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Advancements and Applications of the Discrete Element Method in Mining and Geotechnical Engineering

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Abstract

The application of numerical methods, particularly the Discrete Element Method (DEM), has significantly advanced the understanding of the complex mechanical behaviour of materials in mining and geotechnical engineering. DEM, which simulates systems of particles, enables detailed analysis of the interactions between individual particles, which are crucial for predicting the behaviour of granular materials such as soil, rock and other discrete element systems. This study explores the various applications of DEM in mining, including the modelling of crushing, transport and storage processes of ore materials, leading to process optimization, cost reduction and enhanced safety. In geotechnical engineering, DEM is used to analyse slope stability, foundations, supporting structures, and soil-structure interactions to enable accurate predictions of soil and rock responses to natural and anthropogenic impacts. The study also discusses the importance of selecting appropriate contact models and input parameters in DEM simulations and emphasises the need for calibration procedures to ensure accurate simulations. Examples of DEM simulations in mining and geotechnical applications demonstrate the method's ability to optimise designs, improve efficiency and enhance safety.

Keywords: Discrete Element Method (DEM) simulation; mining; geotechnical engineering

1. Introduction

The application of numerical methods such as the Discrete Element Method (DEM) in mining and geotechnical engineering represents a significant advance in the understanding of the complex mechanical behaviour of materials. DEM is a numerical technique used to simulate the behaviour of systems of particles, such as granular materials, powders, food, and even molecular systems. In DEM, the material is modelled as an assembly of discrete, interacting particles, each of which can have a different shape and move independently. The method calculates the motion and interactions of these particles over time, considering forces such as gravity, contact forces, and friction. DEM is particularly useful for studying complex behaviours like flow, mixing, and breakage in granular systems, where traditional continuum methods may fall short. This numerical method allows for a detailed analysis of interactions between individual particles, crucial for predicting the behaviour of granular materials such as soil, rock, and other materials composed of discrete elements. Discrete elements or granular materials can adopt different states such as solid, liquid or gaslike which can be simulated in DEM with many contact models. Processes in nature or industry that include that discrete elements can also involve static and dynamic behaviour.

In mining, DEM enables the precise modelling of crushing, grinding, transport and storage processes of ore materials, which leads to the optimization of these processes, cost reduction and increased safety. The discrete element method provides deeper insights into the mechanics of rock fractures, the stress distribution within mining structures and the prediction of potential landslides or collapses, which can significantly improve the planning of mining activities and risk management (**Aftabi et al, 2023; Munir et al., 2022; Salkynov et al., 2023; Chehreghani et al., 2022**).

In geotechnical engineering, the application of DEM extends to the analysing the stability of slopes, foundations, retaining structures such as walls and embankments, and the interaction of soil with geotechnical structures such as piles and anchors. Modelling soil and rock behaviour using DEM enables more accurate predictions of their responses to natural and anthropogenic impacts, including seismic actions, loads and changes in water content. This leads to better design, increased safety and cost reduction in geotechnical projects.

With the development of computer capabilities and the possibility of performing calculations in computer clusters, the numerical DEM method is now available to more and more engineers and researchers. The study shows how efficiency can be increased both in mining and in geotechnics through improved simulation possibilities with the DEM.

2. Contact models used in DEM

In the DEM simulation, the simulation takes place in time steps. Each time step deals with a finite number of discrete elements that interact with each other. The calculation is carried out in two phases. In the first phase, the contact forces between the discrete elements are generated. The force-displacement law plays a crucial role here, as the contact forces between neighbouring discrete elements lead to force changes. In the second phase, the discrete elements move or break due to the current state of the contact forces. The force-displacement law is defined by contact models. Therefore, the choice of a contact model plays a crucial role in the interactions between discrete elements. Nowadays, there are many contact models, from basic ones (e.g. elastic contact models) to advanced ones (e.g. elastoplastic adhesive contact models, adhesive rolling resistance contact models, fragmentation contact models). In the second phase, Newton's second law is applied to predict the movement based on the contact force calculated in the first phase. **Figure 1** shows an example of a DEM model for the simulation of the angle of repose due to hopper discharge and the calculation of stress at discrete element contact. The grey contours in **Figure 1b** represent the stress that is above the yield.

