During the first stage, particle assemblies were generated rapidly, with particles initially in contact with their neighbors but still possessing kinetic energy. Time was allowed for the particles to settle and reach a state of negligible kinetic energy. In the next stage, the required normal load was implemented on the assembly. The use of particles with nearly identical diameters to those of the shear testing system, combined with accurately calculated densities, enabled the application of convenient vertical loads. The spherically shaped of the vertical load prevented tilting, a common issue in DEM shear simulations [13]. In the final stage, the DST was conducted by horizontally driving the lower cylinder while keeping a constant vertical stress. This study was divided into phases: the first phase determined the internal friction angle (ϕ) of the granular soil alone, with the soil properties summarized as shown at Table 1. Subsequently, the interface friction angle (δ) of the soil–geomembrane system was evaluated. PVC geomembranes, widely used in geotechnical engineering, typically range in thickness from 0.5 mm to 3 mm [21]. PVC geomembranes of 1.5 mm and 3.0 mm thickness were selected to represent commonly used field applications in geotechnical engineering, covering both thinner and thicker configurations typically employed for soil containment and lining systems. These thicknesses are within the standard market range of approximately 0.2 mm to 3.0 mm, with products frequently available in (1.0 1.5, 2.0, 2.5, and 3.0) mm sheets. The thicker membranes offer greater puncture strength and durability, making them appropriate for high-stress applications like landfill liners and providing a more reliable barrier to prevent leakage. Conversely, the thinner membranes are more ductile, easier to install, and more cost-effective for lighter applications [22, 23]. Selecting these two thicknesses enables examination of the effects of geomembrane stiffness and surface interaction on interface shear response, providing insight into how thickness influences frictional response at the soil-geomembrane interface. For testing, the geomembrane was laid over a concrete block to form the shear surface between the geomembrane and the granular soil. The concrete block was positioned in the lower jaw of the shear box, while the soil was placed in the upper jaw, establishing the soil–geomembrane interface as the shear plane [24]. The use of a concrete block prevents soil settlement during simulation and ensures the stability of the geomembrane during shearing, as illustrated in Figure 2. Shear tests were performed under various normal stresses (12.5, 25, and 50 kPa) and shear rates (0.5, 1, and 2 mm/s), chosen according to established guidelines [25] and previous experimental studies. The parameters in Table 1 were selected based on values commonly reported in previous DEM studies and standard material data. The properties for sand and the contact parameters match established ranges in the literature [2, 3, 24], and the values for PVC and steel come from typical material references [4, 24]. The time-step was selected according to DEM stability guidelines to remain below the Rayleigh limit [15]. Trial simulations showed that these parameters yielded stable, realistic results.

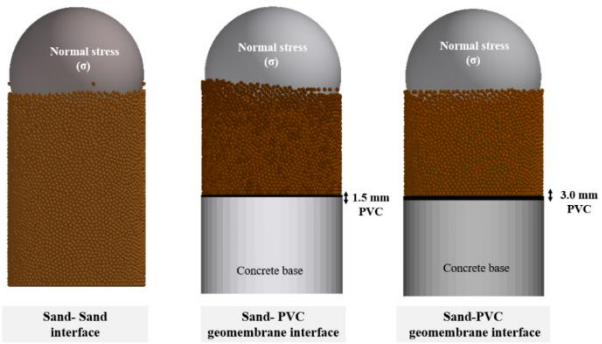


Figure 2. Direct shear test setup illustrating the soil–geomembrane interface

Celal Bayar University Journal of Science
Volume 22, Issue 1, 2026, p 154-162
Doi: 10.18466/cbayarfbe.1783279

Table 1. Input Parameters Used in the DEM Simulation

	Variable	Value
sand grains	Solid density (ρ)	2100 kg/m^3
	Shear modulus (G)	1e+07 pa
	Poisson ratio (v)	0.3
	Restitution coef.	0.6
	Static Friction coef.	0.5
	Rolling Friction coef.	0.05
	Number of sand particles	20000
PVC Geomembrane	Density (ρ)	1350 kg/m^3
	Shear modulus (G)	9e+08 pa
	Poisson ratio (v)	0.35
	Restitution coef.	0.7
	Static Friction coef.	0.6
	Rolling Friction coef.	0.05
	The fixed-time step	1.328e-05
Steel Mode	Density (ρ)	7500 kg/m^3
	Shear modulus (G)	8e+10 pa
	Poisson ratio (v)	0.3

