

Measuring the sensitivity of sand pile geometry to substrate roughness for calibrating friction parameters in DEM

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ABSTRACT

Accurate calibration of contact parameters in the discrete element method (DEM) remains one of the critical challenges for predictive modelling of granular flows and wear processes. In this work, we propose and experimentally validate a novel calibration strategy based on the morphological analysis of granular heaps formed under controlled low-mass deposition. Operating deliberately in the sensitivity-threshold regime, where reproducibility is preserved while local interactions remain highly distinguishable, we demonstrate that the geometry of the heap provides diagnostic information beyond the conventional single-angle-of-repose test. A systematic series of experiments with sand deposited on substrates of varying roughness revealed a distinct dual-slope profile, reflecting the separation between particle–substrate and particle–particle interaction domains. Internal and external slope angles, along with height distribution and top-shape descriptors, were employed as multi-criteria calibration metrics. These features proved highly sensitive to substrate roughness and feed conditions, allowing for the independent identification of friction and rolling resistance parameters in DEM simulations. Numerical modelling combined with surrogate-based regression confirmed the feasibility of recovering key particle–surface parameters from the experimental heap geometry. The proposed framework offers a resource-efficient and reproducible approach to DEM calibration, reducing the computational load while maintaining sensitivity to local contact mechanics. The methodology is directly applicable in tribological modelling of granular-induced wear, particle-surface interactions, and powder-based processing systems.

Keywords: discrete element method, parameter calibration, angle of repose, dual-slope pile, particle-wall interaction, surface roughness.

INTRODUCTION

Granular flow over surfaces with different frictional and adhesive properties occurs in many industrial and natural processes, including abrasive wear, powder deposition, and erosion. Accurate determination of particle–surface interaction properties is essential for predictive wear simulations and optimised surface design. Therefore, this work was motivated by the need for reliable calibration of local contact parameters in discrete element method (DEM) simulations used in tribological and wear modelling. DEM, established in

the classical work of Cundall and Strack [1], has become the foundation for modelling the behaviour of such granular media by approximating the interactions between individual particles through contact laws. Already in the first formulation, it was noted that the realism of numerical calculations directly depends on the choice of interaction parameters. These parameters are not universal but must be empirically determined for specific conditions. In the following decades, this thesis was developed in a number of generalisations and applied studies emphasising the need for adaptive, context-dependent calibration of DEM models.

Modern approaches, such as those presented by Rackl and Hanley [2] and Coetzee [3], emphasise that calibration is not an auxiliary but an integral and key part of DEM modelling. There is no universal set of parameters: the model requires tuning not only basic characteristics (friction, elasticity, damping), but also additional ones, such as rolling resistance [4], which allows indirectly taking into account particle shape within models with simplified geometry. Moreover, calibration requires a multi-criteria approach combining various experimental tests, from slope angle to drop and shear, with an analysis of the macroscopic behaviour of the system.

Despite these advancements, calibration parameters are often underdetermined: different combinations of them can give similar output characteristics. This makes the calibration problem inverse and multivalued, and thus particularly sensitive to the choice of evaluation criteria and procedures. In some cases, as Coetzee [3] emphasised, calibration becomes impossible without a series of accurate and sensitive experiments capable of differentiating the contribution of different parameters.

These fundamental considerations form the basis of the present approach as well. Instead of minimising physical instability to maintain a purely static state – which is typical of most works [5, 6] – a region of increased parametric sensitivity is deliberately exploited. Specifically, the focus is directed to the transition zone between an unstable and a static sand pile shape, where the macroscopic geometry is highly responsive to microscopic inputs. This approach allows not only for the reliable identification of the effect of DEM parameters on slope geometry but also for a significant reduction in the volume of modelled material, which is critical in problems involving resource-intensive DEM modelling.

Shi et al. [7] investigated the calibration of DEM parameters based on the transition of particles from fast flow regime to steady-state accumulation in transport troughs. The methodology was based on the comparison of numerical simulation results with experiments, which included the estimation of shock loads and accumulated material density. The focus was on the selection of effective friction and damping coefficients to ensure accuracy in the two regimes. The substrate was modelled as an idealised rigid surface with no varying characteristics, and the analysis of the pile geometry was limited to integral parameters.

Marín Pérez et al. [8] calibrated the slip and roll coefficients in a DEM model for an unbound bulk material. The authors used a draw down test with three hole sizes and particles modelled as multispheres to evaluate the effect of particle shape and flow velocity on the model parameters. The response criteria were angle of repose, shear angle, mass flow rate and mass loss. The results showed that the use of multispherical particles and different orifice sizes can narrow the range of possible values of friction coefficients to a small region, providing an accurate calibration of the parameters. The calibrated coefficients were verified, showing a maximum deviation of 5.9% from the experimental data.

Hu and Lu [9] proposed a new methodology for calibrating DEM parameters for sand and soil-rock mixtures. The authors developed a multi-stage procedure including numerical optimisation and verification based on experimental data to improve the accuracy of modelling the mechanical behaviour of these materials. Particular attention is paid to accounting for the heterogeneity of the mixtures and the influence of various parameters on the macroscopic characteristics.

Scheffler and Coetzee [10] present a methodology for calibrating DEM parameters for bulk cohesive materials. The authors investigate various contact models, including the full Johnson-Kendall-Roberts (JKR) model and its simplified versions (SJKR), as well as rolling resistance models such as the elastoplastic model with damping and the model with adhesion hysteresis component.

The results show that the full JKR model with a hysteresis component predicts the slope angle more accurately, while the simplified SJKR models show less accuracy. However, the proposed methodology focuses on steady flow regimes and does not take into account the influence of substrate or minimum sand pile masses, which may limit its applicability in conditions close to the pile stability boundary.

The paper [11] presented a methodology for calibrating the parameters of a DEM for compost, a material with high heterogeneity and pronounced particle entanglement effects. The authors used an iterative approach, including laboratory tests and numerical simulations to evaluate the influence of model parameters on the material behaviour during composting. Particular attention was paid to modelling particle interactions, taking into account particle shape and inter-particle friction.

The described approaches [8, 9, 10, 11] are limited by the use of idealised geometries and do not take into account the influence of the substrate or minimum bulk masses, which may be critical for accurate calibration of interaction parameters under conditions close to the bulk stability boundary. Obvious in such a case is the need to use precision methods for measuring parameters characterising the geometry of the calibration mass. In this aspect, attention should be paid, for example, to the paper [12], which presents an innovative approach to the automated measurement of the numerical angle of natural slope (aMAoR) of biomass particles in EDEM software. The authors [12] developed a novel algorithm integrated into a graphical user interface that allows accurate and reproducible determination of aMAoR without subjective operator intervention. This approach is relevant for materials with irregular shape and inhomogeneous particle size distributions, where traditional slope angle measurement methods may be unreliable.

In Zhang et al. [13] proposed a method for calibrating microscopic parameters for rockfill type material considering flexible boundary conditions, which improved the agreement between the results of DEM modelling and laboratory experiments. The use of 3D particle scanning and the implementation of flexible walls provide a more realistic simulation of the pile behaviour under load. However, this approach is focused on coarse, fractional, angular material and requires resource-intensive geometric and computational preparation, making it difficult to directly apply to finer and more sensitive materials such as sand. In addition, the technique lacks multi-criteria analysis, and calibration is based on a limited set of attributes, predominantly relating to total strain. This reduces the sensitivity to the subtle effects of particle-substrate interactions, which are key in the context of our study.

The paper by Chen et al. [14] presented a procedure for calibrating the contact parameters of a DEM for modelling the motion and distribution of potato minitubers. The authors used laboratory tests on slope angle, friction coefficient, and recovery coefficient as a physical basis for subsequent numerical calibration in the EDEM software environment. The main focus is on reproducing the behaviour of complex shapes and the texture of agricultural products in mechanised transport systems. Despite its practical value, the proposed method is limited to application to

relatively large and deformable objects that are not sensitive to the roughness of the substrate. The calibration was carried out on the basis of averaged parameters (average area of coverage (AoR) and trajectory), without analysing the geometric characteristics of the pile or the dynamics of pile formation, which reduces the method's sensitivity to microfactors and interactions between particles and the surface. In addition, the variability of the initial conditions is not discussed, which is critical in stability boundary operations.

When performing calibration experiments using the AoR test, one usually seeks to ensure stability of the sand pile shape by increasing the mass of the material to be filled. This approach partially offsets the effect of the curvature of the slope profile and makes the pile profile more stable. However, this is accompanied by a decrease in the sensitivity of the system to the parameters of microinteractions, in particular between particles and substrate. In practice, this means that information about subtle effects - such as surface adhesion, roughness effects, or transient shaping modes - is partially lost when using large mounds. Moreover, in wear modelling problems where it is the particle-surface contact that is critical, smoothing out this interaction can lead to significant calibration errors.

However, as shown in a number of papers [15, 16], this test is highly sensitive to a variety of factors, in particular, substrate geometry, pour rate, material dispersion, and mass of the poured portion.

In [15], the scalability of the slope angle test was demonstrated by varying the particle and bench sizes, as well as the effect of lift rate on the morphology of the sand pile. Although the test shows good stability at slow velocities, the authors aim for invariance and smoothing of the pile profile. In contrast, the present study aimed to analyse sensitivity, with minimal suspensions, varying substrate roughness and emphasis on double slope angle. This approach allows for a deeper identification of particle-substrate interaction parameters critical in the task of accurately calibrating DEM models.

In [16], the substrate is excluded from the analysis by gluing the particle layer. This approach provides stability but does not allow for analysing the contribution of the particle-substrate interaction. In the present study, the substrate is considered as a controllable factor directly affecting the geometry of the bulk. The work is carried out in

the small-volume regime, which allows revealing the sensitivity of the system to local contact conditions and utilising this in the multi-criteria calibration of the DEM parameters.

The angle of repose is significantly influenced by the nature of the substrate surface. Smooth substrates such as glass or ground steel reduce the slope angle due to the sliding of the lower particle layer, while rough substrates (e.g. sandpaper with different gradations) favour a steeper slope due to the mechanical entanglement effect [17, 18].

This is not only due to the macroscopic coefficient of friction, but also to microscopic mechanisms of adhesion that depend on roughness, chemical interactions, and even surface contamination. Adhesion models (e.g., JKR, DMT) allow for accounting for this adhesion in numerical simulations. In [17], advanced statistical methods (Plackett-Burman plan, response modelling) are applied to accurately calibrate the DEM parameters of complex cohesive materials. However, in such approaches, the particle-base interaction is considered secondary and is actually excluded.

