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CONTACT PROPERTIES AND MODELLING OF BENTONITE PELLETS DISPLACEMENT FOR PLUGGING AND ABANDONMENT IN OFFSHORE OIL WELLS

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Abstract. *In recent years, oil and gas companies have been looking for alternative materials for plugging and abandonment (P&A) of wells. One of the emerging options is bentonite pellets, an expansive clay that, when in contact with water, forms a plug. This plug seems to make a more impermeable and environmentally safe barrier, with a much lower cost than the usual Portland cement. One of the multiple technical challenges in the offshore scenario is to pump vast amounts of bentonite pellets as a two-phase mixture with oil towards a plugging target, an environment that presents high temperatures and pressures. To that end, it is crucial to predict the solid-fluid interactions to avoid troubles such as excessive pressure drop or jamming. In the present work, contact models used in discrete element method (DEM) simulations are calibrated through a series of experimental routines. It is known that the montmorillonite, the major component of bentonite, does not expand in oil, which makes the granularity proprieties much more relevant to achieve accurate computational results. Therefore, three experiments widespread in the granular field are conducted, namely, inclined plane, pour angle of repose, and angle of repose with a cylinder. The first one measures the angle at which the displacement begins of a clay sample, thus obtaining the friction coefficient. The second consists of the angle of repose presented in a pile formed by the particles after pouring from a specific height. Finally, the third is the angle of repose obtained after the vertical displacement of a cylindrical recipient. This approach differs from the conventional granular studies since the immersing medium is diesel oil, while most investigations use air or water. With the experimental results in hand, it was possible to properly calibrate the many physical parameters from DEM and obtain a reliable numerical representation of the problem. The simulation results showed excellent agreement with the experimental test cases, allowing us to confidently develop horizontal granular flow studies in an efficient framework.*

Keywords: *Oil and gas well, Discrete element method, Bentonite pellets, Plugging and abandonment.*

1. INTRODUCTION

The plugging and abandonment process of oil and gas wells has received particular attention from companies and researchers that aim to reduce the process cost and raise its efficiency (Towler and Ehlers, 1997) (Towler *et al*., 2015) (Towler *et al*., 2016). The change of the traditionally used material, Portland cement, is a possible solution. One of the most prominent alternatives is bentonite, an expansive clay that presents the capability to expand when in contact with water. Swelling, its expansion may reach values larger than 1000% of the original size and a high level of adhesion with others surfaces, allowing the formation of a resistant plug inside the well (Komine and Ogata, 1996) (Romero *et al.*, 2005).

The enlargement of bentonite is caused by the swelling capability of Montmorillonite, one of its components. The water penetrates interlayer molecular spaces and increases its volume. On the other hand, when in contact with different fluids, the clay does not expand. Therefore, the usage of oils to transport bentonite pellets towards the desired region inside a pipeline is a plausible option since there is a low risk of obstruction caused by the non-swelling of the clay.

To properly control and understand this transport, CFD coupled with DEM simulations are an essential tool to predict the real process (Tan *et al.*, 2021) (Müller *et al.*, 2021) (Roessler and Katterfeld, 2018). Hence, accurate simulation results are essential and only obtained after properly calibrating the material properties when immersed in the fluid. This work concerns, therefore, in this calibrations process, analyzing experimental results with its numerical representation, achieving an accurate correlation.

For this purpose, three different tests, which are already widely applied in the study of particles, will be conducted experimentally to obtain the real behavior of the material-fluid interaction. Their simulation will properly represent them by using a CFD-DEM model and the input parameters will be calibrated to obtain a valid numerical methodology for the development of future flow simulations and their validations.

It is expected by the end of this work to define a simple and efficient methodology in the calibration of pellets immersed in fluids properties and accurate numerical representations for further research projects.