3. Simulation Results:

The shear behavior at the interface between polyvinyl chloride (PVC) geomembranes as well as granular soil was investigated using the DEM, with both macro- and micro-scale observations derived from stress–strain curves. The analysis focused on shear stress, interface friction angle, and cohesion. The interface friction angle (δ) was determined using Mohr–Coulomb's law by assessing the inverse tangent of the ratio between shear and normal stress. The study was conducted in multiple phases: the primary phase evaluated the internal friction angle (ϕ) of the granular soil alone, followed by the assessment of the interface friction angle (δ) for the soil–geomembrane system. PVC geomembranes having thicknesses of 1.5 mm and 3.0 mm were used in the simulations. Figure 3 illustrates the interface behavior obtained from DEM. The denser concentration of red points observed in the 1.5 mm PVC interface compared to the 3.0 mm interface indicates greater shear deformation in thinner geomembranes. This demonstrates that shear deformation decreases with increasing geomembrane thickness, highlighting the thickness's significant role in controlling interface deformation between sand and PVC.

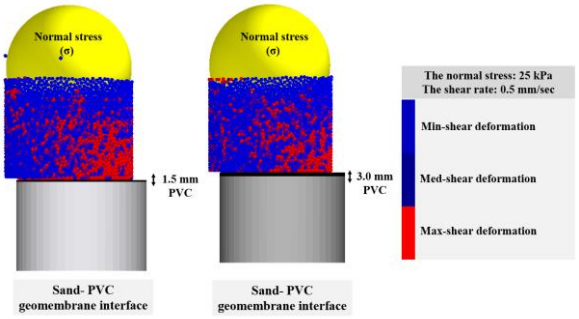


Figure 3. DEM analysis of PVC- soil interface shear behavior for 1.5 mm and 3.0 mm geomembranes

3.1 The soil-soil interface

Initially, the soil-soil interface was evaluated with granular soil under normal stress (12.5, 25, and 50 kPa) and shear rates (0.5, 1, and 2 mm/s). The internal friction angles of the granular soil were 30.6°, 33.4°, and 37.1°, respectively. As shown in Figures 4, 5, 6, and Table 2.

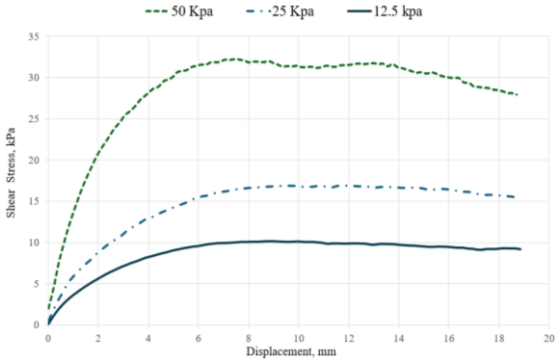


Figure 4. S-1 shear stress–strain response under varying normal stresses at 0.5 mm/s shear rate

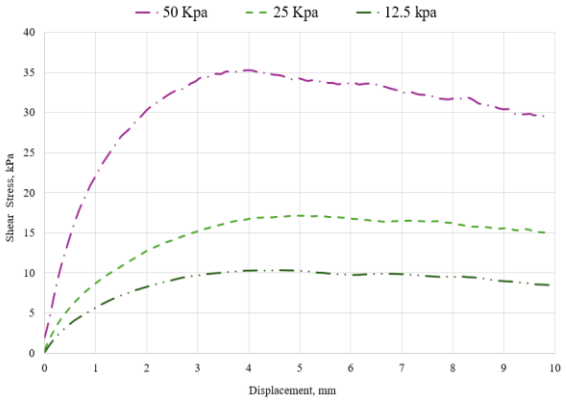


Figure 5. S-2 shear stress–strain response under varying normal stresses at 1.0 mm/s shear rate

Celal Bayar University Journal of Science
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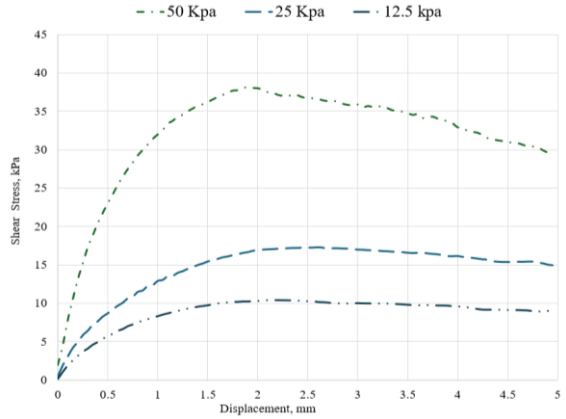