In the present work, the opposite approach was proposed: targeted operation in the mode of the minimum possible mass of the poured material, which preserves the reproducibility of the pile profile and, at the same time, achieves high sensitivity to changes in the characteristics of the substrate. This mode can be conditionally called the “sensitivity threshold” mode. It opens up the possibility of finer tuning of DEM-parameters and allows working under the conditions closest to the problems of abrasive wear and local contact.

As noted in some works devoted to the study of the processes accompanying calibration, the profile of the mound can be characterised by two different angles: AoR_1 in the central zone, where particles are more often at rest, and AoR_2 closer to the edges of the mound where sliding and mass redistribution are observed.

This double-angle phenomenon is mentioned fragmentarily in the literature, in particular in [19], as a result of localised shear zones and differences in particle motion within and on the surface of the pile. However, in most cases, it is ignored in the calibration, which may lead to the choice of incorrect parameters. The review paper [19] represents an important body of knowledge on the flow of dense bulk media. Stable shear regimes are considered, and

a generalised rheological model linking effective friction to density and velocity gradient is introduced. However, the geometries of the sand pile formed during the dumping process, as well as the role of the substrate in its formation, are not analysed in this work.

In [20], a global sensitivity analysis of DEM model parameters on pile formation was performed. Friction coefficients, including particle-wall friction, have the greatest influence. However, the substrate in these studies is fixed and not varied, which limits the calibration potential of the particle-surface interaction parameters.

Limiting the calibration to a single AoR value (as is often done) is a potential source of error. Therefore, one solution may be a multi-criteria approach including:

- splitting the slope angle into internal and external;
- introduction of a geometric parameter for the shape of the top of the sand pile;
- taking into account the height of the pile and the packing density, depending on the substrate and the pouring rate.

This approach will allow a more accurate selection of:

- coefficients of friction between particles (μ_s) and with surfaces (μ_w),
- rolling coefficients (μ_r),
- adhesion parameters (adhesion energy, γ),
- contact stiffness parameters (E , ν), which are important in modelling wear and load transfer.

Studies such as [20] indicate the need to consider scaling in AoR tests and to select ranges of conditions under which the system achieves stable, representative behaviour.

The aim of this manuscript is to obtain reliable experimental data necessary to refine the granular material parameters used in numerical modelling of abrasive wear processes. To achieve this objective, a comprehensive analysis of the processes accompanying the formation of a free mound cone is carried out, with emphasis on the morphological features of the profile, sensitivity to the conditions of interaction with the substrate, and the influence of mass, feed rate, and substrate roughness. Based on the identified geometric and dynamic characteristics, recommendations are formulated for calibrating the DEM microparameters responsible for particle-particle and particle-surface interactions.

The aim of the study:

- To conduct a series of experiments on the formation of sand piles on substrates with different roughness under conditions of strictly controlled material feeding.
- To record and quantitatively characterise the pile geometry, including double slope angle (AoR_1 , AoR_2), top shape and height parameters (h_1 , h_2 , h), for different feeding conditions and substrate types.
- Evaluate the effects of bulk material mass, feed rate, and substrate characteristics on the sensitivity of bulk geometric parameters, and identify modes of high sensitivity and stable reproducibility.
- Analyse the physical nature of the double slope, taking into account the dynamics of particle motion and kinetic energy distribution during pile formation.
- Establish relationships between measured geometric characteristics and interaction parameters in DEM models (friction, adhesion, contact with the substrate).
- Conduct preliminary calibration of the parameters of the discrete element model aimed at further use in the modelling of abrasive wear processes.
- To formulate recommendations on the choice of calibration conditions (mass, roughness, feed rate), providing a balance between sensitivity and reproducibility.

Figure 1 presents a conceptual representation of the calibration methodology for DEM-based modeling of particle–surface interactions, structured according to a cognitive and cluster-based logic. Rather than following a strictly linear or iterative sequence, the diagram illustrates a set of interlinked modules distributed across a multidimensional process space, where functional and thematic layers intersect.

Horizontally, the scheme distinguishes three concurrent data flows: the upper stream relates to substrate characteristics and response functions; the middle stream concerns mechanical parameters such as friction, restitution, and density; the lower stream addresses the granular material, including its physical properties and DEM implementation. Each stream contributes distinct information to the calibration process, capturing different aspects of system behavior and model sensitivity.

Vertically, the structure is organised into four methodological domains: the input parameter space, the experimental domain (comprising both physical and numerical experiments), the data processing and analysis domain, and the domain of application—namely, the pathway toward tribological DEM modelling. These domains function both sequentially and reciprocally, forming a network of data flow and feedback that enables dynamic refinement of input parameters.

Particularly noteworthy is the integration of heap geometry analysis as a high-sensitivity

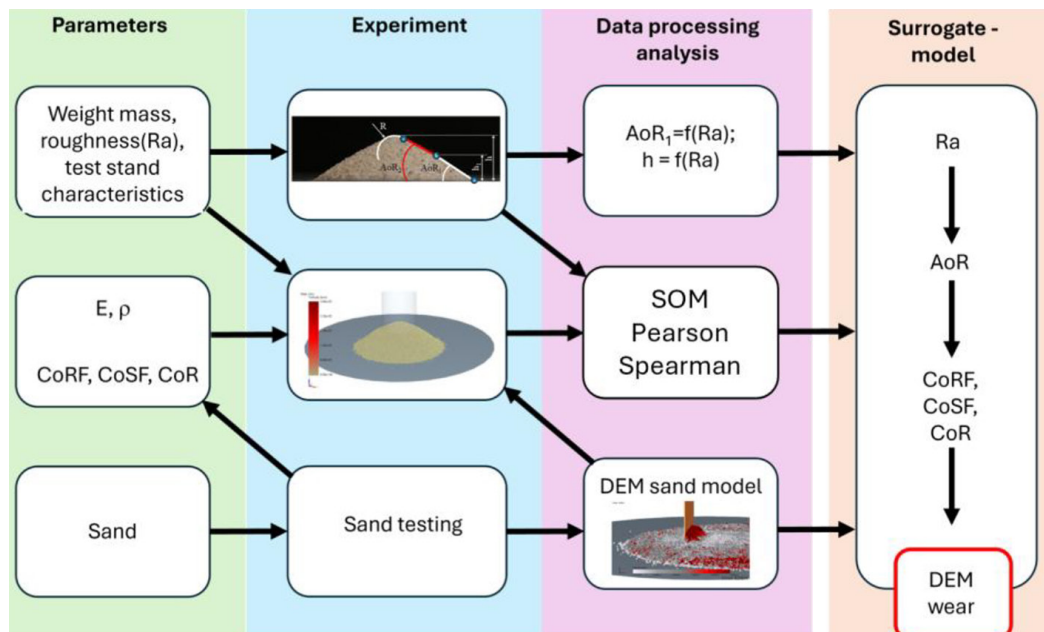


Figure 1. Conceptual layout of the parameter–response calibration framework showing three horizontal data streams and four vertical methodological domains

diagnostic, with specific emphasis on the detection of sidewall profile discontinuities. This feature serves as a key indicator of local stability conditions and enhances the resolution of the calibration framework. The resulting structure allows for an informed and precise adjustment of contact parameters, ultimately supporting the development of DEM models tailored to wear prediction and surface load analysis in tribological applications.

MATERIAL AND METHODS

The object of the study is the processes of granular material bulk formation on a solid substrate under controlled feeding conditions, accompanied by the development of contact interactions between particles and between particles and the surface of the substrate.

Natural sea sand was used as the bulk material, which was washed and sieved through a 0.5 mm sieve to remove impurities. All plant debris and the very few larger grains of sand that remained on the 0.5 mm mesh sieve were removed. Before use, it was divided into fractions in accordance with the European standard PN-EN 933-1:2012.

Sieve analysis (Figure 2) showed that the main fraction consists of particles ranging in size from 0.1 to 0.25 mm (approximately 71%) and from 0.25 to 0.5 mm (almost 29%). This composition makes the material suitable for laboratory testing: it is stable, repeatable, and well-suited for numerical characterisation.

In order to ensure consistency between the actual and model abrasive material, the particles were subjected to geometric analysis using a Keyence VHX7000 digital microscope. The grain size was assessed on a sample of approximately 320 grains of each fraction.

Based on the determined values of the equivalent circle diameter of the abrasive grains, the values of the equivalent sphere volumes used in the DEM model were determined (Table 1).

The distributions of percentage shares of grains with a given equivalent circle diameter in the population of individual grain fractions are presented in Figure 3, and the distributions of percentage shares of grains with a given equivalent sphere volume are presented in Figure 4.

Subject of the research – geometrical and morphological characteristics of the mound (slope angles, height parameters, top shape), sensitive to the substrate parameters and feeding modes, used

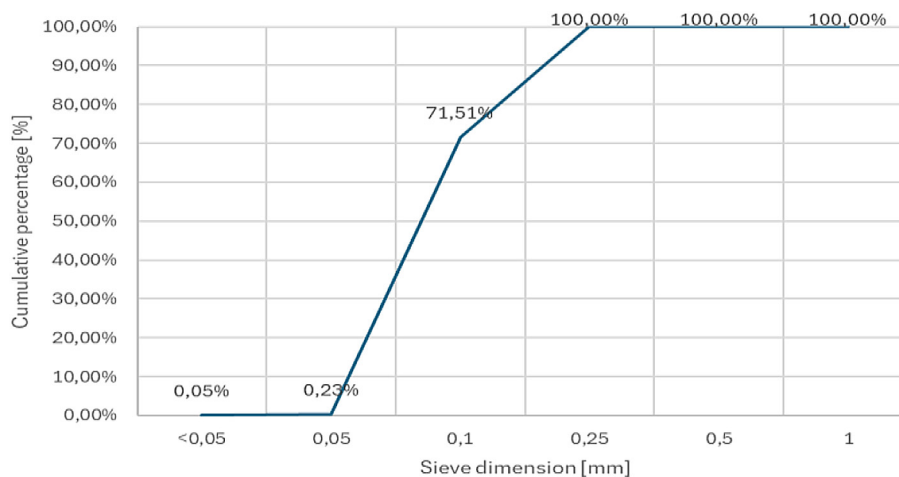


Figure 2. Results of sieve analysis of sand used for testing

Table 1. Statistical values of the equivalent circle diameter and equivalent sphere volume for sand grains

