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Bias of cohesive bulk materials sampled by falling-stream cutters

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Discrete element modelling (DEM) has proved to be a useful method for analysing sample bias for falling-stream cutters. It provides detailed information on bias and size dependent extraction ratios based on closely matched reference and actual samples taken from the same simulations. It has allowed the identification of additional operational and design parameters which influence sample cutter performance. To date, this has been performed for cohesionless bulk materials. Wet bulk materials typically become sticky and this strongly influences their flow behaviour and particularly the mobility of fine particles and the overall flowability of the material. The interaction of the degree of cohesiveness of the material with the size of the cutter is investigated. The effect of cohesion on the mechanisms that lead to sample bias in falling-stream cutters is discussed.

Keywords: sampling, DEM simulation, sample bias, accuracy, precision

Introduction

Many materials, which need to be sampled, can be regarded as particulate materials for which any cohesive forces between particles can be neglected. However, cohesive forces between particles can be very important for damp or wet bulk materials such as in process and waste streams from mineral processing plants, bulk materials with significant fines fractions (such as coal and iron ore) and materials with sticky interstitial material such as clay. Such materials are sometimes described as ‘sticky’. This stickiness reduces the mobility of fine particles more than it affects the mobility of large particles, so it would be expected to affect the bias of sampling procedures.

In this paper, we describe a way of incorporating cohesiveness into discrete element modelling (DEM) and investigate the effect of cohesion on sample bias for a falling-stream cutter. Such cutters are commonly used as the first-stage sampling devices in economically important situations.

Including cohesion within DEM

To predict the forces occurring in a collision, we use a classical linear spring and dashpot collision model. The collisional forces and the basic DEM method are as described in detail in Cleary (1998, 2004) therefore, details are not included here.

The aim of this investigation is to explore the effect on sample bias of the cohesion that occurs in some bulk materials. Cohesion can originate from liquid bridges, from saturated, interstitial fluid or from the inclusion of inherently sticky materials such as clay. The detailed micro-mechanical behaviour of the forces between particles in such situations is not well understood. We, therefore, choose the simplest possible form of the cohesive force for this study. The cohesive force is assumed to depend, linearly, on the extent of inter penetration of a cohesive layer of thickness, δ, covering each of the particles and to only apply in the normal direction. For particles whose cohesive layers overlap by Δx, but whose underlying particles are not in contact, the overlap Δx, the force has the form:

$$F_c = k_c(\delta - \Delta x) \qquad [1]$$

if $\Delta x < \delta$ and zero, otherwise, where k_c is the stiffness of the cohesive layer. The cohesive force is a maximum when the particle surfaces are in contact and decreases linearly as the particles separate. This reflects the declining strength of a cohesive bond with extension due to the declining cross-sectional area of the cohesive bond for the clay type case or the decreasing number of fine particle bonds in the case of cohesive fines. Within DEM, the cohesive force is added to the collisional force to give the net, normal force that is then used in the solution of the equations of motion in the normal way. The tangential force is given by the conventional tangential force.

To see how this works in practice, consider two particles that are stuck together. The cohesive force pulls the particles together and the collisional, repulsive force balances this leaving the pair bound in equilibrium and with no relative motion. The normal component of the contact force controls the tangential force through the Coulomb limit, which gives the bound pair an inherent tangential resistance to motion. The Coulomb frictional limit relates to asperities that prevent sliding on the surfaces of real particles. The same considerations still apply even when there are small amounts of interstitial material. This neglects any additional tangential resistance from viscous type forces within the cohesive interstitial layer. The tangential force already provides significant resistance to motion so changes due to any additional forces are at most minor. Their explicit inclusion into DEM would require significant experimental characterization of the behaviour of such materials in order to develop improved, cohesive models including these effects. The example pair of cohesive particles will remain in contact until some external force (caused by collision with a wall or another particle) is applied to the pair. Such a collision can press the particles closer together or cause them to be pulled away from each other. If enough energy is supplied by the external collision to stretch the cohesive bond to its breaking point (when the cohesive layers lose contact with each other) then the cohesive bond will be broken.

DEM simulations could allow the parameters describing cohesion to be different for every pair of particles or to be functions of particle attributes, such as particle size. In the absence of any measured data on the cohesive strength distribution across pairs of particles within bulk materials, and because this is intended to be a generic study, we choose a relatively simple approach where all the particles have the same cohesive layer thickness and the same cohesion stiffness. The maximum cohesive force, which is given by $k\delta$ is, therefore, the same for all pairs of particles.

A simple way to characterize the strength of cohesive forces is the ratio of the maximum cohesive force to the weight of the largest particle. This is referred to as the Bond number. If a particle was stuck to the bottom of a horizontal surface, the Bond number measures how many particles of that size a cohesive bond could support.

