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Predicting Bulk Flow and Behaviour for Design and Operation of Handling and Processing Plants

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Abstract

The reliable design and operation of bulk materials handling and processing plants can be difficult when dealing with complex geometries and difficult-to-handle materials, such as wet and sticky ore. Often a lack of detailed analysis of bulk material flow and process boundary interactions can lead to costly mistakes which can typically be identified easily once in operation. These problems can occur due to inaccurate characterisation during design, miscalculation of particle trajectories and velocities, and a lack of engineering tools to thoroughly visualise and analyse material flow through complex dynamic designs. This paper investigates the application of DE (Discrete Element) simulation to bulk material plant design by identifying current issues and presenting new methods of calibration and length-scale/dynamic validation. Examples and a case study are presented to demonstrate the key issues of this paper.

Keywords

processing, handling, operation, design, behaviour, plants, flow, predicting, bulk

Publication Details

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Predicting Bulk Flow and Behaviour for Design and Operation of Handling and Processing Plants

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Abstract

The reliable design and operation of bulk materials handling and processing plants can be difficult when dealing with complex geometries and difficult-to-handle materials, such as wet and sticky ore. Often a lack of detailed analysis of bulk material flow and process boundary interactions can lead to costly mistakes which can typically be identified easily once in operation. These problems can occur due to inaccurate characterisation during design, miscalculation of particle trajectories and velocities, and a lack of engineering tools to thoroughly visualise and analyse material flow through complex dynamic designs. This paper investigates the application of DE (Discrete Element) simulation to bulk material plant design by identifying current issues and presenting new methods of calibration and length-scale/dynamic validation. Examples and a case study are presented to demonstrate the key issues of this paper.

1. Introduction

Bulk materials handling equipment, such as transfer towers and chutes, are often responsible for significant challenges and down-time in the operation of ore processing plants and port facilities. 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, such approaches need to be combined with appropriate methodologies to provide maximum value during the design phase. This is especially true when designing systems that require complex equipment designs, and faced with difficult-to-handle materials, such as wet and sticky ore.

In the past, these critical components of a bulk materials handling system have been designed using methods such as analytical or continuum modelling, which do not appropriately describe the dynamics of the motion of the bulk material over the range of conditions found in operation. As an alternative to these traditional design methods, simulation-based design approaches are increasingly being used on a day-to-day basis to provide additional insight into the behaviour of bulk materials during processing and transport. This paper outlines the limitations of traditional design methods for the design of conveyor transfer points and chutes and demonstrates the additional insight that is possible through the appropriate deployment of the DE simulation method.

2. Improving Equipment Design through Modelling

In order to provide additional insight into the predicted flow behaviours of a design, modelling approaches can be used. When it comes to modelling bulk materials handling systems, generally two approaches are adopted: a continuum approach, where bulk materials are examined at a macroscopic scale using a 'lumped mass' analogy outlined discussed by Huque [1]; and the DE approach shown by Zhu et al [2], which reproduces the motion and interactions of individual elements within a bulk material as it passes through a design.

Continuum modelling provides engineers with an analytical approach to predicting the flow behaviour of a bulk material stream. Common applications of such approaches are in the prediction of trajectories of a material as it is discharged from a conveyor belt (see Figure 1). Grima and Wypych [3] show the application of continuum modelling and DE simulation to model an entire transfer chute.

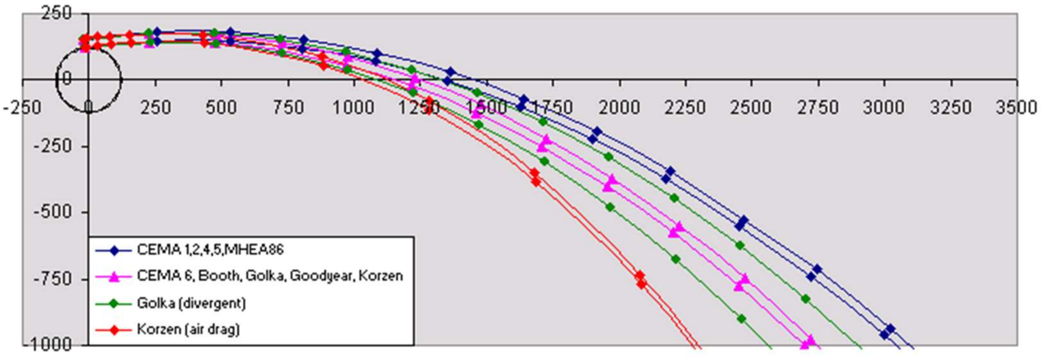


Figure 1 - Comparison of trajectory model predictions for a belt speed of 5 m/s (Hastie [4])

In recent times the DE approach has been increasingly used to study the behaviour of bulk materials where discontinuous flow occurs, such as conveyor transfer design (see Figure 2). DE 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, DE 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.