Figure 6. S-3 shear stress–strain response under varying normal stresses at 2.0 mm/s shear rate

3.2 The soil-PVC interface behaviour:

In this section, the interface response between sand and PVC geomembranes was investigated using DEM. The analysis was with a 1.5 mm-thick PVC geomembrane, subsequently by a 3.0 mm-thick geomembrane. For each thickness, three samples were prepared and was placed under to normal stresses of 12.5, 25, and 50 kPa, with the lateral rate at 0.5, 1, and 2 mm/s. This design allowed the study of how shear rate influences the mechanical response and shear strength of the sand–geomembrane interface.

The samples for the 1.5 mm PVC were labelled as S-1.5PVC-0.5RS, S-1.5PVC-1.0RS, and S-1.5PVC-2.0RS, whereas the 3.0 mm PVC samples were labelled S-3.0PVC-0.5RS, S-3.0PVC-1.0RS, and S-3.0PVC-2.0RS. The abbreviations used in the sample names are: “S” for sand, “PVC” for PVC thickness, and “RS” for shear rate. For example, S-1.5PVC-0.5RS represents a sand–PVC interface with a 1.5 mm thick geomembrane subjected to a Lateral displacement rate of 0.5 mm/s. Figures 7 and 8 show the shear stress–strain curves for S-1.5PVC-0.5RS and S-3.0PVC-0.5RS, respectively.

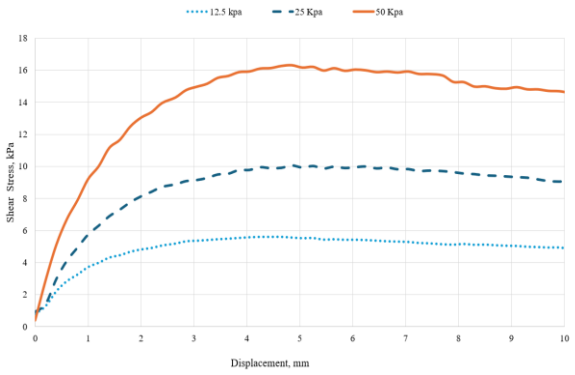


Figure 7. Stress versus strain plot of S-1.5PVC-0.5RS sample with a rate of shear 0.5 mm/sec

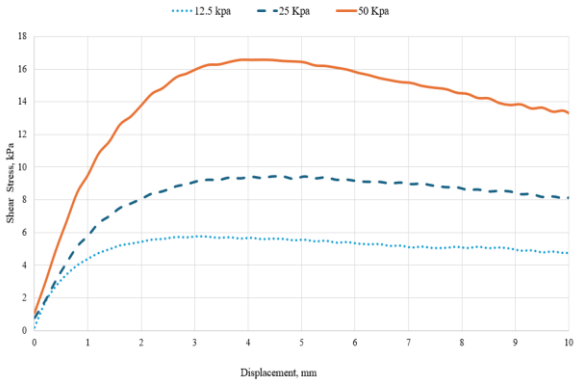


Figure 8. Stress versus strain plot of S-3.0PVC-0.5RS sample with a rate of shear 0.5 mm/sec

The shear strength at the interface between soils and geosynthetics (GSs) was evaluated using “The Standard Test Method for Determining the Shear Strength of Soil–Geosynthetic Interfaces by Direct Shear” [25]. According to ASTM D-5321, the interface friction angle (δ) is commonly evaluated using the experimental range $0.33\phi<\delta<0.67\phi$, where ϕ represents the soil’s internal friction angle. When δ falls within this range, it indicates a medium level of interaction between the soil and the GS, meaning the interface shear strength is less than the soil’s internal shear strength but still provides significant resistance against sliding. Values near the lower bound (0.33 ϕ) correspond to weaker interaction or lower friction. In contrast, values near the upper bound (0.67 ϕ) indicate stronger interaction, greater interlocking, and higher shear strength at the interface.

Table 3 presents the values of the shear strength of the sand–PVC geomembrane interface samples obtained from the DEM simulations, while Table 4 lists the corresponding interface friction angles for all samples.