In this study, we consider a range of Bond numbers from 0.01 to 1.0, which covers the range from where cohesion has only very weak effects up to where the material is quite sticky. In practice, Bond numbers can exceed 100 for very small particles, so the current range is representative of the cohesion that can be found in coarse bulk materials but is far from extreme. A cohesive bond will have a much weaker effect on a coarse particle than it does on a smaller particle. Big particles have more inertia and are relatively more able to break a cohesive bond than a small particle stuck in the same cohesive material and, therefore, experiencing the same cohesive force. So, for a given level of cohesion smaller particles stick together more than do coarser particles.

In comparison to real situations, moisture and small particles are not explicitly modelled. The effects of moisture and small particles on larger particles are being approximately modelled by inclusion of calibrated short range cohesive forces.

Simulation configuration

The setup used here was based on the falling-stream cutter used in Cleary *et al*. (2005, 2008a and b). Specifically:

- All particles were spherical
- The particle size distribution was uniform on a mass basis between 6 mm and 30 mm. The bottom size had been 7.5 mm in the earlier work
- The coefficient of restitution was 0.3
- The friction coefficient was 0.5
- The material density was 3 000 kg/m^3.
- Cutter blades were 10 mm thick with rounded leading edges
- The conveyor belt was 1.2 m wide and had a speed of 3 m/s
- The tonnage on the belt was 1 000 tonnes/hr
- The cutter moved at 0.6 m/s
- Material falls about 1.5 m vertically from the head pulley before hitting the cutter blades.

Two DEM experiments were conducted for this study. The first experiment, investigated the effect of the amount of cohesion for a cutter with an aperture of 100 mm, which is about 3.3 times the top size, D, of the material being sampled. The second experiment ,investigated the effect of cutter aperture for the most cohesive material. Five replicates were run for each of the conditions investigated.

Cutter bias was measured for particle size, which was measured by categorising particles into 12 size categories: 6 to 8 mm diameter, 8 to 10 mm diameter, … , 28 to 30 mm diameter.

The samples taken by the sample cutter were compared with reference samples. The method for determining these is the same as discussed in Cleary *et al*. (2005, 2008a). Briefly, as particles pass through a sampling plane situated just after the head pulley, their current trajectories are computed to see whether they will pass between the blades of the sample cutter. If so, they are considered to belong to the reference sample. This eliminates most sources of variability other than that arising from the interaction with the cutter and so only five replicate simulations are required to detect even small biases. Particles in the reference sample which are not sampled are described as 'missed' and particles which are sampled but were not in the reference sample are described as 'extra'.

A very small number of missed particles sometimes remain attached to the cutter blades at the completion of DEM simulations. This is analogous to the build-up of material on cutter blades which sometimes occurs in practice when very cohesive materials are sampled. However, we do not claim that the current modelling of the amount of build-up is realistic.

Experiment investigating effect of amount of cohesion

Once a cohesive material separates from the head pulley, its behaviour is quite different from that of non cohesive material. The cohesive bonds of particles with their neighbours hold groups of particles together. When water falls from a tap, cohesion causes the stream to narrow as it accelerates. Particles in cohesive granular material have very limited ability to locally re arrange themselves so that the stream can become thinner. Instead, the stream fractures into clusters. Each of the clusters then moves through the air like a single large particle. The size of the clusters is controlled by the level of the cohesion. For Bond numbers of 0.01 to 0.1, many fine particles form small clusters that behave as if they were larger particles. As the level of cohesion increases, then so does the cluster size. For Bond numbers near to 1, the clusters are generally much larger than the largest individual particles. They are better characterised as large blocks or fragments of material.

Figure 1 shows the progress of the cutter across the falling stream for the most cohesive case (Bond number 1.0) viewed from above. For ease of reference, we will refer to the cohesion level as a percentage of the maximum Bond number in our simulations (which is 1.0). So this case is labelled as 100% cohesion. In Figure 1a, the sampler has not yet contacted the particle stream. Note that the particle stream fragments as it falls. In Figure 1b, the cutter has moved well into the stream and is cutting into the falling cohesive blocks of particles. The material deflected by hitting the cutter blades tends to break into small agglomerates and many individual particles are also visible. As for cohesionless material, the vast majority of the reference sample (coloured yellow/light grey) enters the cutter with a moderate spray of this material being deflected to either side. Figure 1c shows the cutter about 70% of its way through the falling stream. The spray of particles created by the cutter is much stronger than in Figure 1b. There is clearly much more material deflected by the cutter blades. A significant amount of this sprayed material is yellow/light grey and represents missed material. Some large non reference particles are clearly visible entering the cutter as well.

In Figure 1d, the cutter has already passed beyond the edge of the stream, but there is still much sprayed material visible and still quite of lot of material within the cutter that has not yet fallen down into the collection chute. This highlights the role of cohesive forces in slowing the passage of the particles once they are within the cutter body.

