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Influence of inter-particle friction on the angle of repose and stress wave propagation in granular soils: a DEM study

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Abstract

In geotechnical engineering, the angle of repose (AoR) is widely adopted as an indicator of soil stability and particle interaction. However, AoR can arise from different combinations of inter-particle sliding and rolling friction, each representing different mechanical characteristics. This study systematically investigates the influence of sliding and rolling friction coefficients on AoR using the Discrete Element Method (DEM). Lifting cylinder tests were simulated while varying both sliding and rolling coefficients from 0.1 to 0.9 to examine their combined effects on AoR formation. Additionally, a stress wave propagation model was developed to simulate laboratory stress wave testing and to explore the relationship between inter-particle friction and wave response characteristics. The results reveal that while sliding and rolling frictions significantly influence stress wave responses, such as stress magnitude, particle velocity, and displacement, the AoR alone does not exhibit a consistent correlation with these dynamic properties. These findings suggest that AoR, although it is useful for static stability, may not be a reliable standalone indicator of dynamic soil behavior.

Keywords Sliding friction, Rolling Friction, Angle of repose, Stress wave, DEM

Introduction

Accurate detection and characterization of subsurface features are critical in geotechnical engineering, as they directly influence the safety and reliability of civil infrastructure. The underground environment contains vital information on soil stratigraphy, geological structures, and potential hazards such as cavities, weak layers, or buried utilities. Subsurface anomalies such as sinkholes, voids, or tunnels pose significant risks, particularly in areas with declining groundwater or karst formation [6, 26]. Therefore, identifying their location and extent is essential to mitigating these risks.

Among non-invasive detection techniques, stress wave methods have become essential tools in geophysics and geotechnical engineering. These methods evaluate wave propagation through soil to infer subsurface properties and detect anomalies. Techniques such as the Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of

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Surface Waves (MASW) are widely used [19]. SASW estimates the thickness and elastic modulus of soil layers based on the dispersive behavior of surface waves under transient loading [14, 21], while MASW analyzes Rayleigh or Love waves to determine shear wave velocity (V_s) profiles with depth [9, 22]. These methods are particularly valuable for near-surface site characterization and infrastructure assessment [4, 17, 23, 24, 27].

To complement these field methods, numerical modeling provides a powerful means of interpreting and simulating soil behavior. The Discrete Element Method (DEM), originally introduced by Cundall and Strack [8], enables detailed simulation of granular materials by modeling individual particles and their interactions. DEM is particularly suited for materials such as sand and gravel, where particle-scale behavior significantly influences bulk response. Unlike continuum-based methods (e.g., finite element method), DEM captures discontinuous behavior, making it especially effective in modeling large deformations, particle rearrangements, and post-failure mechanics [16, 28].

Despite its advantages, DEM is computationally demanding, especially when simulating large-scale or high-resolution problems. Calibrating contact parameters to match experimental data can also be challenging and time intensive. However, its capability to reveal micro-mechanical processes such as force chains, contact forces, and inter-particle energy transfer makes it a valuable tool for advancing understanding in granular mechanics.

In this study, the open-source DEM software LIGGGHTS [15] was employed to systematically investigate how inter-particle sliding and rolling friction influence both the angle of repose (AoR) and stress wave propagation in dry and cohesionless granular soil. A parametric study was conducted by varying the sliding and rolling friction coefficients over a range of 0.1–0.9, using lifting cylinder simulations to quantify AoR and impact-based simulations to evaluate stress magnitude, particle velocity, and displacement. This work addresses a key limitation in current practice: similar AoR values can result from different combinations of micro-scale friction parameters, leading to ambiguity in interpreting soil behavior. By linking these parameters to both static and dynamic responses, the study demonstrates that AoR alone is not a unique or reliable indicator of wave propagation characteristics. These findings provide practical insight for DEM parameter calibration and highlight the need for caution when using AoR as a sole descriptor in geotechnical characterization, particularly in wave-based methods such as SASW and MASW.

Materials and methods

Discrete element method (DEM)

A fundamental component of the Discrete Element Method (DEM) is the accurate representation of particle interactions. When two particles come into contact, DEM applies contact models to calculate the resulting forces and torques. These models can range from simple linear spring-dashpot formulations to more advanced models that incorporate frictional and cohesive behavior, allowing simulation of a wide range of material responses. Consequently, the selection of an appropriate contact model is critical, as it directly influences the accuracy and physical realism of the simulation. The following sections describe the specific contact models adopted in this study.

Contact model

In DEM, the collective behavior of particle assemblies is determined by a predefined contact model. This study utilized the nonlinear Hertzian elastic contact model, which describes the frictional force between two granular particles using the following equation:

$$F = (k_n \delta_{n,ij} - \gamma_n v_{n,ij}) + (k_t \delta_{t,ij} - \gamma_t v_{t,ij}) \quad (1)$$

Where:

- k_n and k_t represent the elastic constants for normal and tangential contact, respectively;
- δ_n is the normal overlap distance between two particles;
- δ_t is the tangential displacement vector;
- γ_n and γ_t are the viscoelastic damping constants for normal and tangential contact;
- v_n and v_t are the normal and tangential components of the relative velocity between the two particles.

The first term in Eq. (1) represents the normal force, consisting of an elastic spring and a viscous damping component. The second term represents the tangential force, which also includes a shear force and a damping term.