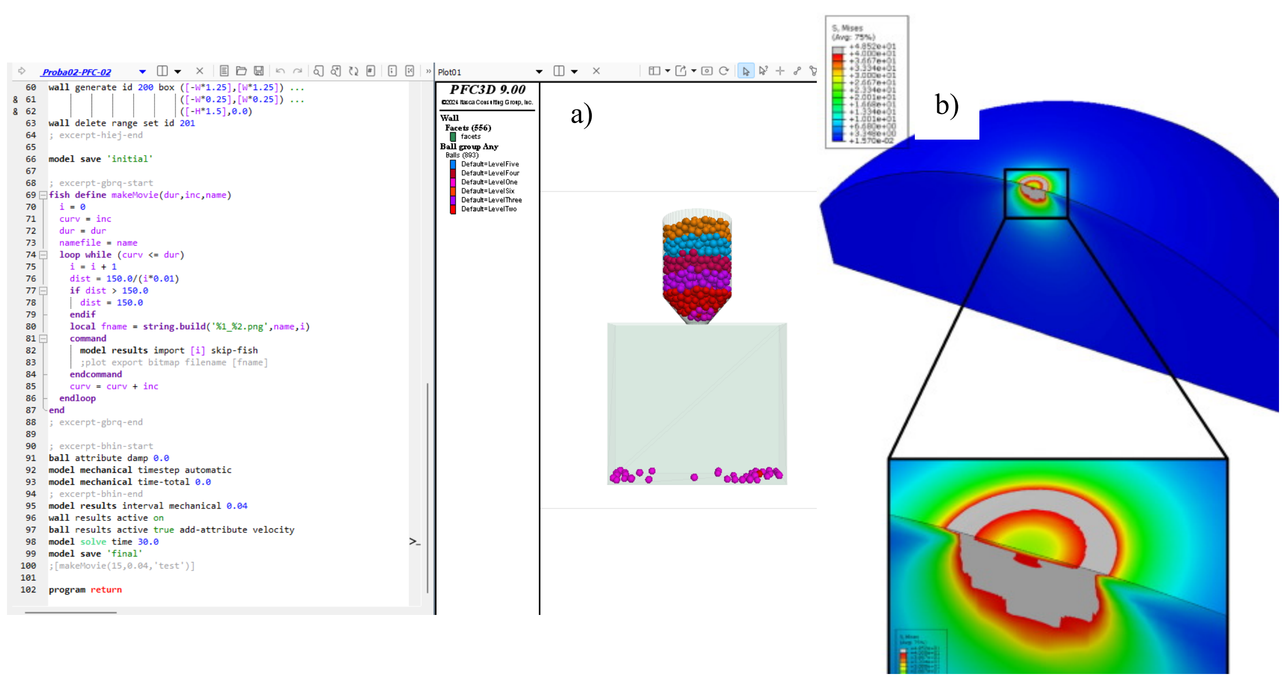

Figure 1: Simulation of the angle of repose due to hopper discharge, created in PFC3D: a) DEM model with input code, b) the contours show the stress on the sphere after the DEM calculation (modified from **Rathbone et al., 2015**).

In elastic contact models, it is assumed that discrete elements are behave elastically on contact. This behaviour can be achieved by a linear relationship, which is the simplest model. The most frequently used non-linear elastic model is the Hertz model (**Hertz, 1881**). Elastic models are suitable for the simulation of materials such as rubber. For other materials where attractive forces between discrete elements, yielding (plastic deformations) or fragmentation play a role, advanced models must be used to realistically represent the static or dynamic behaviour of the material.

3. DEM input parameters

Unlike e.g. finite element methods, where most input parameters can usually be obtained directly by in-situ or laboratory experiments (e.g. internal friction angle, cohesion, particle density) and some can be assumed based on experience (e.g. Poisson's ratio), DEM often requires calibration procedures to determine the input parameters. The reason for this is that material input parameters are needed at the microscale or particle level, e.g. contact properties, cohesion, damping between particles. The determination of these microparameters is a challenge as it is relatively difficult to measure them directly by laboratory experiments. In calibration, numerical tests are used to individually calibrate the parameters used at the particle level one by one through an iteration process until a bulk behaviour observed in the laboratory is satisfactorily predicted (**Coetzee and Nel, 2014**). In mining and geotechnical engineering, bulk material with fines plays an important role and a certain water content is often present. To simulate this type of material during conveyor belt transport, elastoplastic adhesion models (e.g. the Edinburgh Elastoplastic Adhesion Model - EEPA) can be considered (**Morrissey, 2013**). The following parameters would be required for this simulation (**Carr et al., 2023**). The loading spring stiffness defines the initial loading stiffness of the particles, while the unloading spring stiffness defines the unloading/reloading stiffness condition as a ratio to the loading stiffness. The adhesive force indicates the constant pull-off force acting between the particles. The adhesive surface energy quantifies the adhesion that holds the particles together. The adhesion branch exponent determines the strength of the adhesive force after the peak tensile force is reached. Additionally, the sliding friction and the rolling friction of the particles are also required for the model.

If we consider the example of the EEPA model, a unique set of parameters is needed. To calibrate it, a series of non-standard laboratory experiments are required. To meet the requirements of the model, the calibration procedure should include a series of laboratory experiments that cover various dynamic flow conditions in contact with handling equipment.

Apart from the required non-standard experiments, the number of particles or discrete elements in the model also plays a major role in the DEM simulation. With increasing complexity of the chosen contact model and a larger number of particles, the computational requirements and calculation time increase exponentially. In general, more fines mean more discrete elements for the calculation.