Figure 2 shows the cutter mid way across its sample pass for a range of cohesive levels from 0% to 100%. The top row of images shows the low and non cohesive cases (0%, 1% and 3.2%). There is visually little difference between these cases in the flow into or around the cutter. The bottom row shows the more strongly cohesive cases. For a 10% cohesion level the amount of material sprayed by the cutter has visibly increased. For the 31.2% cohesion level, the falling stream can be seen to be breaking up into transverse blocks or fragments. They are less distinct than for the 100% cohesion case. The amount of spray from the cutter is increased. Finally, the 100% cohesion level gives the largest and most visible fragmentation of the stream and the largest amount of spray from the cutter. However, despite these visible changes in the structure of the falling stream, the sampling process continues to operate in more or less the same way as for the cohesionless case.

The width of the stream as it passes over the head pulley is smaller for the more cohesive material. As the material moves away from the head pulley, there is a greater amount

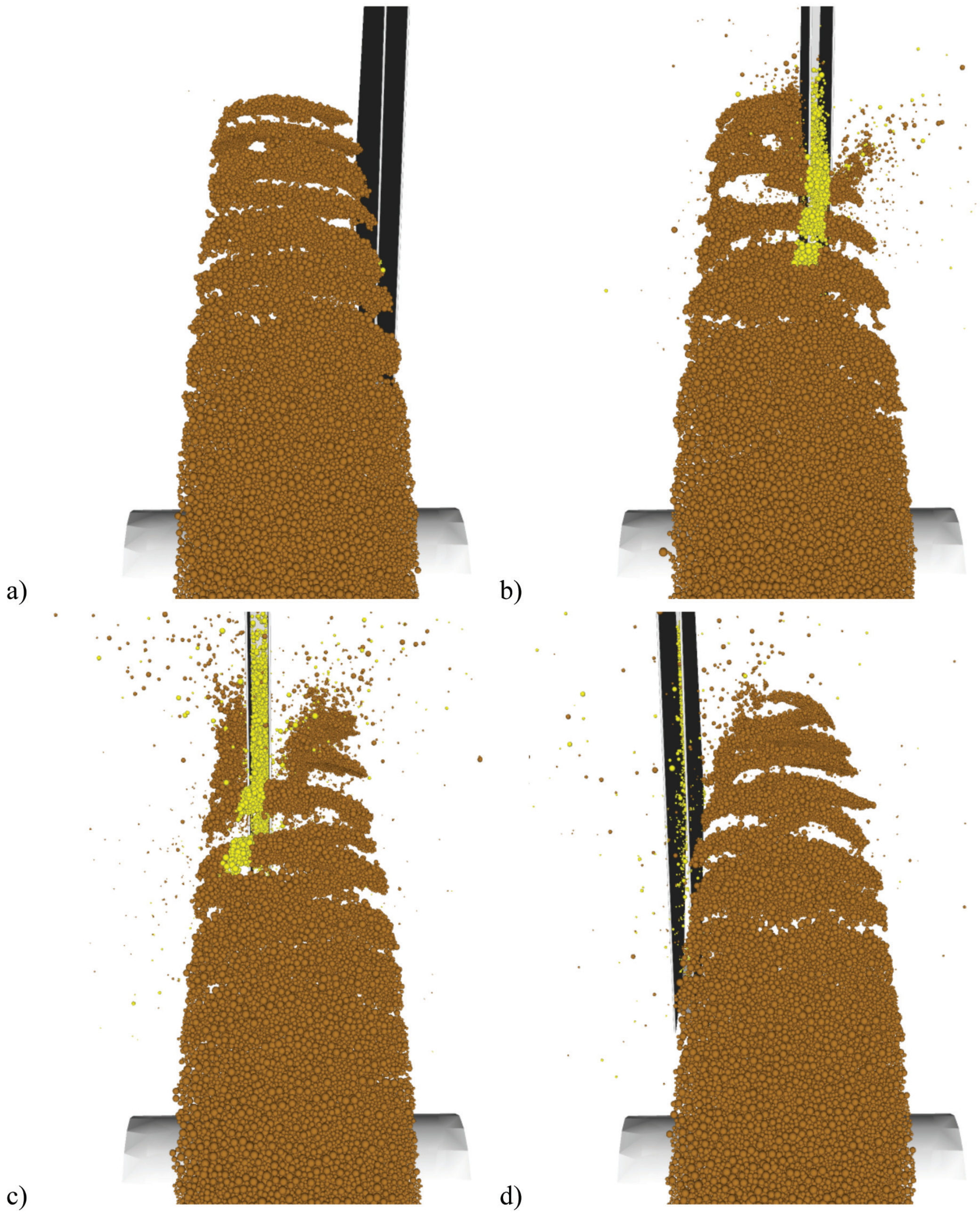

Figure 1. Progress of the cutter through the falling stream for cohesive material with a Bond number of 1.0 (which we will refer to as 100% cohesion level) at four times: a) just after the cutter intersects the stream, b) after 0.5 s, c) after 1.0 s, and d) as the cutter exits the stream 1.6 s after entering. The reference sample particles are coloured yellow (or light grey in greyscale) and the non-reference material is brown (or dark grey)

of relative motion between particles for the less cohesive materials, so the stream of material becomes slightly wider.