The elastic constants k_n and k_t are derived from material properties using:

$$k_n = \frac{4}{3} E^* \sqrt{R^* \delta_n} \quad (2)$$

$$k_t = 8G^* \sqrt{R^* \delta_n} \quad (3)$$

Where:

- E^* and G^* are the effective Young's modulus and shear modulus, respectively;
- R^* is the effective radius of the contacting particles, defined as:

$$\frac{1}{R^*} = \frac{1}{R_i} + \frac{1}{R_j} \quad (4)$$

The effective elastic moduli are calculated as:

$$\frac{1}{E^*} = \frac{1 - \nu_i^2}{E_i} + \frac{1 - \nu_j^2}{E_j} \quad (5)$$

$$\frac{1}{G^*} = \frac{2(2 - \nu_i)(1 + \nu_i)}{E_i} + \frac{2(2 - \nu_j)(1 + \nu_j)}{E_j} \quad (6)$$

Where ν denotes Poisson's ratio and E the Young's modulus of each particle.

The viscoelastic damping coefficients for the normal and tangential directions are calculated as:

$$\gamma_n = -2\sqrt{\frac{5}{6}}\beta\sqrt{S_n m^*} \geq 0 \quad (7)$$

$$\gamma_t = -2\sqrt{\frac{5}{6}}\beta\sqrt{S_t m^*} \geq 0 \quad (8)$$

Where.

- β is a dimensionless damping ratio based on the coefficient of restitution e , given by:

$$\beta = \frac{\ln(e)}{\sqrt{(\ln(e))^2 + \pi^2}} \quad (9)$$

- m^* is the effective mass:

$$\frac{1}{m^*} = \frac{1}{m_i} + \frac{1}{m_j} \quad (10)$$

- S_n and S_t are the normal and tangential contact stiffness, respectively:

$$S_n = 2E^* \sqrt{R^* \delta_n} \quad (11)$$

$$S_t = 8G^* \sqrt{R^* \delta_n} \quad (12)$$

In this model, the tangential force is limited by Coulomb friction ($F_t = \mu F_n$). Consequently, the tangential force between two particles increases according to a tangential spring and dash-pot model until $F_t/F_n = \mu$ (static friction coefficient), and then it is maintained until the particles lose contact.

Additionally, this study incorporates a rolling resistance torque model based on the elastic-plastic spring-dashpot (EPSD2) formulation described by [1] and originally proposed by Iwashita and Oda [13]. The rolling resistance torque M_r is limited by:

$$|M_{r,t+\Delta t}^k| \leq \mu_r R^* |F_n| \quad (13)$$

Where:

- μ_r is the coefficient of rolling friction;
- F_n is the normal contact force;
- R^* is the effective radius at the contact point.

This model captures the resistance to particle rotation due to surface roughness or interlocking, which plays a significant role in the overall mechanical behavior of granular assemblies.

Numerical simulations

Lifting cylinder test

To validate the behavior of a simulated granular assembly representing dry, cohesionless soil, a lifting cylinder test was conducted using the DEM. The main objective of this study was to perform parametric analysis on the sliding and rolling friction coefficients, examining their effects on the resulting AoR.

The DEM simulations employed the Hertzian elastic contact model to compute inter-particle frictional forces and the EPSD2 rolling resistance model to account for rotational resistance. Model parameters subject to variation were selected based on prior

literature. In particular, the coefficient of restitution was set to 0.2, consistent with experimental studies on dry granular media [3, 31].

Approximately 12,000 particles were randomly initialized at heights between 35 cm and 45 cm, then allowed to fall into a confined cylindrical domain under gravity to achieve self-compaction. After the system stabilized, the cylinder was vertically lifted at a constant velocity of 0.02 m/s. Once all particles settled and reached a static condition, the AoR was measured based on the final geometry of the deposit.

The lifting cylinder used in the DEM simulations had a diameter of 60 mm and a height of approximately 80 mm. The particle radius was 1.5 mm, corresponding to a particle diameter of 3 mm, resulting in a diameter-to-particle size ratio of $D/d = 20$.

Container-size effects have been reported in AoR studies, particularly when the pile forms within a finite-width container or between confining walls, where particle-wall interactions can constrain particle mobility and influence the measured AoR [34, 35]. In the present lifting-cylinder method, the particles were initially confined during deposition and self-compaction, but the cylinder was subsequently lifted and the final pile formed on an unconfined base. Therefore, the wall-effect results from confined-container AoR test are not directly equivalent to the present boundary condition. In addition, lifting-cylinder studies have reported that AoR can be nearly scale-invariant with respect to cylinder size under slow/static lifting conditions. Nevertheless, the $D/d = 20$ ratio was selected as a conservative geometry to reduce cylinder-wall influence during initial packing and release. The overall behavior of the granular sample was strongly influenced by the contact parameters, especially the sliding and rolling friction coefficients. Due to their interdependence, a series of simulations was performed across a range of values for both coefficients, from 0.1 to 0.9, to evaluate their combined influence on AoR.

The material properties and input parameters used in the DEM simulations are listed in Table 1, and the simulation stages are illustrated in Fig. 1.

Angle of repose (AoR) measurement

The AoR was measured through post-processing of simulation result images. The process begins with binarization of the images to isolate the soil surface, followed by pixel extraction to obtain the boundary profile of the granular deposit.