Table 2. Shear strength parameters of the soil-soil interface

No.	Rate of shear (mm/sec)	(ϕ), (°)	Cohesion (c) (kPa)
S-01	0.5	30.6	1.3
S-02	1.0	33.4	2.5
S-03	2.00	37.1	0.07

Figure 9 presents the variation in interface friction angles for polyvinyl chloride (PVC) geomembranes with thicknesses of (1.5, and 3.0) mm exposed to lateral rates of (0.5, 1.0, and 2.0) mm/s. The data indicate a slight decrease in friction angle for the 1.5 mm PVC as shear rate increases, whereas the 3.0 mm PVC shows a marked increase, suggesting that thicker membranes are more sensitive to shear rate effects.

Table 3. Shear Strength of Sand-PVC Geomembrane Interface at Varying Normal Stresses

No.		Applied normal stress, kPa		
		12.5	**25**	**50**
S-1.5PVC-0.5RS	**Shear Strength, kPa**	5.70	10.07	16.33
S-1.5 PVC -1.0RS		5.60	10.09	16.23
S-1.5 PVC -2.0RS		5.61	10.09	16.22
S-3.0 PVC -0.5RS		5.76	9.40	16.70
S-3.0 PVC-1.0RS		5.76	9.42	16.55
S-3.0PVC-2.0RS		5.78	9.45	16.79

Table 4. Outcomes of the internal friction angle and cohesion

No.	Shear rate	Internal Friction angle	Interface Friction angle	$0.33\phi<\delta<0.67\phi$
	(mm per sec)	(ϕ), (°)	(δ), (°)	
S-1.5PVC-0.5RS	0.5	30.6	15.6	10.1 < 15.6 < 20.4
S-1.5 PVC -1.0RS	1.0	33.4	15.5	11.1 < 15.5 < 22.3
S-1.5 PVC -2.0RS	2.0	37.1	15.5	12.4 < 15.5 < 24.7
S-3.0 PVC -0.5RS	0.5	30.6	16.0	10.1 < 16.0 < 20.4
S-3.0 PVC -1.0RS	1.0	33.4	16.3	11.1 < 16.3 < 22.3
S-3.0PVC-2.0RS	2.0	37.1	16.4	12.4 < 16.4< 24.7

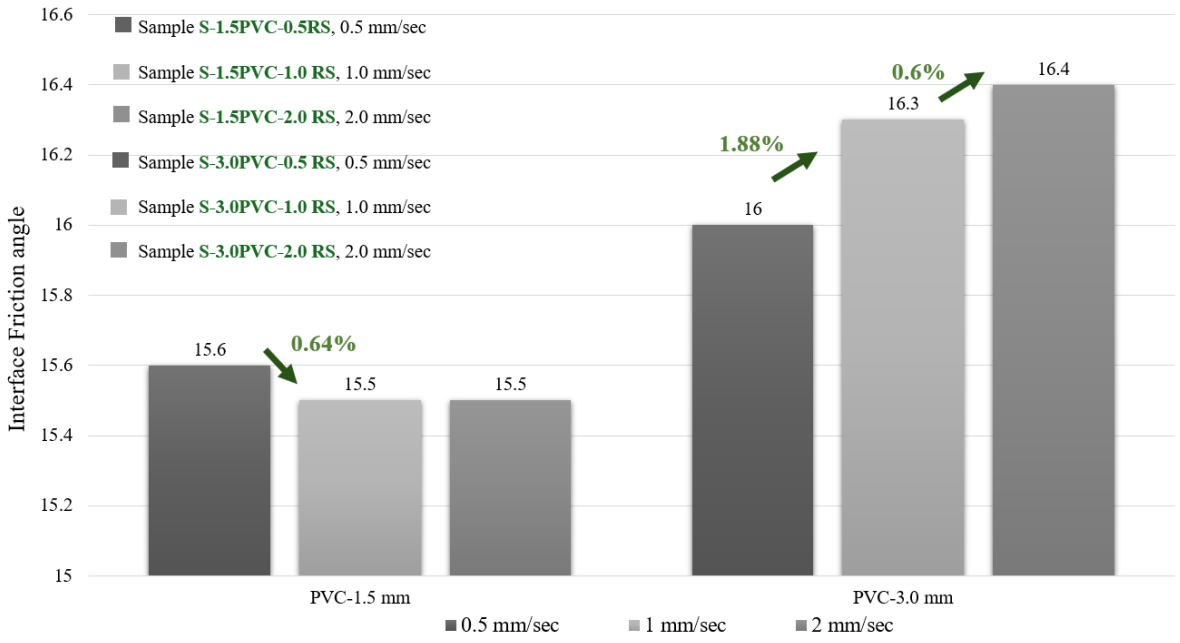


Figure 9. Variation of interface friction angles for 1.5 mm and 3.0 mm PVC at different shear rates

