DEM simulation of simple shear tests of a sandbag used in T-BAGS system (Part 1: DEM modeling)

Discrete Element Method
Sandbag
Simple shear test

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1. INTRODUCTION

The T-BAGS system (Takeuchi et al., 2013) is a low-cost seismic isolation and vibration control technology that utilizes stacked layers of sandbags, which slide against each other through a high-performance polymer film sheet. The system's vibration reduction capabilities arise from the hysteretic shear behavior of the sandbags and their slippage against the film sheet. A numerical analysis of a T-BAGS-reinforced building involves modeling the building, the sandbags, and the sheet as a series of masses and springs. In our previous studies (Vakilazadsarabi et al., 2024), the nonlinear stress-strain behavior of the sandbags was approximated by using the Ramberg-Osgood (R-O) model, with parameters that were rigorously tuned to laboratory test results. While this approach provides a reasonable prediction of the nonlinear behavior of the sandbags, it oversimplifies the granular nature of the sand within the bags, limiting its accuracy when the T-BAGS system is extended beyond the conditions tested in the laboratory experiments. We aim to advance the modeling framework of the T-BAGS system by employing the Discrete Element Method (DEM) to obtain the nonlinear macro-properties of a sandbag subjected to vertical and shearing loads. Since this approach derives the macro-properties of the sandbag from the contact interactions between individual representative particles of sand, it provides more realistic modeling of the sandbag in the T-BAGS system. This series of papers presents the discrete element modeling of sandbag (T-BAGS) and its validation by simulating and replicating simple shear tests.

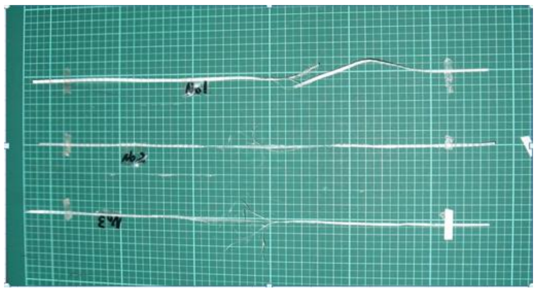
2. DISCRETE ELEMENT MODELING OF T-BAGS

A realistic numerical model of the T-BAGS must account for the discontinuities and heterogeneity between sand particles and the geotextile bag material. Each sand particle transfers loads to adjacent particles through normal, sliding, and rolling interactions. As a result, granular materials such as sand exhibit highly nonlinear mechanical behavior. The Discrete Element Method (DEM) offers a more appropriate approach by deriving the macro-mechanical properties of materials from the micro-properties and interactions of their constituent particles. This makes DEM particularly well-suited for modeling the behavior of granular materials.

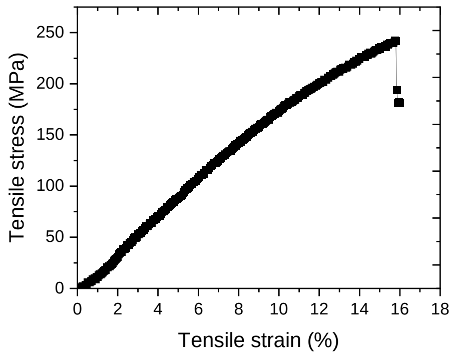
2.1. Geotextile bag

The geotextile bag used in T-BAGS is made of flat interwoven yarns, with each fabric of yarn being 1 mm in width and 0.15 mm in thickness. These yarns possess significant tensile strength but negligible compressive stiffness and strength. Tensile tests were conducted to determine their mechanical properties, with the sample yarns shown in Figure 1a and the results shown in Figure 1b. From the yarn's tensile behavior, it can be seen that the stress and the strain of the yarn have a slightly nonlinear relationship. After reaching a strain of approximately 16%, the yarn breaks.

For the discrete modeling of the geotextile bag, particles arranged in a cuboid shape represent the bag material, with adjacent particles connected by solid bonds modeled as nonlinear springs. These springs resist tension and rotation but not compression, following a method similar to that of Cheng et al. (2016).



