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The beginning of a new era in design: Calibrated discrete element modelling

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Abstract
The reliable storage and flow of bulk materials requires a comprehensive design process and good understanding of the flow properties of a bulk material. Analytical and empirical design techniques form the backbone of many design processes as they have been validated by research, however, theories based on continuum mechanics have many shortcomings and are restricted to 2-D analysis. Discrete element modelling (DEM) is proving to be a popular analysis and simulation method to verify designs for a wide range of bulk material processing and handling operations, such as transfer chutes. With the advances in computing and DEM technology, DEM has become a popular numerical method found on many engineers' desktops.

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The beginning of a new era in design: calibrated discrete element modelling

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Introduction

The reliable storage and flow of bulk materials requires a comprehensive design process and good understanding of the flow properties of a bulk material. Analytical and empirical design techniques form the backbone of many design processes as they have been validated by research, however, theories based on continuum mechanics have many shortcomings and are restricted to 2-D analysis. Discrete element modelling (DEM) is proving to be a popular analysis and simulation method to verify designs for a wide range of bulk material processing and handling operations, such as transfer chutes. With the advances in computing and DEM technology, DEM has become a popular numerical method found on many engineers' desktops.

Background

Profit and sustainable growth are key motives in the material handling industry where under-performing equipment and processes hinder a company's ability to meet their desired goals. Designing and repairing equipment to handle and process bulk materials can be a formidable task especially as the characteristics of a bulk solid can vary greatly depending on the location of exploration, seasonal weather and process efficiencies. Handling and processing systems that have to deal with multiple bulk solids that vary from free flowing and dusty to wet and sticky ores is an increasing concern at port facilities and processing plants.

Often, such designs will under-perform or generate high operating costs due to increased, or unpredictable, maintenance and shut-down periods. There are many factors that can lead to the demise of handling and processing equipment including:

- Lack of detailed analysis of a design and material flow due to time constraints and limitations of existing continuum techniques.
- Selection of inappropriate designs for bulk materials and applications.
- Inadequate understanding of material characteristics and flow behaviour.
- Insufficient knowledge of the equipment and process design.
- Poor maintenance which can lead to wear and flow problems.
- Maintenance engineers and crews applying quick fixes without considering the consequences to the functionality of the equipment.
- Lack of design verification using advanced 3-D modelling techniques.

These factors can result in operators reducing throughput to obtain reliable flow, or being forced to introduce additional hardware to treat the symptoms of a poor design not the cause; for example, adding water to improve flow or reduce dust emissions. Invariably such activities will deteriorate the profit margins of a system.

Approaches to equipment design in the mining industry

The design of new or modified equipment does not always require a painstaking design protocol if simple and valid techniques are available to evaluate the flow and behaviour of a bulk material. Whilst experience and a thorough understanding of the storage and flow of a bulk solid is a great asset when it comes to designing or trouble-shooting systems that store, process or transport bulk solids, these need to be combined with appropriate methodologies to provide maximum value during the design phase.

When it comes to modelling particle systems, generally two approaches are adopted: the continuum approach, where bulk materials are examined at a macroscopic scale using a lumped analogy; and the discrete approach, which models the motion and interactions of individual particles.

There are many analytical techniques available in the literature to assist engineers in designing storage facilities [1] and chutes where rapid flow occurs [2-3]. However, these models are typically limited to 2-D analysis which makes it difficult for engineers to completely visualise and understand how material will actually flow through complex equipment geometries. In recent times the discrete approach has been increasingly used to study the behaviour of bulk materials where discontinuous flow occurs, such as conveyor transfer design. This increase of adoption is primarily due to the considerable advances that have been made in commercially applied DEM methodology, availability and sophistication of commercial software, as well as a significant increase in desktop computing power.

DEM simulations allows numerous what-if scenarios to be assessed on a desktop computer as part of the design process allowing more extensive screening of possible design concepts without the additional costs of designing, constructing and testing scale prototype models or modifying current design via trial-and-error. Through appropriate application, DEM analysis presents engineers the opportunity to better understand the flow dynamics of bulk solids in bulk materials handling equipment. This can lead to improvements in equipment design, process efficiency, throughput, operation and potentially product quality.