Figure 2 illustrates the procedure used to determine the AoR. A curve-fitting procedure was applied using MATLAB. The soil surface was modeled as two intersecting linear segments, with the point of intersection representing the apex of the pile, denoted as $p_t (x_t, y_t)$ as shown in Fig. 2. The slopes of the fitted lines correspond to the tangent of the AoR, θ . The fitted piecewise function is defined as:

Table 1 DEM input parameters for lifting cylinder test

Parameters	Value
Particle radius (mm)	1.5
Particle density (kg/m^3)	2700
Poisson's ratio	0.35
Young's modulus (Pa)	5×10^6
Acceleration of gravity (m/s^2)	9.81
Restitution coefficient	0.2
Sliding friction coefficient	0.1–0.9
Rolling friction coefficient	0.1–0.9

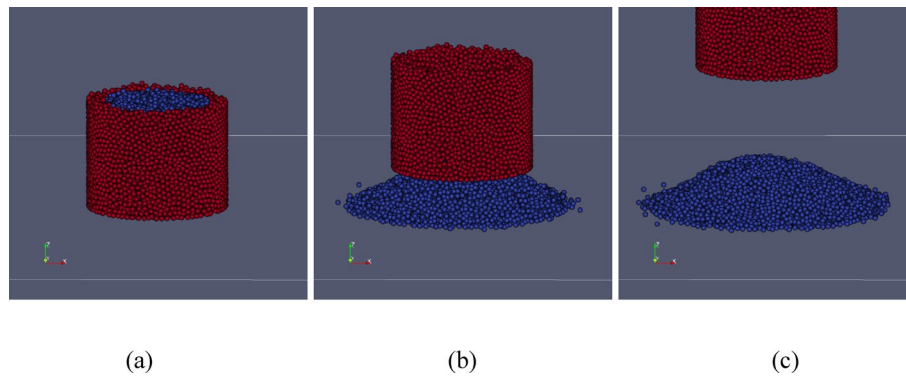


Fig. 1 Stages of the DEM-based lifting cylinder test: **(a)** Initial particle configuration within the cylinder, **(b)** particle migration during cylinder lifting, and **(c)** final deposit exhibiting the angle of repose

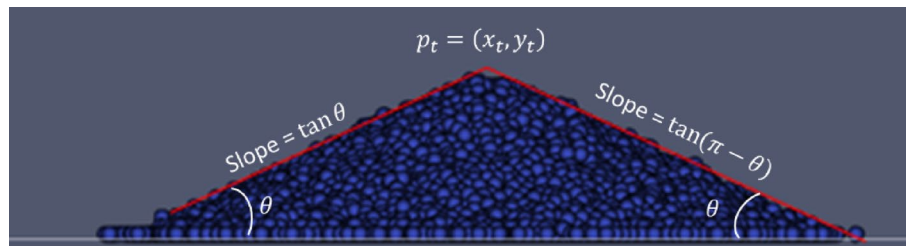


Fig. 2 Example of angle of repose (AoR) measurement based on simulation output

$$f(x) = \begin{cases} y = \tan \theta (x - x_t) + y_t, & x < x_t \\ y = \tan (\pi - \theta) (x - x_t) + y_t, & x \geq x_t \end{cases} \quad (14)$$

Here, θ is the angle of inclination of the granular surface on each side of the apex.

Stress wave propagation

To simulate stress wave propagation in dry, cohesionless granular soil, DEM models were developed using an impact-based loading approach. The simulation domain measured 0.4 m x 0.02 m x 0.5 m in the x, y, and z directions, respectively. A pseudo-2D configuration was adopted to reduce computational cost while maintaining three-dimensional particle interactions. This was achieved by restricting the simulation box thickness in the y-direction while still using full 3D spherical particles, as shown in Fig. 3a.

A total of 102,000 particles were randomly generated within a vertical range of 35–45 cm and allowed to settle under gravity for self-compaction. Because the total packed volume varied slightly with different sliding and rolling friction coefficients, particles exceeding 25 cm in height from the bottom were removed after compaction. This adjustment ensured a consistent soil model volume across all simulations, allowing for fair comparison of stress wave behavior under different frictional conditions.

To replicate the stress wave testing method commonly used in field applications, an impact plate was modeled at the surface of the granular deposit. The plate measured 5 cm x 2 cm x 1 cm and transferred energy from a falling impact particle to the soil. A receiver, mimicking a geophone, was positioned 15 cm horizontally from the impact plate. The receiver measured 1 cm x 2 cm x 5 cm and captured stress wave signals propagating through the medium.

