Executive Summary

Shaft sinking is an important part of the mining process, of which “mucking” (clearing the broken rock from the bottom of the shaft) plays a critical role. The aim of the research was to develop a scaled experimental replica of the so-called *Clamshell Mucker* and compare its performance, over a range of operating parameters, with those yielded by numerical simulations, for the long-term purpose of validating the simulation as a tool for optimizing the design of full-scale machines.

Towards this end a scaled experimental rig of the clamshell mucker was developed and tested over an appropriate range of geometrical and operating parameters, for two different materials: hard plastic balls and thereafter 13 mm decomposed granite stone. Hydraulic actuator forces were established by measuring line pressures, while angular rotation of the jaws of the mucker was monitored using an angular potentiometer. Simple analysis provided a relationship between actuator force and torque on the buckets. The stone in the muck reservoir was agitated after each test run, to ensure random particle arrangements with no structuring, and a constant digging depth.

Testing of the hard plastic balls was used to establish a qualitative comparison between Discrete Element Modelling (DEM) and physical testing, using both video and still photography comparisons, corresponding to the teeth initially touching the surface with a bucket closing velocity of 20 deg/s. Heuristic correlations obtained by this means were generally favourable.

Quantitative testing using 13 mm granite stone yielded the bucket closing torque variation with bucket angle for various combinations of:- (a) bucket closing velocity, (b) initial distance of the bucket from the muck pile, (c) proximity of the bucket to the side and front walls of the container, and (d) the angle at which bucket assembly enters the muck pile. The main set of tests took place with the bucket entering vertically and positioned in the middle of the bed. Three different initial distances from the surface to the starting position of the bucket teeth were investigated (20 mm, 10 mm and 0 mm), with bucket angular velocities of 10 deg/s, 15 deg/s and 20 deg/s. Thereafter, testing was conducted at the forward (polycarbonate) boundary of the container and one of the lateral boundaries (steel) respectively, each for a single bucket velocity of 20 deg/s and covering the three above-mentioned initial distances from the surface. This testing was performed in an attempt to simulate the proximity effects that would be encountered in practice - for example, digging close to a side wall. Finally, torque variations with bucket angle were established at four different angles of attack (0°, 5°, 15° and 30°), at a constant bucket closing velocity of 20 deg/s, with the closest portion of the bucket initially touching the surface.

Data was generally interpreted in the context of the fact the torque required to rotate the buckets appears to depend on an interplay between:- (a) the level of fluidization between particles in the bed, increasing with bucket closing velocity, results in a reduced torque; (b) particulate congestion, increasing as the initial distance from the surface of the granular material decreases, results in an increased torque; and (c) the momentum required to move the particles and change their direction, increasing with bucket velocity, results in an increased torque.

Accordingly, for the larger initial distances from the surface momentum effects are dominant, generally leading to an increase of torque with angular velocity. However, as the initial distance reduces, congestion becomes increasingly important, until for the zero initial separation case, the lowest angular velocity yields the highest torques, probably because fluidization has been inhibited.

Because particle to boundary interactions have lower friction than particle to particle interactions, torques in the presence of boundaries were lower than for the middle position in the initial stages. Beyond a certain point, proximity to the forward boundary led to congestion with a commensurate increase in torque above that of the middle case, whereas proximity to the lat-

eral boundary led to no congestion, so the torques remained generally lower than for the middle case.
When considering the effects of angle of penetration, it was found that the largest angle of penetration (30°) gave the highest torque in the initial stages, probably because the highest volumes of material are captured relative to other angles of attack. Beyond a bucket angle of about 14° congestion becomes increasingly dominant, with the rise in torque due to this effect generally delayed with increasing angles of attack. This phenomenon was ascribed to the fact that in all cases other than zero angle of penetration, only one jaw initially enters the material, with the second following at a later stage: therefore particles escape to a free surface for the mid-range bucket angles, with the onset of congestion commensurately delayed to the larger ones.
Comparisons between DEM data and measurements for various testing parameters showed that the simulated and physical results display similar values of torque towards the beginning and end of the digging motion, but DEM predictions are low in the middle of the range. This is thought to arise primarily from the fact that simplified particle geometries (smooth, with no sharp edges) were incorporated into the DEM model because of computational resource limitations, whereas the real granular particles have sharp edges and are blocky, thus increasing particle interlocking effects and the high level of congestion frequently exhibited in the physical experimentation. This effect was generally reflected by poor comparisons between DEM data and experimentation in the context of torque variations with velocity in the middle range of angular positions. Because the coefficients of rolling friction and restitution were obtained from published data, additional simplified simulations were run to determine the sensitivity of these parameters (in addition to static friction coefficient, for comparative purposes) on the force characteristics of the model. It was established that specifically chosen percentage changes in all of the parameter values relative to the base system led to percentages of force deviation that were at least 3 to 5 times smaller, reinforcing the inference that particle interlocking effects were the dominant reason for poor mid-range correlations between experimentation and the DEM modelling.
The maximum energy to fill the buckets was required at a zero angle of penetration, diminishing significantly to an angle of about 15° and then increasing once again. This trend is attributed to the fact that the 0° case is most affected by congestion, whereas the larger angles of attack (beyond about 20°) cause the weight of the material to significantly affect the energy required to close the buckets. While it was considered possible that similar trends would be observed in practice, that could potentially reflect in improved operational guidelines for the mucking process, further analysis suggested that an energy saving of less than 814.3 kJ might be attainable for clearing a 6 m diameter shaft during a single cycle. While this appears to be inconsequential in the broader context, it should be subjected to a more comprehensive investigation in the context of full-scale cleaning strategies.
It is recommended that:- (a) the test facility be modified to extend the range of bucket angular velocities; (b) testing be conducted with a broader range of particle sizes; (c) research into the interlocking and frictional effects of rock be pursued, to create representative particulate shapes as input to the DEM model; (d) higher friction coefficients be attempted as a means of artificially compensating for interlocking effects that are impractical to achieve because of computer resource limitations; and (e) testing be conducted with a range of different bucket shapes and sizes for the purpose of optimizing the design by way of minimizing structural stresses and the specific energies required to collect individual loads.