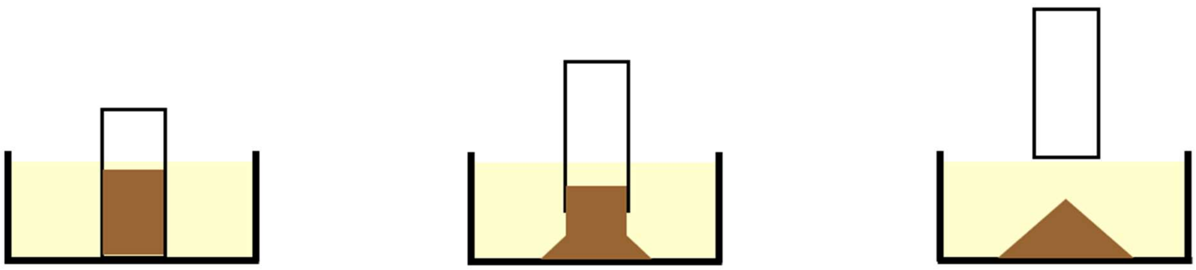
2. METHODOLOGY

In studying particles and their characteristics, multiple experiments can be performed to analyze and measure the properties and interactions between them (Beakawi Al-Hashemi and Al-Amoudi, 2018). They present great importance in predicting material behavior. Examples of its application are present in the transport of grains in silos or even in the pharmacological industry due to the handling of fine particles (Miura *et al.*, 1997).

For this calibration of the CFD-DEM model, it was used, therefore, 3 of these tests to obtain parameters that represent the reality of the phenomenon, namely Static Angle of Repose, Pour Angle of Repose, and Inclined Plane Test. The difference in our approach is that they were all conducted in a situation where the particles were immersed in Diesel, the oil used to transport them.

Diesel was chosen because of its rheological characteristics, representing the behavior of similar oils that may be used in real offshore applications. It is important to mention that it would be highly recommended to recalibrate the material properties and interactions for different kinds of fluids by performing new tests.

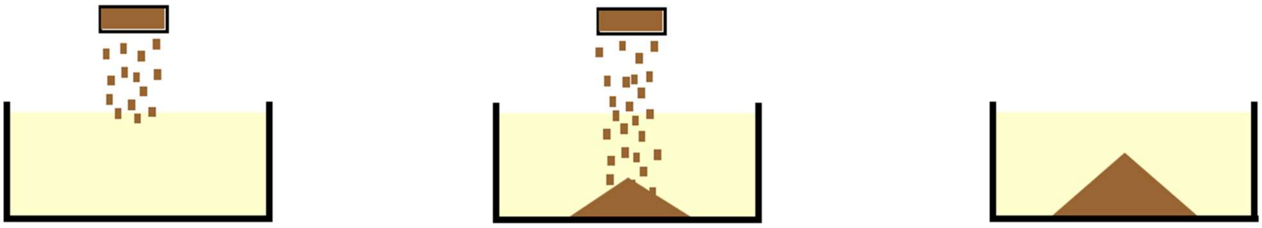
The static angle of repose test (SAOR) consists of removing a cylinder in which its interior is filled with particles. Adjusting a constant vertical speed, the cylinder raises while the particles form a pile. The average inclination of the pile is considered the angle of repose, representing their friction and cohesion. This procedure is represented by Fig. 1.



a) b) c)

Figure 1. SAOR schematics: a) the particles are inside the cylinder and also immersed in Diesel; b) the cylinder begins to raise and the pellets begin to form the pile; c) the pile is formed.

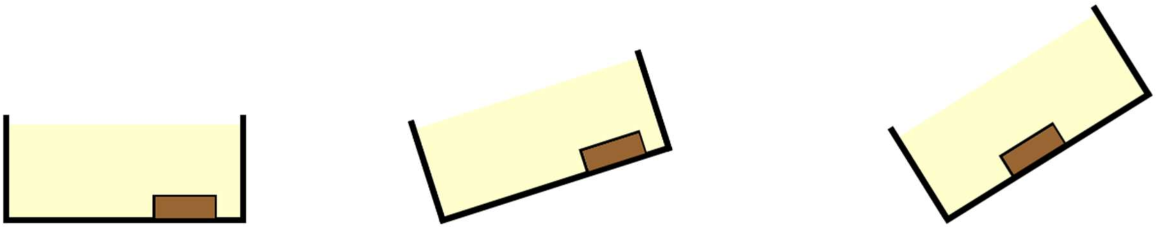
Secondly, the pour angle of the repose test (PAOR) drops the particles from a specific height through a round inlet. The particles reach the plane and form a pile. Just as the SAOR, the angle is an indication of such properties. The steps are presented in Fig. 2.



a) b) c)

Figure 2. PAOR schematics: a) the particles over the surface and begin to be poured; b) the pellets begin to form the pile; c) the pile is formed.