Parameter	Sand fraction	
	0.1 ÷ 0.25 [mm]	0.25 ÷ 0.5 [mm]
Average equivalent circle diameter [mm]	0.2336	0.3567
Standard deviation of the equivalent circle diameter [mm]	0.0403	0.0415
Average value of equivalent sphere volume [mm ³]	0.0073	0.0248
Standard deviation of equivalent sphere volume [mm ³]	0.0038	0.0093

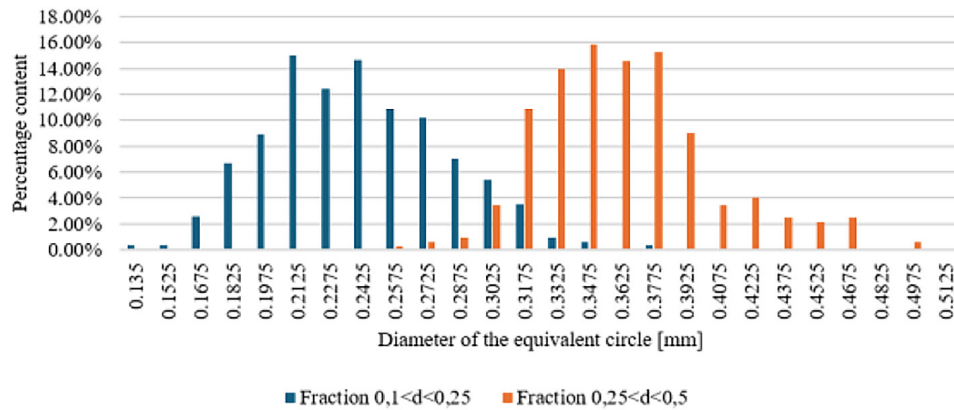


Figure 3. Distribution of percentage shares of equivalent circle diameter in the population of sand grains

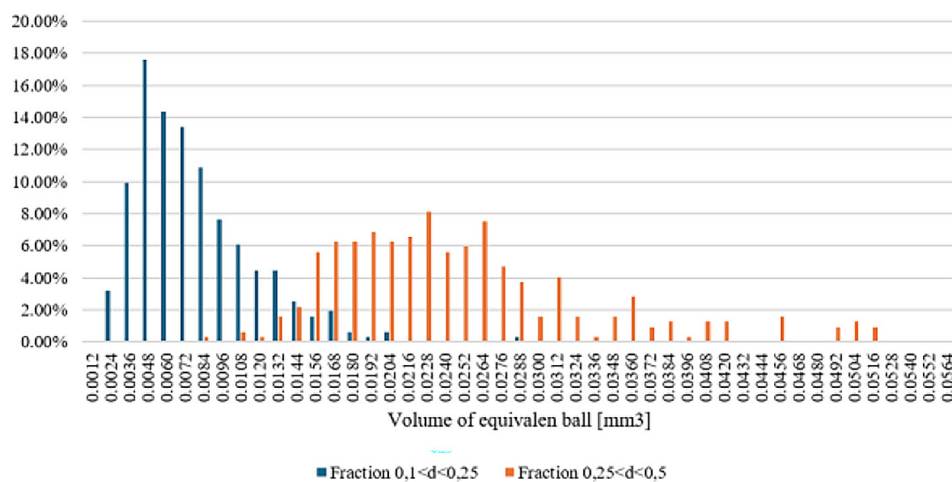


Figure 4. Distribution of percentage shares of equivalent sphere volume in the population of sand grains

for calibration of the parameters of DEM-models used in the modelling of abrasive wear.

Scientific novelty of the research

- A fundamentally new approach to calibration of DEM-models parameters based on the use of small portions of granular material in conditions close to the reproducibility threshold has been proposed and implemented, which allows significantly increasing the sensitivity to the parameters of particle-surface interaction.
- It is established and quantitatively confirmed that at the minimum possible mass of the bulk material, the stability of the bulk geometry, sufficient for use as a calibration standard, is preserved, with simultaneous amplification of differences depending on the substrate characteristics.
- A multicriteria system of morphological parameters of the pile (internal and external slope angles, segment heights, and top shape)

has been developed, which allows separate estimation of particle-particle and particle-substrate interaction parameters in a discrete element model.

- It is shown that the traditional strategy of smoothing the double slope angle by increasing the mass is accompanied by a loss of sensitivity to the micromechanics of interaction, which makes it insufficient for problems related to the modelling of abrasive wear processes.
- The necessity of application of the controlled system of material feeding (stepper drive, glass guide tube) to provide reproducibility of initial conditions at work in the mode of increased sensitivity is substantiated and experimentally confirmed.
- Practical recommendations on the choice of mass, base roughness, and variant modes providing the most informative and reproducible calibration conditions relevant for wear modelling tasks have been formed.

Test stand

In view of the objectives, special attention was paid to ensure the accuracy and reproducibility of the feeding conditions. For this purpose, an experimental setup with a stepper-type drive providing controlled vertical movement of the guide tube at a speed of 0.05 m/s was used. Such a solution allowed excluding the influence of random vibrations and ensuring stable feeding kinematics (Figure 5).

A glass tube with low adhesion and a smooth inner surface was used as a guide tube, which minimised the interaction of particles with the walls in the exit zone and ensured flow symmetry. The tube geometry and its velocity were chosen experimentally based on a series of preliminary tests, with the aim of achieving stable and reproducible mound formation at material masses ranging from 0.5 to 20 g. Their aim was to determine the mass range at which the stability of the morphological parameters of the mound is maintained, and at the same time, a high sensitivity to the microstructure of the substrate is ensured. These data were used both to validate the numerical model and to justify the calibration conditions. At the initial stage, the lower end of the tube was in contact with the substrate. Then, the tube was smoothly moved upwards at a velocity of 0.05 m/s, ensuring a uniform exit of sand from the tube and the formation of a mound on the substrate.

To investigate the effect of particle-surface interaction, substrates with different roughnesses were used, including:

- smooth glass ($R_a \approx 0.04 \mu\text{m}$),

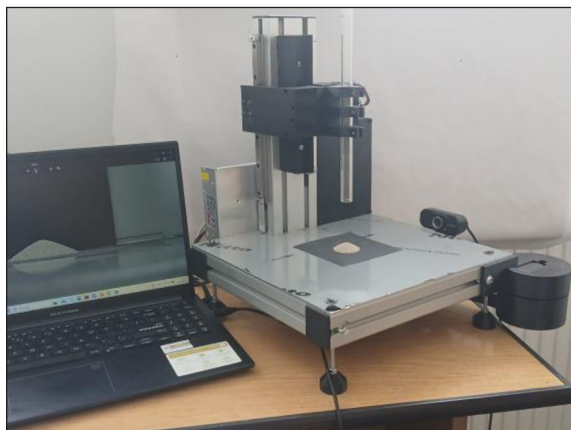


Figure 5. Automated stand for testing the properties of abrasive materials and their interaction with surfaces

- ground metal,
- abrasive sheets with different grain sizes.

After completion of the mounding process, the formed cone-shaped pile was recorded using macro photography from the two perpendicular directions (front and side), at the same camera and lighting position. Two images allowed for the verification of the symmetry of the obtained pile. The resulting images were processed using specialised image analysis software to extract the contour of the pile and measure the following parameters:

- angle of inclination of the lower part of the cone (AoR_1),
- the angle of inclination of the upper part of the cone (AoR_2),
- height of the corresponding pile segments (h_1 , $h_2 = h - h_1$),
- total height (h),
- characteristic radius of the base.

This method ensured the reproducibility of the experiment and the validity of the quantitative analysis of the pile morphology under different material-substrate interaction conditions.

Image processing and extraction of geometric parameters

The authors [21] demonstrated that digital image processing is essential for assessing the geometry of an object without physically interfering with the object itself. Although the material and target being examined are different in both situations, the basis for the assessment is a non-invasive optical technique.

Side-scan images taken after the completion of sand pile formation were used to quantitatively analyse the shape of the pile. Image processing was performed using Tracker (Open Source Physics) software, which allows for frame-by-frame geometric measurements with visual reference to scale. The position of the characteristic segments of the sand pile's contour (Figure 6a) was determined from the digital image based on pixel coordinates. The image scale (0.041 mm/pixel) was established using a scale bar placed within the frame.

After segmenting the granular material area against a dark background, the visible upper contour of the sand pile was extracted. Each side of the profile was approximated by a piecewise linear relationship, which allowed for the identification

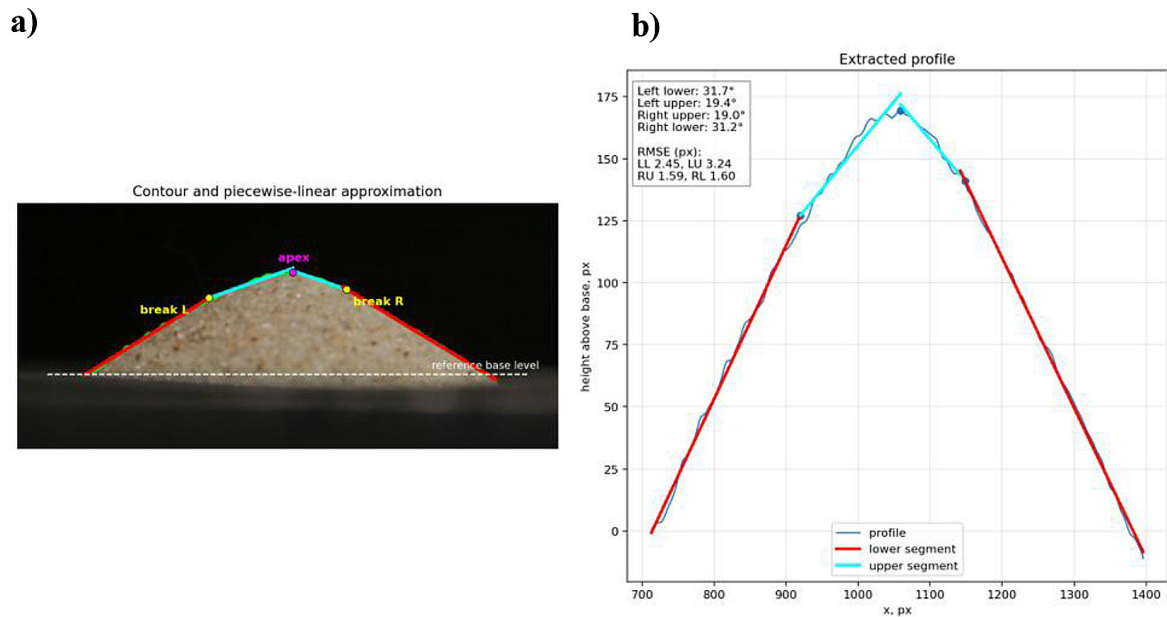


Figure 6. A digital image showing an isolated area of granular material (a) and an approximation of the profile (b)

of two characteristic segments: the lower one, associated with the influence of the substrate, and the upper one, corresponding to the formation of a free surface within the granular material volume.