The quantitative sampling results from this experiment are summarised in Table I. The average reference sample mass is about 46 kg. The extraction ratio decreases as the material becomes more cohesive. This can be seen in Figure 3 which shows the five replicates for each cohesion level. For cohesionless material the extraction ratio is very close to 100%. For 1% and 3% cohesion values, the extraction ratio is greater than 99%. For the 10% and 31.6% cohesion levels, the reduction in the extraction ratio becomes more substantial and the reduction is greater than 4% for the 100% cohesion level. This trend is consistent with the increasing amounts of material that were visibly sprayed away from the sample cutter in Figure 1.

Figure 4 shows the amounts of material missed for various size classes, as percentages of the amounts of reference material in those size classes. The cohesion parameters (CP) are indicated on this graph. We can see that the percentage of material missed increases substantially as the amount of cohesion increases. On the right hand side of Figure 4 we can see that there is more noise about the general trend for the coarser size classes. This happens because the individual particles of the coarser size classes have larger mass. The same percentage of missed material is a smaller number of large particles and the percentage variation in the number of particles becomes larger when the number of particles is smaller.

Figure 5 shows the amounts of material extra for the various size classes as percentages of the size of the amounts of reference material in those size classes. The line types used for Figure 5 are the same as for Figure 4. There is some tendency for the mass of extra material to increase with the amount of cohesion, but the effect is not great.

Figure 6 shows the average sizing of the samples for this experiment. These sizings are shown as the mass weighted averages of particle diameters on the left hand vertical axis. Figure 7 gives a more precise measure of sample bias. For each sample, it shows the bias as the sizing of the sample minus the sizing of the reference sample. The bias is not

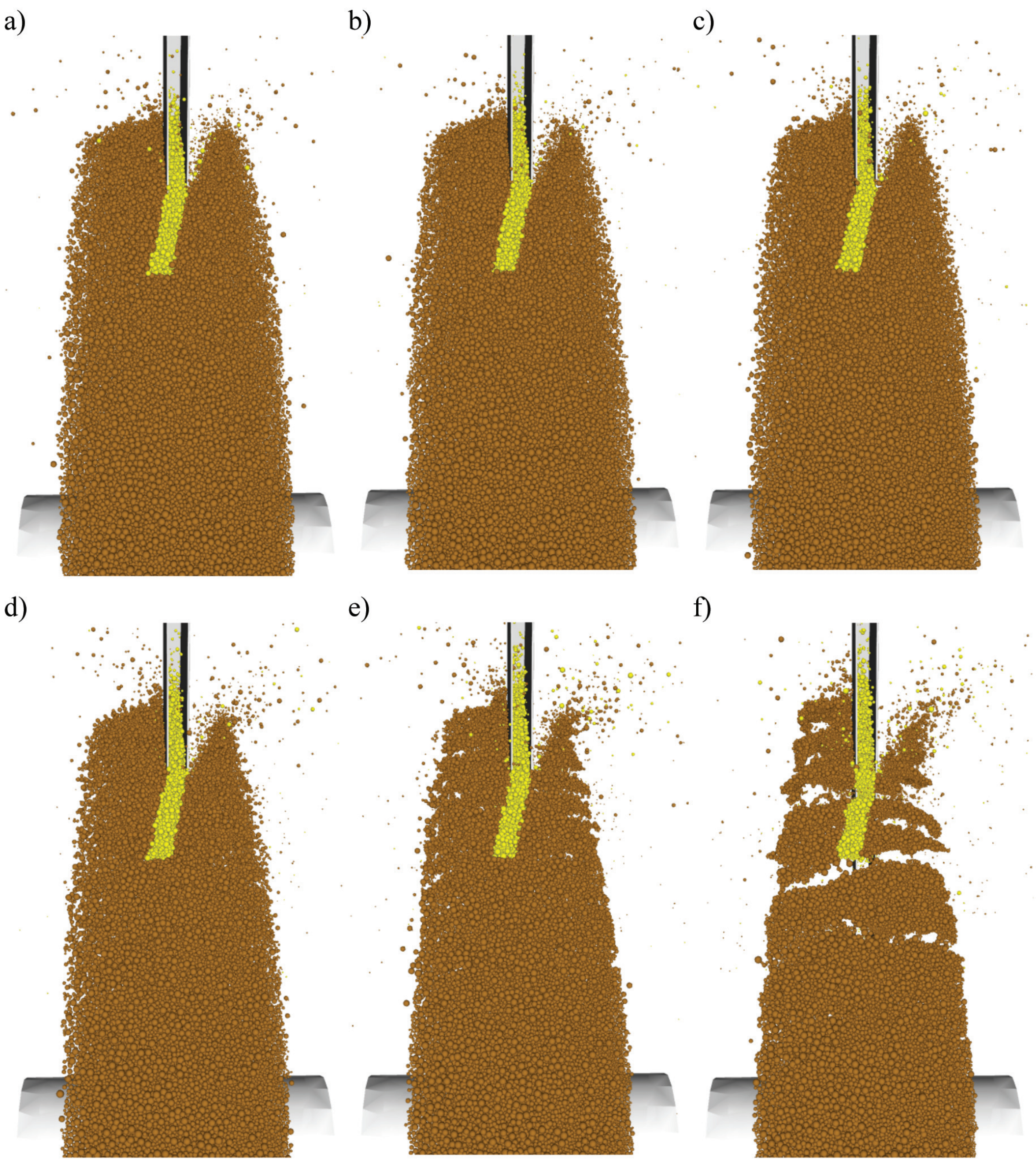

Figure 2. Sampler mid way through the falling stream for a range of cohesion levels (as percentages of the maximum cohesion level used); a) cohesionless, b) 1% s, c) 3.2%, d) 10%, e) 31.2% and f) 100%