The range of particle size distribution used in DEM simulations is also very important. It is often impractical to simulate an industrial material handling system with the complete particle size distribution of the material. For example, an angle of repose which is frequently used as a laboratory test for model parameter input and DEM calibration, would require several million discrete elements for a 50 kg sample if the full particle size distribution of bulk material with fines is used. This issue becomes even more challenging when simulating a transfer system that handles several tonnes per hour. Therefore, it is more feasible to either scalp (remove smaller particles from the DEM model, as shown in **Figure 2**) or scale (increase the particle diameters for some ratio) the particle size distribution of the bulk material for calibration and simulations.

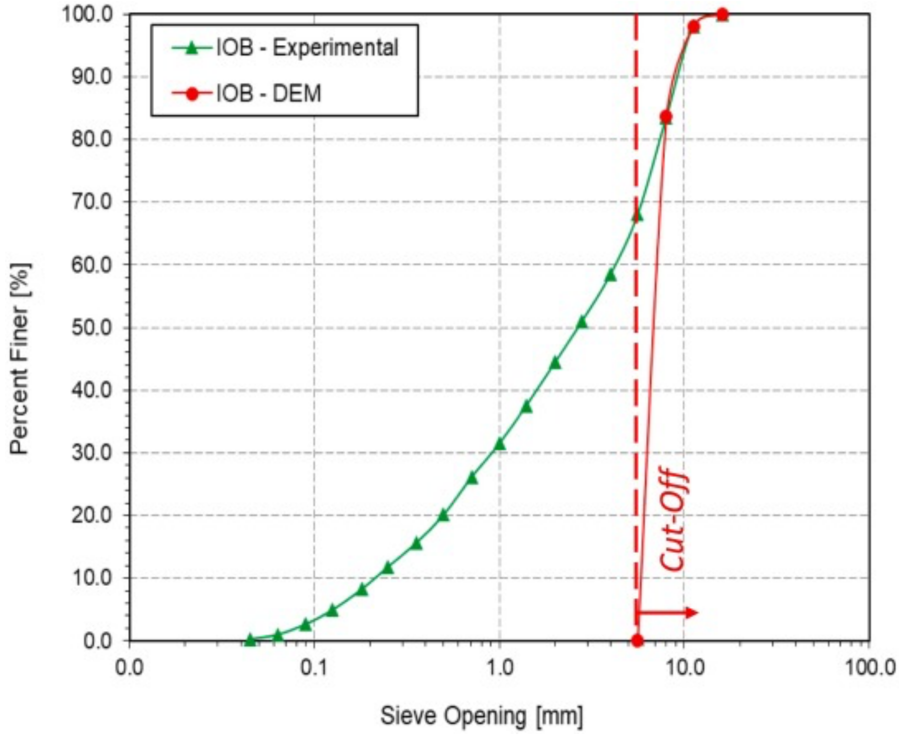

Figure 2: Example of scalping for DEM analysis (**Carr et al., 2023**)

Scaling technique is usually used when only small particles (e.g. powder) are simulated, as there are issues with very small discrete elements (e.g. calculation time). In both cases, it should be kept in mind that smaller particles have a larger contact area than particles with larger diameter, which influences the calculated attraction force (**Thakur et al., 2016**). It is therefore recommended to do sensitivity analysis for these two techniques when deciding on a particle cut-off value or increasing ratio.

If a dry, non-cohesive bulk material is simulated, some of the notable calibration experiments such as the angle of repose test (**Klanfar et al., 2021**), the shear box test (**Ilic, 2013**) and more recently the draw-down test (**Roessler et al., 2019**) can be used. The shear box test and the draw down test are more suitable for cohesive wet materials. A basic schematic of the tests mentioned is shown in **Figure 3**. The most important parameters obtained from these tests are the angle of repose (b_{cyl} and b_{DD}) and the shear angle (j_{SB} and j_{DD}).