The inclined plane test (IPT) is frequently used in the determination of friction coefficient. In this application, the pellets will be placed inside a ring. The angle in that the ring begins to move is considered the angle of repose in this case, test represented in Fig. 3.



a) b) c)

Figure 3. IPT schematics: a) the particles are inside a cylindrical recipient immersed in Diesel; b) the platform begins to incline; c) the angle registered is the one when the cylinder begins to move.

To calibrate, a numerical representation of the experiments was performed by CFD-DEM simulations. Using ROCKY by ESSS it is possible to represent the effect of fluid in four different ways: Lattice Boltzmann Air Flow, Constant One Way, Fluent One Way Steady State, Fluent Two Way, being the last two coupled with Fluent by Ansys. For our application, the usage of Constant One Way is enough to achieve the desired results and save simulation time.

To allow the complete immersion of the pellets in oil, it was necessary to project and build different experimental devices. For both the SAOR and PAOR, the concept is a recipient to be filled by Diesel and that permits its drainage after the formation of the pile, to measure the angle with an angle meter. Finally, for the inclined plane, the goal is to adapt an already existing device for this measurement.

In general, the properties were calibrated for four different granulometry, so it would also be possible to notice the effect of the size in results. Simulations and tests were conducted in all four cases, amplifying our analysis and data basis range thereby achieving a better correlation.

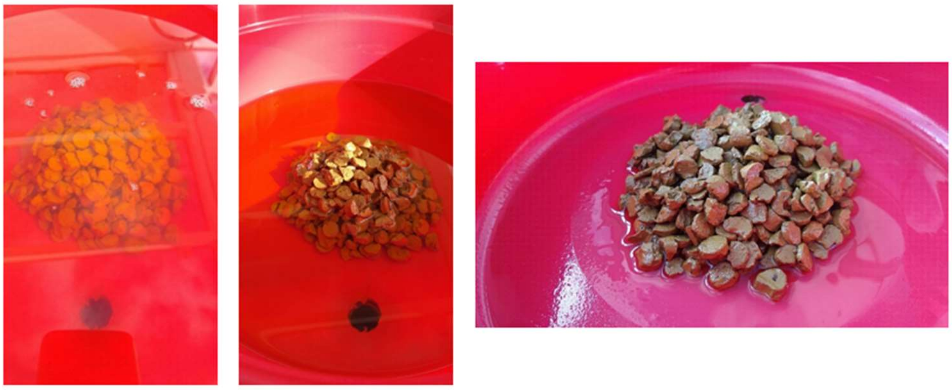
3. EXPERIMENTS

Experimental tests are the basis from which the simulations are calibrated. The procedures adopted here need to be standardized to set simulations correctly. Below is explained the methods, equipment and results obtained.

3.1 STATIC ANGLE OF REPOSE (SAOR)

After building the device, began the experimental analysis. The experiments were made for different particle sizes, but three times for each, always using the same volume of pellets. The recipient worked adequately and allowed the drainage of Diesel. Using a cylindrical tube made of acrylic and with an inner diameter of 52 mm, the pellets were placed inside it until they reached 100 mm. This was used as the volume control for all the tests and also for the simulations.

Tests were conducted three times for each size of particles, totalizing 12 runs. In Fig. 4 the experimental tests are shown and their results are in Fig. 5.



a) b) c)

Figure 4. Test procedures: a) the particles have already formed a pile after the movement of the cylinder; b) the Diesel begins to be drained; c) after the removal of Diesel it is possible to measure the angle.

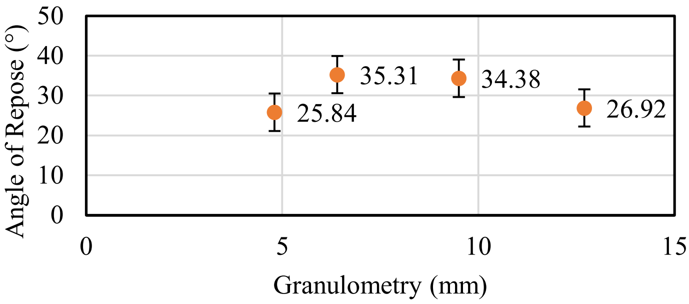
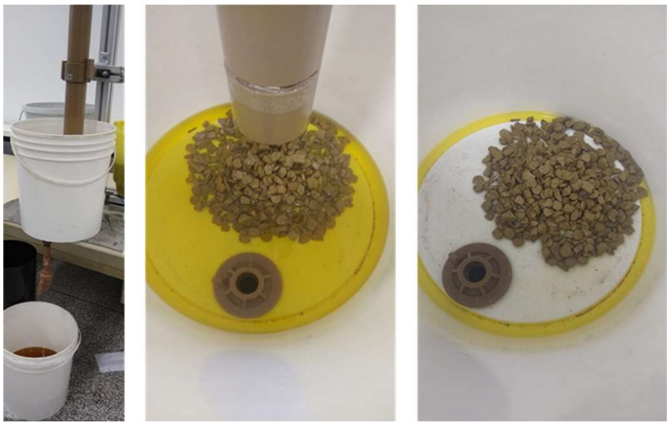