The breakpoint b was determined as part of the geometric post-processing of the extracted contour using an optimisation-based piecewise linear regression. Candidate breakpoint positions were successively tested along the contour. For each position, the lower and upper contour portions were independently approximated by straight lines using the least-squares method. The position providing the minimum combined root-mean-square deviation of the contour points from the two fitted lines was adopted as the breakpoint. For the analysed profiles, the root-mean-square deviation did not exceed 3.3 pixels, corresponding to approximately 0.13 mm at the adopted image scale. Thus, the division of the profile into two segments was determined quantitatively.

The optimised breakpoint b separates the cone profile into two linear segments. The lower segment, extending from the cone base to b , was used to determine AoR_1 , whereas the upper segment, extending from towards the cone apex, was used to determine AoR_2 . Both angles were calculated from the slopes of the corresponding least-squares regression lines.

Figure 7b provides a geometric illustration of the transition between the two fitted profile segments. The change in their direction reflects the difference between AoR_1 and AoR_2 ; however,

local curvature and the angle between adjacent tangents were not used as independent criteria for determining the breakpoint.

Measurement repeatability and accuracy assessment

To evaluate the sensitivity of the pile geometry to the mass of the investigated material, a series of laboratory experiments were carried out using the previously described experimental setup. The tests were conducted under strictly fixed conditions: in particular, a ground steel substrate was used as a contact surface, and the sand feed tube was travelled at a speed of 0.05 m/s. The only variable parameter was the mass of sand poured into the tube, with a range of suspensions from 0.5 to 20 grams.

Each suspension was investigated in five independent repetitions, which allowed not only determining the mean values of the slope angles (AoR_1 and AoR_2), but also evaluating the statistical reproducibility of the measurements. The results were analysed in terms of the formation of a double pile profile, changes in slope at the base and at the top, as well as the degree of variation characterising the metrological reliability of each mode. The dependencies obtained allowed identifying the zones with different types of behaviour: from an unstable pile with no fracture to a stable shape with a pronounced double-angle structure and further to saturation, at which the geometry stabilises.

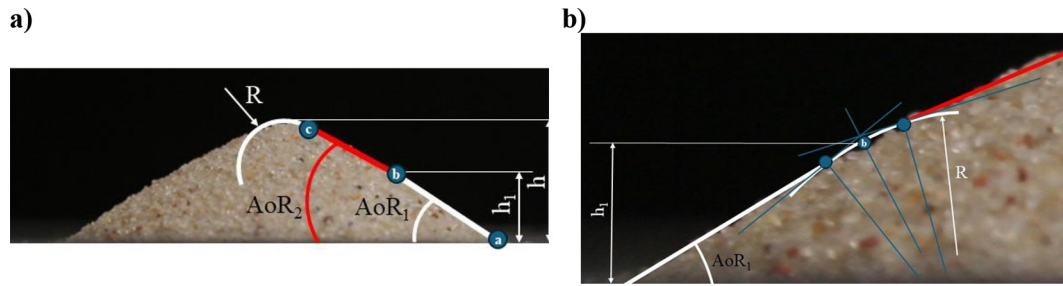


Figure 7. Image of the sand pile with characteristic dimensions (a) and geometric interpretation of the optimised breakpoint b^* separating the lower and upper linear profile segments (b)

These zones serve as a basis for the subsequent justification of the choice of the optimal mass for calibrating the DEM model parameters.

Analyses of the dependence of pile slope angles on the mass of the pile material are presented in Figures 8, 9. Figure 8 shows the values of angles at the base (AoR_1) and at the top of the cone (AoR_2) obtained from a series of experiments in the mass range from 0.5 to 5 g. For each case the scatter intervals (min-max) characterising the reproducibility of measurements are also indicated. The graph is conventionally divided into three zones reflecting different modes of pile formation and associated geometry features.

In the first mass range values (mass < 1 g), a small and almost identical angle is observed along the entire length of the formation ($AoR_1 \approx AoR_2$), indicating the absence of a characteristic fracture. The pile in this regime is unstable: its top is eroded, its shape is flat, and the angles show increased dispersion. This indicates the dominance of random fluctuations due to both local collisions and the influence of substrate microtopography. With all the potential for high sensitivity, this mode is characterised by insufficient reproducibility,

which significantly limits its practical applicability as a basis for reliable calibration.

In the second mass range values (from 1 to 3 g), the formation of a stable conical pile with a characteristic two-angle geometry begins. The angles AoR_1 and AoR_2 begin to differ significantly (up to $\sim 6^\circ$), while the spread at each angle decreases and the shape of the pile becomes reproducible. This state can be considered as the most sensitive to variations in DEM parameters - including particle-substrate friction, rolling resistance, and damping. In this mass range values, despite the remaining influence of initial conditions, it is already possible to reliably separate effects related to specific model parameters from random noise. This regime should be considered as the most promising from the point of view of geometrically reasonable calibration.

In the third mass range values (mass > 3 g), the difference between AoR_1 and AoR_2 gradually levelled out, the angles reached a plateau, and the dependence curve became asymptotic. The spread decreases to a minimum, but at the same time, the sensitivity of the system decreases. The pile profile stabilises, losing geometric features

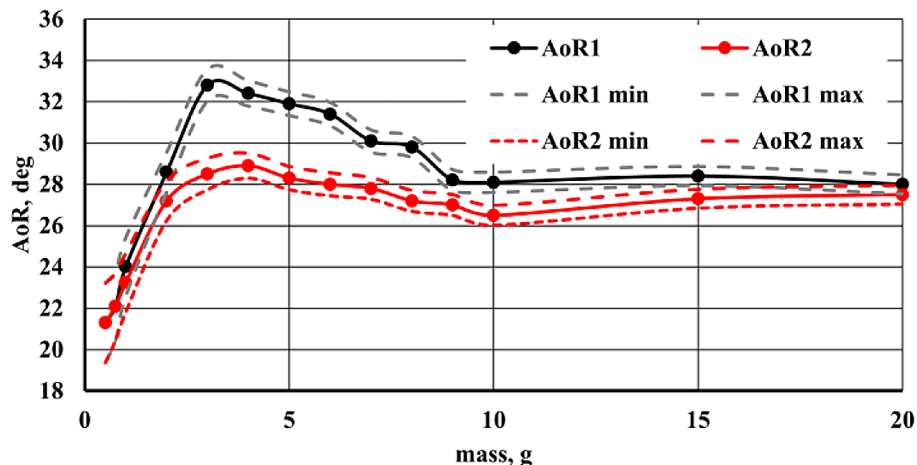


Figure 8. Variation of AoR_1 and AoR_2 angles depending on the mass of the bulk material

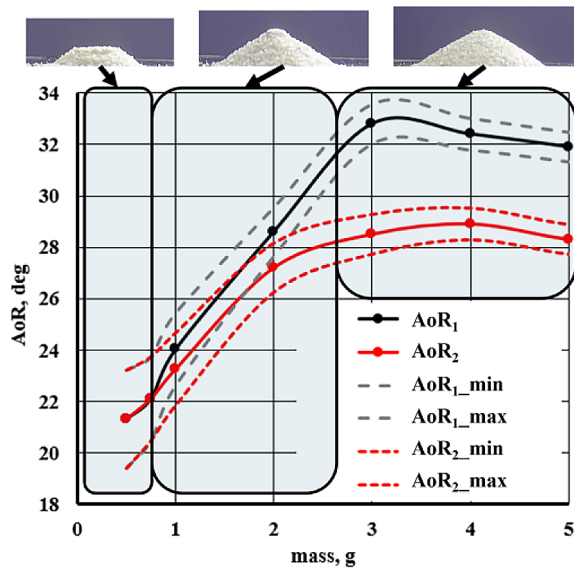


Figure 9. Variation of AoR₁ and AoR₂ angles as a function of the mass of the bulk material between 0.5 and 5 grams

sensitive to changes in the contact model. This mode is well-suited for verification tasks, but is not sufficiently informative for the purpose of initial calibration of DEM parameters.

Thus, the data presented in Figure 9 confirm that the choice of bulk material mass has a key influence on the nature of the pile geometry, its sensitivity, and reproducibility. A mass in the range of 2–3 g appears to be the most productive from the point of view of model calibration, providing sufficient profile fracture and acceptable stability of results.

Starting from 5 g, both angles begin to gradually level off (Figure 4), and at a mass >10 g a plateau is observed: the values of AoR₁ and AoR₂ stabilise at ~28°, i.e., the conical shape of the mound becomes almost uniform.

Figure 10 shows the reproducibility assessment of the bulk geometry expressed through the standard deviation of the angle AoR₁ calculated from five repeated experiments for each material weighting. On the ordinate axis is plotted the deviation (in degrees), and on the abscissa axis is the mass of the bulk sand.

The graph has a typically decreasing character: at small weights (0.5–1 g) the repeatability is minimal, with a deviation exceeding 3.5°, indicating the dominance of fluctuating factors such as random collisions, microshifts, and initial particle distribution. With increasing mass, the reproducibility increases markedly: starting from 3–4 g, the measurement error AoR₁ drops below

1.5°, and at masses above 7–8 g it stabilises at around 1°. Thus, the graph reflects the characteristic transition from unstable to stable pile shape.

The results of the bulk morphology analysis show that a mass of 3 g represents a reasonable compromise between the sensitivity of the bulk geometry and the reproducibility of the experiment. In this range:

- the maximum difference between the angles AoR₁ and AoR₂ is recorded, indicating a pronounced two-angle structure of the pile;
- the pile already forms a stable top, which makes it possible to use the profile as a calibration feature;
- the mean square deviation of the angles is ~1.2°, which is a relatively high value, especially compared to heavier piles.

This fact requires critical evaluation. On the one hand, a high error value can be seen as undesirable from the point of view of metrological accuracy. On the other hand – and this is important to emphasise – such an error is a consequence of the high sensitivity of the bulk profile to interaction parameters, including substrate properties, friction, and microscopic fluctuations. It is sensitivity, not stability, that is the target property in this case, as it allows reliably distinguishing the contribution of different factors.