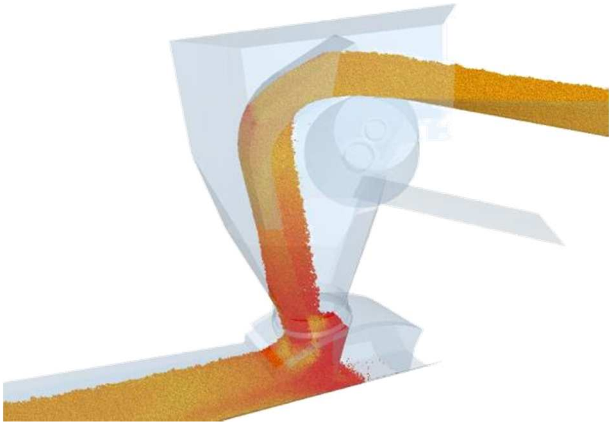
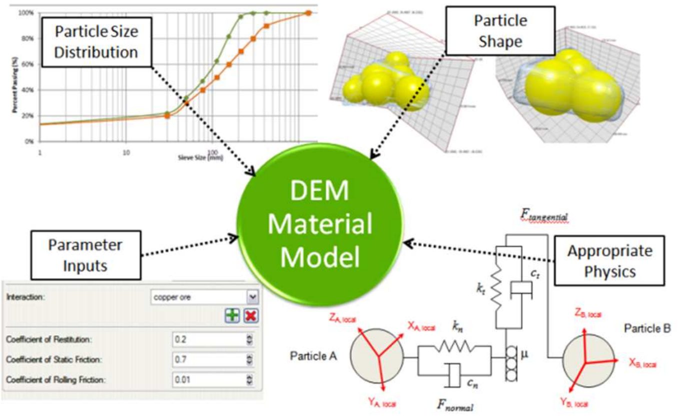


Figure 2 - Example of a DEM simulation for a transfer point where the material has been coloured by velocity

3. Effective Application of DE Simulation

At the centre of any DE simulation is the 'material model', which is the virtual representation of the bulk material. The DE Material Model includes a number of components, including the definition of the shape and size of the representative particles; the required physics models (for example, contact, cohesion); material properties such as density; and values for the parameters that are required for the physics calculations (Figure 3).



Interaction: copper ore
Coefficient of Restitution: 0.2
Coefficient of Static Friction: 0.7
Coefficient of Rolling Friction: 0.01

Figure 3 - The key components that make up a DE Material Model

When setting up a simulation using DE software, these parameter inputs are ultimately what dictate the manner in which a simulated material will behave. Designing bulk material handling equipment based on non-calibrated or an improperly calibrated DE model 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 incapacity of systems in handling surges. Reducing the uncertainty of parameter selection is central to using DE 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, as discussed by Curry et al. [5] and Grima et al. [6].

To establish this link, the application of an appropriate testing program is required that meets the following criteria:

- Be sufficiently scaled to allow the real material to be tested without additional pre-processing and must include the full size range.
- Reproduce the flow regimes likely to occur within the industrial application.
- Provide measurements that correlate with those that can be observed in a DE simulation to allow parameter calibration to be performed.

Figure 4 and Figure 5 show examples of the type of experiments that are conducted on the real bulk material and equipment material to examine the static and dynamic behaviour of the bulk material under various regimes.

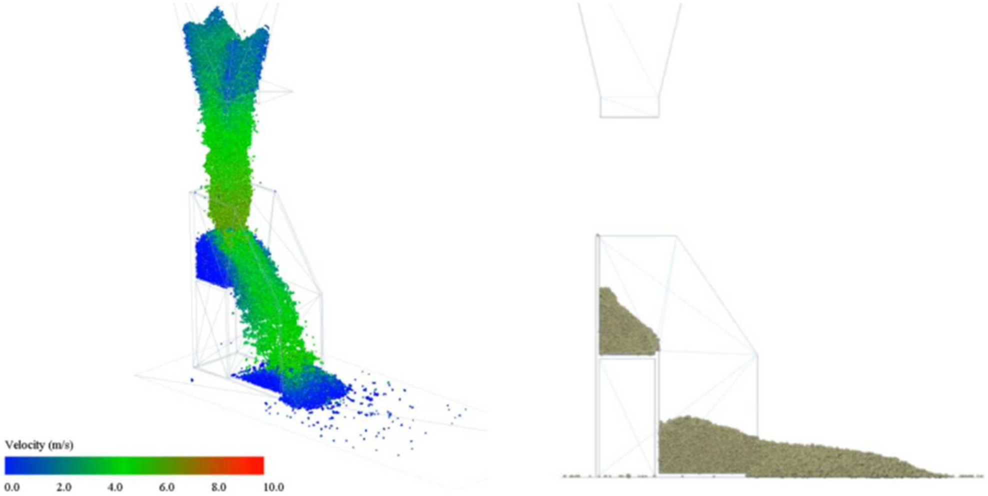


Figure 4 - Example of experiment to calibrate particle-to-particle interactions under dynamic conditions