Discrete element modelling

DEM has been known for several decades now. The method considers a finite number of particles interacting by means of contact and non-contact forces (e.g. electrostatic and capillary forces) and can generate detailed particle-scale information such as flow trajectories and the forces acting on individual particles and equipment surfaces. This is fundamental for deducing the mechanisms governing the complex flow behaviour of bulk solids.

There have been considerable advances in the development of DEM methodology [4] and an outburst of the use of DEM in wide range of industrial applications [5]. The popularity of DEM demonstrates the considerable potential of gaining valuable, previously unattainable, insight into the behaviour of bulk materials in industrial processes, thus increasing the level of engineering confidence that can be achieved during a design phase. This increased confidence serves to reduce the risk of major projects allowing optimal, reliable and sustainable supplies of bulk commodities to be realised.

Challenges facing the application of DEM in the mining sector

Although increasingly used in the mining sector, time constraints and a lack of experience with DEM methodology have seen bad habits being introduced when making use of this technology. Input parameters required for a DEM simulation are often assumed without careful assessment or calibration, which can lead to unrealistic bulk flow behaviours and misleading results. Designing a transfer chute based on non-calibrated DEM models can lead to serious problems in handling and processing operations such as flow blockages (e.g. due to wet and sticky ore), spillages, segregation, dust emissions, unexpected wear patterns, reduced throughput and systems not being able to handle surges.

An additional challenge facing DEM is in modelling the effect of fine size fraction on the bulk flow of a material. The number and size of particles used in a simulation are dependent upon both the available computational resource and required design-phase time lines. Particle size scaling is often employed in many applications to obtain feasible simulation run times. There are, however, no clear rules on how the input parameters need to be varied to still produce a fit-for-purpose flow behaviour following particle size increase. Again this promotes the use of inaccurate, best-guess, parameters as inputs to a DEM simulation, causing high levels of uncertainty that the flow behaviours present are fit-for-purpose.

Reducing this uncertainty is central to using DEM with confidence. To achieve a fit-for-purpose bulk flow behaviour during simulation it is essential to form a link between the real and the simulated bulk material. This link can be achieved by using a process of calibration.

Approaches to DEM calibration

A commonly asked question in industry is: what inputs into my simulation should I use so that the bulk flow behaviour in the simulation represents that of the real material? The answer to this question is not immediately obvious even if a detailed report containing material flow properties is available. Although DEM has been applied industrially for a number of years, there has been no standardised methodology to determine the best input parameters for a specific material or process.

This is due in part to the mathematics of the contact models and simulation inputs varying across DEM codes. Further to this is the unavoidable fact that a DEM material, as is the case with all types of simulation, is an approximation of the real bulk material. It is simply not computationally feasible to produce a high-fidelity model that includes all the randomness of particle shape, cohesion and friction displayed by most real bulk solids. Because of these constraints, the inputs to a DEM simulation need to be calibrated against real, physical test data in order to produce a realistic result.

Traditional material testing devices, such as Jenike direct shear testers, have been shown to be an unreliable approach for generating suitable data to calibrate a DEM material model for industrial use. Although standard flow property tests are ideal for measuring bulk material characteristics under static or quasi-static conditions suitable for bin, stockpile or feeder design, they are not sufficient for dynamic flow situations, such as transfer chutes. Due to the nature of these standard tests, there are often limitations on material size, so the sample tested may not be truly representative of the material present in the full-scale application. However, these standard tests are still

Figure 1: Schematic of the components of an EDEM Material Model.