Figure 5. Experimental SAOR tests results. The error bars consider one time the average standard deviation of results.

Diesel was drained through a valve placed on the bottom surface. Since it was possible to control, the flow did not change the angle formed. It was possible to conclude that the angle does not has a linear relationship with the size of particles.

3.2 POUR ANGLE OF REPOSE (PAOR)

PAOR tests required a different device to be performed. Since the particles needed to be poured from a specific height, a support was built to fix the inlet of pellets. By removing a plate, the pellets inside a tube fall into the diesel recipient and form, therefore, the expected pile. The device is shown in Fig. 6. As in the SAOR device, it was possible to drain Diesel without changing the geometry of the formation.



a) b) c)

Figure 6 PAOR equipment and procedures. a) Apparatus with the tube from where particles are poured from a specific height. b) It is possible to see the inlet of particles in the tube, a horizontal cut. Below is the pile formed and the Diesel that was being removed. c) The recipient, after the removal of Diesel, the situation in which the angle is measured.

Two heights were set, knowing that they directly influence the velocity at which the particles reach the bottom of the recipient. The first one of 160 mm from the bottom of the recipient was proper to form piles, whether the second one of 260 mm did not permit the formation and the particles were dispersed entirely.

Tests were conducted three times for every granulometry, for each run was used an amount of 250 g of pellets. The ambient temperature was set at 17°C, which was defined as a standard condition for this work. Figure 7 presents the results obtained for the 160 mm height. In particular, the 4,8 granulometry did not form a pile and therefore is any value of SAOR presented. For the height of 260 mm, there was no pile formed for all granulometry. The final results presented are obtained after 3 runs for each granulometry, measured 4 times the angle of each formed pile.

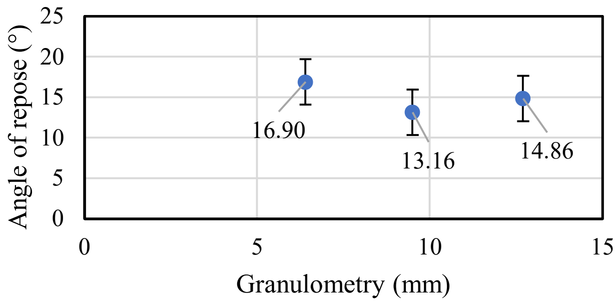
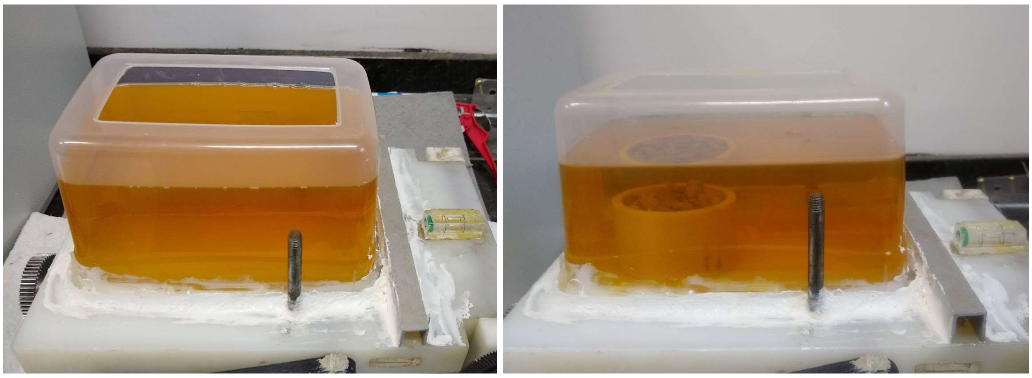


Figure 7. Experimental results of PAOR according to the granulometry for an inlet height of 160 mm. The error bars consider one time the average standard deviation of results.

