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Influence of Particle Shape on Soil Arching Formation in Trapdoor Tests: A DEM Investigation

TUZAK KAPI DENEYLERİNDE TANE ŞEKLİNİN ZEMİN KEMERLENMESİ OLUŞUMUNA ETKİSİ: BİR DEM İNCELEMESİ

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ÖZET

Yumuşak zeminler üzerine inşa edilen kazık destekli dolguların davranışı ve tasarımı, yer değiştiren zemin bölgeleri ile komşu hareketsiz zemin bölgeleri arasında gerilme yeniden dağılımını sağlayan zemin kemerlenmesi mekanizması tarafından belirlenmektedir. Kazık destekli dolgularda kemerlenme mekanizmasının ve buna bağlı yük yeniden dağılımının doğru bir şekilde yorumlanabilmesi için, granüler dolgu malzemesinin mikromekanik davranışının, özellikle de tane ölçeğindeki etkileşimlerin, kapsamlı bir şekilde anlaşılması gerekmektedir. Dolgu malzemesinin taneli ve granüler yapısı nedeniyle zemin kemerlenmesi, Ayrık Elemanlar Yöntemi (DEM) kullanılarak gerçekleştirilen sayısal analizlerle etkin bir şekilde incelenebilmektedir. Tuzak kapı (trapdoor) deneyi, granüler ortamlardaki kemerlenme davranışının araştırılmasında literatürde yaygın olarak kullanılan ve kabul görmüş deneysel bir yöntemdir. Bu çalışmada, tek tuzak kapılı bir düzenek kullanılarak üç boyutlu DEM analizleri gerçekleştirilmiştir. Tane morfolojisinin etkisini değerlendirmek amacıyla küresel, kübik, küresel-silindirik (spherocylindrical) ve üçgen piramit biçimli farklı tane geometrilerinin kullanıldığı bir dizi DEM modeli, tam kemerlenme koşulunda oluşturulmuştur. Her bir tane geometrisinin kemerlenme performansı, Zemin Kemerlenme Oranı (Soil Arching Ratio, SAR) ve düşey yer değiştirme konturları kullanılarak değerlendirilmiştir.

Anahtar Kelimeler: *Zemin kemerlenmesi; Ayrık Elemanlar Yöntemi (DEM); Tuzak kapı (trapdoor) deneyi; Zemin Kemerlenme Oranı (SAR); Tane morfolojisi; Yuvarlanma sürtünmesi katsayısı*

ABSTRACT

The behaviour and design of piled embankments constructed over soft soils are governed by soil arching, which triggers stress redistribution between yielding zones and adjacent non-yielding soil zones. To accurately interpret the arching mechanism and the associated load transfer in pile-supported systems, a comprehensive understanding of the micromechanical behaviour of the granular fill material, specifically particle-scale interactions, is essential. Due to the particulate and granular nature of the embankment fill, soil arching can be effectively investigated through numerical simulations using the Discrete Element Method (DEM). The trapdoor experiment is a well-established experimental approach in the literature for investigating arching behaviour in granular media. In this study, three-dimensional DEM simulations were conducted using a single-trapdoor configuration. To evaluate the influence of particle morphology, a series of DEM models incorporating various particle shapes, namely spherical, cubic, sphero-cylindrical, and triangular pyramidal,

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were developed in a full-arching state. Arching performance was evaluated for each particle type using the Soil Arching Ratio (SAR) and vertical displacement contours.
Keywords: *Soil arching; Discrete Element Method (DEM), Trapdoor test, Soil Arching Ratio (SAR), Particle morphology; Coefficient of rolling friction*

1. INTRODUCTION

The Discrete Element Method (DEM) is widely applied to simulate the behaviour of granular materials by representing them as assemblies of distinct particles. The motion of each particle is determined by repeatedly calculating its position, velocity, and the contact forces acting between neighbouring particles over small time increments (Cundall and Strack, 1979). Within this framework, particle geometry is an important factor governing contact interactions and, consequently, the macroscopic response of the granular assembly. Compared with spherical or regularly shaped particles, irregular particles generally exhibit greater mechanical interlocking, which limits relative movement and influences the overall deformation and flow characteristics of the material.