Figure 5 - Example of experiment to calibrate particle-to-wall interactions under static conditions

4. Industrial Case Study

4.1 Overview and Continuum Modelling

Figure 6 shows a micro-ledged transfer chute that is designed to handle crushed copper ore. The chute is designed with cascading ledges that allows ore to build up between the ledges to help protect the underlying structure. The handleability of the copper ore varies from free flowing when the moisture level is low to cohesive when the ore is wet. The ore also consists of a high proportion of fines. To evaluate the performance and reliability of the transfer chute, the flow through the transfer point was examined using available continuum models (presented by Huque [1]) and DE simulation.

The transfer chute has a design capacity of 1,300 tph. The conveyor interchange consists of a delivery belt conveyor (CV01) that operates at 4 m/s and a receival conveyor (CV02) with a belt speed of 1.2 m/s. Continuum models were used to predict the discharge trajectory and the stream velocity through the chute. The CEMA [7] model was used to determine the discharge trajectory and rapid flow models presented by Huque [1] for a straight inclined chute were used to evaluate the stream velocity. Modelling bulk flow through a cascading ledged chute is complex due to the internal shearing and interlocking of particles. There is no continuum model available specifically designed to calculate the velocity of bulk material through the chute configuration shown in Figure 6. However, rapid flow models for curved and straight chutes can be adapted to estimate the stream velocity through the ledged head and feed chute in Figure 6. Generally the drag/resistance between the bulk material and chute surface is governed by wall friction but as internal shear is governing resistance, the internal friction of the ore can be considered. The approach adopted in this paper is to approximate the friction between the flowing and dead ore based on the effective angle of internal friction, δ_e (i.e. $\mu=\tan(\sin(\delta_e))$).

Table 1 provides a summary of the key design parameters used to estimate the stream velocity at two locations: the exit of the head chute (Bin A); and exit of the feed chute at the last ledge before the V-Plate/Slot (Bin B) shown in Figure 6. The stream velocity has been evaluated based on a range of δ_e. The slip velocity between the bulk material and the belt conveyor at the point of impact has also been evaluated in Table 1. Although the continuum doesn’t account for the complex flow patterns at a particle scale level, the approach adopted appears to provide plausible results to evaluate the chute design. For reliable performance of a chute, maintaining rapid flow conditions is advised where the material continues to accelerate in the direction of flow. Table 1 indicates that the material velocity is increasing through the chute, however as the material is presented onto a slower conveyor; the material velocity is greater than the belt speed. This indicates a potential issue with notable deceleration of the material reducing the ability of CV02 to efficiently draw ore from the transfer point. Use of continuum techniques to model the interfacing of the feed chute with CV02 is limiting to predict the complex 3D flow patterns occurring to ensure the chute geometry is sufficient for continual flow.