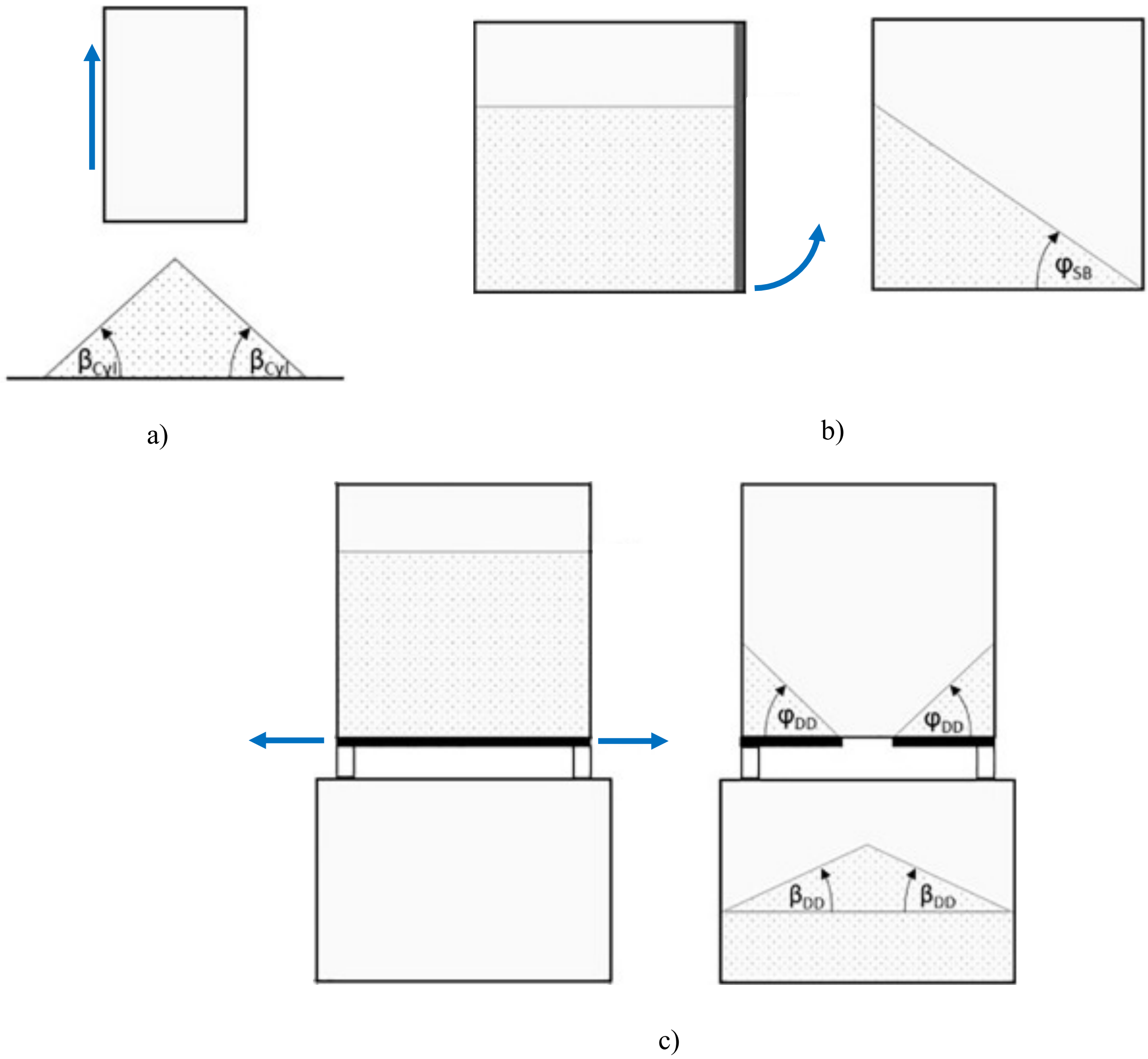

Figure 3: Basic schematic of calibration laboratory tests: a) the angle of repose, b) the shear box test and c) the draw down test (modified from **Roessler et al., 2019**)

4. Application of DEM simulation in mining

DEM is a powerful computational technique that is widely used in the mining industry today to simulate and analyse the behaviour of granular systems, rock and soil. It is able to provide valuable insights into various processes (e.g. griding, crushing, cyclones, rock and soil deformation, etc.) and helps to optimise operations, improve efficiency and enhance safety (e.g. conveyor systems, transfer chutes, etc.). Some of the key applications of DEM are outlined here. In the material handling and transfer, the simulation of conveyor systems and bulk material such as ore, coal and aggregates on conveyer belts leads to design optimization, spillage reduction and improved efficiency. Also, optimization of storage and retrieval operations can be done by analysis of stockpile formation, reclaiming processes, and flow patterns. The analysis of bulk material flow through transport chutes can be used to minimise wear, blockage and materials degradation. The modelling of crushers and crushing processes provides the particle size distribution after the crushing process, wear patterns and energy consumption. In addition to crushers, griding mills are also an integral part of the mineral processing and are used to separate and purify raw minerals. Simulation of ball mills and other types of mills analyses the impact of various operating conditions on grinding efficiency, throughput, and wear. Processes for particles screening and separation can also be successfully analysed. In this case, the screening efficiency and wear of vibrating screens are obtained. The simulation of hydrocyclones helps to optimise separation efficiency and reduce energy consumption. The first step in mining is the extraction of ore. To get to the ore, the solid rock is usually blasted. The modelling of rock blasting describes the fragmentation process, predicts the particle size distribution and optimises the blasting. DEM is able to simulate even and a leaching process to study the flow of solutions through the ore heaps and optimise the efficiency of the leaching.

Before showing an example of simulations, it should be noted that the real advantage of DEM simulations is the possibility of coupling them with other types of numerical simulations, for example with CFD (Computational Fluid Dynamics) or FEM (Finite Element Method) method. An example of a DEM simulation and the coupling of DEM and FEM methods is the analysis of the dynamic deflection of conveyor belts (**Munir et al., 2022**), the results of which can be seen in **Figure 4**. The results show the deflection of the belt, the energy required to overcome the elastic deformation of the belt and the maximum stress in the belt for two cases, case one with the rollers gap of 1 m and case two with the rollers gap of 2 m.