Thus, the choice of the 3 g mass as the primary mass for calibration is a conscious compromise. It provides sufficient geometric complexity of the profile (double angle), moderate reproducibility, and high sensitivity needed to fine-tune the interaction parameters in the DEM.

Additionally, it should be noted that an increase in mass, although it reduces the variance, leads to a

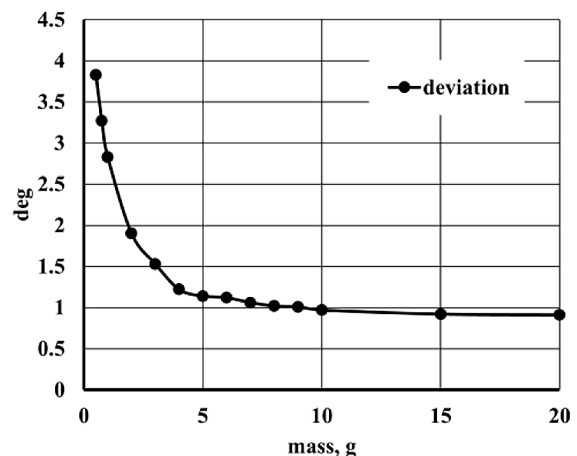


Figure 10. RMS deviation of the angle AoR₁ as a function of the mass of the material suspension

smoothing of the profile and loss of diagnostic features, as well as a significant increase in the computational cost of numerical modelling.

Methodology for adaptive parametric calibration of the DEM model using intelligent point selection

In order to interpret the experimental relationships and to proceed to a quantitative calibration of the DEM parameters, additional numerical calculations were performed using Altair EDEM software, on a generated sample of 128 points (Figure 11).

In order to systematically and reproducibly calibrate particle-substrate interaction parameters in a DEM, a hybrid approach combining numerical modelling, experimental data and machine learning is proposed. The method includes the following steps:

1. Training sample generation of a set of trial vectors of DEM parameters is performed. In this paper, 128 design points were used, covering acceptable ranges of 10 model parameters, with emphasis on particle-substrate interaction parameters. For each parameter vector, the geometric characteristics of the pile – slope angles AoR_1 and AoR_2 , height and top radius – were calculated using DEM modelling.
2. Comparison with experiment (by Ra), based on the experimental data linking the base roughness (Ra) to the angles AoR_1 and AoR_2 , for each Ra the closest design vector out of 128

trial vectors is selected. The fitting metric is the total deviation at both pile's angles. These matched vectors were further used as reference points to verify the surrogate model.

3. Sensitivity and correlation analyses – before training the model, quantitative analyses were performed:
 - correlation coefficients between parameters and slope angles;
 - visualisation of correlations (heat maps, scatter diagrams);
 - selection of key features (in this paper - particle-substrate interaction parameters: friction_p-m, rolling friction p-m).
4. Training of the surrogate model – regression training of the substitutive model was performed (in the basic variant – linear regression). The target variables were the angles of inclination AoR_1 and AoR_2 . In order to improve accuracy, a pre-training strategy was used for reference points corresponding to known Ra values. This allows for high accuracy in the area relevant for further calibration and practical modelling.
5. Presentation of the surrogate model – was visualised as a response surface $AoR_1 = f(\text{friction_p-m, rolling friction p-m})$. Parameter selection can be performed for different Ra using the criterion of minimum deviation between predicted and experimental angles. The model can be used for generation of new design points, active learning and further automated calibration of DEM parameters.

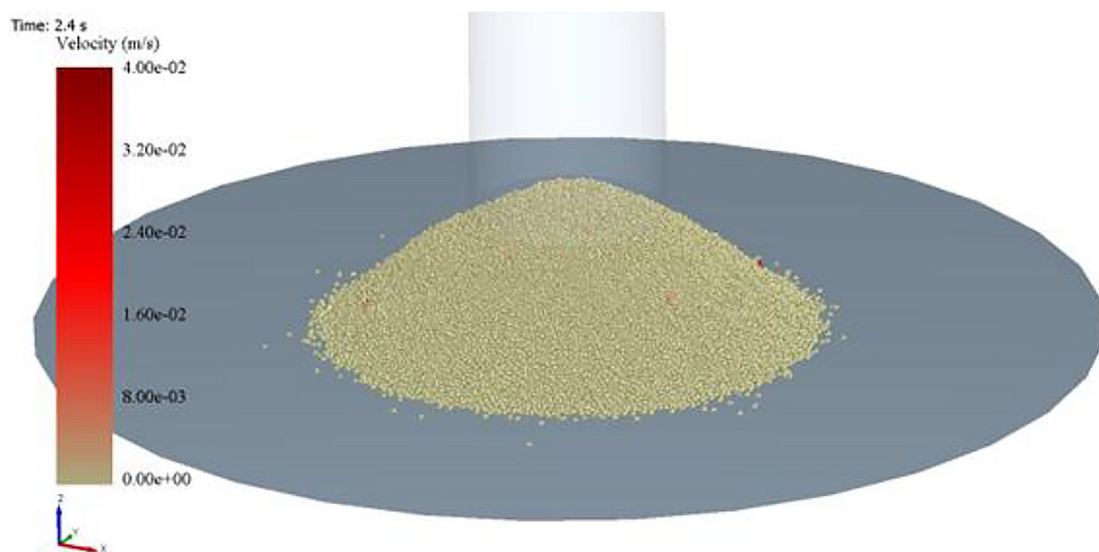


Figure 11. The pile model obtained from 3 g of sand

RESULTS

Analysing the effect of substrate roughness on the shape of sand mounds

Pile slope angles

In order to study the influence of the substrate surface condition on the shape of the granular material (sand) pile, laboratory experiments were conducted using substrates of different roughness. As substrates were used: glass ($R_a \approx 0.04 \mu\text{m}$), a polished metal plate, as well as abrasive sheets of different grain size. The roughness of the glass surface was measured with a Mitutoyo SurfTest profilometer in accordance with the standard ISO 1997, and the roughness of the other surfaces was measured with a Keyence VR 6000 optical profilometer. The surface roughness was quantitatively characterised by the parameter R_a in the range from 0.04 to 20.48 μm . The mass of material to be poured and the feed rate were kept constant in all series.

Figure 12 shows the results of measuring the slope angles of the pile formed when sand is poured onto substrates of different roughness. The angle at the base of the pile (labelled AoR_1) shows a pronounced dependence on the R_a parameter: from $\sim 30^\circ$ on a smooth surface (glass) to $\sim 40^\circ$ on rough sandpaper ($R_a \approx 20 \mu\text{m}$). This increase is explained by the increase in adhesion between sand grains and the substrate as the microrelief

increases, which prevents the particles from sliding near the base of the mound.

At the same time, the angle of the upper part of the pile (AoR_2), corresponding to the central “inner” cone, practically does not change at small values of R_a and is about $28\text{--}29^\circ$, which is close to the natural slope angle of dry sand. At R_a above $2.5 \mu\text{m}$, a smooth increase in AoR_2 is observed, but its value still remains significantly lower than AoR_1 . This suggests that there are two different modes of pile shaping sensitive to different types of interaction:

- The AoR_1 angle reflects mainly the particle-surface interaction,
- the AoR_2 angle depends more on particle-particle interactions.

This separation is important for calibrating the parameters of DEM models, allowing independent determination of friction and elasticity parameters between particles and between particles and substrate. To describe the empirical dependences of the pile slope angle AoR_1 and AoR_2 on the substrate roughness parameter R_a , expressed in micrometres, a piecewise linear model was applied in the present work. Such a model allows reflecting the non-linear nature of the angle change at the transition between different ranges of roughness, while maintaining interpretability and suitability for use in calculation algorithms.

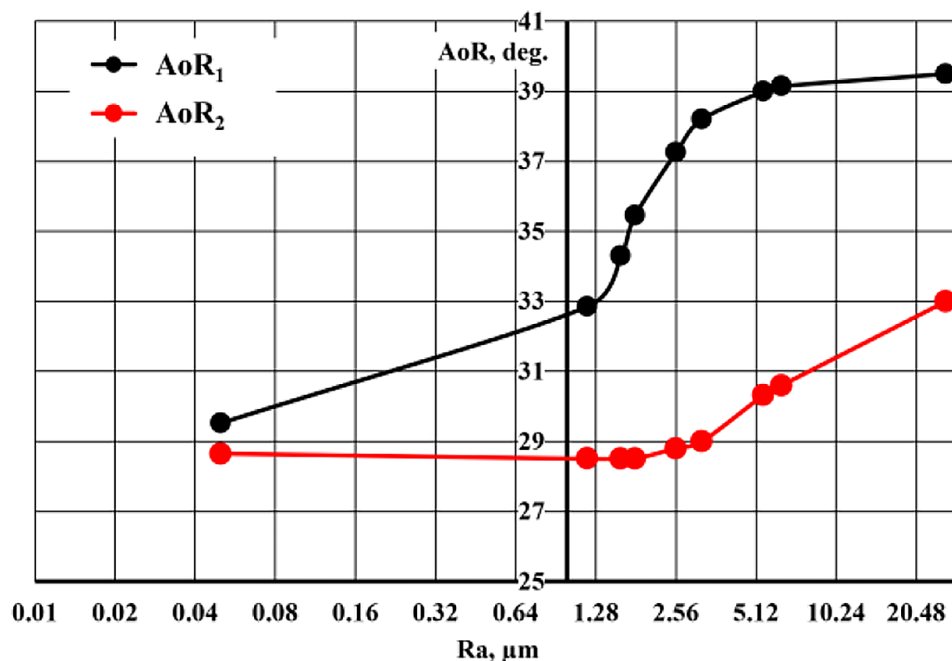


Figure 12. Change of the angles of repose AoR_1 , AoR_2 , depending on the roughness of the substrate surface

Formally, the dependence has the following form $AoR_i = k_i \cdot Ra + b_i$ where k_i and b_i are coefficients determined by the method of least squares on the basis of pairs of experimental points $(Ra_{(i)}, AoR_{i(i)})$.