The results offer important understanding of the shear behavior interface between PVC geomembranes and granular soil. In the present study, a novel direct shear test model was developed within the DEM framework to simulate the mechanics of the laboratory test, thereby improving the reliability of the results. A key challenge addressed was simulating lower shear rates, which typically require substantial computational time in DEM. Nevertheless, high accuracy was achieved by closely calibrating the granular soil and geomembrane properties to values commonly used in geotechnical engineering. The simulated interface behavior was found to be consistent with ranges reported in previous experimental studies, validating the model. Moreover, the influence of geomembrane thickness on shear behavior was analyzed, providing further understanding of the factors affecting interface performance.

- Using DEM, both macroscopic and microscopic behaviours were analysed, focusing on stress-strain responses. The study showed that internal friction angles (ϕ) of granular soil increase with Lateral displacement rates. At rates of 0.5, 1.0, and 2.0 mm/sec, the angles were 30.6°, 33.4°, and 37.1°, respectively, under normal stresses of 12.5, 25, and 50 kPa. This validates DEM's capability to simulate direct shear tests (DST) and aligns with geotechnical principles of soil interface behaviour.
- The interface friction angles (δ) between sand and PVC geomembranes were consistently less than the internal friction angles of the sand–sand interface for both 1.5 mm and 3.0 mm thick geomembranes. For the 1.5 mm thick PVC, the interface friction angle was approximately 49%, 53.6%, and 58.2% lower than that of granular soil at shear rates of 0.5, 1, and 2 mm/s, respectively. For the 3.0 mm thick PVC, the reductions were about 47.7%, 51.2%, and 55.8% at the same shear rates. This reduction is primarily due to the absence of interlocking between soil particles and the geomembrane, which decreases resistance to shear and lowers the friction angle. In granular soil, particles interlock and generate additional resistance under shear, whereas geomembranes lack such interlocking, limiting the interface friction. Moreover, soil particle interactions occur at multiple contact points, producing complex three-dimensional shear mechanisms. In contrast, contact between the geomembrane and soil is predominantly planar, reducing the ability to develop the full shear strength characteristic of the soil's internal friction angle [26, 31].
- According to ASTM D5321M-21 [25], the measured interface friction angles fall within the range $0.33\,\phi < \delta < 0.67\,\phi$. This indicates that the interface shear strength is less than the soil's internal shear strength (ϕ) but still provides a significant resistance to sliding.
- In this study, the thickness of the PVC geomembrane was found to influence the interface behavior. For the 1.5 mm PVC samples, the interface friction angle (δ) ranged from 15.5° to 15.6°, whereas for the 3.0 mm PVC samples, δ varied from 16.0° to 16.4°. The thicker 3.0 mm geomembrane can deform slightly under load, promoting a more even stress distribution across the sand–geomembrane interface. This enhanced deformation facilitates more effective interlocking of sand particles with the geomembrane surface, improving resistance to movement. Additionally, the greater thickness increases the contact area, thereby reducing localized stress concentrations that are more pronounced in thinner membranes. In contrast, the thinner 1.5 mm geomembrane deforms less under the same load, limiting stress redistribution and the opportunity for particle interlocking. As a result, the interface exhibits a slightly lower friction angle due to higher localized stresses and reduced overall frictional resistance.
- The influence of lateral displacement rate on geomembranes depends on factors such as surface roughness and membrane thickness. However precisely modelling surface roughness in EDEM poses challenges [27, 28], whereas asperity thickness in geomembranes plays a more critical role [29, 31]. In this study, it was observed that while shear rate markedly affects the shear strength of granular soils, its impact on the geomembrane interface is minimal. For granular soils, increasing the shear rate generally increases shear strength. In contrast, the shear strength of geomembrane interfaces is primarily governed by membrane thickness rather than shear rate. As the thickness increases, the interface shear strength stabilizes, and further variations in shear rate have little effect. This explains why the influence of shear rate is less pronounced in geomembranes than in granular soils, where it plays a more significant role in determining shear strength.
- The results fall within the range of previously reported laboratory results [22, 29, 30], which investigated interfaces between PVC geomembranes (1.5–3.0 mm thick) and dry granular soil, as illustrated in Figure 10. This consistency supports the reliability and effectiveness of the present DEM-based analysis in evaluating geotechnical soil–geomembrane interfaces.
- Finally, this study's findings offer essential perspectives for geotechnical design that include soil–geomembrane interfaces. The influence of geomembrane thickness on interface friction underscores the need to select a suitable membrane based on expected loading conditions, as thicker geomembranes promote more consistent stress distribution and marginally increased shear resistance. The consistently lower interface friction relative to the internal friction of granular soil underscores that interface characteristics, rather than the soil's inherent strength, dictate the stability of systems such as retaining walls, landfill liners, and containment structures. Additionally, the constrained effect of shear rate on interface performance suggests that design calculations can appropriately depend on static or quasi-