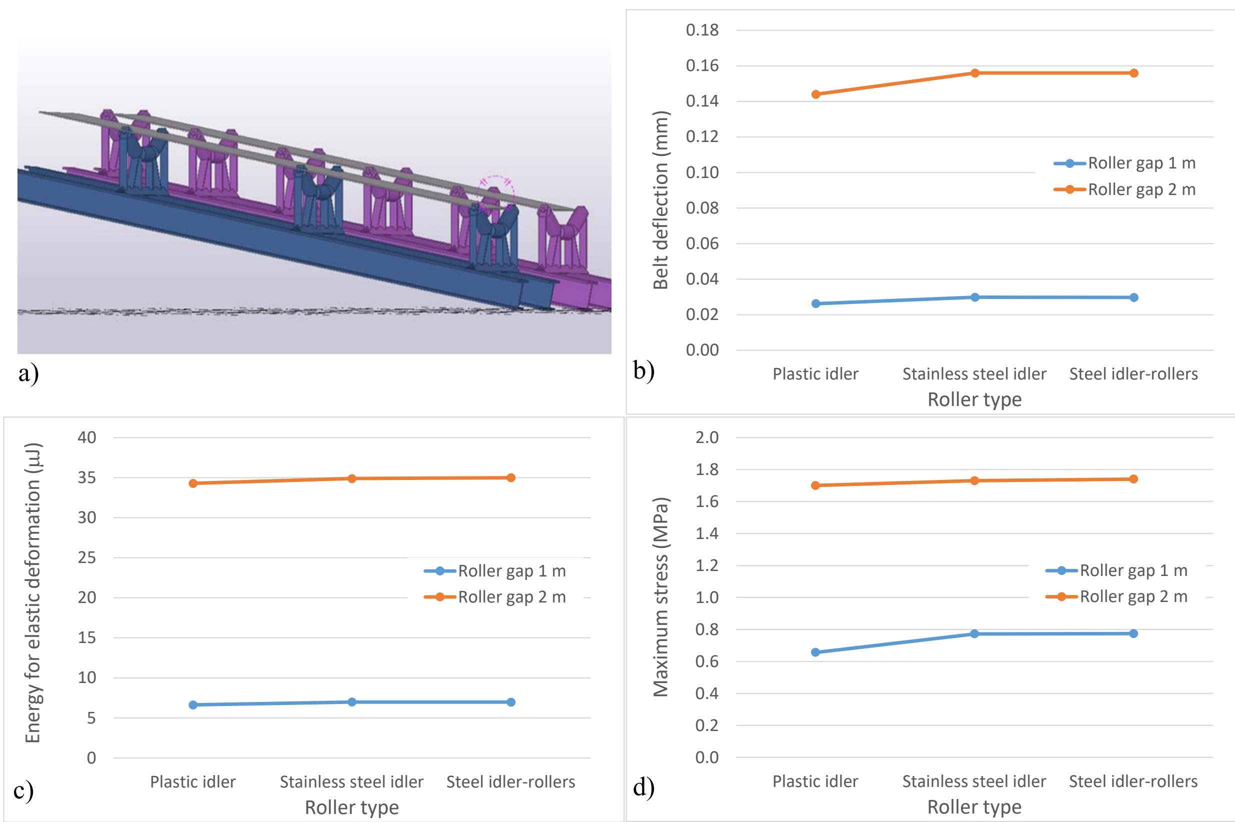

Figure 4: Simulation results of the dynamic deflection of a conveyor belt, a) conveyor belt model, b) deflection of the belt, c) energy required to overcome the elastic deformation during transport and d) maximum stress in the belt (modified from **Munir et al., 2022**)

Another example of DEM simulation shows the comparison of the results of an industrial-scale crusher for problematic material such as copper ore with a DEM simulation (**Doroszuk and Krol, 2022**). The aim was to optimise the design of the hammers in the crusher. The experiment in the jaw crusher was used for DEM model calibration. The simulation of the hammer crusher was then used to optimise the hammers (**Figure 5)**.