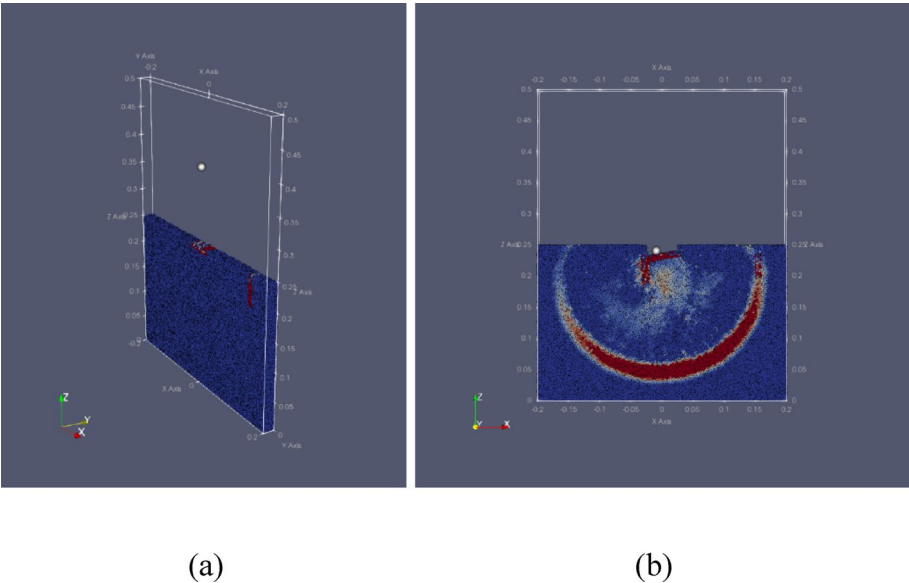


Fig. 3 DEM-based stress wave simulation: **(a)** pseudo-2D model configuration highlighting the impact particle, impact plate, and receiver, **(b)** snapshot of stress wave propagation at the moment it is detected by the receiver

Table 2 DEM parameters for impact particle

Parameters	Value
Particle radius (mm)	7.5
Particle density (kg/m ³)	270,000
Poisson's ratio	0.35
Young's modulus (Pa)	5×10^8
Acceleration of gravity (m/s ²)	9.81
Restitution coefficient	0.2

The impact energy was delivered by a spherical particle that dropped from a height of 40 cm, corresponding to 15 cm above the soil surface. To generate a clear and distinguishable stress wave signal that is separable from background soil stress, a high-density, large-radius particle was used. The impact particle had a density of 270,000 kg/m³ (100 times that of the soil particles) and a radius of 7.5 mm. Its DEM material parameters are listed in Table 2. Furthermore, Fig. 3a shows the pseudo-2D simulation setup, including the impact plate and receiver. Figure 3b illustrates the moment the stress wave reaches the receiver.

Results

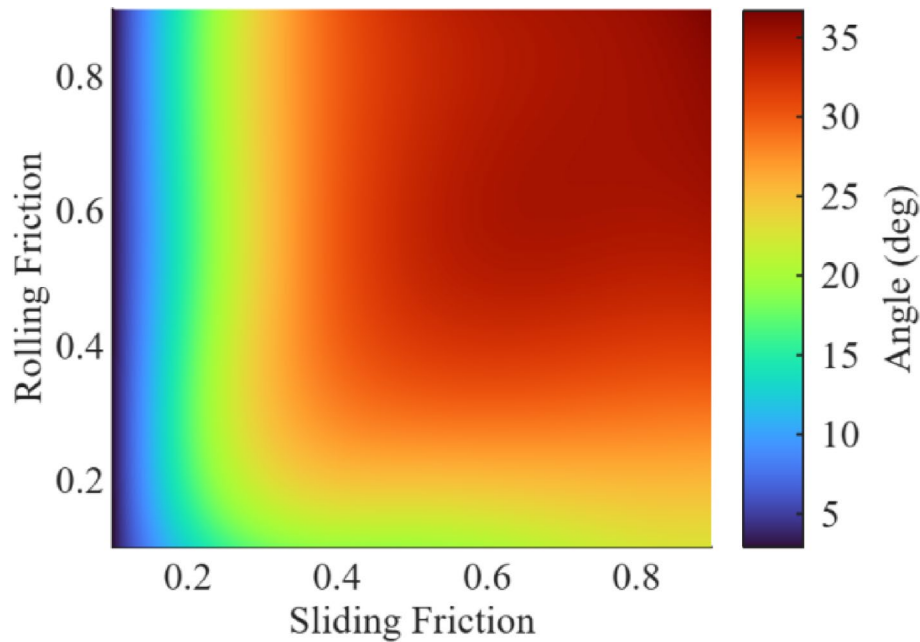
Effect of sliding and rolling friction on angle of repose

In DEM simulations, the sliding and rolling friction coefficients are critical parameters that govern particle interaction mechanics. Sliding friction represents resistance to transitional motion at contact surfaces, while rolling friction accounts for resistance to rotational movement. Both significantly influence the AoR, which is defined as the steepest angle relative to the horizontal plane at which a material can be piled without slumping or sliding. AoR is an important property in disciplines such as geotechnical engineering, powder processing, and granular flow analysis [7, 12, 20, 25, 32].

This study examined a comprehensive range of sliding and rolling friction coefficients (0.1–0.9) to investigate their influence on AoR. As shown in Table 3; Fig. 4, AoR

Table 3 Angle of repose for various sliding and rolling friction coefficients

Sliding\rolling	0.1	0.3	0.5	0.7	0.9
0.1	2.9	2.9	3.1	3.1	3.2
0.3	17.8	24.5	26.9	27.5	28.8
0.5	19.6	29.0	32.9	34.5	35.1
0.7	21.4	29.1	34.0	34.8	36.0
0.9	22.7	28.7	33.8	35.5	36.7

**Fig. 4** Contour map of the angle of repose (AoR) as a function of sliding and rolling friction coefficients. The color scale represents the magnitude of the AoR, ranging from blue (low AoR, approximately 0°) to red (high AoR, approximately 35°). Warmer colors indicate steeper, while cooler colors indicate flatter deposits

generally increased with higher values of both friction coefficients, ranging from 2.9° to 36.7°, which is consistent with typical AoR values observed in dry sands (e.g., ~ 34° for quartz sand [2, 10] and ~ 31.0° for Ottawa sand [5]).