The efficient representation of particle geometry remains an important challenge in DEM modelling. Spherical particles are used in most DEM codes because their simple geometry enables rapid contact detection and reduces computational cost, although natural granular materials generally consist of irregularly shaped particles. Several methods have therefore been developed to represent non-spherical particles, among which the multi-sphere approach is one of the most widely used. In this approach, multiple overlapping spheres are rigidly connected to form a single particle whose geometry approximates a prescribed irregular shape. As an alternative, particle morphology may be represented using simplified regular geometries, including spheres, cubes, sphero-cylinders, and triangular pyramids. Such idealised shapes can provide a practical balance between computational efficiency and geometrical realism. They reproduce several important characteristics of real particles, such as angularity, rotational resistance, and interlocking, thereby extending the range of granular behaviours that can be simulated using DEM (Stahl and Konietzky, 2011; Chen et al., 2012; Stahl et al., 2014; Indraratna et al., 2014; Miao et al., 2017).

Arching is a fundamental response of granular materials and is encountered in numerous engineering applications, including silos, hoppers, piled embankments, tunnels, and buried pipelines. When part of a granular mass undergoes relative movement or settlement, particle rearrangement and inter-particle force transmission may lead to the development of arch-shaped load-carrying formations. Arching reduces the pressure acting on the moving or settling region by transferring a portion of the load towards the adjacent stationary zones. Although continuum-based approaches can represent the macroscopic stress redistribution associated with arching, they do not directly resolve the particle-scale mechanisms governing the formation, evolution, degradation, and reformation of arches. Physical model tests and Discrete Element Method simulations are therefore particularly useful for examining these mechanisms in micro-scale. One of the most widely adopted experimental methods for investigating soil arching was conducted by Terzaghi (1936). Subsequent researchers have employed similar experimental arrangements to investigate arching under different geometrical, loading, and material conditions (Vardoulakis et al., 1981; Costa et al., 2009; Chevalier et al., 2012). Nevertheless, further experimental investigation remains necessary to clarify how arch formation and evolution vary across different particle shapes.

2. NUMERICAL MODELLING – DEM

2.1. Materials and Methods

The DEM models were developed using a single trapdoor configuration based on the concept of Terzaghi's trapdoor test. The principal properties and input parameters of the DEM models are summarised in Table 1. For models with a fill height of 30 cm, the total numbers of particles and contacts, together with the corresponding computational times, are presented in Table 2. During the simulations, the trapdoor was displaced downward at a constant velocity of 0.05 m/s. The fill height was set to 30 cm to provide sufficient overburden for the development of a fully formed arch, following the observations of Lai et al. (2018). The trapdoor had a width of 7.5 cm, while the out-of-plane dimension of the models was 10 cm. Also, the width of the stationary parts was 3.75cm (Figure 1). The fill unit weight before lowering the trapdoor was equal to 14.5 kN/m^3 for all models.

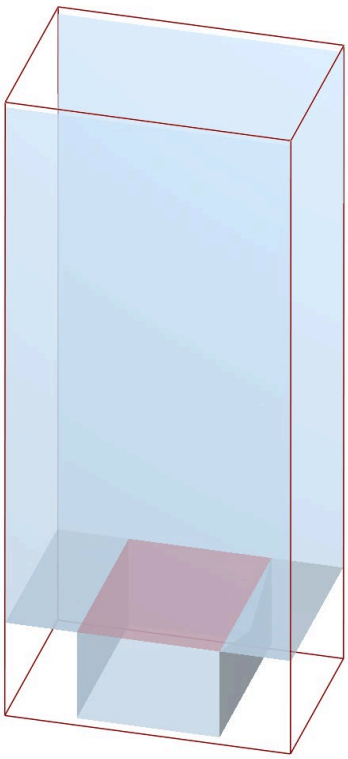

Figure 1. Trapdoor test box used in DEM analyses

The range of motion for the trapdoor in the vertical (Z) direction was 5cm. Frictionless physical boundaries were assigned in the (y)-direction (in-plane), while periodic boundary conditions were applied in the (x)-direction. Five particle shapes were considered in this study. The first was a multi-spherical clump designed to approximate the irregular morphology of a real crushed-stone particle. Two polyhedral shapes, namely a cuboid and a triangular pyramid, were also generated. The remaining particle types consisted of spherical and sphero-cylindrical particles (Figure 2).