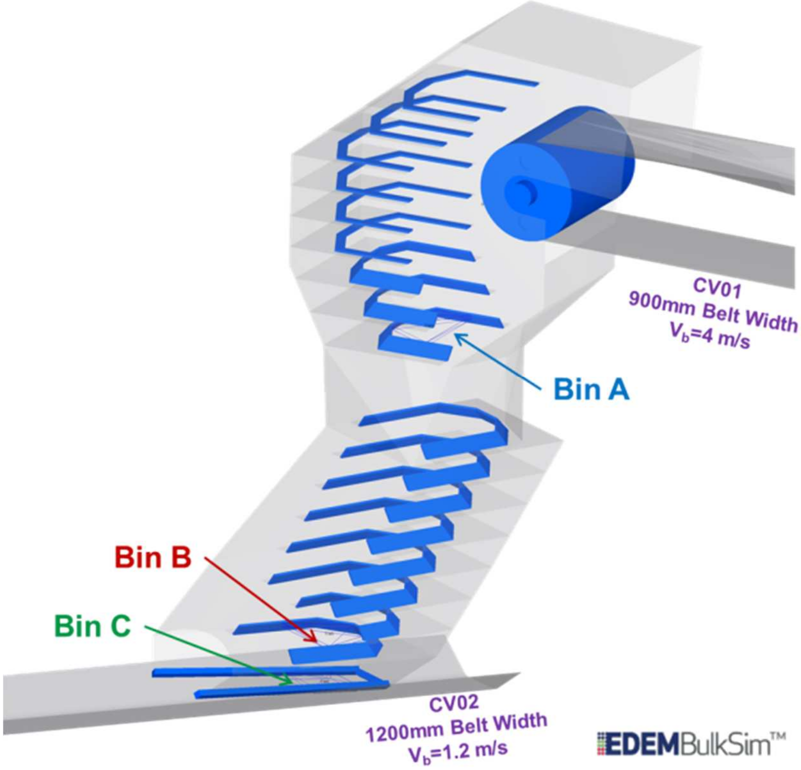


Figure 6 – General arrangement of transfer chute

Table 1 - Summary of design parameters and results from continuum analysis

Parameter	Value			
Bulk Density (kg/m^3)	1,750			
Effective Internal Friction (deg)	45	55	45	55
Flow Rate (tph)	1,300		650	
CV01 Belt Speed (m/s)	4			
CV02 Belt Speed (m/s)	1.2			
Bin A - Velocity (m/s)	3	2.9	3	2.8
Bin B - Velocity (m/s)	4.1	4	4	3.9
Slip Velocity on CV02 (m/s)*	-0.78	-0.74	-0.72	-0.68

*Note: -ve means material velocity > belt speed

4.2 DE Simulation

DE simulation was employed to examine the shortcomings of the analytical methods to determine if the proposed chute design will retain continual flow, central loading with no blockages and spillages. DE simulation provided the opportunity to test the design, not only at the design flow rates, but also under extreme material conditions (i.e. cohesion) to determine operational limits. To begin the modelling process, the material properties of the ore were examined to assist in the development of a calibrated DE Material Model at various moisture levels. Initially a free flowing copper ore was modelled to assess the chute design that is commonly used for free flowing products that display low cohesion. Figure 7 shows one of the calibration simulations that was conducted to develop the DE Material Model. The angles of repose of the poured conical pile are relatively low between 27 and 28 degrees indicating that the material is free flowing according to Hill [8]. Non-spherical particles and a non-cohesive contact model (Hertz-Mindlin non-linear elastic model) were used in this investigation to model the bulk flow of the copper ore.

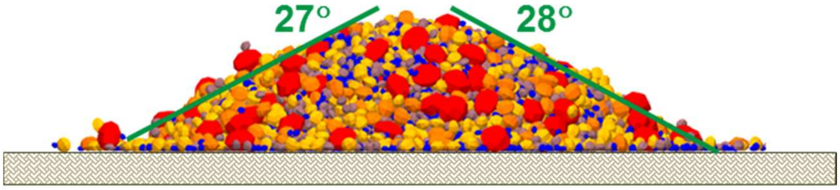


Figure 7 – Pile formation of free flowing copper ore

Figure 8 shows the DE simulation of the copper ore chute at the design capacity with the proposed design where the particles are coloured according to velocity. Figure 8 shows that the transfer chute at an arbitrary intersection angle manages well to capture the discharged material and redirect the model centrally onto CV02. However, over a short operating period (160 seconds) a blockage occurs. Reviewing Figure 9a, there is a discrepancy between the mass flow rate on CV01 and CV02 that results in a blockage as the material retained in the chute increases. A possible cause for this blockage is poor interfacing of the exit of the chute with the receiving conveyor (CV02). This result confirms the concerns that were identified with analytical calculations that loading and acceleration of material on to CV02 could be problematic.

Another simulation was conducted to examine the capability of the transfer chute to handle a reduced throughput at 650tph. When the chute was operated at half capacity, Figure 9b indicates that the likelihood of blockage is reduced as there is a better match between the mass flow rates in and out of the transfer chute. Improvements in the chute design were explored by firstly improving the interfacing of the chute with CV02 by providing greater relief and clearance. Figure 10 shows a significant improvement with the flow of material through the exit of the chute where the outlet appears to be more active with ore flowing along the V-Plate/Slot. Also Figure 9c shows a substantial improvement of the mass flow rate on CV02 when compared to Figure 9a.

