A Calibration Procedure for Modeling HDPE Geomembrane Using Discrete Element Method

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ABSTRACT

Geomembranes are geosynthetic impermeable materials used as hydraulic barriers in waste containment facilities. Continuum methods are generally used to analyze the behaviour of geomemberanes and calculate tensile and interface stresses under various loading conditions. However, it is sometimes desired to simulate the interaction behaviour between a geomembrane liner and granular soil subjected to large movements. Discrete element methods have proven to be efficient in modeling granular materials using discrete particles. Using the same procedure to model geomembranes would lead to significant reduction in calculation cost and eliminates the need to use hybrid methods, which require simultaneous use of both continuum and discontinuum modeling approaches. This study presents a procedure to calibrate a discrete element model of a HDPE geomembrane using spherical particles. A constitutive model that takes into account particle normal and shear cohesion is used. Standard index tests used to measure the properties of HDPE geomembrane including tensile and puncture tests are applied to validate the model developed. The effect of microscopic parameters on the overall response is examined and recommendations are made regarding to the optimum approach to simulate continuous geomembrane materials using discrete element method.

RÉSUMÉ

Les géomembranes sont des matériaux imperméables géosynthétiques utilisés comme barrières hydrauliques dans les installations de confinement des déchets. Les méthodes de Continuum sont généralement utilisés pour analyser le comportement des geomemberanes et calculer la traction et contraintes d'interface dans diverses conditions de charge. Cependant, il est parfois souhaitable de simuler le comportement d'une interaction entre une géomembrane et un sol granulaire soumis à de grands mouvements. Les méthodes d'éléments discrets se sont avérés efficaces dans la modélisation de matériaux granulaires en utilisant des particules discrètes. En utilisant la même procédure pour modéliser les géomembranes conduirait à une réduction significative des coûts de calcul et élimine la nécessité d'utiliser des méthodes hybrides qui nécessitent simultanément l'utilisation des approches de continuum et de discontinuum. Cette étude présente une procédure pour calibrer un modèle d'élément discret d'une géomembrane en HDPE en utilisant des particules sphériques. Un modèle constitutif est utilise qui tient compte des cohésions normale et de cisaillement de particule. Les tests d'index standards utilisés pour mesurer les propriétés de HDPE géomembrane, y compris des essais de traction et de perforation sont appliquées pour valider le modèle développé. L'effet des paramètres microscopiques sur la réponse globale est examiné et des recommandations sont formulées en ce qui concerne l'approche optimale pour simuler des matériaux de géomembrane en continu en utilisant la méthode des éléments discrets.

1 INTRODUCTION

In the field of solid waste landfill engineering, the use and acceptance of geosynthetics and high density polyethylene (HDPE) geomembrane (GM) has increased over the past few years. HDPE geomembrane is usually used as a hydraulic barrier in waste containment applications including municipal solid waste facilities.

One of the greatest risk of damage in geomembranes is associated with stress concentrations from direct contact with coarse soil particles (e.g., gravel or stones), which can occur from an underlying soil subgrade or an overlying granular soil layer (Nosko and Touze-Foltz 2000; Giroud and Touze-Foltz 2003). Extensive research has been conducted on granular soil-geomembrane interaction using experimental and numerical methods (Reddy et al. 1996a; Koerner et al. 2010; Hornsey and Wishaw 2012; Brachman and Sabir 2013). Among the different numerical methods that have been developed by researchers to study this interaction, the discrete element method (DEM) has proven to be efficient in modeling granular materials involving large deformations. Also, using the same approach to model geomembrane leads to significant reduction in calculation cost in comparison with other methods such as hybrid procedure that requires simultaneous use of both continuum and discontinuum modeling approaches.

The discrete element method (DEM) has gained popularity in the past few decades among geotechnical engineers and researchers involved in granular soil-structure interaction problems. The method was first proposed by Cundall and Strack (1979) and has been used to analyse geotechnical engineering problems. Laboratory tests such as triaxial and direct shear have been modelled using DEM to investigate the microscopic behaviour of soil samples (Cui and O'Sullivan 2006). Also, several researchers applied this method to model soil-geosynthetics problems including elements such as textiles, grids and membranes (McDowell et al. 2006; Effeindzourou et al. 2016). In most of these studies a membrane is modelled using a set of spherical particles bonded together. These bonded particles can simulate the membrane behaviour correctly if the input parameters are chosen precisely.