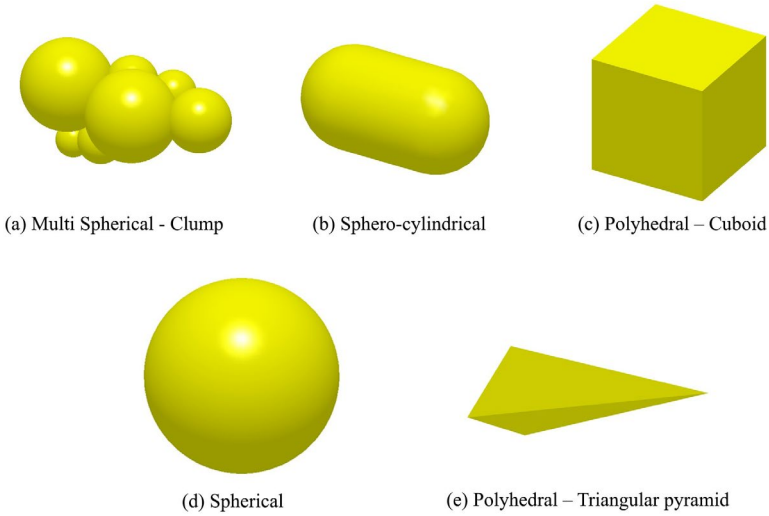

Figure 2. The generated particle shapes for the DEM analyses

For all models involving non-spherical particles, the rolling friction coefficient was set to zero, and the Hertz–Mindlin (no-slip) contact model without rolling friction was adopted. For the models composed of spherical particles, three particle–particle rolling friction coefficients, namely 0, 0.1, and 0.5, were considered. In these models, the rolling friction coefficient between the particles and the model base, including both the stationary sections and the trapdoor, was fixed at 0.35. Accordingly, the Hertz–Mindlin (no-slip) contact model with standard rolling friction was used for the spherical-particle simulations.

The degree of load transfer associated with arch formation was evaluated using the Soil Arching Ratio (SAR). At a given trapdoor displacement, the SAR was calculated as the ratio of the average pressure acting on the trapdoor to its initial value before any displacement occurred. Accordingly, a lower SAR indicates a greater reduction in the load carried by the trapdoor and, therefore, more effective load transfer due to arching.

Table 1. DEM model properties

Parameter	Value
Density (particle) ρ [kg/m³]	2734
Coefficient of particle-particle static friction μ^s_{pp}	0.68
Coefficient of particle-wall static friction $\mu^s_{p}w$	0
Coefficient of particle-base static friction μ^s_{pB}	0.5
Coefficient of restitution (particle-particle), ε_{PP}	0.5
Coefficient of restitution (particle-wall), ε_{pW}	0.0001
Coefficient of restitution (particle-base), ε_{pB}	0.3
Poisson ratio (particles), ν_p	0.25
Poisson ratio (wall and base), ν_w, ν_B	0.25
Shear modulus (particles), G_p [Pa]	10^7
Shear modulus (wall and base), G_w, G_B [Pa]	10^{10}

Table 2. Total number of particles, contacts, and elapsed time for DEM models

Full-arching model analysis	Total number of particles	Contacts total	Elapsed computation time (h)
Multi Spherical - Clump	54847	164758	4.4793
Sphero-cylindrical	33031	83249	1.9252
Polyhedral – Cuboid	31523	72399	3.6883

Spherical, CoRF=0.1	11591	22223	3.4726
Spherical, CoRF=0.5	11591	24194	3.6712
Spherical, CoRF=0	11591	25863	2.632
Polyhedral – Triangular pyramid	136300	415676	5.4011

3. RESULTS AND DISCUSSION

Figure 3 presents the Soil Arching Ratio (SAR) obtained from the DEM simulations. Before the trapdoor is lowered, the SAR is equal to 1. Immediately after trapdoor lowering begins, the SAR decreases sharply. It then increases due to stress recovery and gradually stabilises towards the end of the test.