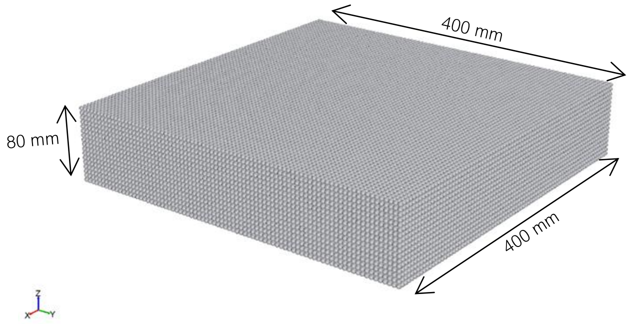
(a) Sample flat yarns in the experiment



(b) Tensile behavior of the flat yarn

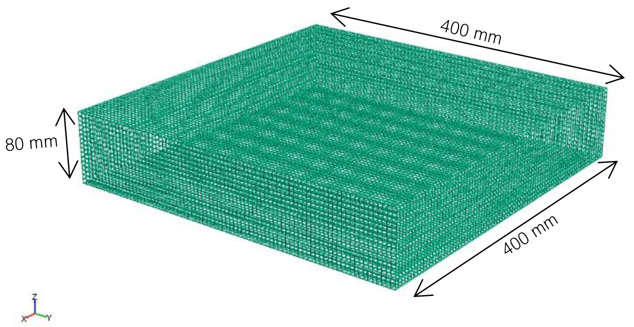
Fig. 1. Flat yarn used in the geotextile bag

Figure 2 presents the DEM model of the geotextile bag. Figure 2a shows the arrangement of the particles and Figure 2b illustrates the solid bond connections. Each bag particle has a diameter of 5 mm with a center-to-center spacing of 5 mm, such that each particle is in contact with surrounding particles (Figure 2a). Cylindrical solid bonds with a diameter of 1 mm are arranged between the centers of two neighboring particles (Figure 2b). The tension stiffness of the solid bonds was derived from the tension test of the flat yarn. The numerical model consists of 17,922 bag particles and 35,840 solid bonds.



(a) Bag particles

Fig. 2. Discrete element model of the geotextile bag



(b) Solid bonds

Fig. 2. Discrete element model of the geotextile bag (*continued*)

2.2. Sand

The sand used in the simple shear test of the T-BAGS was Toyoura sand, a material widely used in civil engineering and construction in Japan. Toyoura sand is uniformly graded, with a uniformity coefficient of 1.3, an average particle diameter of 0.2 mm, and a particle density of 2650 kg/m^3.

Following the calibration procedure of Cheng et al. (2016), a DEM packing was generated for a 50 mm × 50 mm × 100 mm sample to simulate triaxial tests. Sand particles were packed at a void ratio of 0.68, with their size distribution detailed in Table 1. After generating the packing, triaxial compression simulations were conducted, with particle parameters calibrated to match the triaxial test results reported by Cheng et al. (2016). The parameters in Table 2 yielded the best agreement with the calibration data.

Table 1. Particle size distribution of sand

Diameter (mm)	Fraction	Diameter (mm)	Fraction
3.60465	0.1	5.15504	0.1
3.91473	0.1	5.46512	0.1
4.22481	0.1	5.77519	0.1
4.53488	0.1	6.08527	0.1
4.84496	0.1	6.39535	0.1

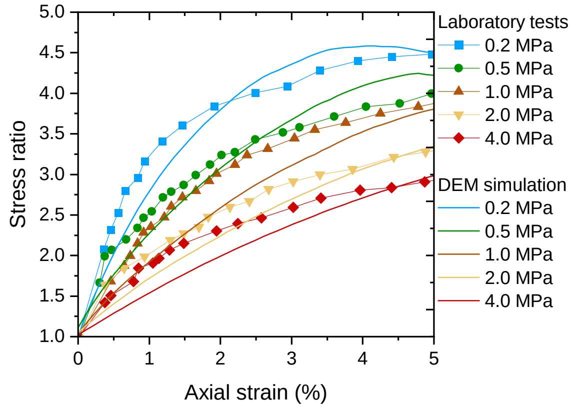
Table 2. Micro-parameters of sand particles

Parameter	Value	Units
Particle density, ρ	2650	kg/m^3
Contact Young's modulus, E	1.8	GPa
Coefficient of sliding friction, μ_s	0.31	-
Coefficient of rolling friction, μ_{ro}	0.05	-
Poisson's ratio, ν	0.1	-

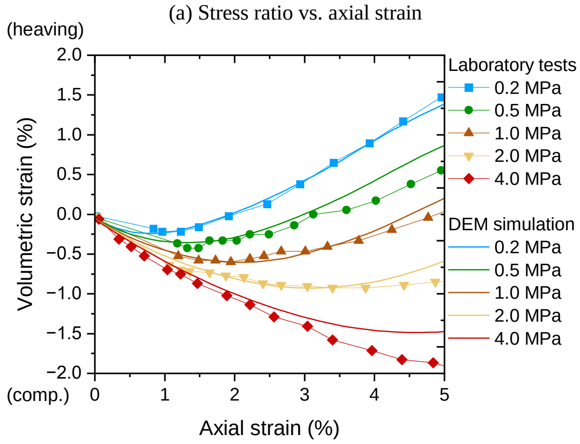
Figure 3 compares the DEM simulation results with the triaxial test data for Toyoura sand for various confining stresses, σ_c. The stress ratio in Figure 3a corresponds to the ratio of the axial stress, σ_a, to σ_c. The simulation closely aligns with the experimental results, confirming that the DEM packing and calibrated parameters effectively represent the material's behaviors.