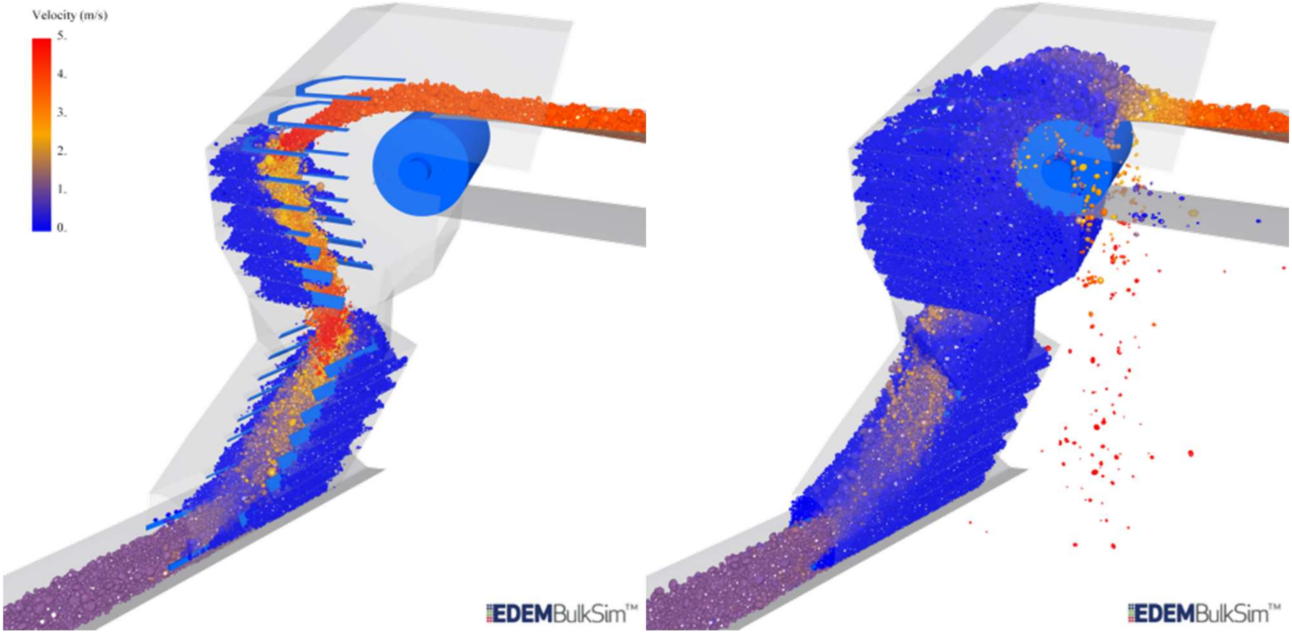
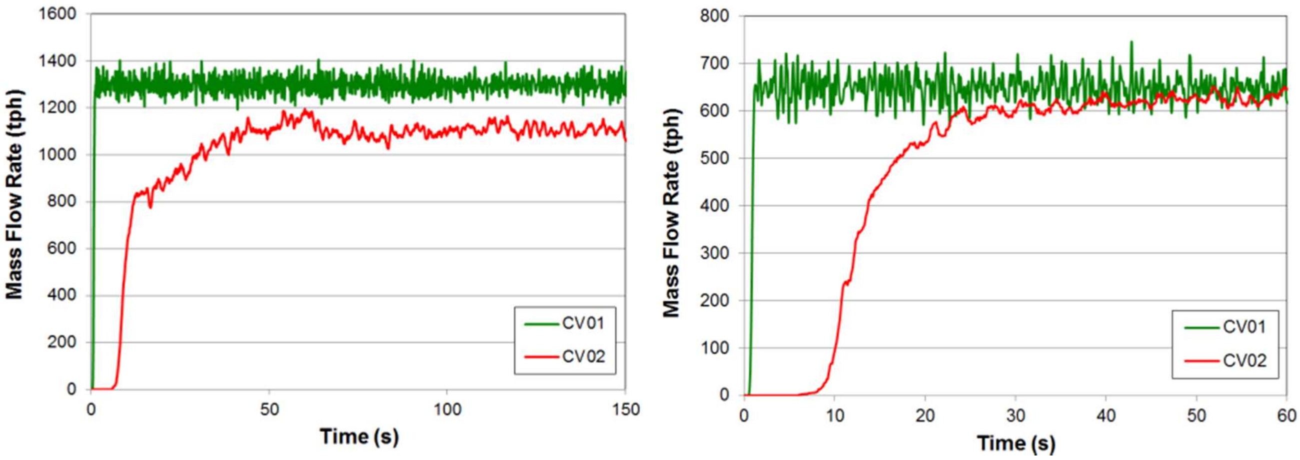
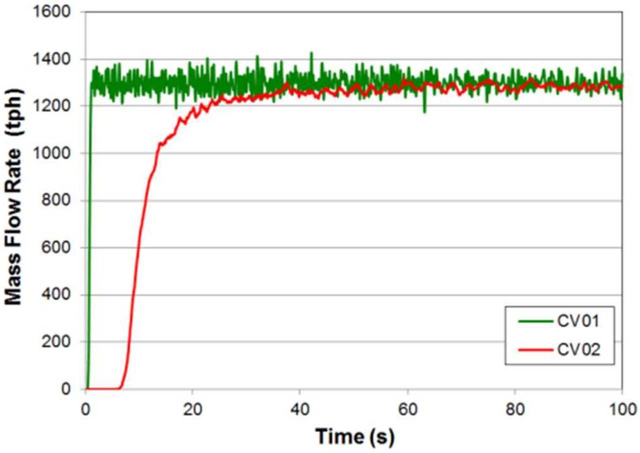