The model with spherical particles and a coefficient of rolling friction (CoRF) of 0.5 exhibited the highest soil-arching efficiency. In contrast, the model with the same particle shape but a CoRF of 0 showed the lowest load-redistribution efficiency. The models with polyhedral cuboid particles, multi-spherical clumps, polyhedral triangular-pyramid particles, and spherical particles with a CoRF of 0.1 exhibited nearly identical variations in SAR over time. However, the model with polyhedral triangular-pyramid particles reached a higher final SAR, indicating a lower arching efficiency at the end of the test.

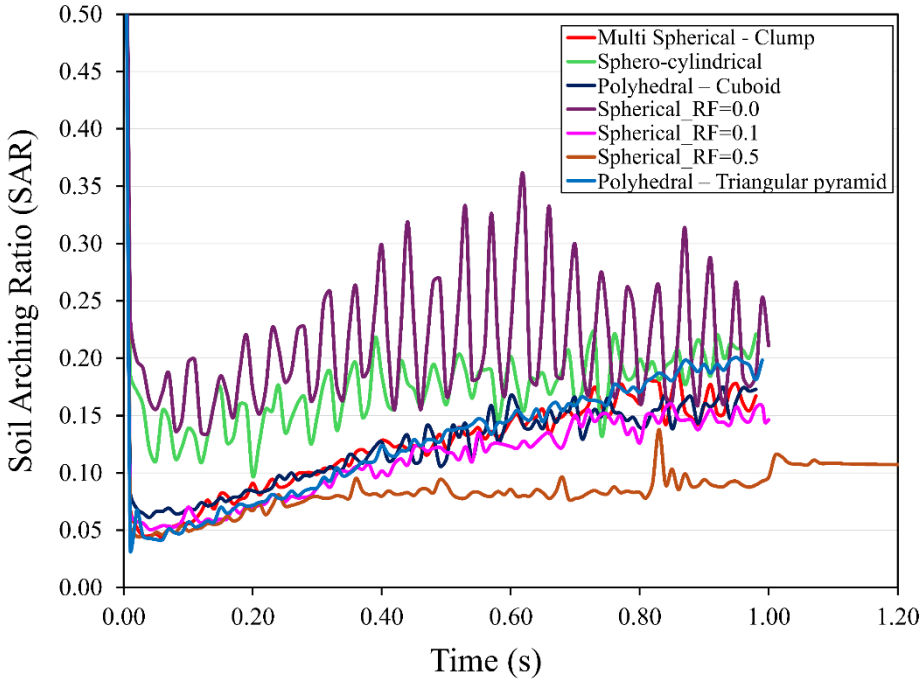

Figure 3. Variation of the Soil Arching Ratio (SAR) with time during trapdoor lowering

The model with sphero-cylindrical particles exhibited behaviour similar to that of the spherical-particle model with a CoRF of 0. The pronounced fluctuations observed in the results of these two models can be attributed to the absence of rolling friction. Because these particles have curved and relatively smooth surfaces and provide limited opportunity for mechanical interlocking, they continuously roll over one another and rearrange during trapdoor lowering.

The results further indicate that polyhedral cuboid and triangular-pyramid particles can reasonably reproduce the stress-redistribution behaviour of irregular real particles. Their

responses were close to those obtained using multi-spherical clumps, which were specifically generated to represent the geometry of real crushed-stone particles.