Table I
Results from experiment investigating effect of level of cohesion

Cohesion parameter (%)	0	1	3.16	10	31.6	100
Reference sample mass (kg)	45.87	46.04	45.84	46.12	46.14	46.06
Extraction (%)	100.04	99.38	99.52	98.67	97.33	95.84
Bias (mm)	0.03	-0.01	0.00	0.00	-0.02	-0.01
Bias (%IQR)	0.26	-0.06	-0.04	-0.04	-0.19	-0.07
Mass of missed material (kg)	1.07	1.26	1.52	1.86	2.71	3.23
Missed material size (mm)	17.13	17.09	17.69	16.84	17.69	17.99
Missed material bias (%IQR)	-7.89	-8.29	-2.84	-10.58	-2.80	-0.11
Mass of extra material (kg)	1.09	0.98	1.29	1.25	1.48	1.32
Extra material size (mm)	18.43	16.53	17.49	16.07	16.90	17.58
Extra material bias (%IQR)	3.94	-13.37	-4.67	-17.54	-9.97	-3.85

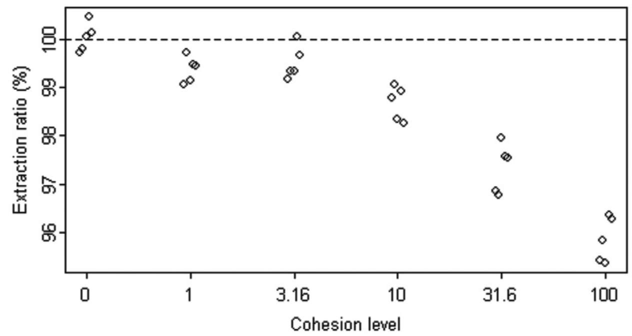

Figure 3. Extraction ratios achieved in replicate DEM runs for experiment varying cohesion level

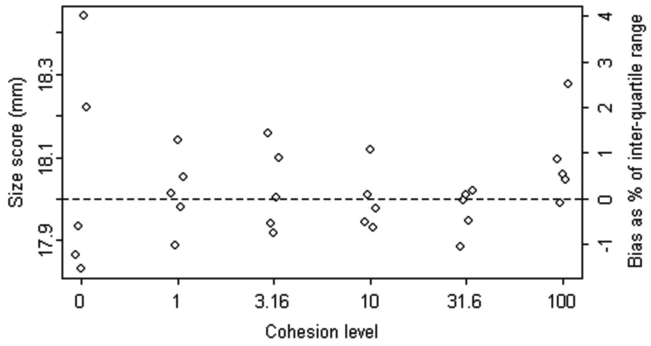

Figure 6. Average sizing of samples for experiment varying cohesion level

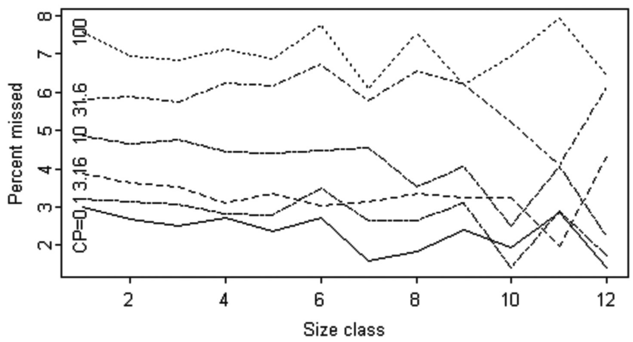

Figure 4. Average percent of material missed for each size class for experiment varying cohesion level

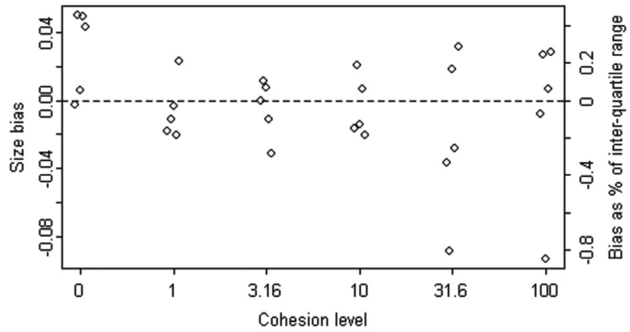

Figure 7. Size biases relative to reference samples for experiment varying cohesion level

