THE AVALANCHING EFFECT: A CRUCIAL FACTOR IN DEM CALIBRATION AND GRANULAR MATERIAL BEHAVIOR

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ABSTRACT

This study introduces a novel method for measuring the angle of repose (AoR) in granular materials, focusing on the often-overlooked avalanching effect. Utilizing a unique autonomous sifting mechanism, high-resolution Raspberry Pi cameras, and advanced real-time analytics, the research provides a more accurate and dynamic understanding of AoR. The findings have significant implications for the calibration of Discrete Element Method (DEM) models and broader applications in geotechnical engineering and space exploration.

Key words: Angle of repose, Avalanching effect, DEM calibration.

1. INTRODUCTION

Discrete Element Method (DEM) serves as a cornerstone in the modeling of granular materials, particularly in applications like soil excavation. The DEM model's parameters need to be meticulously calibrated to reproduce experimental results accurately [5]. In terramechanical simulations, parameters such as the angle of repose (AoR) and shear strength are critical for predicting how granular materials behave under different conditions [1]. However, the complexities inherent in granular materials and the computational intensity of DEM simulations pose significant challenges to accurate modeling. In order to calibrate DEM models, various experiments can be used, namely:

- Angle of Repose (AoR) Test: Involves the pouring of granular material onto a flat surface to form a pile. The steepest angle at which the pile remains stable, known as the angle of repose, is measured.
- Shear Test: Used to measure the shear strength of the material [7].
- 3-Axis Test: Provides data on the three-dimensional stress-strain behavior of the soil.
- Blade cutting test: internal failure planes during dynamic loading with the use of Particle Image Velocitometry (PIV) [3].

An often overlooked factor in traditional AoR measurements is the avalanche effect. Neglected can result in inaccuracies in both the experimental AoR measurements and the calibrated DEM models, leading to flawed predictions and designs.

This paper aims to shed light on the impact of the avalanching effect on the AoR calculation. We introduce a unique experimental setup involving autonomous continuous sifting of the granular material, which allows for a more detailed analysis of the avalanching effect. By employing vision systems and computational methods, we offer a new paradigm in DEM calibration and granular material behavior analysis.

The introduction sets the stage for the rest of the paper, which will further delve into the methodology, results, and implications of our study.

2. ANGLE OF REPOSE TEST

The angle of repose test serves as a fundamental experiment in terramechanics and plays an integral role in various scientific domains, including geotechnical engineering, geology, and space exploration. The test measures the steepest angle at which a pile of granular material remains stable. This angle serves as an essential parameter in the calibration of Discrete Element Method (DEM) models.

The angle of repose test in this study involves a unique approach that employs an autonomous continuous sifting mechanism 1. Granular material is sifted through a funnel equipped with a stirrer, providing a variable flow rate due to cohesion and particle interlocking. The material forms a pile on a round plate placed directly below the funnel, under which a strain gauge is placed that records the weight. The angle of the pile is dynamically captured using a two-camera system. The pile outline is recorded in two perpendicular planes, providing a detailed visual

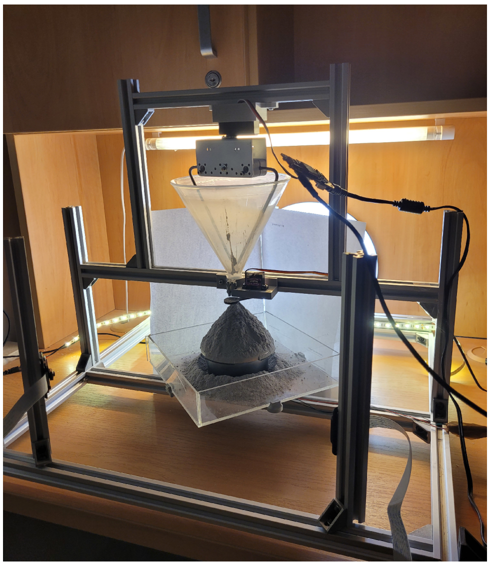

Figure 1. Dual camera experimental setup for recording avalanching effect.

record of the pile formation. The setup also involves a diffused backlight to ensure easier and sharper edge detection.