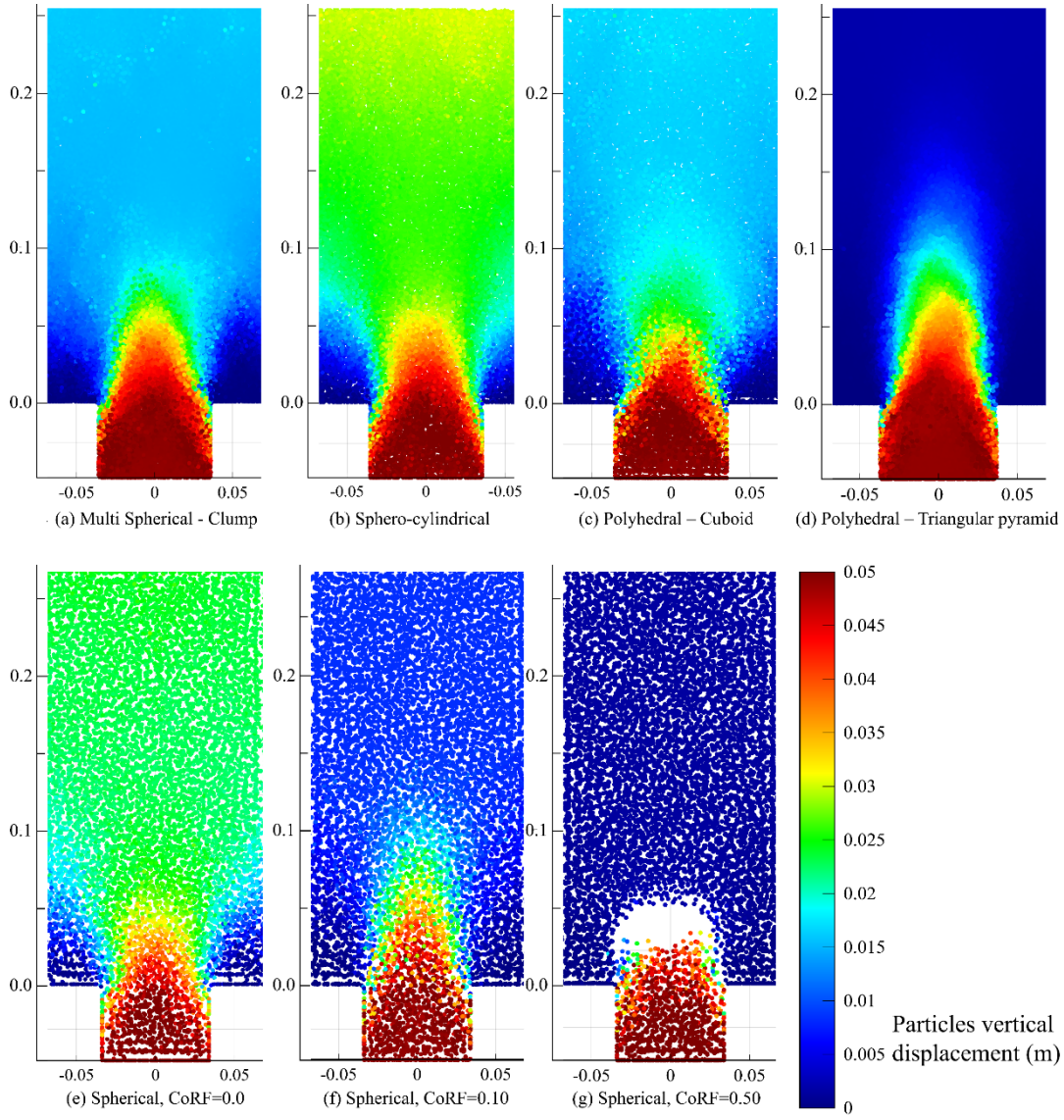

Figure 4. Vertical displacement contours of the fill at the end of trapdoor lowering

Figure 4 presents the particle-displacement contours obtained for the different models. As expected, the maximum displacement, shown in dark red, is equal to 5 cm and occurs within the trapdoor region and immediately above it. In addition, almost no differential settlement is observed at the fill surface in any of the models.

The main difference among the models concerns the extent to which trapdoor lowering is transmitted through the fill body and towards the fill surface. As shown in the figure, the lowest particle displacements were observed in the models containing polyhedral triangular-pyramid particles and spherical particles with a coefficient of rolling friction (CoRF) of 0.5. The relatively low settlement in these models may be attributed to the considerably higher number of particles (136,300) and the greater degree of particle interlocking in the triangular-pyramid model, as well as the high rolling-friction coefficient assigned to the

spherical particles. In both models, only a limited region above the trapdoor was affected by the lowering action, and the resulting settlement did not propagate to the fill surface.