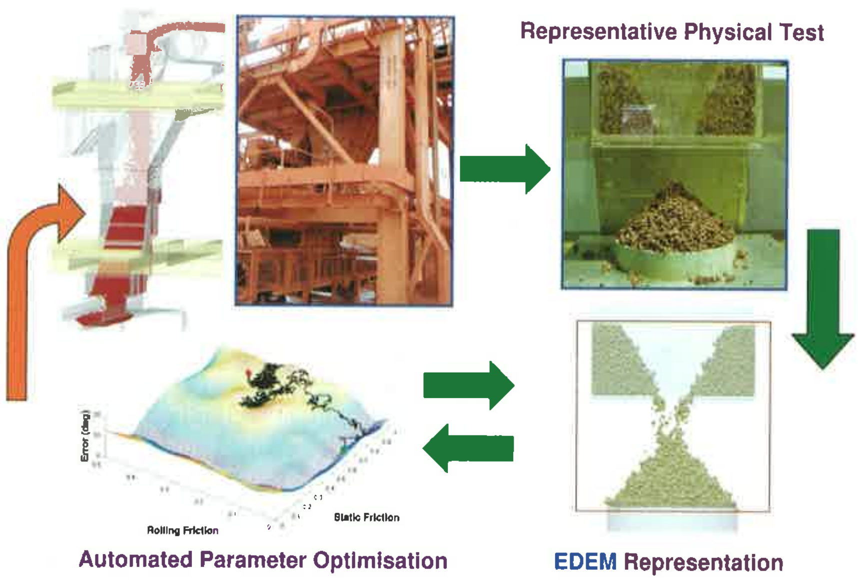

Figure 2: DEM calibration philosophy and methodology.

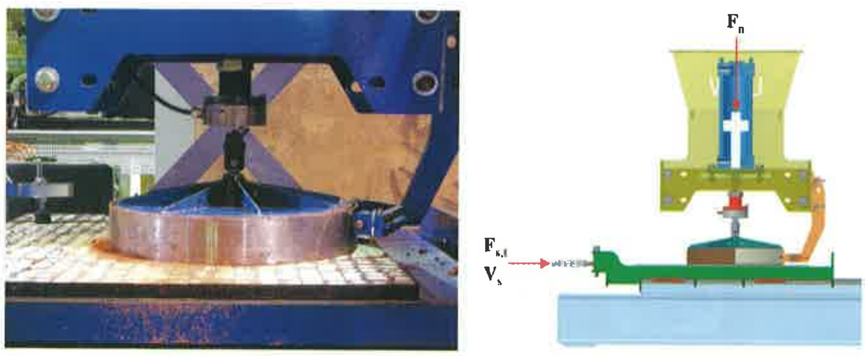

Figure 3: Measurement of wall friction angles of -30mm bulk materials using a large-scale wall friction tester.

of value to assess the flowability of a bulk material and identify the conditions of poor flowability (i.e. moisture content for maximum cohesive strength).

Beyond the physical testing, the determination of suitable input parameters is also a non-trivial task. Generally speaking the approach taken for the calibration of inputs for a DEM simulation is simplistic and based on the manual running of numerous DEM simulations, alternating a combination of parameters until a match is achieved between the numerical and physical results. This process is time consuming and expensive in regards to the man hours and resources required in setting up, solving and analysing the models. In addition, often the procedure is restrained to a limited number of iterations due to the project time constraints and limited insight into the sensitivity of parameters and any inter-parameter relationships taking place.

Overcoming these challenges requires the development of a particle-scale DEM material model that is fit-for-purpose; one that provides an approximation of bulk behaviour sufficiently accurate for the relevant engineering design requirements. This means that the model must capture all relevant effects, such as those manifesting from environmental conditions that dictate the flowability of a real bulk material, for example moisture content. To address this need DEM Solutions [6] and BMEA have devised the EDEM Material Model (Figure 1) and associated calibration methodology to allow DEM to be used with confidence in the mining and bulk materials handling sectors.

EDEM Material Model calibration methodology

The critical necessity for conducting DEM simulations with realism and value is calibration of the material models against real physical tests. To achieve an accurate representation of particle flow in the industrial application being studied using DEM, bench scale experiments which generate the flow conditions expected in the large scale application are required to develop an EDEM Material Model for either static or dynamic conditions.