In this work, a calibration procedure is proposed which takes into account the role of each parameter in the macroscopic behaviour. Two index tests, namely, tensile and puncture tests are numerically simulated to determine the microscopic parameters of the bonded HDPE geomembrane particles.

2 DISCRETE ELEMENT MODELING

2.1 General formulation

The discrete element method (DEM) treats the interaction between particles as a dynamic process that reaches static equilibrium when the internal and external forces are balanced. This dynamic process is usually modeled using a time-step algorithm based on an explicit time-difference scheme. Displacement and rotation of each particle are then determined using Newton's and Euler's equations. The DEM simulation in this study are performed using the open source discrete element code YADE (Kozichi and Donze, 2008; Smilauer et al., 2010).

The contact law between particles is briefly described below:

After collision of particles A and B with radii r_A and r_B, contact penetration depth is defined as

$$\Delta = r_A + r_B - d_0 \quad [1]$$

Where d_0 is the distance between centers of particles A and B. Interaction between the two particles is represented by the force vector F. This vector can be decomposed into normal and tangential forces (Fig. 1)

$$F_N = K_N \ .\Delta_N \quad [2]$$

$$\delta F_T = -K_T \ .\delta\Delta_T \quad [3]$$

Where F_N is the normal force; δF_T is the incremental tangential force; K_N and K_T are the normal and tangential stiffnesses at the contact point; Δ_N is the normal penetration between the two particles and $\delta\Delta_T$ is the incremental tangential displacement between the two particles.

The normal stiffness between particle A and B at contact point is defined by

$$K_N = \frac{K_N^A \ . \ K_N^B}{K_N^A + K_N^B} \quad [4]$$

Where K_N^A and K_N^B are the particles normal stiffnesess calculated using particle radius r and the particle material modulus E_i.

$$K_N^A = 2E_A r_A \qquad and \qquad K_N^B = 2E_B r_B \quad [5]$$

So the normal stiffness at contact point can be written as:

$$K_N = \frac{2E_A r_A . 2E_B r_B}{2E_A r_A + 2E_B r_B} \quad [6]$$

The interaction tangential stiffness K_T is defined as a ratio of the computed K_N as $K_T = \alpha \ K_N$.

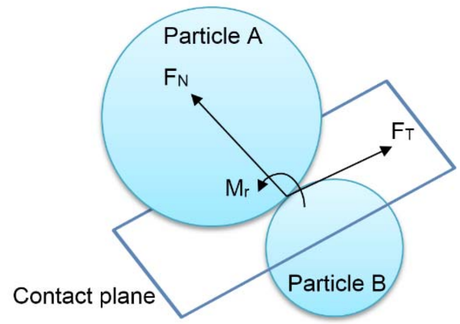

Figure 1. Interaction between two DE particles

Rolling resistance between two particles A and B is determined using a rolling angular vector θ_r. This vector is calculated by summing the angular vector of the incremental rolling (Smilauer et al., 2010)

$$\theta_r = \sum d\,\theta_r \quad [7]$$

A resistant moment M_r is calculated by

$$M_r = K_r \,.\, \theta_r \quad [8]$$

Where K_r is the rolling stiffness of the interaction and is defined as

$$K_r = \beta_r \ . \ (\frac{r_A + r_B}{2})^2 \ . K_T \quad [9]$$

Elastic limits can be defined for Eqs. (2) and (3) using shear (C_T) and tensile strength (C_n).

$$F_N \ \leq \ C_n \ \times A \quad [10]$$

$$F_T \ \leq \ F_N \ \tan\phi_{micro} + C_T \ \times A \quad [11]$$

Where ϕ_{micro} is the microscopic friction angle between particles and $A = \pi R_C^2$ is the reference surface area (R_C is the reference radius of the contact, R_C= min (R_1 and R_2)). Note that normal force is only limited in traction and it is assumed that compression at contact is always elastic.

2.2 Discrete element modeling of a flexible membrane

The developed HDPE geomembrane model consists of an array of bonded spherical particles which are arranged hexagonally. The bonds are defined by shear and normal tensile strength, set high enough that the membrane does not split. Also rotation of particles and the transmission of moments are restricted to ensure membrane flexibility (De Bono et al. 2012). The main properties of the spherical particles which are needed for the calibration procedure are listed in Table 1. Among these parameters, the value of the micro-friction angle (ϕ_{micro}) is assigned to zero based on the findings of De Bono et al. (2012) and Bourrier et al. (2013). All four remaining parameters need to be extracted using the calibration method described in the next section.