The model containing spherical particles with a CoRF of 0.1 exhibited behaviour broadly similar to that of the two aforementioned models. However, it showed greater overall displacement throughout the fill and at the fill surface, highlighting the importance of rolling resistance when perfectly spherical particles are used.

Among the simplified particle geometries, the polyhedral cuboid particles produced the displacement response closest to that of the multi-spherical clumps, which were used to represent the real crushed-stone particles. Therefore, considering both the SAR trends and the displacement contours, the polyhedral cuboid particles appear to reproduce the behaviour of the real crushed-stone particles reasonably well.

In contrast, the models containing spherical particles with a CoRF of 0 and spherocylindrical particles exhibited nearly identical settlement and displacement patterns. Owing to the limited interlocking and rolling resistance between the particles, these models experienced the greatest overall settlement within the fill and at the fill surface.

4. CONCLUSION

This study investigated the effect of particle shape on soil arching in trapdoor models using DEM, focusing on the Soil Arching Ratio (SAR) and fill displacement. Five particle shapes, namely multi-spherical clump, polyhedral-cuboid, polyhedral-triangular pyramid, sphero-cylindrical, and spherical, were considered in this study. The key findings are:

- The polyhedral cuboid, multi-spherical clump, polyhedral triangular-pyramid, and spherical particle models with a CoRF of 0.1 exhibited comparable soil-arching responses, with nearly identical SAR evolution during trapdoor lowering.

- Among the simplified particle shapes, polyhedral cuboid particles provided the closest displacement response to the multi-spherical clumps representing real crushed-stone particles.

- With an appropriate and carefully calibrated coefficient of rolling friction, spherical particles can also be used to approximate the behaviour of more complex particle assemblies while substantially reducing the computational effort.

REFERENCES

Cundall, P.A., Strack, O.D.L. (1979), “A Discrete Numerical Model for Granular Assemblies”, Géotechnique, Vol 29(1), 47-65.

Chen, C., McDowell, G.R., Thom, N.H. (2012), “Discrete Element Modelling of Cyclic Loads of Geogrid-Reinforced Ballast under Confined and Unconfined Conditions”, Geotextiles and Geomembranes, Vol 35, 76-86.

Chevalier, B., Combe, G., Villard, P. (2012), “Experimental and Discrete Element Modeling Studies of the Trapdoor Problem: Influence of the Macro-Mechanical Frictional Parameters”, Acta Geotechnica, Vol 7(1), 15-39.

Costa, Y.D., Zornberg, J.G., Bueno, B.S., Costa, C.L. (2009), "Failure Mechanisms in Sand over a Deep Active Trapdoor", Journal of Geotechnical and Geoenvironmental Engineering, Vol 135(11), 1741-1753.

Stahl, M., Konietzky, H., Te Kamp, L., Jas, H. (2014), "Discrete Element Simulation of Geogrid-Stabilised Soil", Acta Geotechnica, Vol 9(6), 1073-1084.

Stahl, M., Konietzky, H. (2011), "Discrete Element Simulation of Ballast and Gravel under Special Consideration of Grain-Shape, Grain-Size and Relative Density", Granular Matter, Vol 13(4), 417-428.

Indraratna, B., Ngo, N.T., Rujikiatkamjorn, C., Vinod, J.S. (2014), "Behavior of Fresh and Fouled Railway Ballast Subjected to Direct Shear Testing: Discrete Element Simulation", International Journal of Geomechanics, Vol 14(1), 34-44.

Miao, C.X., Zheng, J.J., Zhang, R.J., Cui, L. (2017), "DEM Modeling of Pullout Behavior of Geogrid Reinforced Ballast: The Effect of Particle Shape", Computers and Geotechnics, Vol 81, 249-261.

Terzaghi, K. (1936), "Stress Distribution in Dry and in Saturated Sand above a Yielding Trap-Door".

Vardoulakis, I., Graf, B., Gudehus, G. (1981), "Trap-Door Problem with Dry Sand: A Statical Approach Based upon Model Test Kinematics", International Journal for Numerical and Analytical Methods in Geomechanics, Vol 5(1), 57-78.