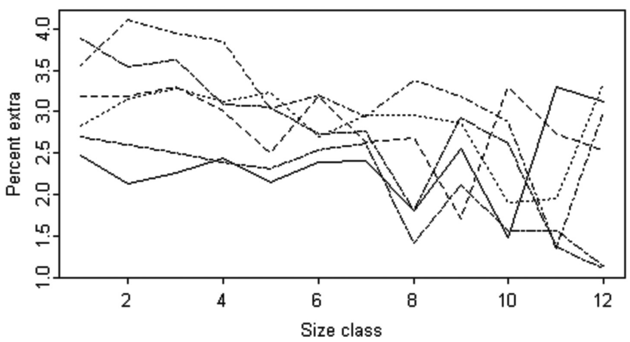

Figure 5. Average percent of material extra for each size class for experiment varying cohesion level

statistically significant for any of the levels of cohesion. A comparison of Figure 6 and Figure 7, illustrates the point made in several previous papers (Cleary *et al*. 2005, 2008a and b) that the matching of samples to reference samples is a very useful noise-reduction technique.

On the right hand side of Figure 6 and Figure 7, the bias is expressed as a percentage of the inter-quartile range of particle sizes with zero being the average sizing of 18 mm. This measure of the amount of bias is likely to be approximately the same even if the distribution of particle sizes were changed. It appears that the bias of our falling-stream cutter with a 3.3 D aperture never exceeds 0.7% on this scale, so the cutter is near enough to unbiased for most practical purposes.

Figure 8 shows the sizing of the missed material. Missed particles were, on average, slightly finer than the average

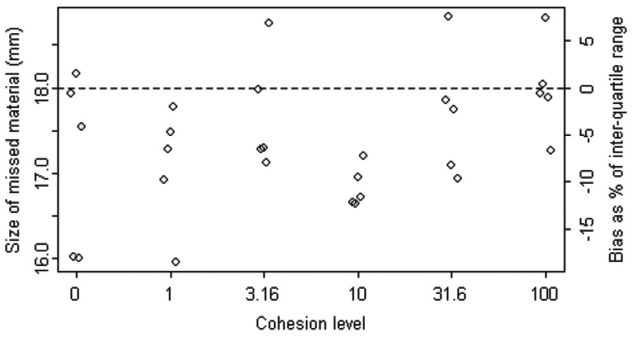

Figure 8. Sizing of missed material for experiment varying cohesion level

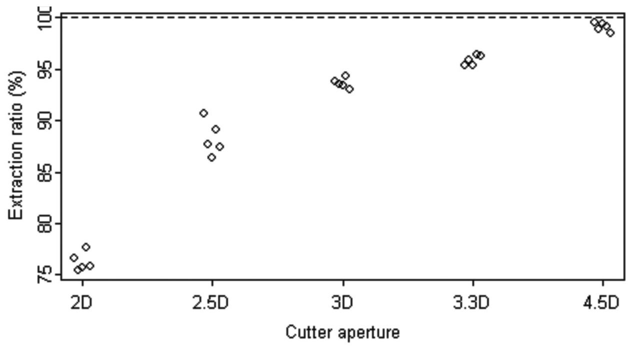

Figure 10. Extraction ratios achieved in replicate DEM runs for experiment varying cutter aperture

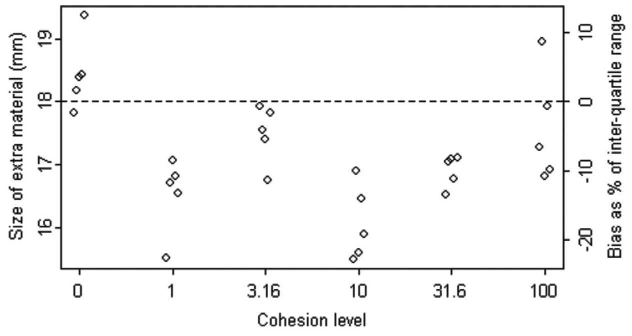

Figure 9. Sizing of extra material for experiment varying cohesion level

for the flow being sampled. Figure 9 shows the sizing of the extra material. These particles were also on average slightly finer than the average for the flow being sampled.

The main conclusion to be drawn from this experiment is that for cohesive materials, it is more likely that the extraction ratio will be poor and that the sample will be badly biased.

Experiment investigating effect of cutter aperture for cohesive materials

In a second experiment, we investigate the effect of changing sample cutter aperture for the most cohesive of the materials. We use Bond number 1.0 (100% cohesion level from the first experiment). Most simulation configuration and particle properties are the same as in the previous case. Only the sample cutter aperture is varied. The measure of cutter aperture used is the tip-to-tip separation of the cutter blades as a multiple of the maximum particle diameter D. The cutter apertures considered are 2.0 D, 2.5 D, 3.0 D, 3.3 D and 4.5 D.

Results of this experiment are summarised in Table II. The cutter aperture of 3.3 D (100 mm) has the same simulation conditions as the runs with cohesion level 100% in the first experiment, so five of the runs are common to the two experiments. The average reference sample mass is approximately proportional to the cutter aperture, as expected.