Rather than relying on the data generated by the traditional tests, the DEM calibration methodology shown in Figure 2 is recommended to reduce the risk associated with DEM modelling and increase realism and confidence. To follow this philosophy, the following criteria and tasks have been identified for calibration of an EDEM Material Model:

- Use the real material as observed on site (where possible).
- Recreate the typical flow regime and bulk behaviour seen in the application via bench scale experiments (i.e. similar to the shear tester shown in Figure 3 to measure wall friction angles of sub 30mm material).
- Provide comparative observable measurements between experiment and simulation.
- Develop a fit-for-purpose EDEM Material Model (i.e. particle shape, particle size distribution and contact model inputs) using an automated optimisation algorithm to select the ideal parameters that best match the simulations with the experiments in the shortest time frame possible.
- If possible, apply the selected EDEM Material Model to a large scale DEM simulation of an existing application to verify the model. (Note: this may not be possible if the application does not yet exist). BMEA's variable geometry conveyor transfer facility (with Aerobelts up to 7 m/s) has been used successfully to validate EDEM simulations with unique flow data (such as, particle position, velocity and impact plate reaction loads).

To address the issues of determining the material and interaction input values that replicate the material flow observed in the smaller tests, DEM Solutions has developed and implemented an automated parameter optimisation technique. This approach eliminates the need for user interaction whilst determining the parameters required for an EDEM material model. By use of mathematical algorithms, inter-parameter dependencies can be handled automatically to achieve the desired results.

To further reduce the time required to obtain the desired EDEM material model, DEM Solutions has also developed a grid computing method that allows multiple simulations to be performed simultaneously. Such an approach is highly scalable with the distributed computer power that is available. By deploying the optimisation on a cluster, or even a cloud computing system such as the Microsoft Azure Cloud [7], it is possible to rapidly trial hundreds of parameter combinations simultaneously. This means the whole calibration process can be performed in a matter of hours or days, rather than weeks and months that can be required when performing a manual calibration process.

In short, a robust calibration exercise can be completed in a commercially viable time frame. The link with the real material provides confidence in DEM simulation results which allows the productivity of a design or trouble-shooting process to be increased.

Case studies: Application of EDEM material model methodology

The use of DEM in the bulk materials handling and processing industry has exploded in recent years especially for the design and analysis of conveyor transfer points. Prior to DEM, transfer chutes were generally designed using only empirical and continuum methods and prototyping designs via scale modelling. Although the analytical methods are not as comprehensive as DEM, they still provide valuable solutions to verify that DEM simulation predictions are realistic under certain conditions. Besides engineering

Figure 4: Simulation of a problematic transfer station conveying bauxite at 5000tph.

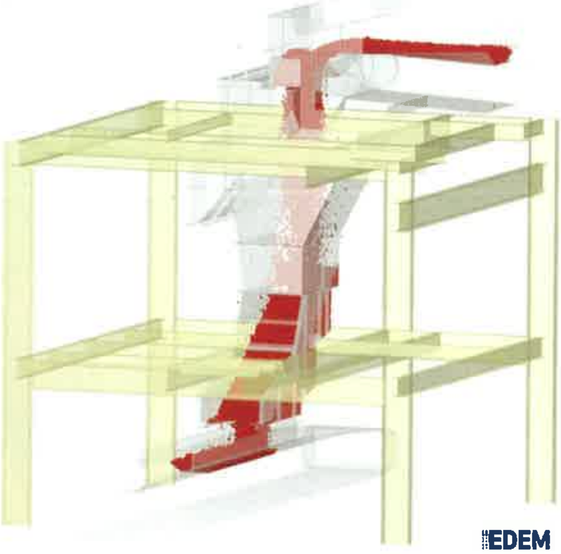

Figure 5: Simulation of current transfer station conveying bauxite at 3400tph.

know-how, conventional design approaches are used to design or trouble-shoot materials handling equipment, such as trajectory, rapid flow, continuity and wear models. DEM simulation then provides an additional design tool to verify a design to investigate any unforeseen issues from the use of analytical methods and design guides as well as optimise a design for increased functionality, capacity, efficiency and service life.