After establishing the DEM parameters, sand particles were generated within a 395 mm by 395 mm by 75 mm domain, fitting tightly inside the bag geometry to model the T-BAGS. Figure 4 illustrates the generated sand particles inside the T-BAGS. A total of 97,130 sand particles were generated in the model.

The discrete element model of the T-BAGS was finalized by integrating the bag particles, solid bonds, and sand particles. As the particle and solid bond properties have been calibrated to match the mechanical behaviors of the constituent materials, this model aims to capture the macroscopic response of T-BAGS.



(a) Stress ratio vs. axial strain



(b) Volumetric strain vs. axial strain

Fig. 3. Comparison of DEM simulation of triaxial compression with laboratory results

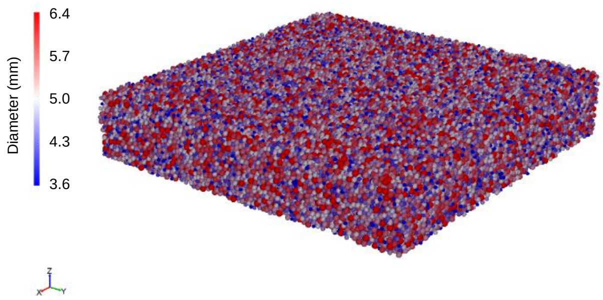


Fig. 4. Discrete element model of the sand in T-BAGS

3. CONCLUDING REMARKS

The simulation results are presented in Part 2 of this series of papers.

REFERENCE

A. Vakilazadsarabi, K. Takeuchi, Y. Tomono, T. Matsumoto, Seismic analyses of a five-story residential building supported by T-BAGS base isolation and vibration control system. Japanese Geotechnical Society Special Publication, 8th International Conference on Earthquake Geotechnical Engineering, 2024.

H. Cheng, H. Yamamoto, K. Thoeni, Numerical study on stress states and fabric anisotropies in soilbags using the DEM. Computers and Geotechnics, 76, 170–183, 2016.

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DEM simulation of simple shear tests of a sandbag used in T-BAGS system
(Part 2: Simulation results)

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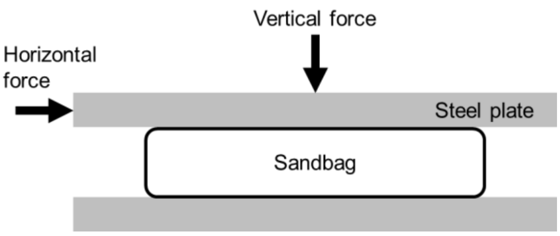
1. INTRODUCTION

In Part 2 of this series of papers, the DEM simulation results of the T-BAGS described in Part 1 are presented.

2. EXPERIMENTAL SETUP – SHEAR TEST

In the laboratory experiments for simple shear, a sandbag was placed between two steel plates, as shown in Figure 1a. A corresponding schematic diagram is provided in Figure 1b. To prevent slippage between the sandbag and the plates, sandpaper was placed at their interfaces. A vertical force was applied to the top steel plate, which was then transmitted to the T-BAGS. Subsequently, the top plate was displaced horizontally, inducing shear deformation in the sandbag. Throughout the test, both the horizontal displacement and the shear force exerted on the T-BAGS were recorded.

(a) Laboratory experiment (after applying vertical load)



(b) Schematic diagram

Fig. 1. Simple shear test of T-BAGS

3. NUMERICAL SETUP – SHEAR SIMULATION

To replicate the shear tests numerically, two rigid plates were incorporated into the DEM model to sandwich the T-BAGS assembly. The top plate was first subjected to a downward displacement to apply a predefined vertical force, F_v . Once the target vertical force was reached, the plate was moved horizontally at a constant velocity of 4 mm/s. To ensure consistency with the laboratory tests, simulations were conducted with vertical loads of 5.50 kN, 3.73 kN, and 1.96 kN. Throughout the simulation of the shearing phase, the vertical force acting on the top plate was continuously tracked and maintained at the prescribed value, while the horizontal force exerted on the plate was recorded as the shear force, *S*. Additionally, the displacement of the top plate, *u*, was tracked. Figure 2 presents the compressed state of the T-BAGS under a vertical load of 5.5 kN.