Figure 8 – DE simulation of proposed transfer chute design with throughput of 1,300tph at 20 seconds (Left) and 160 seconds (Right)



(a) Proposed design with throughput of 1,300tph (b) Proposed design with throughput of 650tph



(c) Revised design with throughput of 1,300tph

Figure 9 – Mass flow rate on CV01 and CV02 from DE simulations

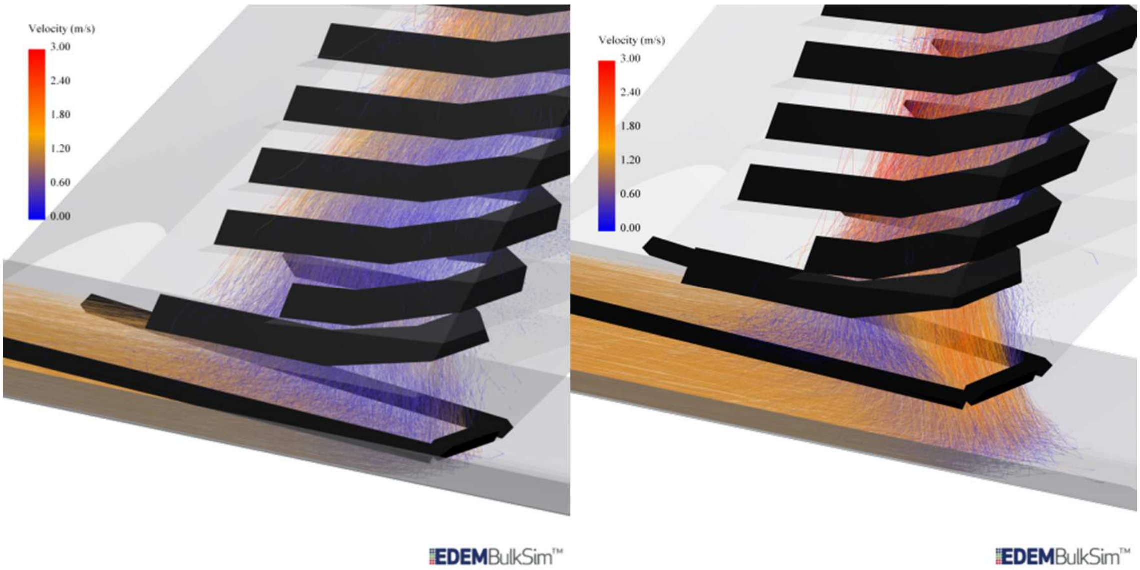


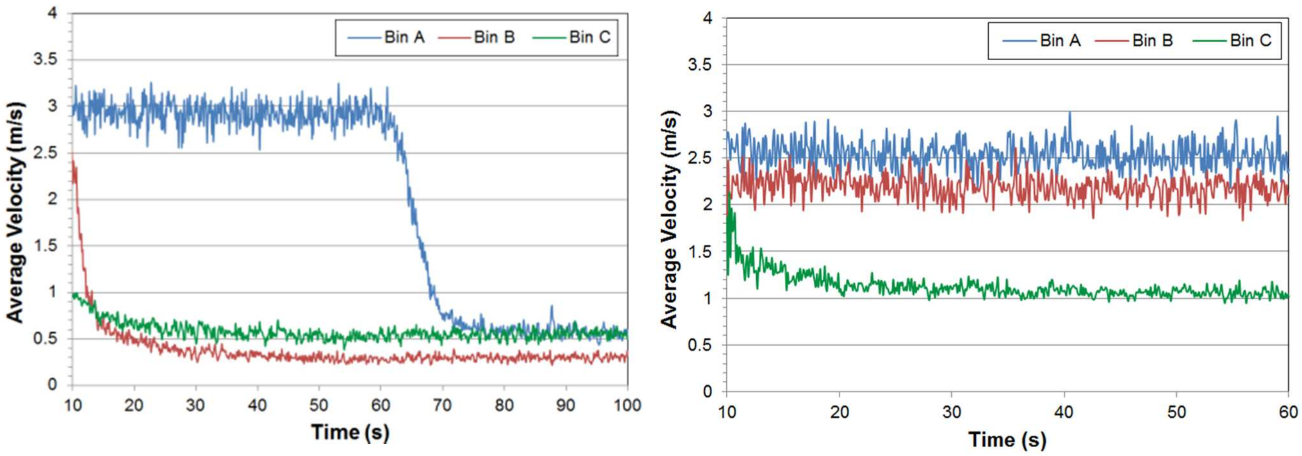
Figure 10 – Interface of feed chute with CV02 from DE simulations at 20 seconds with throughput of 1,300tph; proposed design (Left) and revised design (Right). Note: streaming representation has been used to show the path of the particles