As DEM can model the trajectory of particles in 3-D, visual checks can be performed to examine any potential material build-up, segregation, unwanted flow patterns, wear, spillage, boiling, material degradation and much more. Transfer points that have complex geometries and very limited design tools to evaluate flow conditions such as rock boxes, micro-ledged chutes and cascading chutes are often difficult to design and ensure reliable flow due to the discontinuous nature of material flow and the influence of possible lump material.

Figure 4 shows a simulation of a transfer chute on a ship loader conveying bauxite at 5,000tph. The receiving conveyor belt is situated on a boom where the slewing and luffing angle continually varies during ship loading operations. The design of the chute is basic where material impacts the far wall of the chute and is guided onto the receiving conveyor with a funnel like chute. The presentation of the bauxite onto the receiving conveyor is generally poor resulting in non-central loading and boiling as slip between the belt and conveyor occurs. The consequence of this poor design is high maintenance due to wear of hungry boards, skirts and the belt. Figure 4 clearly shows the boiling and off centre loading predicted by the calibrated DEM model which occurs in reality. The reliability of the chute is reduced and the performance of the ship loader is compromised and detection of this problem during the design stage could have led to a superior design and reduced operating costs.

Figure 5 shows a DEM simulation of another problematic transfer station where the EDEM Material Model was developed using the methodology outlined in Figure 2. As this case study was a trouble-shooting exercise, quantitative measurements and qualitative observations could be obtained to compare against the DEM results to verify the accuracy of the calibrated EDEM Material Model. The transfer station shown in Figure 5 is located between a delivery conveyor (C1) and a receiving conveyor (C2) which run perpendicular to each other and the drop height from the top of conveyor C1 to the top conveyor C2 is approximately 7.3m. Transfer C1/C2 was originally designed to be a low maintenance transfer station where material discharges from C1 then impacts a vertical wall with a small ledge on the bottom which allows material to build up. Product is then redirected into the lower section of the chute which consists of several large horizontal ledges to create a rock box where the product is fed onto conveyor C2 through a V-plate to centralise the product.

A 3-D CAD model of transfer C1/C2 was developed using existing manufacturing drawings and site measurements to import into EDEM to conduct a series of DEM simulations of the flow of bauxite at maximum strength conditions through the current design. The general flow behaviour modelled using a calibrated EDEM Material Model shown in Figure 5 correlates well to the observations on site. The main problems associated with the average functionality of

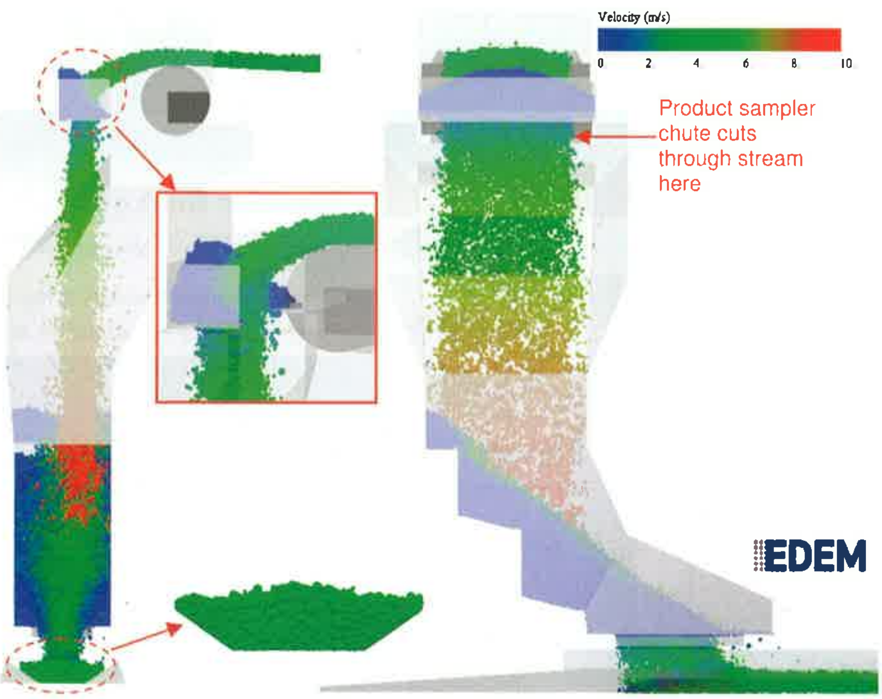

Figure 6: Simulation of current transfer station conveying bauxite at 3400tph.