To prevent slippage between the plates and the bag particles, a sufficiently high sliding friction coefficient was assigned at their interfaces. Furthermore, a time step smaller than the critical time step and a shear strain rate of 5% per second were used to ensure numerical stability. In all simulations, the coefficient of restitution was set to 0.2. Gravitational acceleration was also incorporated to maintain the physical realism of the model. The micro-mechanical properties of the materials used in the DEM simulations are provided in Table 1, while the sliding friction coefficients between different pairs of materials are summarized in Table 2.

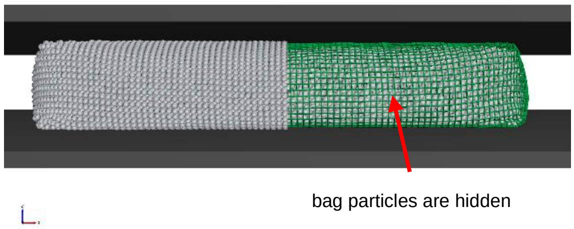


Fig. 2. Numerical setup of simple shear test of T-BAGS (after applying vertical load)

Table 1. Material micro-parameters used in the simulation

Parameter	Bag	Sand	Plate	Units
Particle density, ρ	450	2650	7800	kg/m^3
Contact Young's modulus, E	0.75	1.8	200	GPa
Poisson's ratio, ν	0.1	0.1	0.1	-

Table 2. Sliding friction coefficient matrix used in the simulation

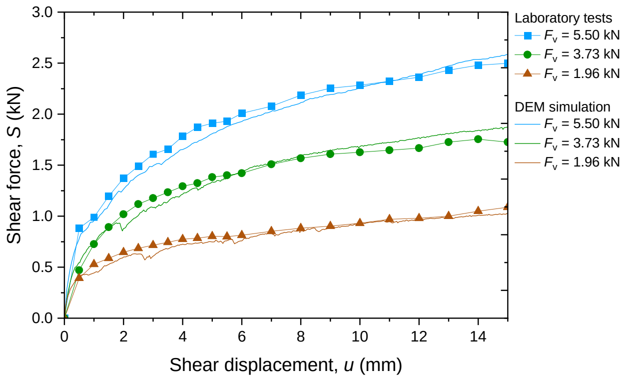
	Bag	Sand	Plate
Bag	0.26	0.26	10^{10}
Sand	0.26	0.31	-
Plate	10^{10}	-	-

4. RESULTS AND DISCUSSION

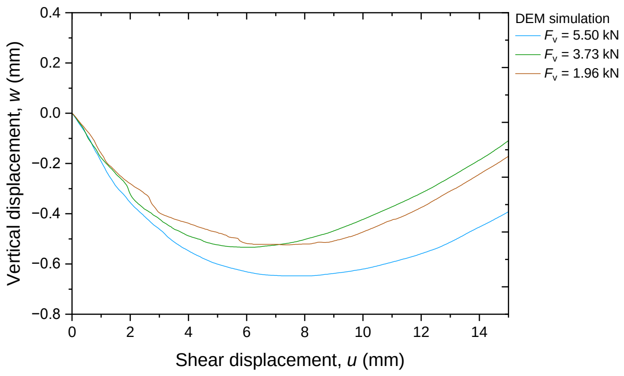
Figure 3a presents a comparison of the shear force, *S*, versus shear displacement, *u*, obtained from the DEM simulations and laboratory experiments. The results demonstrate reasonable agreements between the numerical simulations and experimental data. As expected, the simulations show increasing shear strength with higher normal forces, as observed in the laboratory experiments. The initial slopes of the force-displacement curves for both the simulation and the laboratory test match well, suggesting that the discrete element model can reasonably replicate the material's initial elastic response.

Minor sudden drops in the shear force were observed in simulations conducted under vertical loads. This behavior is likely due to particle rearrangements within the sandbag, which momentarily reduce its shear resistance. The effect was more pronounced at lower vertical loads of 3.73 kN and 1.96 kN, where reduced frictional forces allow for greater particle mobility. However, the simulation reproduced the overall experimental results.