Previous studies corroborate this trend: higher friction coefficients consume more kinetic energy during contact, thereby producing steeper and more stable granular heaps [7, 12, 34]. At low friction coefficients, the system behaves more fluid-like, resulting in flatter piles. Rolling friction also inhibits particle rearrangement, promoting steeper pile formation [31].

Importantly, when the sliding friction coefficient is very low (e.g., 0.1), changes in rolling friction have minimal effect on AoR. In such cases, particles primarily slide rather than roll due to stronger rolling resistance. Conversely, at high sliding friction levels, rolling motion becomes more favorable, making AoR more sensitive to variations in rolling friction. These trends are clearly illustrated in the contour map in Fig. 4.

Wave-induced stress in soil

Stress magnitude is a key parameter in understanding the response of granular materials to dynamic loading. Figure 5 shows a typical stress-time history recorded at the receiver during simulation. The stress wave is initiated by the impact of a falling particle, which

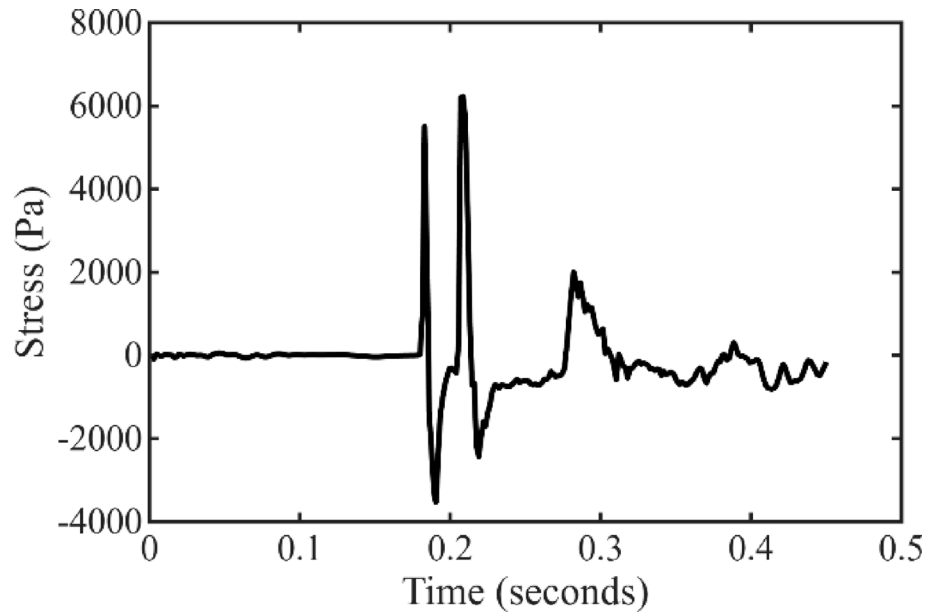


Fig. 5 Time history of particle stress in the dry soil model (sliding and rolling friction coefficients = 0.5)

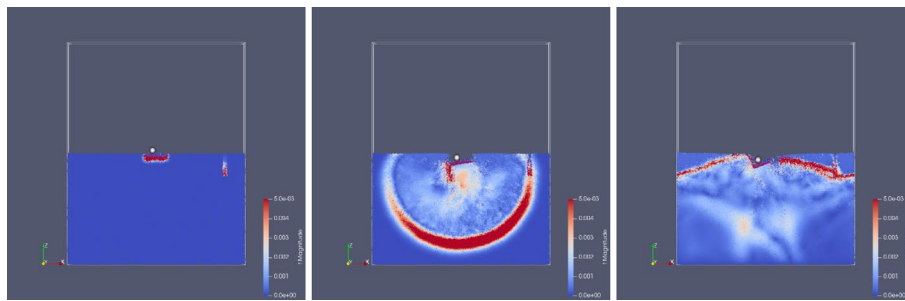


Fig. 6 Stress wave propagation in the granular model: (a) impact initiation, (b) wave arrival at the receiver, and (c) reflection from the bottom boundary (color scale indicates force magnitude)

strikes the impact plate atop the granular column (Fig. 6a). The wave then propagates through the material (Fig. 6b, c).

Two major stress peaks are evident: the first corresponds to the initial wave arrival, and the second arises from reflection at the base of the simulation box. Given that post-peak behavior is influenced by boundary effects, only the first peak was used in subsequent analyses.

Figure 7a presents the effects of sliding and rolling friction on the peak stress detected at the receiver. Average stress was computed from all particles within the receiver region. Sliding friction had a pronounced influence: lower coefficients (0.1–0.5) resulted in higher stress values (> 5000 Pa), while higher coefficients (> 0.5) reduced stress magnitude to around 3000 Pa. This indicates that lower sliding friction facilitates more efficient transmission of impact energy, while higher sliding friction absorbs energy at contact points. For rolling friction, it had a minimal effect on stress when sliding friction remained constant, reinforcing the dominant role of sliding friction in dynamic stress propagation.