static friction values, streamlining practical evaluations. These results provide actionable insights to enhance interface stability and refine geomembrane selection in geotechnical applications.

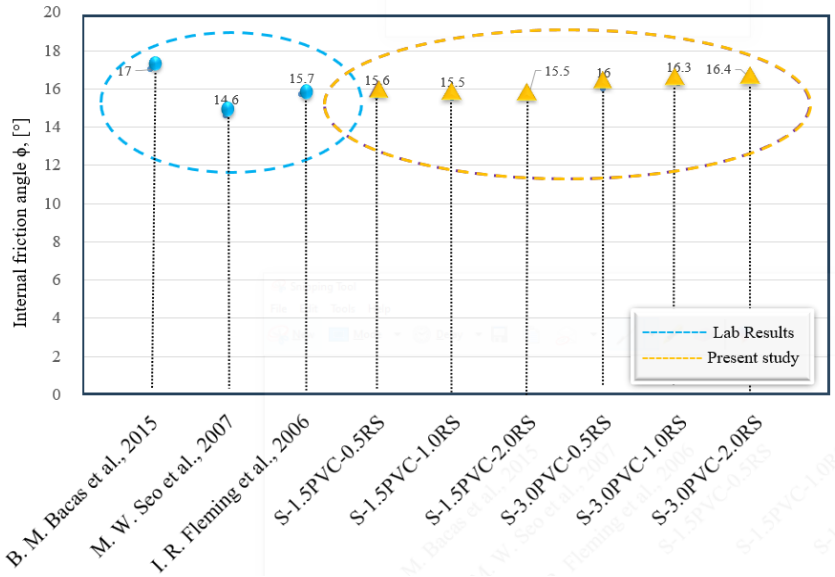


Figure 10. Comparison with laboratory results from previous studies

4. Conclusion:

- The interface shear behaviour between polyvinyl chloride (PVC) geomembranes of 1.5 mm and 3.0 mm thickness and granular soil was investigated using the Discrete Element Methodology (DEM).
- The results showed that the value of friction angles of the granular soil were higher than the interface friction angles.
- This finding in agreement with the established understanding that the interaction between soil particles and the geomembrane is smaller in magnitude than the internal interlocking within the soil.
- Furthermore, the outcomes indicate that differences in shear rate have a negligible effect on the interface friction angles, suggesting that shear rate does not significantly influence the shear strength at the soil-geomembrane interface. This is because there is minimal interlocking between soil and the PVC geomembrane, and the contact between the soil and the membrane is primarily planar. The interface mostly depends on membrane thickness and surface properties, whereas in granular soil, higher shear rates enhance particle contact and friction. Because of this, changes in shear rate result in only minor changes in interface shear resistance, maintaining a relatively constant friction angle [32].
- These findings contribute to the broader understanding of geosynthetic applications in geotechnical engineering by emphasizing the critical role of soil-geomembrane interactions in ensuring the stability and performance of engineered structures.

Author's Contributions

Mohammad Bairoti: Conceptualization; development of the DEM model; execution of numerical analyses; data processing; preliminary interpretation of the results; preparation of the initial draft of the manuscript.

Hasan Fırat Pulat: Conducting the literature review, optimization of experimental and numerical parameters, contribution to the validation of the results, assistance in preparing figures and tables, and critical review of the manuscript draft.

Muath S. Talafha: Assisted in analytical analysis of the tests, supervised the experiment's procedures, result interpretation and helped in manuscript formulation, final proofreading, and academic language editing.

Ethics

No ethical issues are associated with the publication of this manuscript

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