The avalanching effect, characterized by a rapid surface flow of a granular material down the slope of a pile, significantly influences the measurement of the static angle of repose. Moreover, the avalanching effect itself can provide additional data for comparison between the experiment and the simulation, beyond a single value. Avalanches manifest in various forms: they can be small-scale, affecting only the surface layer, or large-scale, influencing the entire pile structure. The effect is particularly pronounced in materials with variable sifting rates and cohesivity [6], such as the AGK2010 simulant used in this study.

The presence of avalanching introduces a dynamic element into the AoR measurement. Traditional methods of measuring the AoR often ignore this dynamic aspect, leading to inaccuracies in both the experimental and modeled data. In our experimental setup, the high-resolution camera system captures these avalanching events in real-time. This allows for a temporally-aligned analysis of how each avalanching event affects the AoR, thereby providing a more nuanced understanding of granular material behavior.

The avalanching events can either increase or decrease the AoR, depending on their scale and timing. Large-scale avalanches that redistribute significant amounts of material can lower the AoR, whereas small-scale avalanches may increase it - the angle is artificially larger as the avalanche is in upper part of the pile during the initial stage of the phenomenon. By capturing these dynamics, our study contributes to a more accurate and robust calibration of DEM models.

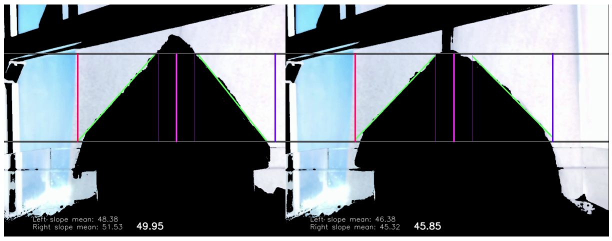

Figure 2. Before (left) and after (right) avalanche images from the vision system.

3. EXPERIMENTAL SETUP

3.1. Materials and Hardware

Experiments were conducted exclusively on AGK2010 simulant, chosen for its specific relevance to geotechnical applications and its cohesive properties that resemble the real world regolith and its availability.

To measure the angle of repose, a line is fitted to the contour of the granular pile using the M-estimator technique, which employs a Welsch function for distance measurement. This allows us to isolate and examine the steepest angle at which the pile remains stable. To minimize the impact of particle collision at the top and friction at the base, regions at least 10mm (10 times the particle size when using software with DEM models results) from the upper and lower extremities of the pile are excluded from the calculation along with the vertical region below funnel of 1.5 outlet's dimension. The overall dimensions of the experimental setup are build with accordance to a standard ISO [2].

The granular material was sifted through a funnel equipped with a servo-operated stirrer. The sifting rate was not consistent due to the cohesive nature of the AGK2010 simulant.

Real-time data synchronization between the strain gauge and the visual capture system was implemented to ensure temporal alignment of flow rate and visual data.

3.2. Hardware

- Test stand description (not too detailed as it is a scientific paper)

Two Raspberry Pi Module 3 cameras were calibrated with respect to the plate on which the granular material was dispensed. Lens imperfections were negated using a checkerboard calibration technique. The camera positions were further calibrated against a 3D-printed cone to negate perspective distortions.

A high-precision NA27 strain gauge, paired with an HX711 digital converter in 80Hz mode, was used for real-time weight measurement and subsequent flow rate calculation.

A 30 kg/cm serial bus servo actuated the stirrer, designed to manage the variable sifting rate and occasional clogging due to the cohesive nature of AGK2010.

An MQTT server with an HTTP interface was hosted to enable real-time control over the experiment, covering aspects like recording sessions and servo operations.

3.3. Software

For real-time control and system orchestration, a Message Queuing Telemetry Transport (MQTT) server with an HTTP interface was employed. This server facilitated on-the-fly modifications to the experiment parameters, such as servo speed and data recording sessions.

Custom software, developed in Python, interfaced with the Raspberry Pi cameras for real-time image capture. The software used OpenCV libraries for image preprocessing and calibration corrections, ensuring that lens distortions and perspective effects were minimized. It employed the M-estimator technique with a Welsch function for angle measurement. The algorithm was designed to capture avalanching events and their impact on the AoR in real-time.

Data from the strain gauge and HX711 converter were captured and processed using a dedicated software module. This software also implemented real-time synchronization with the image data, enabling temporally-aligned analyses of the AoR and avalanching effects.