3.3 INCLINED PLANE TEST (IPT)

For the final test, an IPT device was adapted to create an environment filled with Diesel where the particles are placed and tested. The device consists of a manually operated rotating table, where material samples are placed. A box was placed above the table and firmly sealed to prevent any leakage of Diesel.

The test consists of slowly rotating the table until the static friction is overcome. For the application with particles, the procedure changes from a conventional one, where a material sample is placed on the table. In our case, to hold the pellets together, a ring of PLA was printed, which allowed the contact between particles and the table. For every test it was used 100g of bentonite, occupying the entire interior of the ring. The relationship between the final angle's tangent and the static friction coefficient can not be directly applied for this scenario because it involves two different materials and geometries. Figure 8 shows the adapted apparatus.



a) b)

Figure 8. a) IPT system used for the tests. b) It is possible to see the recipient with Diesel, the cylinder and the pellets

Tests were conducted for every granulometry three times. The results are displayed below in Fig. 9:

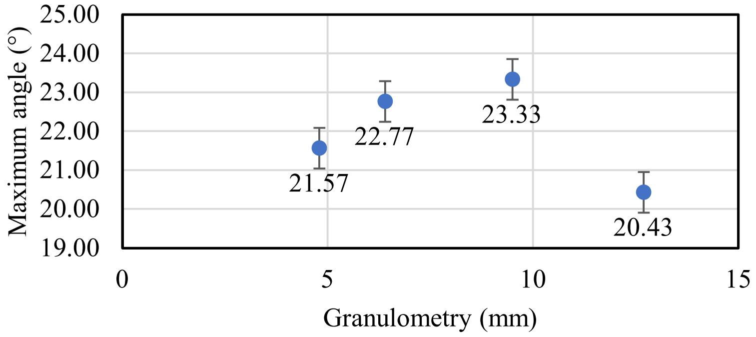


Figure 9. Experimental results for IPT according to the granulometry. The error bars consider one time the average standard deviation of results.

What can already be noticed is that the granulometry has no major impact on the maximum angle, which means it does not interfere with the friction caused by particles.

4. MEASURING PARAMETERS

To calibrate the simulations properly, it is necessary to experimentally measure some characteristics of the fluid and the particles and use the obtained values directly in the simulation.

4.1 BULK DENSITY

One important parameter to be set at the simulations is the bulk density of the material. Having these values, it is already possible to increment the results of simulations. To measure the bulk density, one important variable for calibration, it was necessary to weigh the mass occupied by a determined volume of pellets. The adopted procedure used a graduated beaker and varied the volume and quantity of clay, measuring its mass after every change.

In general, for each of the four granulometry, four different volumes were used and performed 3 measured for each condition, resulting in 48 different measurements. For the granulometry of 4.8, the measured bulk density was 1.31 g/ml, for 6.4 of 1.00 g/ml, 9.5 of 1.04 g/ml, and 12.7 of 1.01 g/ml.

4.2 DIESEL VISCOSITY AND DENSITY

Through tests performed in a ThermoScientific HAAKE MARS-III Rheometer, it was possible to determine the viscosity of Diesel at 17°C as 0,00439 Pa s. The density was also measured and was considered as 846 kg/m³.

4.3 PAOR INJECTION MASS FLOW RATE

The PAOR test requires an indicated mass flow to be set at the simulation, since it interferes with the number of simulated particles and how they develop their velocity. To measure such characteristics, it was made a video analysis and by knowing the total mass of particles, it was possible to find a mass flow of 877.3 g/s during 0.2849 s.