Each segment of the model corresponds to a local roughness range as follows:

$$AoR_1(Ra) = \begin{cases} 2.92 \cdot Ra + 29.37, & \text{for } Ra \in [0.05, 1.28] \\ 2.41 \cdot Ra + 30.47, & \text{for } Ra \in [1.28, 3.21] \\ 0.056 \cdot Ra + 38.02, & \text{for } Ra > 3.21 \end{cases} \quad (1)$$

$$AoR_2(Ra) = \begin{cases} 28.66, & \text{for } Ra \leq 1.8 \\ 0.31 \cdot Ra + 27.53, & \text{for } Ra > 1.8 \end{cases} \quad (2)$$

This approach allows applying these dependencies both in direct calculations of DEM model parameters and in their calibration procedures, including the construction of surrogate models.

Pile height parameters

Figure 13 shows the dependences of the heights of three characteristic pile sections on the substrate roughness:

- h_1 – height of the lower part of the pile (truncated cone),
- h_2 – height of the upper central cone of the pile,
- h – total height of the pile.

The total height of the pile (h) varies insignificantly and is within 14.5–16 mm over the whole range of Ra , which confirms the equal mass of bulk material in each series. However, the behaviour of the components h_1 and h_2 has a pronounced heterogeneous character:

- At low values of Ra ($\leq 0.64 \mu\text{m}$), the lower part of the bulk dominates: h_1 reaches 10–11 mm, while h_2 remains within 3–4 mm.
- In the interval $Ra \approx 1.28$ – $2.56 \mu\text{m}$, a transitional regime is observed, accompanied by a sharp redistribution of height from h_1 to h_2 .
- At $Ra \geq 5 \mu\text{m}$, the height of the lower part stabilises at ~ 3 mm, whereas the upper part increases to 10–11 mm.

These data confirm the presence of a morphological rearrangement of the mound shape with increasing substrate roughness: on a smooth surface, particles readily move towards the periphery, forming a wide and flat base, whereas on a rough surface they brake near the center, contributing to the formation of a compact and high inner cone.

Search for confirmation of the different shear conditions of the sand layer depending on the roughness of the substrate

The results of the pile formation experiments indicated a two-zone cone structure, with

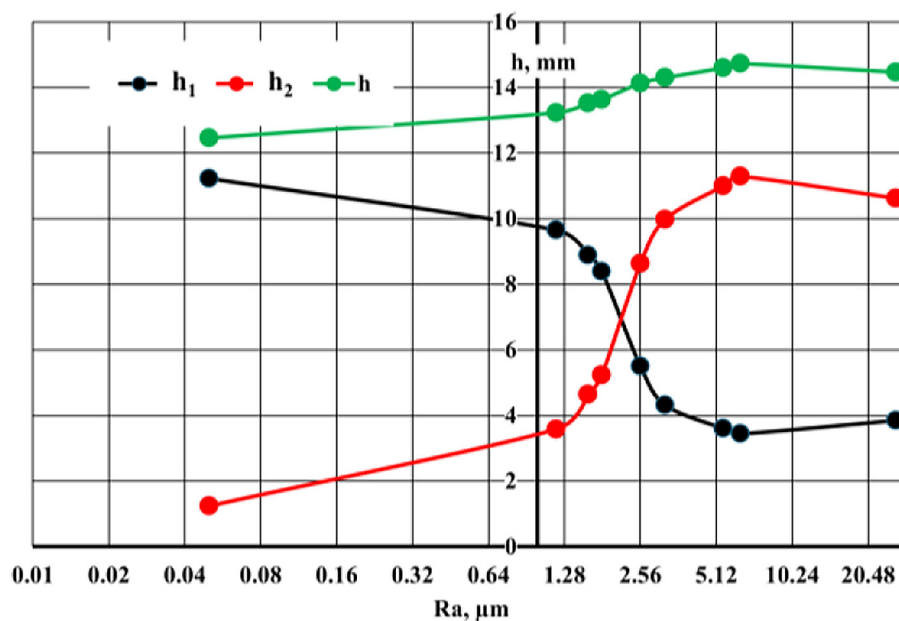


Figure 13. Change of height h_1 , h_2 , and h depending on the roughness Ra of the substrate surface

the lower zone forming at the base showing the highest sensitivity to changes in substrate roughness. As the substrate roughness increased, the propagation of particles in the zone located near the base slowed down, leading to the accumulation of material at the base and inducing changes in the profile geometry. As this observation is geometrical in nature, a natural question arises as to whether the influence of the substrate is also registerable in an independent force test, in which the response of the medium is measured directly through the shear response of the layer. To test this, an additional series of shear tests was performed on a thin layer of dry sand.

Experimental setup and procedure

Shear experiments were conducted using a linear motion test rig (Figure 14), where the supporting surface (1) performs a controlled reciprocating motion, while the force sensor (3) is fixed and stationary to a rigid support. Granular material (2) was placed on surface (1), and contact with the sensor was established via the sensor's elastic element – a full-bridge strain gauge load cell (bending beam). The signal from the bridge was amplified and conditioned by the measurement electronics module (4), while the data recording was handled by the acquisition system (5). During the relative motion of surface (1), the sand layer acts upon sensor (3), causing an elastic deflection

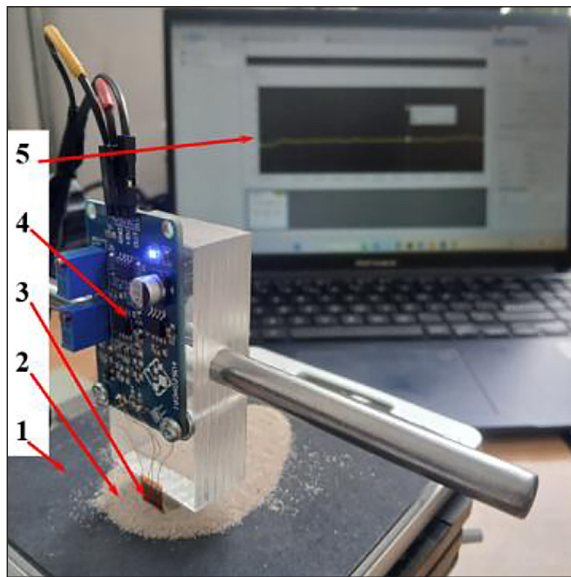


Figure 14. Test rig photograph: 1 – supporting surface (platform), 2 – granular material (sand), 3 – strain gauge bridge, 4 – sensor transducer (signal conditioner), 5 – raw signal

of the beam. This deflection was interpreted as the instantaneous shear force, corresponding to the resistance of the layer's displacement in the direction of the platform's motion.

The working motion was executed as a displacement of 5 mm over a duration of 10 s, corresponding to an average velocity of 0.5 mm/s. The voltage signal $V(t)$ was recorded at a sampling frequency of 1000 Hz. Conversion to force was performed using a constant calibration factor, with the sensor configuration, ambient temperature, and measurement path remaining unchanged across all test series.

The experimental plan included three dry sand layer thicknesses ($H=2, 4$, and 6 mm) and a set of substrates with varying roughness, ranging from smooth surfaces (glass, metal) to sandpapers of different grits. For each combination of substrate type and layer thickness, six independent measurements were performed. After synchronisation relative to the initial contact point t_{on} and zero-level correction using the baseline method (B), an average shear force curve $\langle F(t) \rangle$ was determined for all repetitions. Consequently, response surfaces in the designated space $Ra'H$ were constructed based on 21 empirical points, each representing the average of six independent trials and corresponding to a single mean curve $\langle F(t) \rangle$.

Metrics and determination methods. Based on $\langle F(t) \rangle$, the shear stress $\tau(t)$ was determined by normalising it against the nominal shear area $A=b \cdot h_s$, where $b=8$ mm is the width of the sensor's working element and $h_s=0.7$ mm is the fixed immersion depth. The quasi-stationary level was defined as the mean value over the 2–10 s interval, i.e., $\tau_{dyn,mean} = \langle \tau(t) \rangle_{2-10s}$, which corresponds to the phase following the initial formation of the shear zone. The unit energy dissipation was determined as W/V_{shear} , where the work W was calculated for the 0–10 s interval, and the shear volume was assumed as $V_{shear} = A \cdot L$ with $L=5$ mm. The RMS (root mean square) fluctuation index was calculated for $\tau(t)$ within the 0.5–30 Hz band over the 0–10 s interval. This band-pass filtering was applied to isolate the relevant signal by removing low-frequency baseline drift and high-frequency measurement noise. The RMS metric served as a measure of dynamic activity and local contact structure rearrangements during shearing, acting as a complementary indicator sensitive to the stochastic nature of the process.

Response maps and results analysis. Based on the values of $\tau_{dyn,mean}$, e_v , and RMS determined at the

empirical nodes, response maps were constructed in the (R_a, H) coordinate system (Figure 15).

Interpolation was applied solely for the purpose of trend visualisation, whereas the conclusions are based on values measured at the 21 nodes corresponding to specific combinations of substrate and layer thickness. For all three metrics, a clear gradient is observed with increasing substrate roughness. This provides independent, stating that the substrate influences the sand's behaviour during the quasi-static sensor displacement.

At the same time, the dependence of the sand's behaviour on the distance from the substrate—defined by the layer thickness H —is nonlinear and exhibits a saturation trend. The transition

from 2 to 4 mm typically causes a more significant change in response than the transition from 4 to 6 mm. This is consistent with the shift from a regime of cone formation strongly controlled by boundary conditions to a regime with a greater contribution of “sand-to-sand” interactions.