4.3 DE Simulation Velocity Analysis

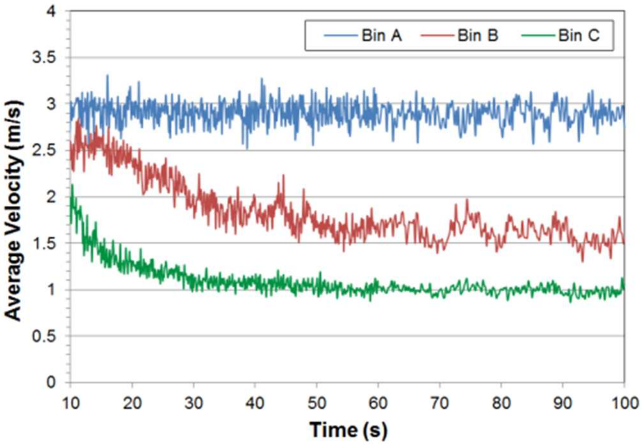
A velocity analysis of the DE simulations was conducted to compare results to the continuum calculations. Three bins were placed into the DE models shown in Figure 6 to evaluate the average velocity (magnitude) of particles within or passing through the three bins at various locations in the head and feed chute. The custom shaped bins were placed in the active region between the ledges so particles that are dead within the ledges were not considered.

Figure 11a shows that the velocity of stream exiting the head chute using the proposed design at design capacity correlates well with the continuum data in Table 1 before the head chute blocks. Once the velocity near the exit of the feed chute stabilises after approximately 30 seconds, there is a significant difference in the DE simulations (all design cases in Figure 11) and the continuum results. Figure 11a shows that the average stream velocity near the exit of the feed chute is below 1 m/s and the velocity in Bin C is greater than the velocity in Bin B. This indicates a significant deceleration of the material and the onset of a blockage. By increasing the clearance between the feed chute and CV02, Figure 11c shows an improvement in the stream velocity where there is a gradual deceleration of the material as it is presented onto CV02.

When the throughput is reduced to 650tph in Figure 11b, there is a minor reduction of the stream velocity exiting the head chute to approximately 2.7 m/s, which was foreseen with the continuum calculations in Table 1. When a reduced quantity of material passes through the feed chute, the average stream velocity increases especially at Bin B when comparing Figure 11a and Figure 11b. As the continuum method is based on a ‘lumped mass’ analogy, the velocity gradients through the material stream due to the material interactions with the horizontal ledges are not modelled with the same intricacy as the DE simulations. Thus DE simulation provides greater insight into the complex flow patterns that occur with transfer chutes with complicated geometry. The current continuum models are well suited for self-cleaning rapid flow chutes where the major frictional drag is present between the bulk material and chute surface/liner. DE simulation also provides superior visualisation of the particle flow and interaction of the bulk material with equipment to evaluate the performance of a design and optimise the design of equipment for reliable operation as demonstrated in Figure 10.



(a) Proposed design with throughput of 1,300tph (b) Proposed design with throughput of 650tph



(c) Revised design with throughput of 1,300tph

Figure 11 – Average particle velocity through analysis bins shown in Figure 6 from DE simulations

4.4 Segregation

Segregation through a transfer station can create undesirable problems at a transfer point and downstream operations. When there is a migration of fines within a transfer chute, blockages and non-symmetrical flow patterns can occur. As the fines are generally the source of material build-up and flow problems, retaining a uniform distribution of particle size throughout the transfer point is beneficial. Examining segregation using analytical techniques is limiting without the capability to model individual particles and their interaction with other particles. DE simulation provides capability to model the physics of individual particles with varying physical (e.g. shape, size and mass) and mechanical (e.g. stiffness and inertial) properties to examine the trajectory of particles within a system or transfer point.

Figure 12 shows the colouring of particles by mass through the transfer chute. The DE simulation has been setup so particles with a fairly uniform size distribution enter the transfer chute (see left image in Figure 12). As the material flows through the chute, there is clear presence of fine particles (indicated by blue particles) situated on the left side of the feed chute and the bottom of material loaded on CV02 (shown by green outlines in Figure 12). The segregation of fines towards one side of the feed chute indicates a high chance of material build-up over extended operation that reduces the cross-sectional area for flow. Once the throat of the chute is reduced causing non-symmetrical flow, off-centre loading on CV02 and blockage is possible. Generally, a blockage caused by segregation and material build-up is a long gradual process that is difficult to emulate with DE simulation (due to computing limitations and minimum particle size that can be modelled) but DE simulation can predict the onset of a blockage when results are interpreted appropriately.