Figure 10 shows the extraction ratios for this experiment. The extraction ratio is very close to 100% for the 4.5 D aperture even for such a high cohesion level. The extraction ratio is reduced by around 4-5% for an aperture of 3.3 D and by around 6-7% for a standard 3 D sampler. This would normally be considered a significant reduction which would be of concern. For a 2.5 D cutter the decline in extraction ratio reaches 12% and for a 2 D cutter reaches a very high value of 24%. This shows that the extraction ratio falls very dramatically for smaller cutters when the material is cohesive. In contrast, Cleary and Robinson (2008a) found a similar but much weaker pattern of deterioration of the sampling with decreasing aperture size for cohesionless material. The decline in extraction ratio for 2.5 D was only 2-3% (compared to 12% here) and for 2 D was only 11% (compared to 24% here).

Figure 11 shows the masses of missed material for each size class for each of the cutter apertures. The mass missed increases substantially as the cutter aperture decreases, and this increase is fairly uniform over the size classes.

Figure 12 shows the percentages of extra material using the same line types as Figure 11. It is not obvious from this

Table II
Results from experiment investigating effect of cutter aperture

Cutter aperture	2D	2.5D	3D	3.3D	4.5D
Reference sample mass (kg)	27.23	34.20	41.46	46.06	66.27
Extraction (%)	76.22	88.25	93.61	95.84	99.08
Bias (mm)	-0.11	-0.03	-0.02	-0.01	-0.01
Bias (%IQR)	-1.02	-0.23	-0.15	-0.07	-0.08
Mass of missing material (kg)	7.39	5.14	4.00	3.23	2.29
Missed material size (mm)	18.46	18.25	18.20	17.99	17.80
Missed material bias (%IQR)	4.22	2.26	1.84	-0.11	-1.82
Mass of extra material (kg)	0.91	1.13	1.35	1.32	1.68
Extra material size (mm)	18.48	17.98	18.25	17.58	17.46
Extra material bias (%IQR)	4.39	-0.17	2.29	-3.85	-4.95

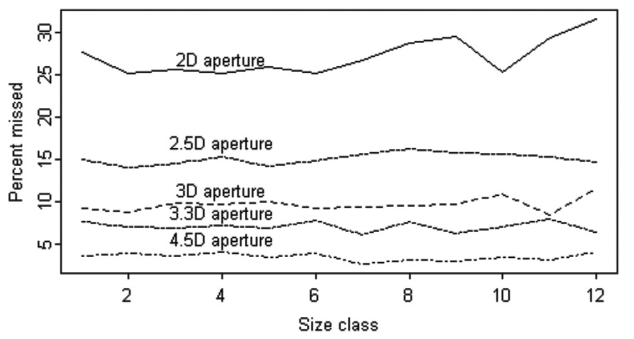

Figure 11. Average percent of material missed for each size class for experiment varying cutter aperture

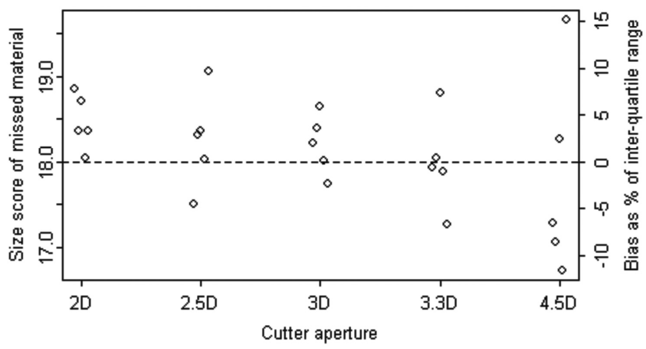

Figure 14. Sizing of missed material for experiment varying cutter aperture

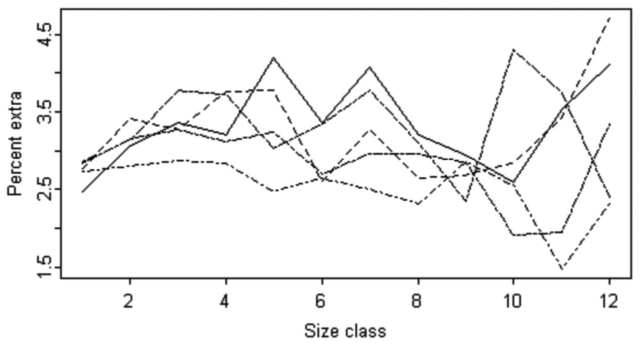

Figure 12. Average percent of material extra for each size class for experiment varying cutter aperture.