2.2.1 Tensile test specimen

The tensile test specimen is created based on ASTM D6693 (standard test method for determining tensile properties of flexible geomembranes). The specimen has a dog bone shape and its dimensions are illustrated in Fig. 2.

Table 1- Parameters of the contact model used in the modeling of HDPE geomembrane

Properties
Particle material modulus (E_i)
Density
Micro friction angle (ϕ_{micro})
$\alpha = \frac{K_T}{K_N}$
Tensile strength (C_n)
Shear strength (C_T)

The test procedure is described below

1- Measuring the width and thickness of the sample (W=6 mm, t=1.5 mm)
2- Placing the specimen in the grips of the test apparatus (to prevent slippage of the specimen). Grip dimension is 25 mm on each side.
3- Installing the strain gage on the specimen (gage initial length=33 mm).
4- Applying the load at a rate of 50 mm/min on the right side while the left grip is fixed. Then, recording the load-displacement data.

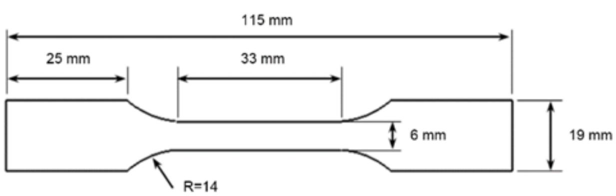

Figure 2. Tensile test specimen dimensions

The diameter of the particles in the discrete element model is chosen considering a balance between simulation time and the geomembrane flexibility. Based on these criteria, spherical particles with diameter of 0.3 mm are created and arranged in hexagonal pattern. Two specimens with different thicknesses are created. First sample with thickness of 0.3 mm consists of 28564 particles arranged in one row. The other sample includes 6 rows of the first specimen with 171,384 particles and final thickness of 1.5 mm. Most of the particles located between the grips do not have interactions with other particles as they have a zero or constant velocity under the specified test condition. Hence, to increase the simulation speed, only 2.5 mm of each grip is modeled. Figure 3 illustrates the final discrete element samples of the tensile test and a close view of the specimen.

2.2.2 Puncture test specimen

The puncture test specimen is created based on ASTM D4833 (standard test method for index puncture resistance of geomembranes). The specimen has a circular shape and its dimensions are illustrated in Fig. 4.

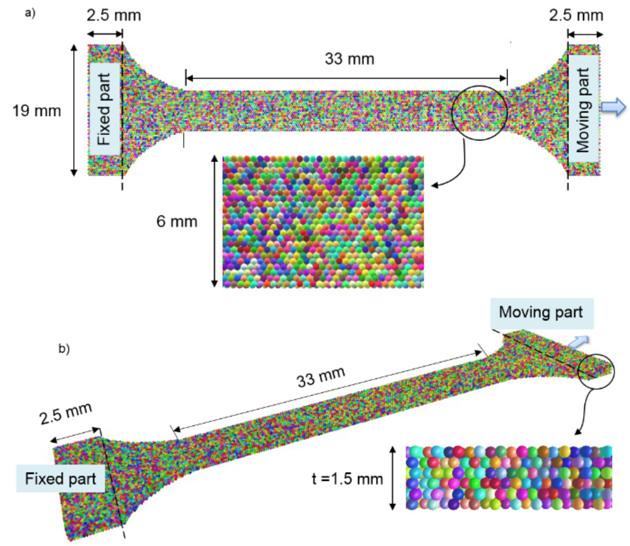

Figure 3. a) Top view of the first test specimen with thickness of 0.3 mm and a partial view of the specimen to illustrate the hexagonal arrangement of particles, b) A 3D view of specimen with a thickness of 1.5 mm.

To perform the puncture test, geomembrane needs to be fixed among an O-ring plate with outer diameter of 100 mm and an open internal diameter of 45 mm. Then a solid steel rod (test probe) is pushed downward with a speed of 300 mm/min towards the center. Probe load (puncture resistance) is recorded until the steel rod completely ruptures the test specimen.