To further assess the role of AoR in dynamic soil behavior, Fig. 7b illustrates the relationship between AoR and the stress magnitude. While AoR is a commonly used

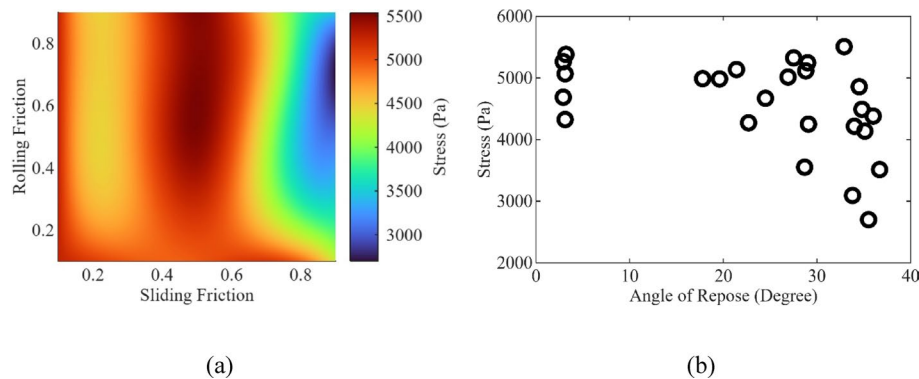


Fig. 7 Stress magnitude detected by the receiver: **(a)** variation in peak stress as a function of sliding and rolling friction coefficients, and **(b)** relationship between angle of repose (AoR) and stress magnitude. In Fig. 7a, the color scale represents the peak stress magnitude measured at the receiver, with cooler colors indicating lower stress values and warmer colors indicating higher stress values

indicator of soil behavior in geotechnical engineering, its applicability in stress wave propagation remains less understood. For example, prior studies have shown that softer deposits can amplify ground motion more than stiffer ones [18, 30]. In a finite element analysis, Tavakoli and Kutanaei [29] reported that increasing the soil's friction angle reduced seismic amplification. However, such findings may not directly translate to DEM-based particulate models, where AoR is governed by the combinations of sliding and rolling friction at the micro-scale. The current results reveal no consistent correlation between AoR and stress magnitude (i.e., stress values diverge for similar AoR values), highlighting that AoR alone does not capture the complexity of wave propagation behavior in granular materials. This suggests the need for caution when using AoR as a sole proxy for dynamic soil response in DEM analyses.

Particle velocity

The velocity-time profile of particles within the receiver (Fig. 8) mirrors the stress response: two peaks are observed, corresponding to the initial wave and its reflection. Peak velocities decay as the wave propagates due to internal energy dissipation. This profile provides insight into the granular medium's dynamic response and energy transfer mechanisms.

As shown in Fig. 9a, sliding friction again dominates the behavior, with higher values reducing particle velocity due to increased resistance to movement. Rolling friction exerts comparatively less influence. These results are consistent with prior findings in granular flow studies [11, 33].

Figure 9b presents the relationship between AoR and particle velocity. A general trend is observed in which velocity decreases as AoR increases. Since AoR is influenced by the combination of sliding and rolling friction, this trend reflects the increasing resistance to particle motion under higher friction conditions. However, the effect is relatively modest in magnitude, suggesting that while higher AoR may correspond to lower velocity, AoR alone is not a strong predictor of particle velocity in impact-driven granular systems.

Particle displacement

Stress waves induce particle displacements within the soil model. Figure 10 illustrates the time evolution of horizontal particle displacements, showing two peaks corresponding

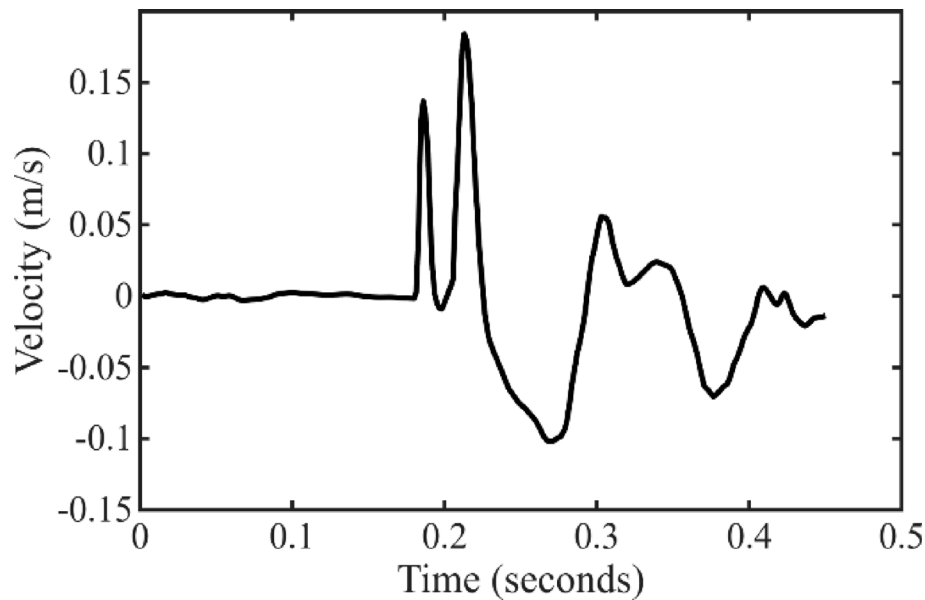


Fig. 8 Time history of particle velocity in the dry soil model (sliding and rolling friction coefficients = 0.5)