The recorded time series was further analyzed using the Python, SciPy, and stattools libraries.

4. EXPERIMENTAL TESTS

A series of 20 experiments were conducted on the AGK2010 simulant. The data collected was further evaluated and used for statistical analysis. Correlation, spectral analysis, and basic descriptive statistics were calculated 6.

The spectral analysis has shown only a single peak converging at zero, which could imply that the time series is non-stationary, so its properties change over time. This thesis is confirmed by large p-values in Augmented Dickey-Fuller statistics.

5. DEM MODEL CALIBRATION

The experiment can be used as a more advanced way to calibrate DEM models [4]. It is important to pay attention to the avalanching effect, as incorrect measurements

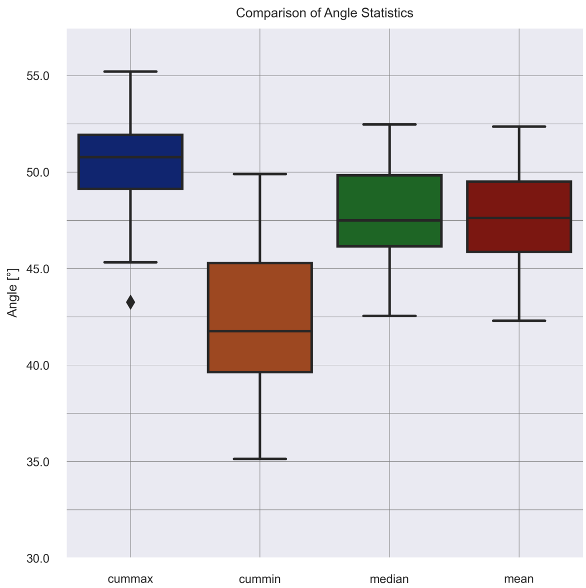

Figure 3. Basic Descriptive Statistics for AGK2010.

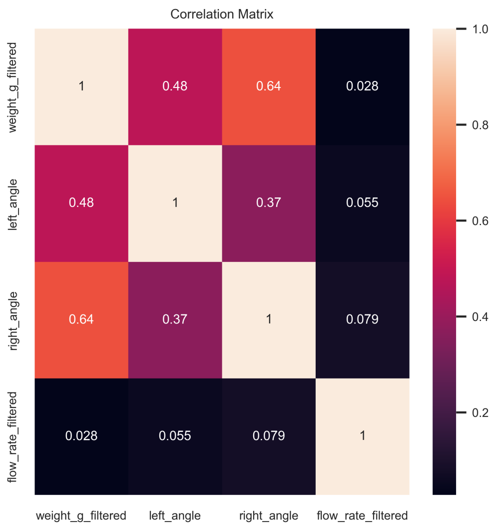

Figure 4. Correlation Matrix.

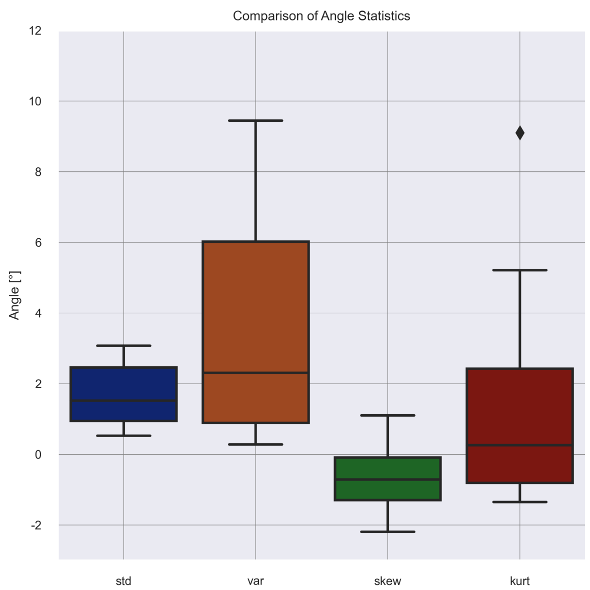

Figure 5. Basic Descriptive Statistics for AGK2010.