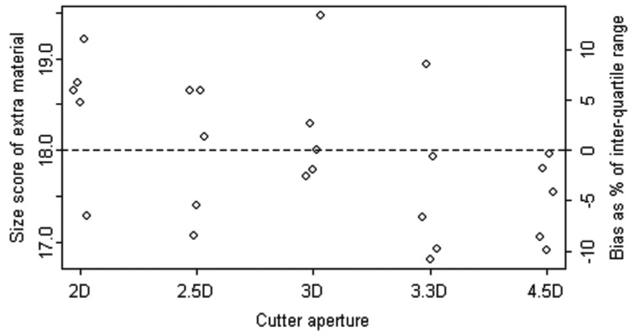

Figure 15. Sizing of extra material for experiment varying cutter aperture

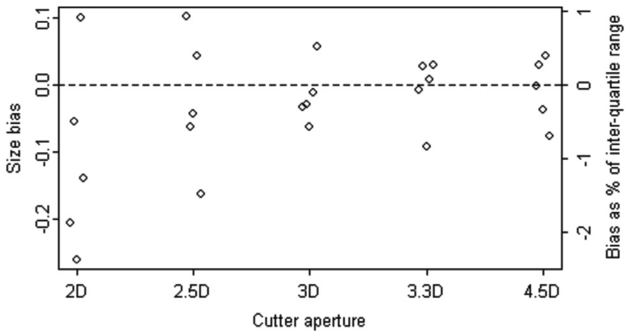

Figure 13. Size biases relative to reference samples for experiment varying cutter aperture

figure that there is any trend in mass of extra material with cutter aperture. However, Table II shows that the total mass of extra material does increase with cutter aperture.

There is a much more substantial trend in the amount of missed material with changing cutter aperture than in the amount of extra material, so it appears that this is the main cause of the trend in extraction ratio.

Figure 13 shows the size biases of all samples in this experiment. It indicates that size bias is not statistically significant, even for the 2 D cutter aperture. This contrasts with the finding of Cleary *et al*. (2008b) that such a cutter aperture causes a significant size bias for non-cohesive particles.

Figure 14 and Figure 15 show the size biases for missed and extra material separately. Students' t-tests show that the amount by which the average sizing of missed material is greater than 18 for the 2 D aperture is just statistically significant, but the amount by which the average sizing of extra material for the 4.5 D aperture is lower than 18 is not quite statistically significant at the 95% significance level.

Conclusion

The bias of the falling-stream cutter studied here with a 3.3 D aperture never exceeds 0.7%, so it is near enough to unbiased for most practical purposes. Importantly, this does not change with increasing cohesion level. Increasing cohesion, despite leading to reductions in the extraction ratio (by increasing the resistance to flow between the cutter blades) does not lead to sample bias. To create sample bias there needs to be a differential behaviour of the coarse and fine material in the congested region at the cutter opening. A critically, important effect of cohesion is that it influences small particles much more than larger particles and it does this by binding them together and to the large particles. This means that cohesion significantly reduces the mobility of the finer particles in flowing granular materials. The inhibition of fine particle mobility is the reason that the missed material has no size dependence despite the overall amount of missed material rising sharply. Since the amount of missed material is much greater than the amount of extra material, there is little opportunity for the sizing of extra material to affect the average sizing of the sample. So although cohesion reduces the extraction ratio, which, traditionally, would be interpreted as a strong indicator of likely bias generation, the cohesion also removes the ability of the fine particles to move independently and therefore to generate bias.

The extraction ratio is very close to 100% for the 4.5 D aperture even for high cohesion levels. The extraction ratio is reduced by around 4 to 5% for an aperture of 3.3 D and by around 6 to 7% for a standard 3 D sampler. This would normally be considered to be a reduction in extraction ratio which would be of concern. For a 2.5 D cutter the decline in extraction ratio reaches 12% and for a 2 D cutter reaches a very high value of 24%. This shows that the extraction ratio falls very dramatically for smaller cutters when the material is cohesive. In contrast, we previously found a similar but much weaker pattern of deterioration of the sampling with decreasing aperture size for cohesionless material. The decline in extraction ratio for 2.5 D was only 2-3% (compared to 12% here) and for 2 D was only 11% (compared to 24% here).

Overall, the DEM study reported in this paper suggests that the sample bias of a falling-stream cutter tends to be consistently small for cohesive materials, even though the extraction ratio may be much less than 100%. Even quite narrow cutters (such as 2 D) do not generate much bias. This is due to the low mobility of fine particles in the congested flow around the cutter where bias is normally generated for cohesionless materials.

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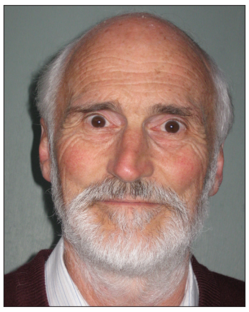

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He has had a continuing interest in mineral sampling and mineral stockpiles since becoming involved with a review of Hamersley Iron's grade control system in 1987-8. He has used a general-purpose three-dimensional stockpile model called CHASM for investigating the relative merits of stockpiling options for a variety of proposed mine developments for iron ore, coal, copper, nickel and phosphate rock. He has completed several research projects studying sampling procedures and sampling devices, and has served on International Standards Organization subcommittee ISO/TC 102/SC 1 and a few Standards Australia Subcommittees.