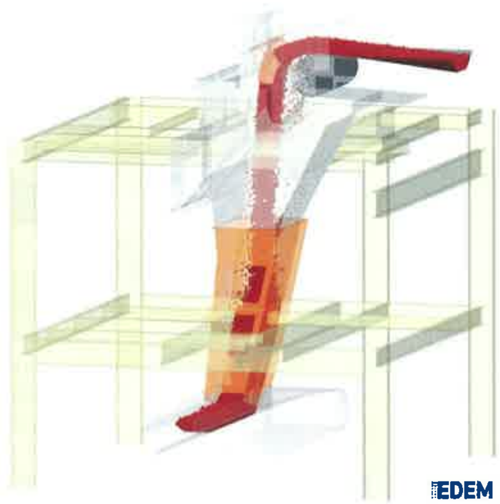

Figure 7: Simulation of modified transfer station conveying bauxite at 3400tph.

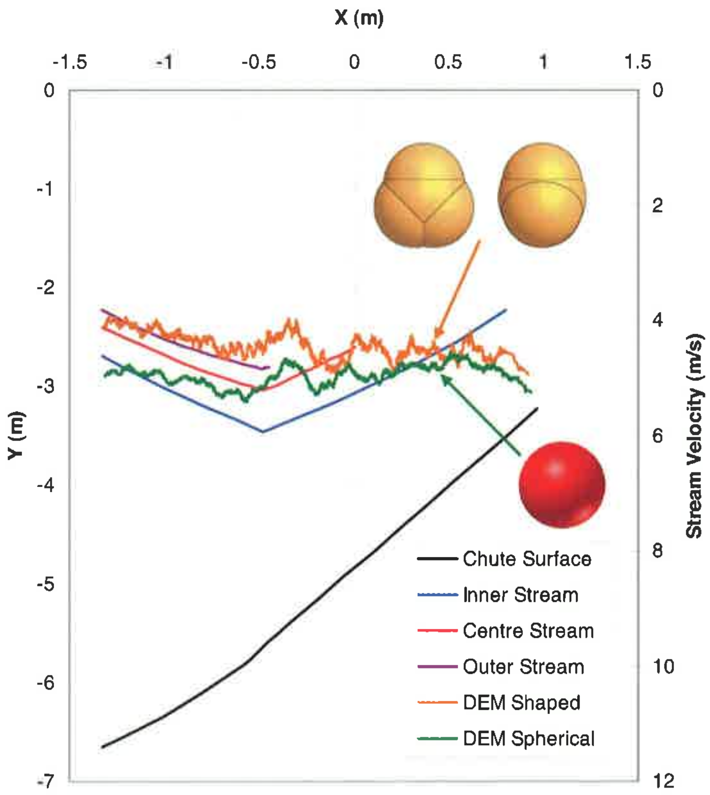

Figure 8: Comparison between DEM and analytical results in lower spoon of design shown in Figure 7 at 3400tph.

the current design can be identified from the EDEM simulations shown in Figure 6 directly or anticipated as follows:

- Asymmetrical flow from the upper head chute into the lower chute due to incorrect geometry in the upper head chute.
- Due to segregation and the restriction of flow due to the V-plate, dead regions are eventually created which lead to plugging and off centre loading onto C2.
- Blockages occur in the lower section of the chute due to the large horizontal ledges in the rock box and the presence of the V-plate which decelerates material flow (requiring regular hosing to remove the bauxite once plugged or prevent plugging).