5. SIMULATIONS

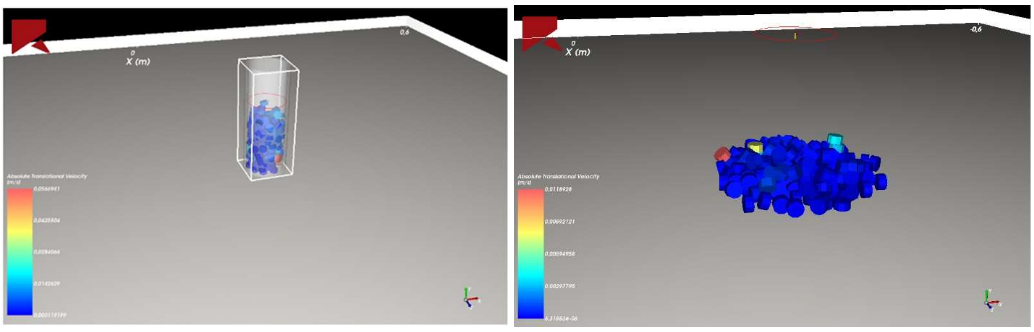
In this current phase of the project, simulations are performed to comprehend the numerical model used and begin the calibration process by correctly representing the experiments and observing the effect of different variables in the final result. The input parameters of simulations were defined in a way to represent the reality of the experiments. The used geometries were modeled in 3D with the correct dimensions and later exported to the software. The particles were generated by ROCKY and adjusted to represent the different granulometry of pellets accurately. It was chosen a faceted cylinder geometry, using 20 faces, since that will be the standard number for further simulations in the study of its transportation. Concerning the diameter, it was set as 11 mm, and the height adjusted for each size, in the range from 0.5 up to 1.15.

5.1 STATIC ANGLE OF REPOSE (SAOR)

After providing the software with experimental inputs, such as diesel properties and bulk density, it was necessary to adapt the insertion of particles into the system. The pellets need to be placed inside the cylinder, performed by a continuous injection until they reach a specific height and quantity. This procedure was chosen to represent the bulk density and natural arrangement of pellets. To remove the cylindrical recipient, it was set a vertical displacement with a constant speed of 10 mm/s.

To calculate the inclination angle of the formed pile, a system macro, a Python program used to simplify post-processing, developed by ESSS is performed. In general lines, the procedure is to cut the pile into 36 planes that rotate vertically, always crossing its middle. Then, the maximum height of particles spaced by a set distance is used to perform the interpolation and find the angle of repose.

The following images in Fig. 10 represent the steps performed.



a) b)

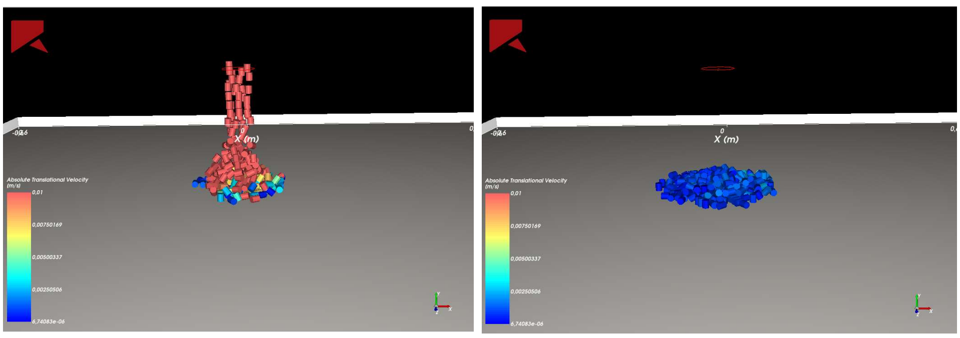
Figure 10. SAOR simulations procedure: a) the cylinder is surrounded by Diesel. and the particles are placed inside the cylinder at a specified maximum height. b) After the cylinder rises, the pile of pellets is formed.

5.2 POUR ANGLE OF REPOSE (PAOR)

For such an application, it was necessary to place the inlet of particles according to the experimental parameters. It is possible to separate the simulations into two primary groups, according to the height (160 mm and 260 mm). A default condition of parameters was the same for SAOR tests.

Characteristics as the size and height for the injection inlet were adjusted following the experimental ones. The mass flow of particles was set as the experimentally calculated one. To calculate the angle of repose, it is also used a macro, just as the one for SAOR. The steps are presented in Figure 10.

The analysis process is similar to the one adopted for SAOR simulations, meaning that the effects of input parameters were valued individually. The procedure is presented in Fig.11.



a) b)

Figure 11. PAOR simulations procedure: a) the pellets are dropped constantly from a specific heigh, and it begins the formation of the pile; b) the pile is formed.

5.3 INCLINED PLANE TESTS (IPT)

In this group of simulations, the adopted method of placing the particles inside the ring was the same as in the SAOR, allowing the pellets to occupy the entire interior. One important aspect that needs to be considered about this case is that the numerical model does not consider the contact formed between two geometries that are not particles. It means that the ring/plane contact has no friction considered.