The diameter of the particles in the discrete element model and their arrangement are chosen the same method as the tensile test specimens; and two samples with different thickness are created as well. Particles in the fixed part of the sample don't have any effects on the outcome force. Hence, to decrease the number of particles and duration of the simulation, only 2.5 mm of the fixed part is created. Thus, the diameter of the DE sample is 50 mm. Two samples with thicknesses of 0.3 mm and 1.5 mm and total number of particles of 25,198 and 151,188, respectively, are created. The discrete element model of the puncture test and a partial view of the sample are presented in Fig. 5.

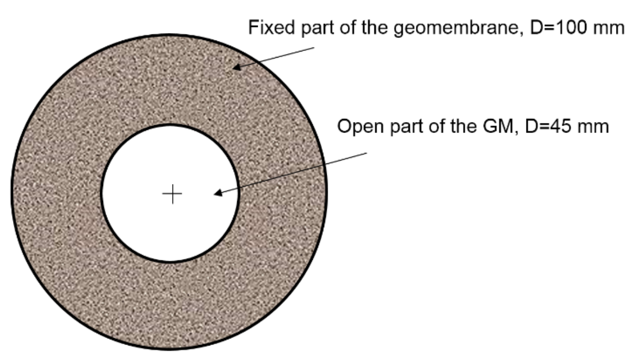

Figure 4. Puncture test details

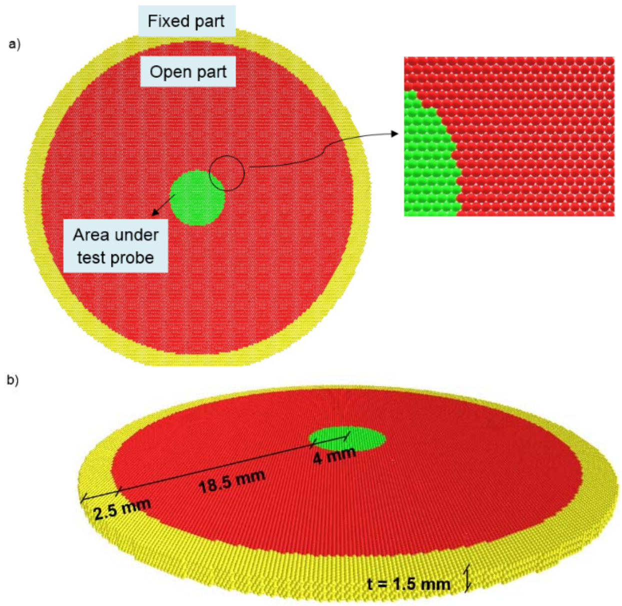

Figure 5. a) Top view of first puncture test specimen with thickness of 0.3 mm and a partial view of the specimen to illustrate the hexagonal arrangement of particles, b) A 3D view of specimen with thickness of 1.5 mm.

3 CALIBRATION OF THE LOCAL PARAMETERS

The calibration of the material properties with respect to the real geomembrane is performed by comparing a simulated and a laboratory test results. Once calibrated, the predictive capabilities of the numerical model is checked and validated by simulating the puncture test. For the calibration step, the selected local parameters include, particle material modulus (E_i), Tensile strength (C_n), Shear strength (C_T) and the ratio between tangential and normal stiffness (α). The choice of these parameters should allow for the correct macroscopic values (Young's modulus E, tensile strength at the yield point, tensile elongation at yield and puncture resistance) to be reproduced. To achieve this objective, the impact of each local parameter on the macroscopic response needs to be identified. Based on the previous studies (Calvetti et al. 2003, Sibille et al. 2006, Plassiard et al. 2009) it was found that elastic parameters (E_i and α) and rupture parameters (C_n, C_T) can be calibrated separately.

The particle modulus (E_i) is known to play an important role in the elastic response whereas, the ratio between tangential and normal stiffness (α) has no significant impact on material Young's modulus E. Therefore, E_i will be used first to calibrate the macroscopic elastic behavior. The value of α is set to 0.3 based on that reported by Effeindzourou et al. (2016) in modeling a deformable structure using DEM. Using this value for α, E_i is set such that the target Young's modulus based on the tensile test results is obtained. As presented in Fig. 6, as the particle modulus (E_i) increases, the Young's modulus of the geomembrane increases.