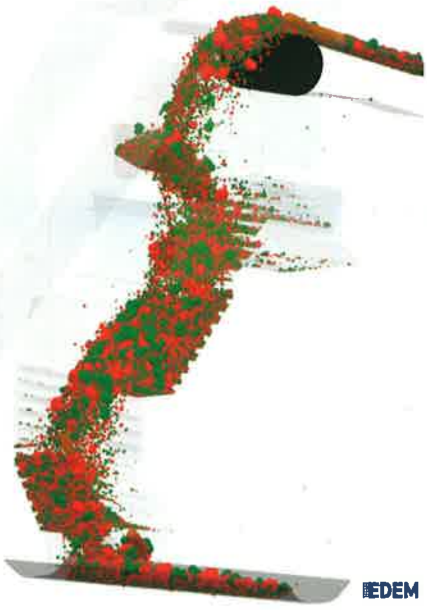

Figure 9: Simulation of a transfer station conveying coarse hard rock at 2200tph with occasional log debris.

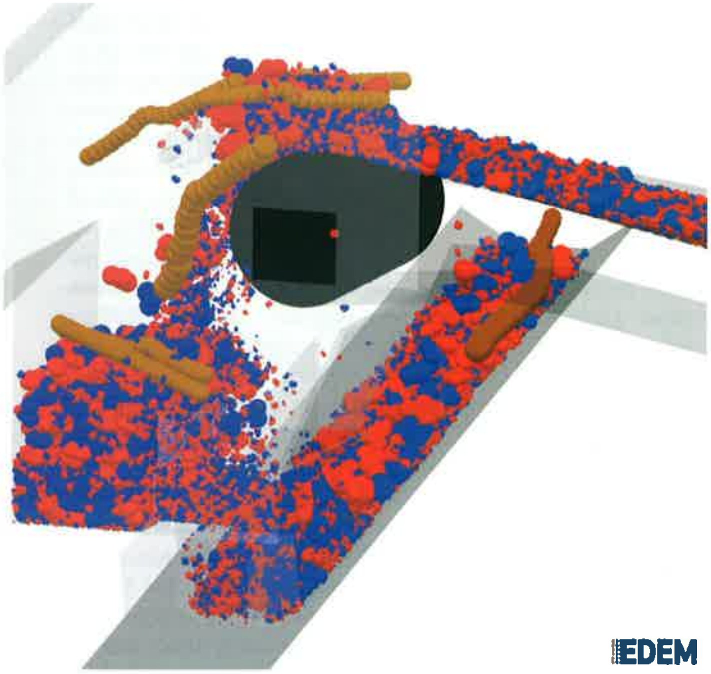

Figure 10: Simulation of an unstable blockage due to log debris at a transfer point conveying coarse hard rock at 1250tph.

- The V-plate in the feed chute is situated about 700mm above C2 which causes the material to almost drop vertically from the feed chute and splat onto the conveyor belt and skirting that leads to eventual wear of the skirts and belt cover.
- As shown in Figure 6, the effective inclination through the rock box and feed chute or the slope of the upper surface of the bulk material is rather low which reduces the material stream velocity and exacerbates the slow build-up of material. Also, as illustrated in Figure 6, the occupancy of the lower chute is high which does not adequately provide provision for transient flow rates or surges leading to blockages.

As the EDEM simulations of the design shown in Figures 5 and 6 matched well to the observed behaviour on-site and a good correlation between the stream velocity measurements existed, confidence was established in the developed EDEM Material Model. EDEM was then used to investigate several design modifications to improve flow through the transfer station and also reliability. Numerous concept designs were developed where modifications were made to the design of the upper head chute and the lower chute to centralise the flow into the lower section of the chute and establish rapid flow conditions.

These design options included the use of an impact plate or hood in the upper section of the chute and a straight inclined chute with a spoon to feed the material onto the receiving conveyor. To examine techniques to reduce wear on the lower chute, several methods were investigated to minimise impact and abrasive wear by placing micro-ledges around the impact zone on the lower chute. However, as bauxite is a wet and sticky material, the risk of material build-up was high so a more reliable design was pursued, shown in Figure 7.