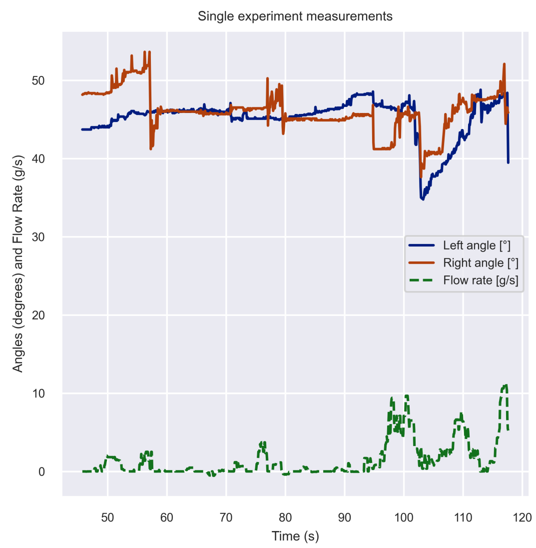

Figure 6. Sample experiment data.

can lead to large differences and discrepancies between each iteration of the experiment. Future research aims at implementing a variable outlet's flow rate DEM simulation that would be correlated with weight measurements from the experiment instead of the same funnel. Allowing for comparison of time series of an experiment with a simulation [10]. This approach provides many more parameters to monitor rather than a single AoR value. Furthermore, an experiment could be carried out on celestial body by a rover with a gripper that would pour simulant onto a pile, whilst registering data with a vision system equipped with a depth sensor.

6. CONCLUSIONS

The phenomenon of avalanching in granular materials has historically been underestimated in the measurement of the Angle of Repose (AoR), a crucial parameter for calibrating Discrete Element Method (DEM) models [8]. Avalanching introduces a temporal variability to the AoR, deviating from the traditional assumption that it remains static. Overlooking this dynamic aspect can result in inaccurately calibrated DEM models [9], undermining the fidelity of subsequent simulations. In extreme cases, the discrepancy between AoR measurements can reach 20°, although the average difference observed is approximately up to 9°.

Regarding the experimental setup, left and right cameras were operated independently but captured synchronous data. This dual-camera system not only reinforces the accuracy of AoR measurements but also opens the door for more advanced investigations, such as volumetric estimations of the granular pile.

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REFERENCES

[1] Elekes F., Parteli R., "An expression for the angle of repose of dry cohesive granular materials on Earth and in planetary environments", 2021, Proceedings of the National Academy of Sciences, 118, 38

[2] International Organization for Standardization, "Surface active agents — Powders and granules — Measurement of the angle of repose", 1977

[3] Just G.H., Smith K., Joy K.H., Roy M.J., "Parametric review of existing regolith excavation techniques for lunar In Situ Resource Utilisation (ISRU) and recommendations for future excavation experiments", 2020, Planetary and Space Science, 180, 104746

[4] Li C., Yin H., Wu C., Zhang Y., Zhang J., Wu Z., Wang W., Jia D., Guan S., Ren R., ”Calibration of the Discrete Element Method and Modeling of Shortening Experiments”, 2021, Frontiers in Earth Science, 9, 636512

[5] Liu T., Liang L., Zhao Y., Dengqing C., ”An alterable constitutive law of high-accuracy DEM model of lunar soil”, 2020, Advances in Space Research, 66, 1286-1302

[6] Wilkinson A., DeGennaro A., ”Digging and pushing lunar regolith: Classical soil mechanics and the forces needed for excavation and traction”, 2007, Journal of Terramechanics, 4, 133-152

[7] Karapiperis K., Marshall J., Andrade J., ”Reduced Gravity Effects on the Strength of Granular Matter: DEM Simulations versus Experiments”, 2020, Journal of Geotechnical and Geoenvironmental Engineering, 146, 06020005

[8] Zhu L., Zou M., Liu Y., Gao K., Su B., Qi Y., ”Measurement and calibration of DEM parameters of lunar soil simulant”, 2022, Acta Astronautica, 191, 169-177

[9] Xi B., Jiang M., Cui L., ”3D DEM analysis of soil excavation test on lunar regolith simulant”, 2021, Granular Matter, 23, 1

[10] Młynarczyk P., Kolusz A., Gallina A., ”Sensitivity analysis of the DEM model numerical parameters on the value of the angle of repose of lunar regolith analogs”, 2023, Artificial Satellites, 58, SI1 - 2023