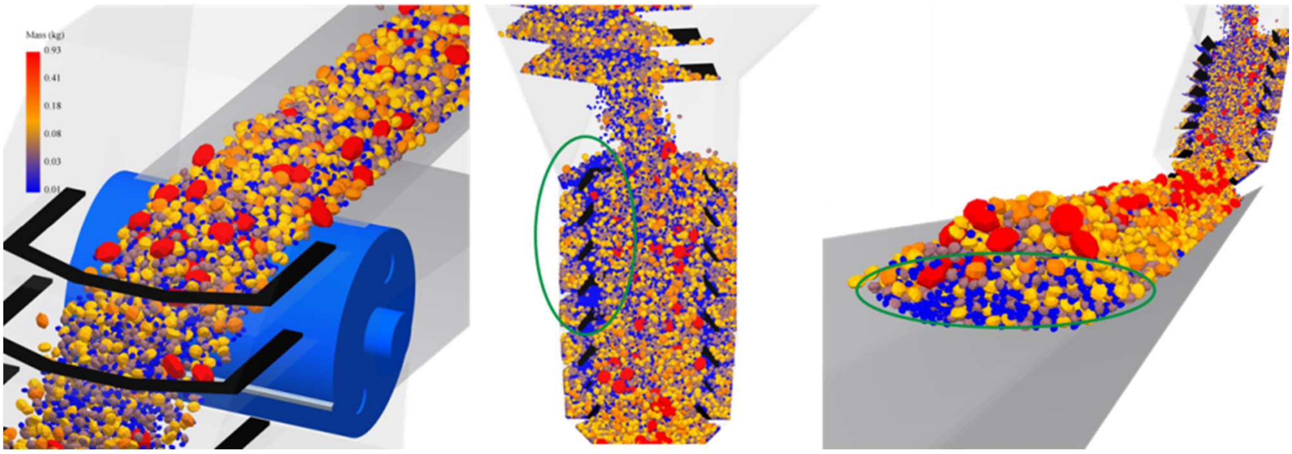


Figure 12 – DE simulation detecting segregation in feed chute and on CV02

5. Concluding Remarks

Through a case study it is demonstrated that the use of DE simulation in the design and evaluation of bulk materials handling equipment can lead to a more reliable and robust materials handling system. In order to have the confidence to make design decisions based on DE simulation results, it is imperative that there is a link between the material represented in the simulation and the real-world bulk flow behaviours via a calibration methodology. By calibrating DE Material Models against dynamic tests that use material samples representative of the material to be handled, it is possible to define the necessary input values that allow real world flow behaviours to be reproduced.

As presented in this paper, DE simulation that is based on an appropriately calibrated material model can then be used to provide insight into equipment performance, even for complex equipment designs and also in processes that involve multiple, hard-to-handle materials.

6. References

[1] Huque, S.T., Analytical and Numerical Investigations into Belt Conveyor Transfers, PhD Thesis, University of Wollongong, Wollongong, NSW, Australia, 2004.

[2] Zhu, H. P., Zhou, Z. Y., Yang, R. Y. and Yu, A. B., Discrete particle simulation of particulate systems: A review of major applications and findings, Chemical Engineering Science, Vol. 63, No. 23, 2008, pp. 5728-5770.

[3] Grima, A. and Wypych, P., Application of EDEM to Chute Design using a Calibrated Material Model in Proceedings of the 3rd EDEM Conference, Edinburgh, Scotland, 31 March - 1 April 2011.

[4] Hastie, D. B., Belt Conveyor Transfers - Quantifying and Modelling Mechanisms of Particle Flow, PhD Thesis, University of Wollongong, Wollongong, NSW, Australia, 2010.

[5] Curry, D., Favier, J. and LaRoche, R. D., A Systematic Approach to DEM Material Model Calibration, in Proceedings of the 6th International Conference for Conveying and Handling of Particulate Solids (CHoPS), Brisbane, Queensland, Australia, 3-7 August 2009, Proceedings on USB, pp. 51-54.

[6] Grima, A. P., Hastie, D. B., Curry, D., Wypych, P. W. and LaRoche, R. D., The beginning of a new era in design: calibrated discrete element modelling, Australian Bulk Handling Review, Informa Australia, Vol. 16, No. 6, 2011, pp. 14-21.

[7] CEMA, Belt Conveyors for Bulk Materials, 6th Ed. 2nd Print, Florida, USA, Conveyor Equipment Manufacturers Association, 2007.

[8] Hill, L., Bulk solids handling: an introduction to the practice and technology, 1st Ed. New York, Chapman and Hall, 1987.