In collaboration with Minerva Engineers, the design shown in Figure 7 was first designed using classical trajectory models to determine the location of an adjustable hood that is placed in the head chute to help centralise the flow into the lower chute. Chute flow models were then used to evaluate the flow of ore through the lower spoon to determine adequate geometry for reliable flow and presentation of material onto C2. The effects of surges and transient flow on the functionality of the chute were also modelled using EDEM to investigate any potential blockages and spillage which cannot be modelled using continuum methods that are based on steady-state conditions.

Figure 8 shows the stream velocity analysis in the lower chute which feeds the product onto C2, where the profile of the chute is drawn on Figure 8. As the transfer chute is a perpendicular arrangement, the initial impact velocity on the inclined chute surface varies with the changing drop height along the chute.

For the analytical analysis the stream velocity has been calculated based on three trajectories, these being the inner, centre and outer stream, where the drop height from the upper impact plate to the lower chute increases, respectively. The function of the spoon at the end of the inclined surface is to decelerate the material and reduce the normal component of velocity onto C2 to improve presentation and wear which is clearly shown by the analytical predictions in Figure 8.

The average velocity of the particles along the lower chute surface for both the EDEM simulations using spherical and non-spherical (shaped) particle shape representations has been overlayed on the analytical calculations in Figure 8. The predicted fluctuations shown in Figure 8 have been confirmed by high-speed video footage and subsequent velocity analyses. The parameters in the EDEM Material Models have been accordingly calibrated against experimental data and are dependent on the particle shape adopted and the particle size distribution to achieve similar bulk behaviour for both particle shape representations. As the moment of inertia is greater for the non-spherical particle compared to a single sphere, the rotational characteristics of a particle modelled using DEM are dissimilar where spherical particles can roll easier and obtain greater rotational energy. The shortcomings of using spherical particles and appropriate rolling friction models are noticeable when closely comparing the DEM results against non-spherical particle shape representations.

Generally, there was a good correlation between the results obtained using continuum methods and results obtained using DEM modelling for the concept design. As the transfer chute is of a perpendicular arrangement, it makes it more difficult to accurately apply the continuum models to analyse the stream velocity unlike DEM modelling which is a thorough 3-D analysis tool.

DEM modelling is also a valuable tool to examine the performance of equipment that has to handle lump material or even foreign objects such as metal rods and logs. Understanding how coarse particles or foreign objects affect particle flow in a system is a difficult task using analytical methods or even physical scale modelling. Figures 9 and 10 show examples of the application of DEM to model the complex flow of hard rock through rock box and micro-ledged type chutes.

These figures also show the flow of log debris through the chutes to examine potential blockages which are evident in Figure 10 and can be costly in terms of down time to unblock the chute and damage to the conveyor belt system (e.g. belt tear). As there is no V-plate or spoon to feed the material onto the receiving belt, DEM simulation has the capability to explore how well material flows through complex chutes and presents onto receiving equipment. It is also possible to analyse the forces and moments acting on different parts of equipment to examine the wear and life of equipment.

Conclusion

With the adoption of a systematic calibration process, such as the EDEM Material Model approach, DEM simulation provides a powerful design tool to improve bulk material flow and prevent plugging, spillage, belt mistracking, belt wear and minimise wear of structural parts. Incorporating DEM simulations early in the design process can have major positive impacts on revenue in terms of savings and efficiency.

It is very dangerous to assume or extrapolate anything when it comes to bulk material properties and behaviour. The consequences of making too many assumptions can be very serious with potential flow and reliability problems in handling and processing operations, such as conveyor transfers, reclaimers and ship loaders.

To avoid this problem in the DEM computer simulation approach to design, a new optimised calibration technology has been developed to adequately represent bulk material properties and flow behaviour. With new parameter optimisation techniques and the automated, grid computing approach, a fit-for-purpose EDEM Material Model can be delivered in a timeframe acceptable to industry.

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