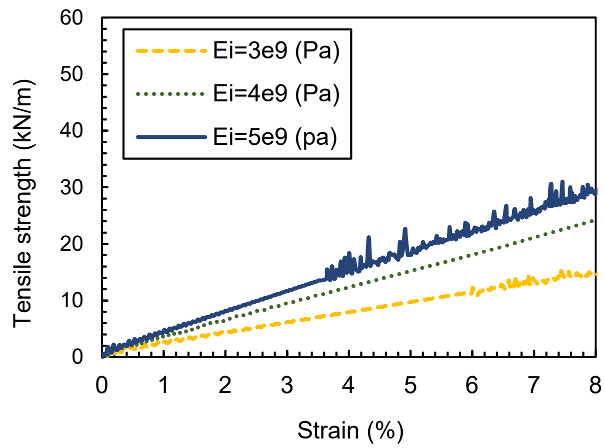

Figure 6. Dependency of Young's modulus on particles material modulus (E_i)

Once the elastic parameters are set, the values of the rupture parameters (C_n, C_T) can be determined. Changing these two parameters separately was found to lead to divergence in the results. Equal values for the two parameters were considered in consistency with De Bono et al. (2012), Bourrier et al. (2013) and Effeindzourou et al. (2016). These two parameters were found to affect the peak stresses with little to no effect on Young's modulus as illustrated in Figure 7.

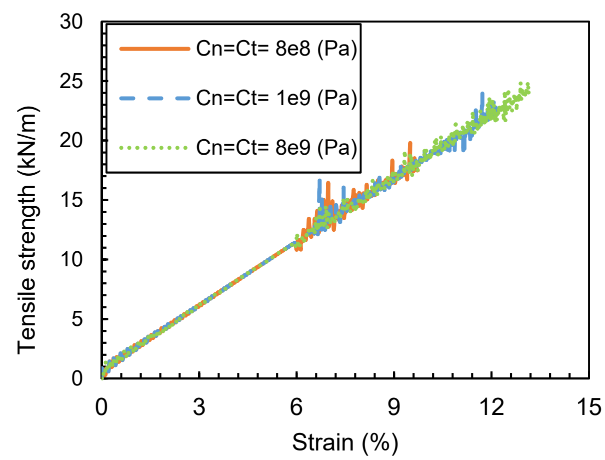

Figure 7. Dependency of peak stress on particles tensile and shear strength

4 APPLICATION OF THE PROPOSED METHOD TO SIMULATE GEOMEMBRANE RESPONSE TO LOADING

The selected HDPE GM was manufactured by Layfield Corp. (USA and Canada). Geomembrane specimen has a thickness of 1.5 mm with blown-film texturing on both sides. The GM material properties are given in Table 2.

Following the calibration procedure described in section 2, tensile test is modeled using DEM. At first a specimen with thickness of 0.3 mm is created and the input parameters are determined using the calibration method (see Table 3). To validate these parameters a second tensile test specimen with a thickness of 1.5 mm is created and the micro-parameters are assigned to the particles. Results are summarized in Table 4 which show consistency between the calculated results and the experimental data.

Table 2- Material properties of the selected HDPE geomembrane

Properties	Value
Thickness	1.5 mm
Density	0.94 g/cc
Tensile strength at yield	22 kN/m
Tensile elongation at yield	12 %
Puncture resistance	480 N

The effect of the applied tension force can be further examined by inspecting the contact force distribution within the geomembrane specimen. Figure 8 shows the contact force network in the geomembrane during the test (ε = 6%). Most of the contact forces are directed parallel to the applied external load. In addition, the magnitude of the forces is larger for the narrow section as compared to the rest of sample.

Table 3- Input parameters of the contact model obtained from the selected HDPE geomembrane using the proposed calibration method

Properties	Value (Unit)
Particle material modulus (E_i)	3.0E9 (Pa)
Density	0.94 (g/cc)
Micro friction angle (ϕ_{micro})	0 (Degree)
$\alpha = \frac{K_T}{K_N}$	0.3
Tensile strength (C_n)	1.0E9 (Pa)
Shear strength (C_T)	1.0E9 (Pa)

Table 4- Comparison between calculated and measured tensile strength and Young's modulus of the geomembrane

Properties	Test method	Thickness (mm)	
		0.3	1.5
Tensile strength at yield (kN/m)	Experiment	22	22
	Numerical	23	25
Tensile elongation at yield (%)	Experiment	12	12
	Numerical	12.2	12.5