The metrics $\tau_{\text{dyn,mean}}$ and e_v show consistent trends, indicating the internal consistency of the measured resistance levels and process energetics. Meanwhile, RMS maintains the same direction of change but with lower contrast, which is expected given the stochastic nature of fluctuations in granular media. Consequently, the additional shear test reinforces the study's primary conclusion: substrate properties constitute

Final polished surfaces and contour maps (view B)

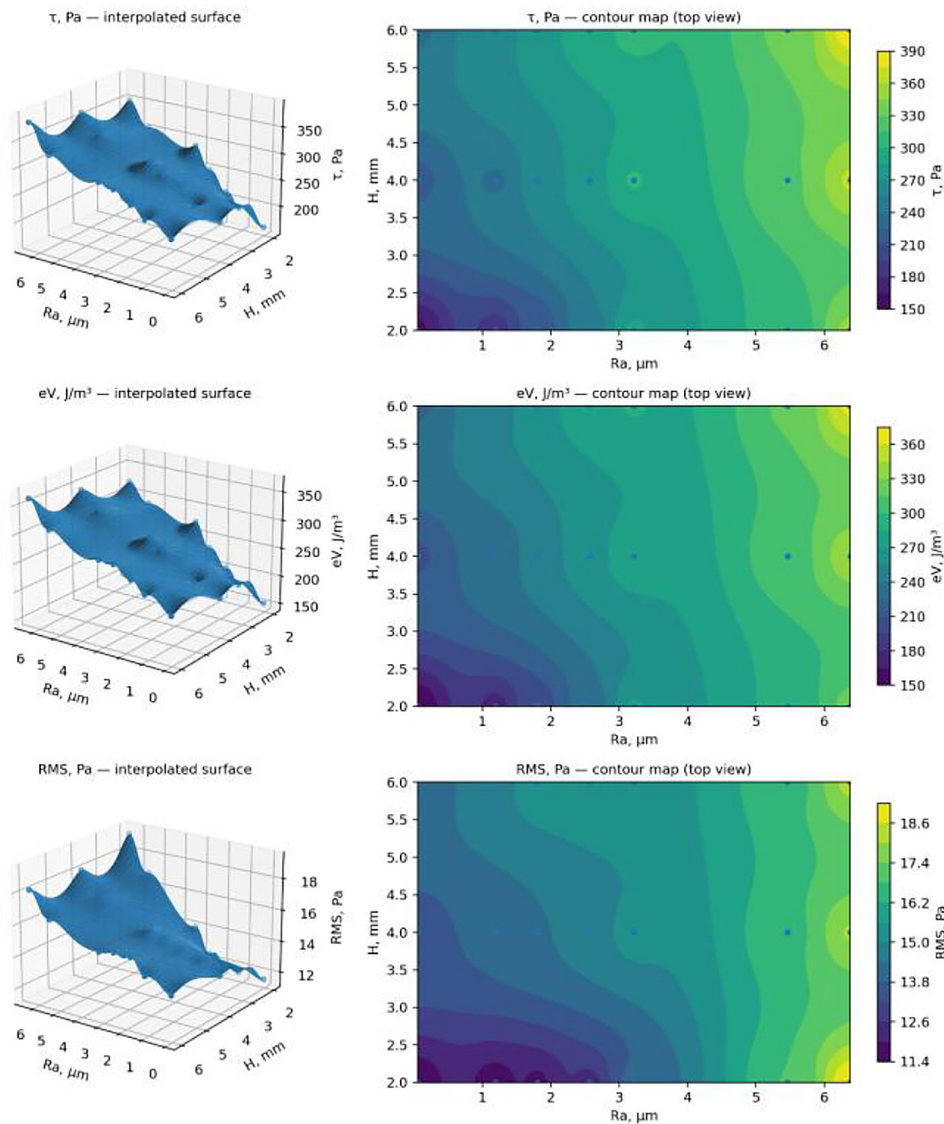


Figure 15. Interpolated response surfaces and contour maps (top view) for tangential stress τ , unit interaction energy e_v , and signal RMS characteristics in the (R_a, H) coordinate system

an independent factor shaping the motion and redistribution conditions of dry sand, and the observed sensitivity is neither an artefact of a single procedure nor solely the result of the pile's geometric analysis.

Influence of substrate on the pile forming process

The separation of the sand pile shape into two clearly distinguishable regions - with different slope angles and formation dynamics - demonstrates the complex influence of the substrate on the macroscopic morphology of the bulk material. This observation confirms that for sand as a granular medium, the interaction with the substrate is not limited to initial conditions, but has a sustained influence on the entire process of pile formation (Figure 16).

The experimentally confirmed hypothesis, is the assumption of independence of the slope angles: theoretically, they could coincide only if the interactions with the substrate are excluded, for example, when pouring on a smooth and wetted surface. However, in this case, additional physical phenomena (capillary bridges, cohesion) come into play, which violates the purity of the calibration experiment for DEM.

Thus, the proposed approach allows using experimental data not only for physical understanding of the pile formation process, but also as a calibration tool for DEM models, allowing separately accounting for the coefficients:

- particle-particle friction (by top angle and h_2),
- particle-surface friction (bottom corner and h_1).

Role of dynamic conditions and kinetic factors

The previously presented results show that when the substrate roughness is changed, the shape of the sand pile changes significantly: the lower angle of repose (AoR_1) increases, the upper angle (AoR_2) responds only weakly, while the height distribution also shows morphological rearrangement. However, it was observed that even when using identical surfaces in terms of material (in particular, glass as both the substrate and the inner surface of the guide tube), the AoR_1 and AoR_2 angles did not coincide. This observation confirms the presence of an additional influencing factor besides the material and roughness - the dynamic component of the pile formation process.

Indeed, when passing along the inclined surface of the tube, the particles receive additional kinetic energy, in addition to potential (gravitational) energy, as a result of accelerated motion along the smooth surface. After leaving the tube and interacting with the stationary substrate, the energy of these particles already affects their ability to move along the pile and form the central part of the pile's cone. Thus, the upper zone of the mound (AoR_2) is formed under different conditions than the lower one (AoR_1), even if both layers touch the same material. This naturally leads to angle mismatch and separation of the pile shape.

Based on these observations, it can be assumed that under certain conditions, it is possible to achieve the inequality $AoR_1 < AoR_2$, which is rare for dry bulk materials. To realise such an effect it is necessary to:

- either to increase the feed rate and, consequently, the kinetic energy of sand grains;
- or use a surface with viscoelastic properties, e.g., a slightly wet surface simulating a non-Newtonian fluid.

Thus, the observation made has significant implications for numerical modelling. It shows that particle-surface interaction coefficients must be considered not only as a function of material, but also as a function of kinematic conditions such as feed rate, angle of incidence, and the presence of relative motion. When constructing DEM models, the same parameters for a moving and a resting surface cannot be directly used,

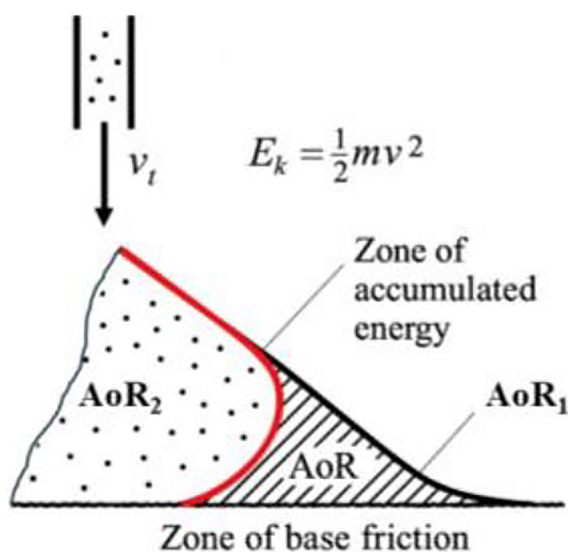


Figure 16. Scheme of interpretation - how AoR_1 is related to particle-surface friction, and AoR_2 is related to particle-particle friction

even if they are identical in chemical nature. This approach will increase the accuracy and verifiability of the models, especially in tasks sensitive to local dynamics, such as in dispensers, silos, or 3D printing with bulk materials.

Comparison with experiment (by Ra)

Table 2 presents the results of the search for the nearest by the main criteria trial points in the field of investigated surface roughnesses.

Sensitivity and correlation analyses

Evaluation of the influence of DEM parameters on the sand pile criteria

To evaluate the influence of the model parameters on the generated pile, a method of sensitivity analysis was used, using 128 points of the parametric space obtained by generating vectors using the Sobol method. For each point, the values of the slope angles of the first (AoR₁) and second (AoR₂) pile segments, the base and top heights (h₁ and h₂), and the rounding radius of

the pile top (R) were calculated. Ten parameters of DEM interactions were investigated: particle mechanical characteristics and coefficients of particle-particle and particle-surface interactions. All parameters were varied within the following limits: - $\pm 10\%$ for particle-particle parameters, - $\pm 50\%$ for particle-surface parameters.

Sensitivity analyses conclusion

The analysis shows that:

- Parameters responsible for interaction with a flat surface (friction, recovery, rolling) are maximally important.
- Parameters related to interparticle interaction as well as material properties have almost no influence on cone formation and slope angles.
- The Spearman method allowed further clarifying the presence of possible nonlinear dependencies, confirming the dominance of p-m parameters (Figure 17).

This analysis justifies the priority choice of parameters for DEM model calibration and simplifies the optimisation procedure. In the future,

Table 2. Results criteria trial points in the field of investigated surface roughnesses

Ra, μm	Results of experiment		Results of simulation		Best_Point	Error, %
	AoR ₁ , deg	AoR ₂ , deg	AoR ₁ , deg	AoR ₂ , deg		
26.40	39.50	33.00	40	33	17	-1.27
6.38	39.15	30.60	39	31	106	0.38
5.46	39.00	29.00	39	30	24	0.00
3.21	38.20	28.80	38	29	35	0.52
2.56	37.25	28.50	38	29	35	-2.01
1.80	35.45	28.50	35	29	120	1.27
1.59	34.30	28.50	35	29	120	-2.04
1.19	32.85	28.50	33	28	9	-0.46
0.05	29.52	28.65	29	29	70	1.76

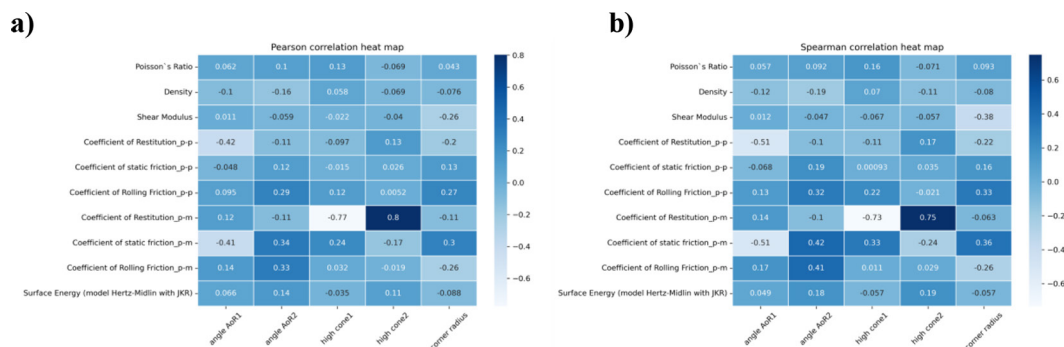


Figure 17. Spearman (a), Pearson (b) Correlation between DEM parameters and experimental criteria

it can be used as a basis for building surrogate models or active planning of experiments.