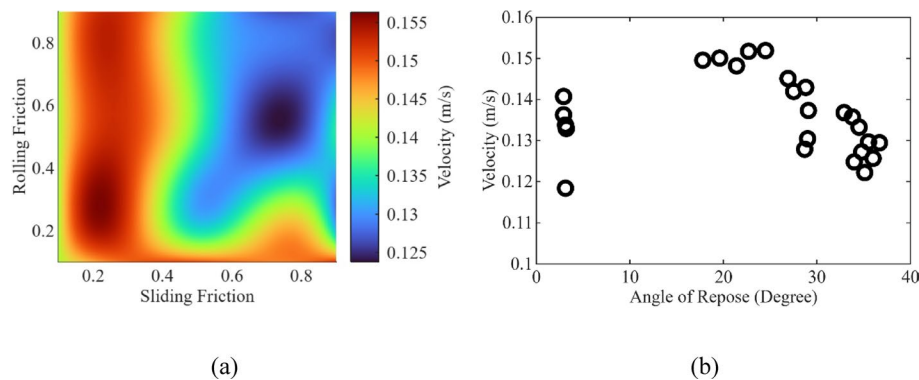


Fig. 9 Particle velocities detected by the receiver: **(a)** variation in peak particle velocity as a function of sliding and rolling friction coefficients, and **(b)** relationship between angle of repose (AoR) and particle velocity. In Fig. 9a, the color scale represents the peak particle velocity measured at the receiver, with cooler colors indicating lower velocities and warmer colors indicating higher velocities

to the primary and reflected waves. A time lag is evident between peak stress and displacement, due to gradual momentum transfer. For example, while peak stress occurred at 0.183 s, significant displacement was not observed until 0.193 s.

The contour plot in Fig. 11a shows that increasing sliding friction significantly reduces displacement, as it resists particle motion. Rolling friction has a lesser effect. This is consistent with earlier observations for stress and velocity.

Fig. 11b examines the relationship between AoR and displacement. No clear trend is observed, which is similar to the AoR-stress analysis, suggesting that AoR is not a direct proxy for displacement response. This reinforces the idea that AoR, being a function of both friction coefficients, cannot uniquely determine dynamic behavior under impact loading

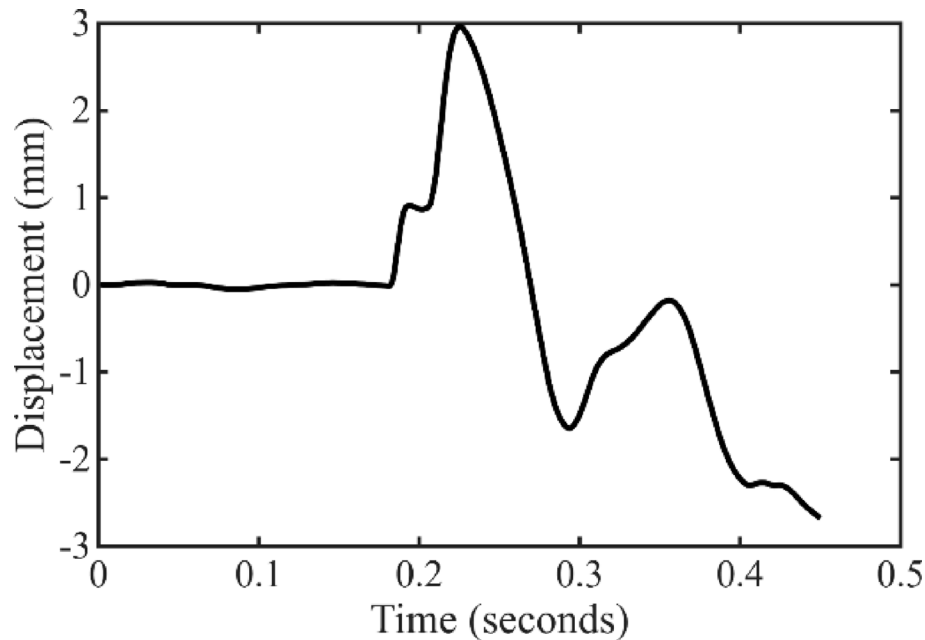


Fig. 10 Time history of particle displacement in the dry soil model (sliding and rolling friction coefficients = 0.5)