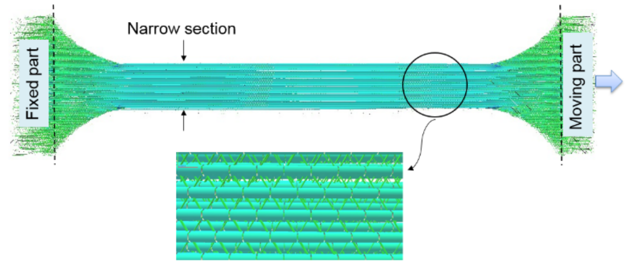

Figure 8. Contact force network in tensile test simulation

The puncture test was also simulated using two specimens of different thicknesses and the input parameters are assigned to the used particles. Numerical results were found to be in agreement with the experimental data as shown in Table 5. The contact force network distribution during the puncture test before and after failure are illustrated in Figures 9 and 10. As presented in Fig. 9 contact forces are higher near the edge and under the test probe in comparison with the rest of the sample. Also, the specimen failure mode is found to be similar to that observed in the experiment. The above results confirm that the proposed DEM based method is acceptable in modeling the response of geomembrane material.

Table 5- Comparison between calculated and measured puncture resistance of the geomembrane

Thickness (mm)	Puncture resistance (kN)	
	Experiment	Numerical
1.5	480	505
0.3	96	101

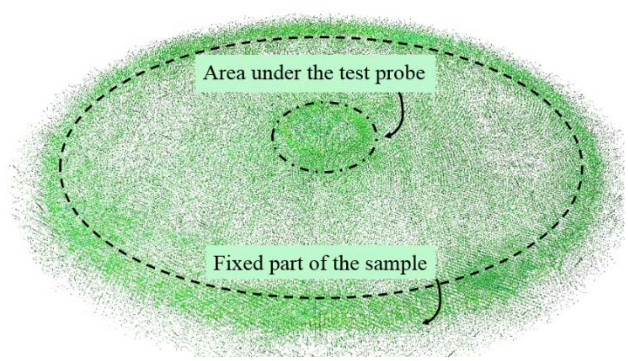

Figure 9. Contact force network in puncture test before the failure

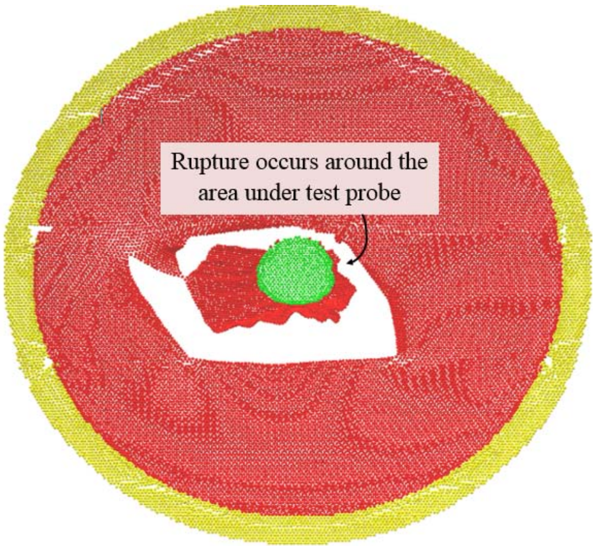

Figure 10. Top view of the puncture test simulation at failure state

5 CONCLUSION

A DEM model has been created that can simulates tensile and puncture tests performed on HDPE geomembrane. Bonded spherical particles are used to create a flexible membrane material allowing for the correct deformation pattern to develop. A calibration procedure is proposed which attempts to consider the respective roles of each local parameter on the macroscopic behaviour of the material.

Numerical simulations are performed to simulate tensile and puncture tests conducted on a specific HDPE geomembrane to evaluate the applicability of the proposed method. An acceptable agreement between the numerical and experimental results is obtained. In spite of the simplicity of the suggested calibration method, the numerical model was able to reproduce the main features of the tensile and puncture tests up to the yielding point. The calibration method presented in this study and the ability of creating a flexible membrane using DEM, shows that discontinuous methods are promising in modeling the interaction between granular soil and geomembrane material.

6 ACKNOWLEDGEMENT

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