Independent validation of the DEM model based on the results of the shear experiment

After determining a set of DEM parameters based on the results of the main calibration procedure, additional modelling was carried out for an independent shear experiment on a thin layer of sand (Figure 18), under the experimental conditions described above.

A 2 mm thick layer was selected for the analysis, as this is where the influence of the substrate is most pronounced. Two extreme surface variants were considered: a smooth surface ($R_a = 1.19 \mu\text{m}$) and a rough surface with the maximum roughness under investigation ($R_a = 6.38 \mu\text{m}$).

This choice made it possible to verify whether the model reproduces the difference between the most contrasting boundary conditions without additional parameter tuning.

Figure 19 shows a comparison of the experimental and calculated dependencies of shear force on time. In all calculations, the same set of parameters was used, which had previously been obtained from the results of calibration based on the pile formation experiment. The results show that the model correctly reproduces the main experimental trend. For the rough $R_a = 6.38 \mu\text{m}$ surface, a higher level of shear force is observed in both the experiment and the calculation than for glass. Thus, the model accurately captures both the direction of the substrate's influence and the relative position of the curves for the two cases under consideration.

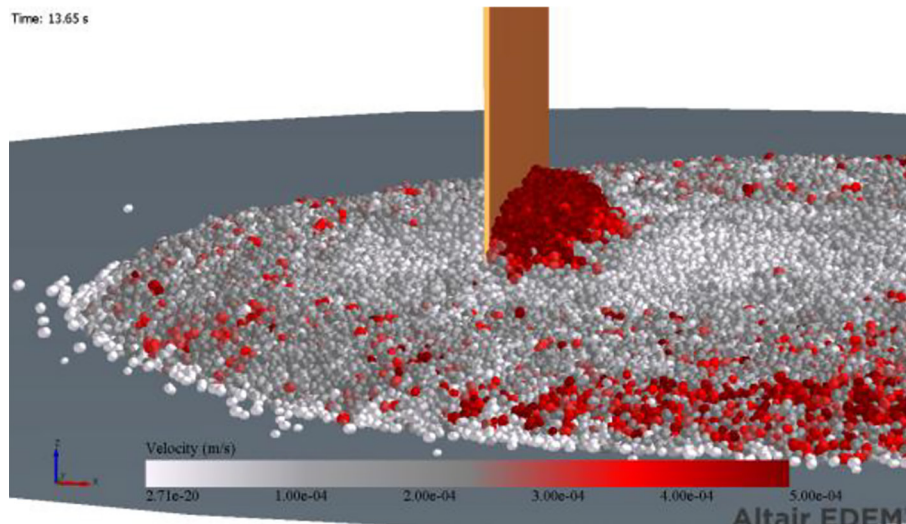


Figure 18. Snapshot of particle velocity distribution in the DEM simulation of 2 mm sand-layer shearing. The color scale represents the particle velocity magnitude

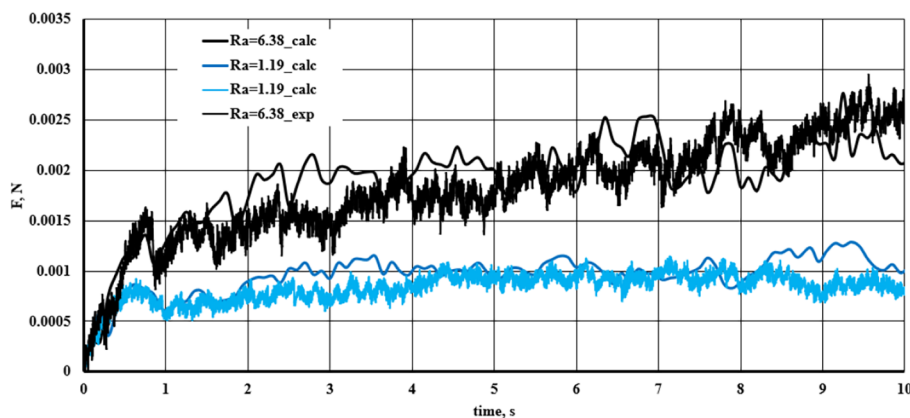


Figure 19. Experimental and calculated time-dependent shear force curves for a 2 mm-thick layer of sand on a smooth surface $R_a = 1.19 \mu\text{m}$, and a $R_a = 6.38 \mu\text{m}$ surface

A complete match between the experimental and calculated dependencies should not be expected. The virtual experiment does not fully replicate the actual measurement setup: the oscillations of the experimental signal in Figure 18 are associated not only with the rearrangement of the contact structure of the granular layer, but also with the elastically deformed state of the force sensor and the elements of the measurement assembly. This component was not taken into account in the DEM model, so the calculated signal does not contain the corresponding oscillations. For this reason, unfiltered experimental signals were used for comparison, and the main focus was on the overall force level, the nature of the response variation, and the difference between smooth and rough surfaces.

The resulting surrogate was used as a surrogate for the DEM block when searching for optimal parameters within the numerical optimiser. Due to the significantly shorter computation time (less than 0.01 sec per point), the search for the global minimum on the target function (error between model and experimental values) was possible in a reasonable time. Special attention was paid to the interpretability of the results. Based on the surrogate model, it was possible to identify the key parameters affecting the shape of the pile, as well as the parameter regions corresponding to the experimental slope angles and heights.

CLOSING REMARKS

The results obtained in the course of the study demonstrate that the traditional strategy of increasing the mass of the material to stabilise the slope angle is accompanied by a significant decrease in the sensitivity of the pile profile to key contact interactions. At the same time, it is the particle-substrate interaction parameters (friction, adhesion, roughness) that play a decisive role in problems related to modelling abrasive wear, local loading, and boundary friction. Thus, the calibration strategy adopted in this work in the low-weight mode (sensitivity mode) represents a deliberate alternative to the existing approach.

Experimental data confirm that for masses of the order of 1–5 g, a stable sand pile shape can be achieved while maintaining a high sensitivity of slope angles and elevation parameters to changes in base roughness. This opens up the possibility of using the sand pile as a diagnostic tool for

calibrating DEM parameters, taking into account the separate contribution of particle-particle and particle-surface interactions. The presence of a double slope angle and the variation of pile morphology with height demonstrate that single-criterion calibration methods (e.g., AoR alone) are insufficient when building models for problems sensitive to local contact mechanics.

The use of a system with a controlled stepper drive and glass guide tube allowed for stable initial conditions and eliminated parasitic effects due to flow asymmetry or random material sticking. This level of reproducibility is a prerequisite when working in the mass limit region, where the bulk profile is particularly sensitive to fluctuations.

The shear test results confirm that the substrate's influence remains an independent factor: a consistent increase in mean dynamic shear stress $\tau_{\text{dyn,mean}}$ and unit interaction energy e_v is observed when transitioning from smooth substrates to rougher abrasive surfaces. This is generally accompanied by an increase in RMS, indicating enhanced contact “grip” and transient rearrangements within the shear zone. Simultaneously, the influence of layer thickness was revealed: for a constant sensor immersion depth h_s , increasing the layer thickness H leads to higher force and energy levels. This indicates an increased contribution of intergranular interactions and bulk material rearrangement as the active deformation zone moves further away from the substrate. In conclusion, these observations are consistent with the results obtained for sand piles: the substrate influences the sand's behaviour, but the extent of this influence depends on the layer geometry. As H increases, the contribution of the “sand-to-sand” mechanism grows, whereas at low H values, the “sand-to-substrate” boundary effects become more pronounced.

The dependencies obtained and the methodology for analysing the mound shape are applicable to the calibration of models aimed at numerical reproduction of abrasive wear, where the control of particle-surface contacts is critical. At the same time, the modelling is also economical: by using smaller volumes of material and, consequently, fewer particles in DEM calculations, the computational load is reduced without loss of accuracy.

The proposed method of contact parameter calibration via deposit geometry is directly applicable in modelling granular-induced wear and surface loading. The ability to extract effective friction and rolling resistance coefficients based

on macroscopic geometry provides a novel tool for setting up DEM-based tribological simulations. This is particularly relevant for modelling impact-induced wear, powder-based coating, or additive manufacturing processes.

Thus, the results of the work not only confirm the theoretical possibility of working on the “stability boundary”, but also demonstrate its applied value for accurate, reproducible, and resource-efficient calibration in DEM-modelling problems focused on friction and wear processes.

CONCLUSIONS

1. A series of experiments was carried out to form a mound cone on substrates of varying roughness under controlled feed conditions using a stepper drive and a glass guide tube. This ensured high reproducibility of the initial conditions and allowed excluding the influence of feeding as a source of variability of the mound shape.
2. The stable manifestation of double slope angle (AoR_1 , AoR_2) and morphological separation of the pile into a zone at the base and a central part were established. The dependence of the top geometry and height parameters on the substrate characteristics and formation conditions was recorded.
3. It was shown that reducing the mass of the bulk material to the level of 1–5 g allows increasing the sensitivity of morphological characteristics to the substrate parameters, while the reproducibility boundary is preserved. A critical mass zone was found, at which an optimal balance between the stability of the profile and its informativeness for calibration is achieved.
4. Analyses of particle motion at the exit of the guide tube show that the kinetic component contributes to the formation of AoR_2 . The angles AoR_1 and AoR_2 reflect different interaction mechanisms: with the substrate and between particles, respectively.
5. An additional thin sand layer shear test, analysed in (R_a , H) space, confirmed the simultaneous sensitivity of the response to substrate roughness and the nonlinear, saturating effect of layer thickness, which indicates the coexistence of boundary (grain–substrate) and bulk (grain–grain) mechanisms in shaping resistance and energy dissipation.
6. A correlation between the geometrical characteristics of the pile and key DEM parameters

was established: friction coefficients (μ_s , μ_w), cohesion (γ), and contact stiffness parameters. The pile profile can be used as a diagnostic tool to separately calibrate these interactions.

7. A preliminary calibration of the DEM model parameters has been carried out taking into account the multi-criteria approach. The use of slope angles and heights as calibration criteria improves the reproducibility of particle-surface contact, which is critical for modelling abrasion processes.
8. The results of an independent shear experiment, replicated in the DEM without any additional parameter adjustments, confirmed that the calibrated set of contact characteristics remains valid even under a different type of loading. The agreement obtained between the experiment and the calculation can be regarded as a partial validation of the model for a thin layer that is sensitive to substrate properties.
9. Recommendations on the choice of mass and types of substrates for calibration of DEM-models are formulated, providing sensitivity to microparameters while maintaining experimental stability.

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