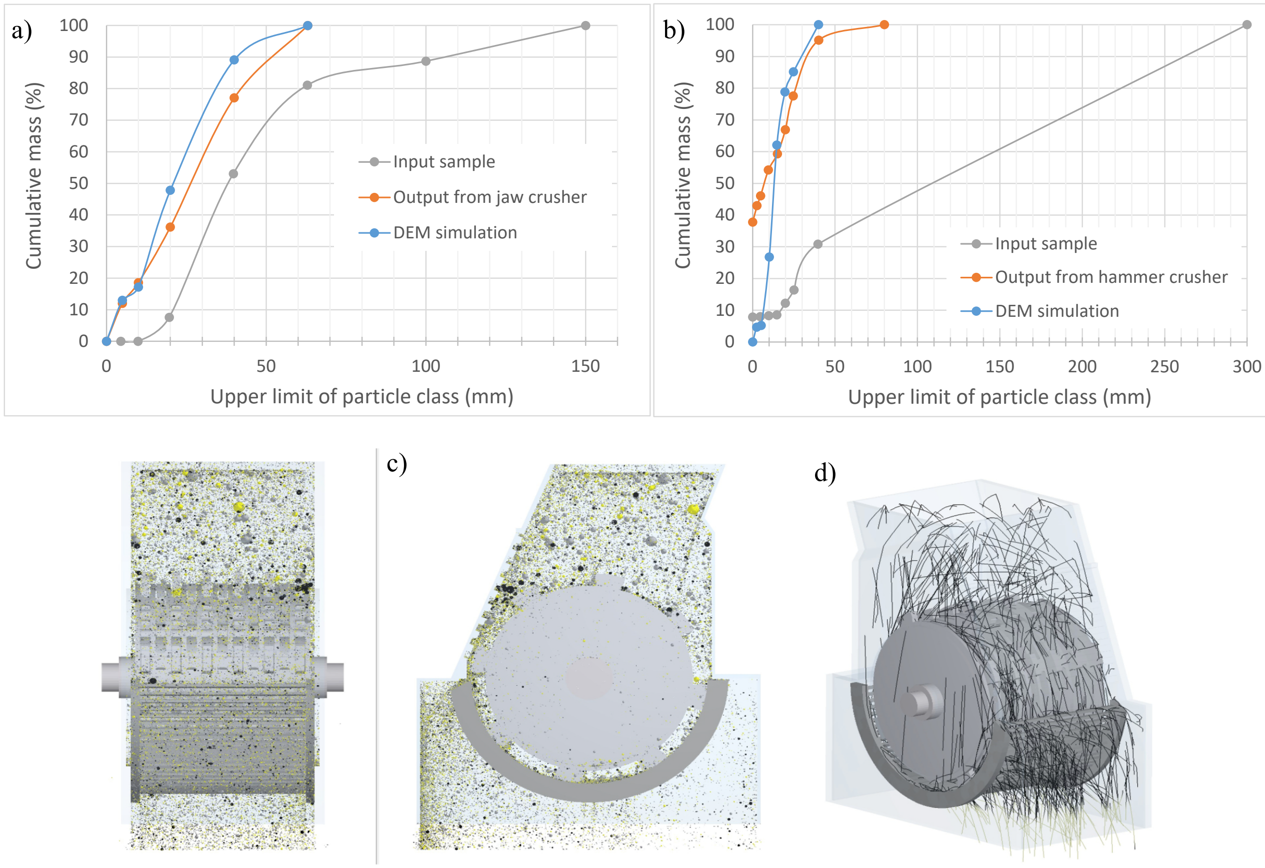

Figure 5: Results of the analysis of industrial-scale crusher work: a) particle size distribution from the jaw crusher, b) particle size distribution from hammer crusher, c) particles in hammer crusher and d) particle trajectories in hammer crusher (modified from **Doroszuk and Krol, 2022**)

5. Application of DEM simulation in geotechnical engineering

Complex geotechnical processes and the behaviour of granular materials, rock masses and soil deposits can also be simulated with DEM. The simulation of stress-strain responses in soils and rocks predicts their mechanical behaviour under different loading conditions. Analysing the shear strength and potential failure surfaces in soils and rock masses leads to stability assessments and the bearing capacity of shallow and deep foundations under various loading conditions. The effectiveness of slope reinforcement techniques such as soil nails, retaining walls and geosynthetics can be evaluated. The settlement behaviour of foundations on different soil types can be predicted, leading to an optimisation of structural design. The DEM can be useful for underground excavations. The modelling the underground excavations, tunnels and their support systems such as rock bolts and shotcrete ensures prevention of collapses and safety. The compaction process is one of the most important factors in geotechnical engineering, ensuring sufficient density of soil particles and thus suitable mechanical properties of the soil for foundations, embankments, dams and other earthworks. The simulation of soil compaction techniques helps to achieve the desired soil density and mechanical properties.

Man-made materials such as geosynthetics are nowadays commonly used in mining and geotechnical engineering (**Herceg et al., 2023**). Geotextiles and geogrids are commonly utilized in road embankments, retaining walls and slopes because of their superior properties and high economic efficiency compared to natural materials. The interaction between soil and reinforcement is widely acknowledged as a critical factor in the performance and design of geosynthetic-reinforced structures. As an example of the use of DEM, a pullout test with geogrids can be modelled. **Miao et al. (2017)** modelled the pullout behaviour of geogrid reinforcement with an emphasis on the influence of grain shapes on the pullout force. The peak pullout forces are shown because they reflect the yielding properties of a geogrid-reinforced system (**Figure 6**). **Figure 6** also shows the final axial deformation of the geogrid at the end of the pullout test.