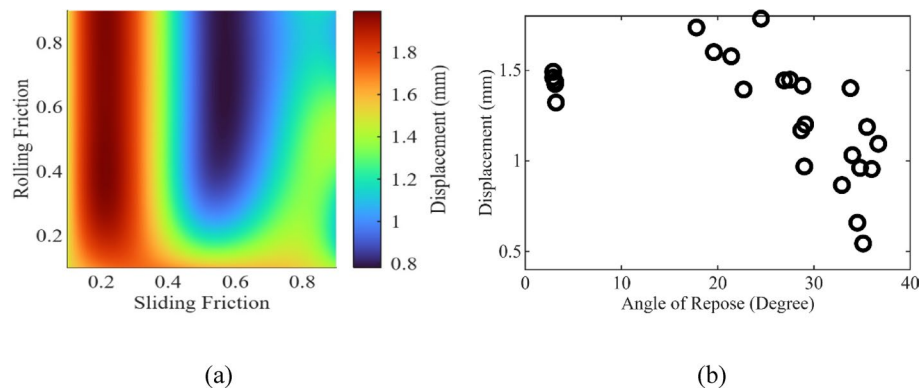


Fig. 11 Particle displacement detected by the receiver: **(a)** variation in peak particle displacement as a function of sliding and rolling friction coefficients, and **(b)** relationship between angle of repose (AoR) and particle displacement. In Fig. 11a, the color scale represents the peak particle displacement measured at the receiver, with cooler colors indicating smaller displacements and warmer colors indicating larger displacements

Discussion

This study utilized uniform-sized spherical particles to represent dry sandy soil and evaluate the angle of repose (AoR). While this simplification offers clarity in isolating the effects of inter-particle friction, it is important to recognize that AoR is a complex property influenced by a variety of factors, including particle size and shape, surface roughness, moisture content, grain size distribution, and compaction density. The unique combination of these variables ultimately determines the AoR in natural soils.

As such, the DEM models developed in this study do not fully replicate the multifaceted behavior of real soils. Rather, the focus here was specifically on examining how sliding and rolling friction coefficients affect AoR. While DEM offers a range of contact models that may yield varying AoR results, evaluating differences among those models lies outside the scope of this work. Future studies should consider the comparative

performance of alternative contact models to provide a more comprehensive understanding of their implications on granular behavior. It should be also noted that the findings of this study are based on simulations of dry, uniform, spherical particles and are intended to illustrate fundamental trends in granular behavior rather than to represent the full complexity of natural soils.

The stronger influence of sliding friction on stress-wave attenuation can be interpreted from the perspective of contact-level energy dissipation and particle mobility. During impact-induced wave propagation, stress transmission occurs through successive particle contacts, where relative tangential motion between particles plays an important role in transferring translational momentum. Higher sliding friction increases resistance to this tangential motion and likely dissipates a larger portion of the wave-induced translational kinetic energy at the contacts, thereby reducing the transmitted stress magnitude, particle velocity, and displacement [11, 33]. It may also limit particle mobility and promote more constrained contact interactions, which can reduce the efficiency of stress transfer through the granular assembly [7, 34]. In contrast, rolling resistance primarily restricts particle rotation, which is important for dynamic flow conditions, rather than directly opposing translational motion along the wave path [1, 13]. Therefore, although rolling friction contributes to particle rearrangement resistance and overall granular stability, its effect on stress-wave attenuation may be comparatively weaker than that of sliding friction in the present impact-based DEM simulations.

Regarding stress wave simulations, this study employed a finite-sized pseudo-2D model (dimensions: 40 cm x 2 cm x 50 cm; soil depth: 25 cm) to manage computational demands. The use of a small-scale impact particle (radius: 7.5 mm) and a high-density impact source enabled the generation of distinguishable stress waves but also introduced scaling limitations. The finite dimensions of the model inevitably affect stress wave behavior, particularly due to boundary reflections and constrained wave paths.

To minimize these effects, only the initial wave prior to reflection was analyzed. Although the model successfully captured the dynamics of wave propagation in granular media, the authors acknowledge that larger-scale simulations are necessary to investigate scale effects more comprehensively and better replicate field conditions.

Conclusion

This study employed the Discrete Element Method (DEM) to investigate the influence of inter-particle sliding and rolling friction on the angle of repose (AoR) and its relationship to stress wave propagation, particle velocity, and displacement in a dry granular soil model. The principal findings from this study can be summarized as follows:

1. Both sliding and rolling friction coefficients significantly affected AoR. As these coefficients increased, AoR increased accordingly, reaching a maximum of 36.7° at a coefficient of 0.9. When the friction coefficient was low (e.g., 0.1), variations in rolling friction had little effect on AoR, conforming to the dominant role of sliding friction.
2. Inter-particle friction markedly influenced stress amplitude within the soil model, with sliding friction playing a more substantial role than rolling friction. Higher sliding friction led to lower stress amplitude. However, no consistent correlation was observed between AoR and stress amplitude.
3. Particle velocity during wave propagation showed a clear inverse relationship with sliding friction. As sliding friction increased, the velocity decreased. Although a

general trend of decreasing velocity with increasing AoR was observed, the effect remained minor.

4. Particle displacement followed a pattern similar to velocity, primarily governed by sliding friction. Higher sliding friction reduced displacement, while rolling friction showed minimal influence. No strong correlation was found between AoR and displacement.

Overall, these results emphasize that although AoR is influenced by inter-particle friction, it does not reliably predict dynamic responses such as stress amplitude, velocity, or displacement in DEM-based simulations. Therefore, AoR should not be used as a sole descriptor of soil behavior in wave-based testing. A more comprehensive understanding of inter-particle interactions is essential for improving predictive models in geotechnical engineering and granular mechanics.

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Author contributions

SJN: Conceptualization, Methodology, Analysis, Writing original draft. DHK: Data analysis, Visualization, JHK and HJY: Review and editing. All authors approved the submitted version.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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