Therefore, some conditions needed to be considered and adapted to calibrate the particle properties properly. It is possible to admit that the particles majorly cause the friction force caused in the system (particles and ring) since they present a much greater mass than the ring. Another significant aspect concerns that the maximum inclination obtained by only the ring is very close to those caused by the particles (maximum deviation of 12%). To represent those aspects and reduce the inaccuracy caused by the absence of friction between geometries, the mass of the cylinder was considered as low as possible (1 g) so the movement of the particles would not be interfered by the weight of the ring.

The calculation of the maximum angle achieved was performed knowing the rotational speed of the plane and the moment when the ring begins to move, the information provided as post-processing in ROCKY.

6. CALIBRATION

In total there were performed more than 105 combinations of parameters to calibrate the numerical model. Calibration demands understanding how input variables impact the final output result. By defining standard values for parameters and later changing them individually, it was possible to separately identify those effects, which can later be compiled in a new set of parameters, aiming to achieve the proper calibration for this specific test. The available parameters to be changed are bulk Young's modulus, friction between particle and particle and also between particle and boundary, rolling resistance and restitution coefficient. The effect of the parameters in SAOR and PAOR for a specific 9.5 granulometry on the results are showed in Table 1.

Table 1. Effect of parameters changes on final results for SAOR and PAOR simulations.

	Parameter	**Value**	**Result**
SAOR	Restitution Coefficient	0.5	3.9
SAOR	Restitution Coefficient	0.3	5.65
SAOR	Friction Boundary-Particle	0.5	10.85
SAOR	Friction Boundary-Particle	0.8	4.1
SAOR	Friction Boundary-Particle	0.3	5.65
SAOR	Friction Particle-Particle	0.3	5.65
SAOR	Friction Particle-Particle	0.5	8.65
SAOR	Friction Particle-Particle	0.8	8.95
SAOR	Rolling Resistance	0.3	5.65
SAOR	Rolling Resistance	0.5	7.6
SAOR	Rolling Resistance	0.8	6.3
SAOR	Bulk Young's Modulus (N/m²)	1.00E+07	14.6
SAOR	Bulk Young's Modulus (N/m²)	1.00E+09	33.2
SAOR	Bulk Young's Modulus (N/m²)	1.00E+10	34.6
PAOR	Restitution Coefficient	0.3	5.5
PAOR	Friction Boundary-Particle	0.8	8.1
PAOR	Friction Boundary-Particle	0.3	5.5
PAOR	Friction Particle-Particle	0.3	5.5
PAOR	Friction Particle-Particle	0.8	14.1
PAOR	Rolling Resistance	0.3	5.5
PAOR	Rolling Resistance	0.8	23.7

Concerning the ITP tests, the parameters that showed the more significant impact were both frictions. Their effect is present in the graphic of Fig. 12.

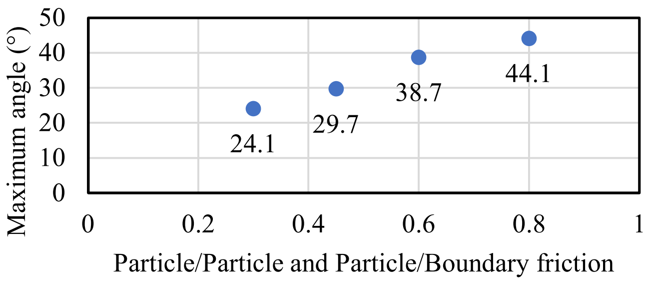


Figure 12. ITP simulation effect of friction coefficients.

Combining the individual effects of parameters made it possible to adjust with greater precision and achieve e better correlation. The final calibration was achieved only after setting a standard value for most of the parameters that had a great impact on the output, *e.g.* Bulk Young Modulus. The parameters achieved were: 0.3 for Restitution Coefficient, Friction Boundary-Particle and Friction Particle-Particle; 0.8 for Rolling Resistance and 1e8 for Bulk Young's Modulus (N/m²). The results obtained are presented in Fig. 13.