The simulated vertical displacements, *w*, vs. horizontal displacements, *u*, are presented in Figure 3b. For technical reasons, the laboratory data for *w* is unavailable. Initially, as the shear displacement increases, the T-BAGS undergoes vertical contraction. Thereafter, dilatancy (vertical expansion) occurs in the T-BAGS. As F_v increases, larger contraction and smaller dilatancy occur. The simulations match the behavior of densely compacted sands.



(a) S vs. u



(b) w vs. u

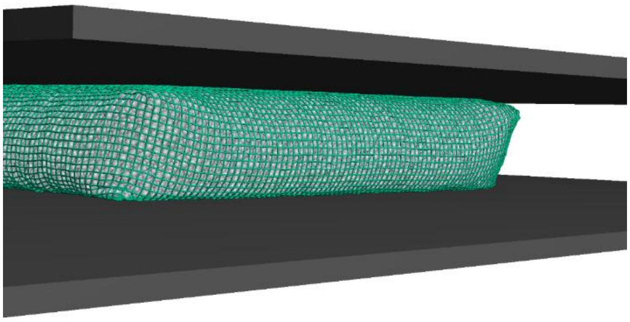
Fig. 3. Shear force and vertical displacement vs. shear displacement in simple shear tests and DEM simulation

The above-mentioned results indicate that the discrete element model adequately captures the nonlinear shear behavior of T-BAGS until the shear displacement of 15 mm. In practice, the maximum shear displacement of T-BAGS is 5 mm.

A qualitative comparison of the deformed T-BAGS shapes, shown in Figure 4, further validates the DEM model. Both the simulation and laboratory experiments revealed that the top surface of the sandbag detached from the steel plate, a behavior not considered by spring models, which assumes that the bag surfaces remain fixed to the plates. This observation highlights the advantage of the discrete element model in accurately representing the mechanical response of T-BAGS.

In both the experimental and simulated results, noticeable bulging along the sides of the sandbag is observed, along with localized deformation patterns that result from internal particle rearrangements and the properties of the geotextile fabric. The DEM simulation effectively replicates these features, demonstrating its capability to model complex behaviors like particle movement and dilation within the sandbag.

(a) Laboratory experiment



(b) DEM simulation

Fig. 4. Qualitative comparison of actual and simulated deformed shape of T-BAGS

Figure 5 presents the resultant contact forces of normal and shear forces in the sand particles for the simulated shearing of T-BAGS under F_v = 5.5 kN at u = 15 mm. In the figure, the 3D view, the section view along the center plane, and the view from the side of the T-BAGS are shown. During shearing, the resultant contact forces at the central cross-section remain relatively small and uniform while those at the edge become larger. It is inferred at present that as the T-BAGS undergoes shearing, higher tensile forces are generated in the geotextile bag, which makes the bag push the sand particles near the edge region.

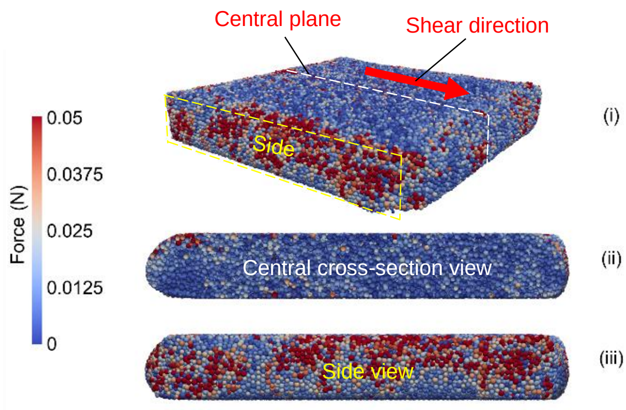


Fig. 5. Simulated resultant contact forces in the sand particles for F_v = 5.5 kN at u = 15 mm

5. CONCLUSION

This study presented a Discrete Element Method (DEM) model of T-BAGS, incorporating both the bag material and the sand fill. The bag material was represented using particles connected by solid bonds in a cuboid arrangement, while the sand material was modeled using particles with different sizes. The tensile behavior of the bag particles was derived from the tensile experiments of the flat yarn used in the bag of T-BAGS. The parameters of the sand particles were calibrated from the simulations of triaxial tests of Toyoura sand. The DEM model was validated through simulating and replicating simple shear tests conducted on T-BAGS.

This research contributes to the development of the T-BAGS system, offering a more affordable alternative to the traditional base isolation technologies.

REFERENCE

Panganiban et al. (2025). DEM simulation of simple shear tests of a sandbag used in T-BAGS system. (Part 1: DEM modeling), 60th Annual Meeting of Japanese Geotechnical Society, Japan (to be presented).