EXPERIMENTAL TESTING AND NUMERICAL CALIBRATION OF THE REGOLITH SIMULANTS DISCRETE ELEMENT MODELS.
D. Pietrusiak[1], P. Moczko[1] , J. Wróbel[1], M. Pawłowski[1], M. Baranowicz[2]
[1]Wroclaw University of Science and Technology (Lukasiewicza 5, 50-370 Wroclaw, Poland; damian.pietrusiak@pwr.edu.pl), [2] White Raven Academy sp. z o.o. (Wystawowa 1/125 51-618 Wrocław, Poland)

Introduction:

Rapid increase of the space exploration, especially lunar exploration, brings to common engineering actions topics related to excavation and handling of extraterrestrial mineral. As a consequence, increase in demand on design and testing of the handling/excavation and general purpose equipment interacting with extraterrestrial "soils", rocks etc.is noticed. That poses a challenge to conventional engineering due to out-of-planet phenomena such as microgravity or the absence of an atmosphere, which affect electrostatics, heat exchange, and other factors, as well as operations under extreme temperature gradients. Experiments on large scale are difficult and expensive [1] However, a numerical approach can yield effective solutions .

When talking about the bulk and granular material simulations, Discrete Element Method (DEM) is the leading approach. As it is simulation environment, challenges like lack of the gravity becomes trivial.

On the other hand, valid behavior of the bulk and granular materials comes to play. It is the more challenging the more the scale of the interest is macro (excavation, conveying, scooping etc.) and the actual physical interaction of particles is on the micro scale (grains interaction of micron diameter). It becomes even more complex where the real shape of the material particles is highly irregular while the most effective computational particle is spherical.

To compromise between the actual micro-scale physics and useful macro scale application the computational effective macro/meso-scale numerical model have to be developed.

The main macro-scale parameters of the bulk and granular materials behavior is: static angle of repose, dynamic angle of repose and the external friction representing interaction between handled material and equipment used for that. The static angle of repose natural tendency of the material to create stable piles and is described by the angle created by the line, which can describe the created slope side, and the horizontal direction (Fig. 1.) The dynamic angle of repose is also angel which can be described as an angle between the line described the slope side and the horizontal direction, however in this case the slope stabilizes in the stable flow of the material (Fig. 2). One should notice, that while changing the flow parameters (for example RPM in case of drum test) the angle quantitative value will change. However, when the process parameters are changed, the qualitative flow regime can also shift—ranging from sliding and slipping to cascading and cataracting as the main motion types. Among these, the surging, slumping, and rolling subtypes of motion are considered most useful for determining the DAR [1].

Fig. 1 Static angle of repose – pipe test

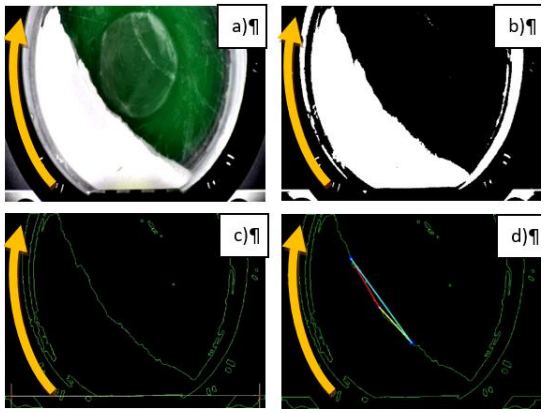

Fig. 2 Dynamic angle of repose – drum test with visual system for automatic measure

The so called angle of external friction represents the interaction of a bulk/granular material with handling equipment material. Figure 3 present a slope test at which the platform is inclined with low speed (targeting a quasi-static motion). The measurement is taken on the inclinometer while the bulk material, placed on the plate made of the specific construction material, slippage is observed.

Fig. 3 External friction angle/equipment interaction – platform test

Experiment and calibration:

On one hand, there are several parameters to measure and validate and on the other hand there are numerous of extraterrestrial mineral materials of different characteristics. Big interest in actual moment is around the lunar regolith which can be divided on to two main groups: Lunar Mare and Lunar Highland [3]. Figure 4 presents top view of a piles formed while determining the static angle of repose. The presented simulants differs mimicking the place of origin (mare/highland) as well as granulometric and mineral composition.

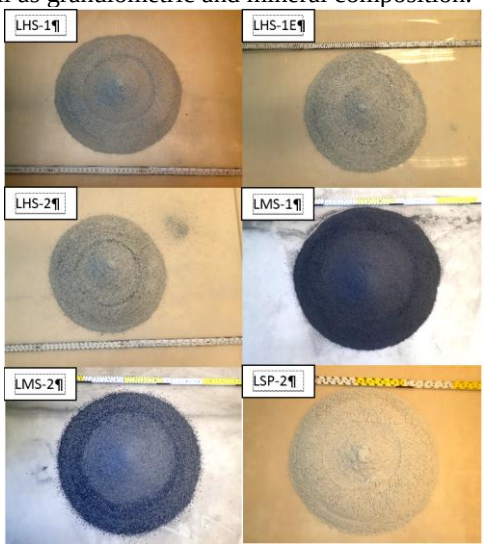

Fig. 4 Static angle of repose measurements

On the basis of each experimental test, with multiple parameters and trials, the averaged values are determined.

As the next step the set of numerical simulations is performed to obtained the experimentally validated data. One have to notice, that the model tuning is based on the modification parameters like static friction, rolling friction, particle size and shape which no longer represents the actual values but are tuned to obtain scaled meso/macro scale model where particles of micrometer size are substituted with particles of mm size giving this way computational efficiency. Figure 5 presents comparison of the experimental test and numerical model of great correlation.

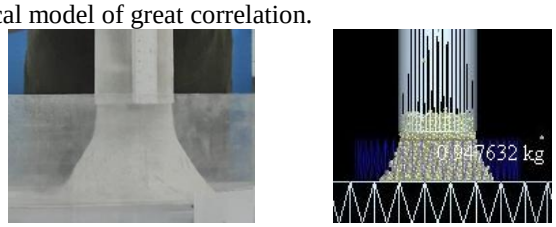

Fig. 5 Static angle of repose – model calibration(motion capture), left – real test, right - simulation

In purpose to obtain the highest quality models, all the experiments and numerical models calibration are supported by Design of Experiment (DoE) approach. It is a great alternative for common trial-and-error method or "one-factor-at-a-time" (OFAT) approach. When applying the DoE deepen the understanding of newly designed processes or products and to enhance existing ones.

Additionally, results of the experiment were put for the statistical investigation to double check the data credibility and identification of the variations of the factors indicating test/process character while changing factors.

When the granular material numerical model (DEM) is calibrated in terrestrial conditions, it can be used for further analysis with equipment and non-terrestrial physics.

Summary and conclusions:

Main advantages of the application for extraterrestrial bulk material handling:

- **easy gravity/no gravity adjustment**
- simple material (regolith etc) type change
- modeling material machine interaction: excavation, conveying etc
- possible to include physical phenomena of:
  - electrostatics/tribocharging
  - particles heat transfer
  - equipment wear
  - particles fracture/breakage
  - …

However, as a final remark it must be underlined that most of the available lunar regolith simulants are based on the Apollo mission processed samples, not representing the rough material which is present on the Moon surface [2][4]. When targeting the processing of raw regolith one should expect particles of μm up to cm size.

References:

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