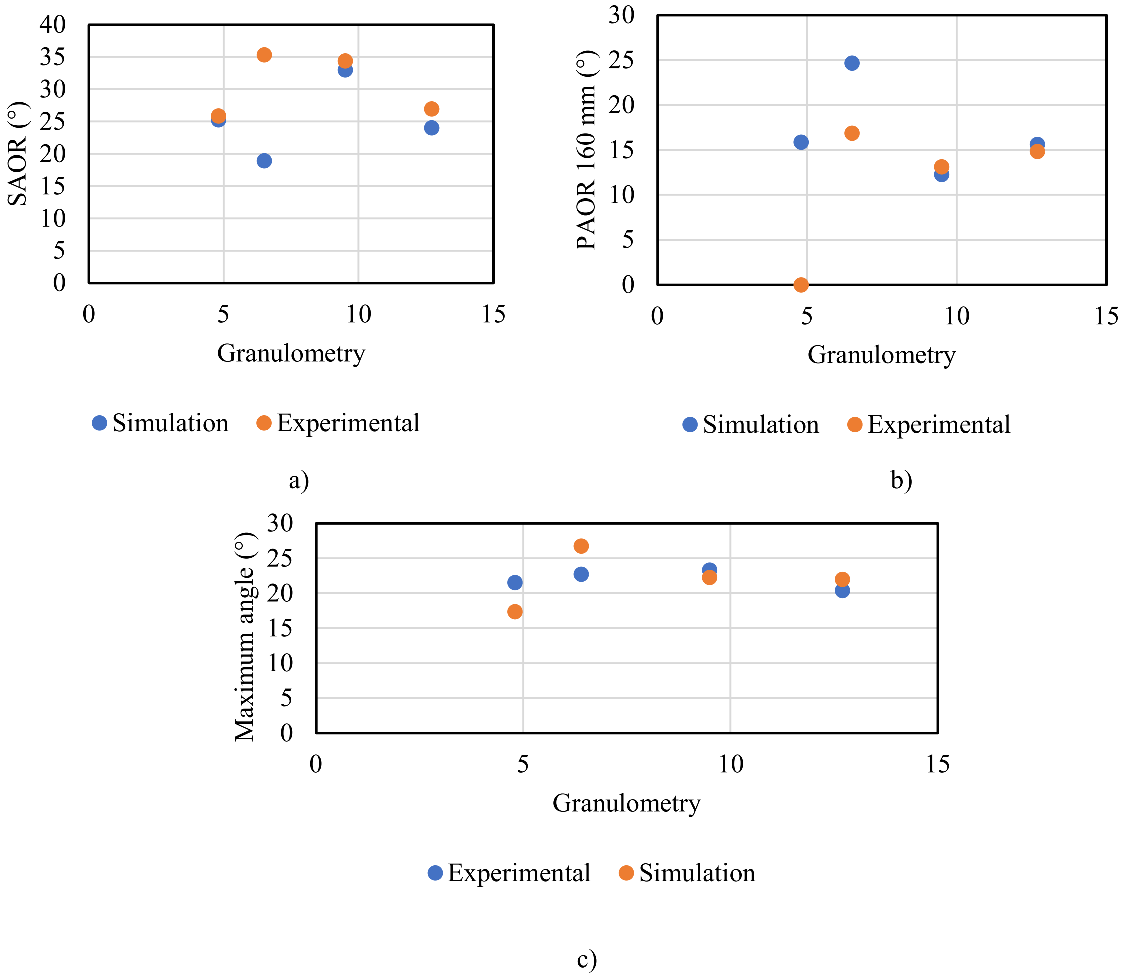


Figure 13. Simulation results after calibration process: a) presents the SAOR results; b) presents the PAOR results; c) presents the IPT results.

7. CONCLUSIONS

With the conclusion of experiments and their numerical correlation, it is possible to affirm that the calibration process and its methodology reached their objective. The obtained parameters can now be applied to further simulations to be performed with a higher level of accuracy.

Regarding the methodology, concerning the use of Diesel, it is possible to affirm that the adopted approach was effective since it was possible to represent the experimental tests in a simulation with low computational costs.

Even though it is notable that there are minor deviations in some specific cases, which can be noticed in Fig. 13. A possible reason for such a phenomenon is that experimentally, there is a considerable variation on particle size for a single granulometry, which was not represented in DEM. Most specifically, the 4.8 granulometry contains a thin powder of bentonite that interacts with diesel Diesel differently in addition to the particles. For the other granulometry, such variation caused a different arrangement of particles, changing the inclination of formed piles.

Throughout the development of the presented work, it was possible to analyze the possibilities of particle behavior when combining the multiple input parameters of a DEM model. The calibration process is, therefore, a demanding phase to obtain accurate numerical results. The calibration process that through simple tests allowed a great correlation was possible to achieve with this work.

8. ACKNOWLEDGEMENTS

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