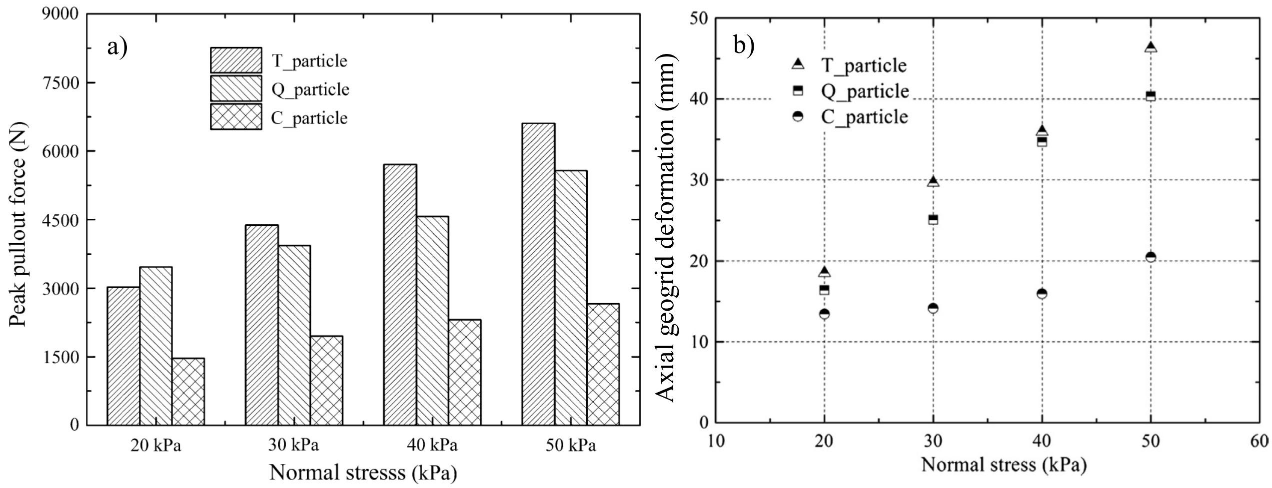

Figure 6: Results of DEM simulation of pullout test on geogrid (**Miao et al., 2017)**: a) peak pullout forces in respect to particle shape and normal stress during pullout test and b) final axial deformation of geogrid in respect to particle shape and normal stress during pullout test

Another example of DEM usage in geotechnical engineering is the simulation of the shear behaviour in the critical state at the soil-structure interface. **Gu et al. (2017)** showed results from a series of monotonic direct shear tests using a sand-structure interface in tests with constant normal stiffness tests. A comparison was made between the laboratory tests and the DEM simulation. **Figure 7** shows the simulation results of particle displacements in vicinity of soil-structure interface at a horizontal displacement of 12 mm. In laboratory experiments, particle movements during testing can be measured. However, these measurements are usually associated with various problems (e.g. measurements in certain points, the accuracy of the measurements is questionable, especially if you want to measure the rotation of the particles). Therefore, this type of simulation is often the only way to get a good picture of what happens in the soil during the critical state shear behaviour in the soil or at the soil-structure interface.

The advantage of the DEM method is the possibility of coupling simulations with other numerical methods (e.g. FEM, CFD), as already mentioned. The water and pore pressure can be simulated in DEM, but if you only use DEM simulation, this effect is modelled by microscale or particle-to-particle contact input parameters (e.g. contact properties, cohesion). On the other hand, if a real physical fluid needs to be modelled, a coupling of DEM and CFD can be performed. Dynamic loading conditions in soil can also be modelled by combining DEM and FEM. One of the examples where pore pressure and dynamic loading play a role is the study of **Flores-Johnson et al. (2016)**. In this case, the FEM is used to specify the dynamic loading in the model.

Modelling clay particles would be more challenging due to their non-spherical shape. In this case, a particle is considered as a group of connected discrete elements. The disadvantage of such a model is the enormous enlargement of the model and the computational effort. An example of such a modelling approach is the study of **Bono and McDowell (2016)**, in which the authors used the DEM method to model the compression of clay.

Another advantage of the DEM method is that we can theoretically define each particle or even each molecule separately. So it is relatively easy to define the particle size distribution of the input sample and the particle shapes. Then the sample can randomly fill a certain space and confinement can be defined. As a result of the DEM simulation, the rotation of the particles, their breakage and stress distribution can then be monitored during the numerical simulation.

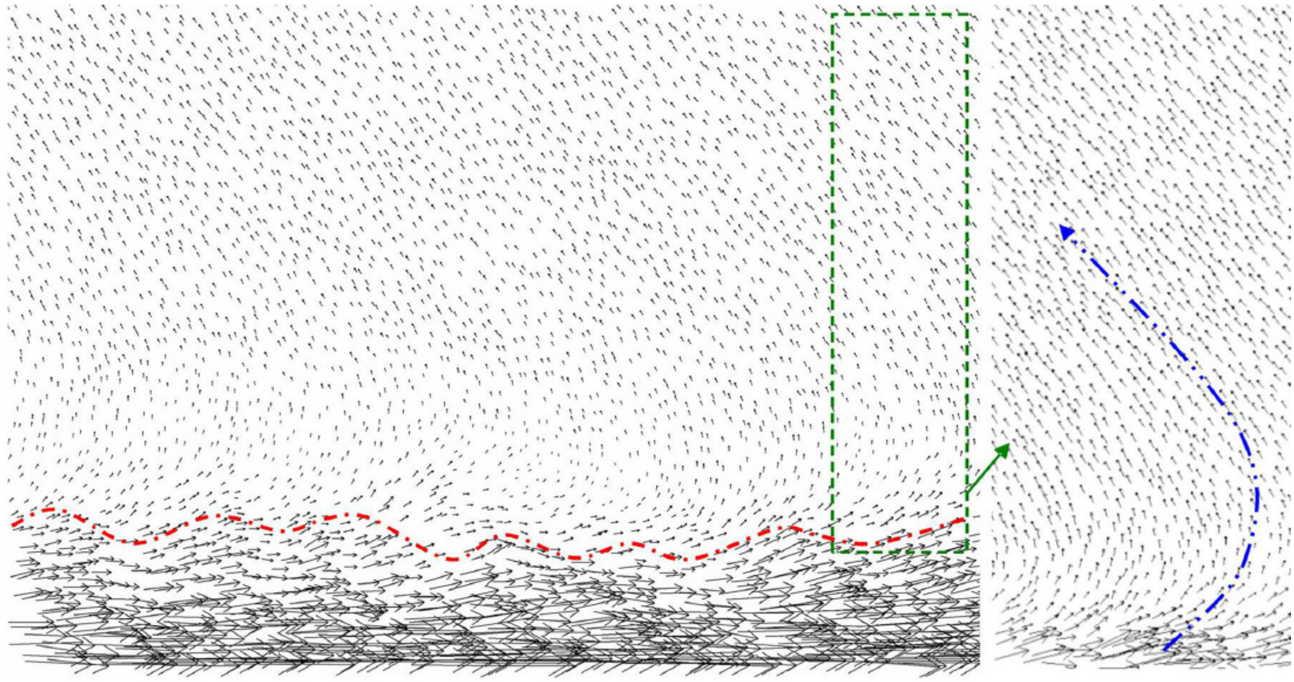

Figure 7: A simulation results of the particle displacement (as vectors) in vicinity of soil-structure interface at a horizontal displacement of 12 mm (**Gu et al., 2017**)

6. Conclusions

The Discrete Element Method (DEM) has proven to be an invaluable tool in both mining and geotechnical engineering, providing deep insights into the behaviour of granular materials and the complex interactions within particle systems. In mining, DEM has enabled accurate modelling of processes such as crushing, grinding and material handling, leading to significant improvements in process efficiency, cost reduction, and operational safety. The ability to simulate rock fracture mechanics and stress distribution within mining structures has enhanced planning and risk management.

In geotechnical engineering, DEM has contributed to a better understanding of soil and rock behaviour under various loading conditions, enabling more accurate predictions of slope stability, foundation performance and soil-structure interactions. The application of the method in the simulation of compaction processes and geosynthetic reinforcement has further optimised design and construction practices and ensures greater safety and reliability in geotechnical projects.

The study emphasises the critical importance of selecting appropriate contact models and accurately calibrating input parameters to achieve reliable simulation results. The examples given illustrate the practical benefits of DEM in optimising design plans and improving operational outcomes in both areas. It is expected that future research and advances in DEM technology will further improve its application and enable even greater accuracy and efficiency in mining and geotechnical projects.

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SAŽETAK

Razvoj i primjena metode diskretnih elemenata u rudarstvu i geotehničkom inženjerstvu

Primjena numeričkih metoda, posebno metode diskretnih elemenata (DEM), značajno je unaprijedila razumijevanje složenog mehaničkog ponašanja materijala u rudarstvu i geotehničkom inženjerstvu. DEM, simulira sustave čestica i omogućava detaljnu analizu interakcija između pojedinih čestica, što je ključno za predviđanje ponašanja granuliranih materijala poput tla, stijena i drugih sustava diskretnih elemenata. Ova rad daje pregled različitih primjena DEM-a u rudarstvu, uključujući modeliranje procesa drobljenja, transporta i skladištenja rudnih materijala, s ciljem optimizacije procesa, smanjenja troškova i povećane sigurnosti. U geotehničkom inženjerstvu, DEM se koristi za analizu stabilnosti kosina, temelja, potpornih struktura i interakcija tla i struktura, kako bi se omogućila točna predviđanja ponašanja tla i stijena na prirodne i antropogene utjecaje. U radu je posebno naglašena važnost odabira odgovarajućih kontaktnih modela i ulaznih parametara u DEM simulacijama te potreba za kalibracijskim postupcima kako bi se osigurale točne simulacije. Primjeri DEM simulacija u rudarskoj i geotehničkoj praksi ukazuje na uspješnu primjenu metode u optimizaciji dizajna, poboljšanju učinkovitosti i povećanoj sigurnosti.

Ključne riječi: simulacija metodom diskretnih elemenata (DEM); rudarstvo; geotehničko inženjerstvo

Author’s contribution

Dubravko Domitrović (1) (Associate professor) preformed conceptualization, methodology, data collection writing - original draft. **Tomislav Korman (2) (**Associate professor) preformed visualization, data collection, writing - original draft. **Mario Klanfar (3) (**Associate professor) preformed data collection, writing - original draft. **Vjekoslav Herceg (4) (**Senior assistant) preformed data collection**,** writing - original draft.