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Application of particle flow code to evaluate a concept for detecting hazardous voids in surge piles using profile scanning

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ABSTRACT: Researchers from the Spokane Research Laboratory of the National Institute for Occupational Safety and Health have used the Particle Flow Code (PFC2D) computer program to determine whether detecting large voids in surge piles is feasible. The method is to determine profile volume—the volume calculated by determining the profile of the top surface—of the pile near a drawpoint, monitor the volume drawn, and compare the two volumes in real time to detect the formation of voids. If void formation could be detected early, a warning could alert workers of hazardous conditions.

Six numerical experiments were run to simulate various conditions. Results show that when no material was added to the pile, voids could be detected by comparing real-time curves of volume scanned and volume drawn. Slopes and differences of the curves were used to detect a void. When material flowed into the area from a stacker tube, void detection was difficult. Prior knowledge of flow curve slopes and an additional indicator of flow from a stacker tube may be necessary to detect voids. An indicator of the presence of a bulldozer in the area is necessary to help identify material added to the pile.

1 INTRODUCTION

The Mine Safety and Health Administration (MSHA) issued Program Information Bulletin P99-1 on January 13, 1999, to alert the coal mining industry about hazards associated with coal surge piles and the large number of fatalities associated with surge pile accidents since 1980 (17 fatalities from 13 accidents). Twelve of these 13 accidents occurred when a void formed in the surge pile during drawdown and collapsed. Ten of the victims were bulldozer operators.

Iverson and others (2001) performed a fault-tree analysis to determine the most probable root cause(s) of bulldozers falling into voids. Although several conditions must be present before a bulldozer can fall into a void, two necessary conditions are the formation of a void and the presence of a bulldozer over the draw cone area. Bulldozers must work near draw cones, and rules and safeguards must be in place to prevent operators from driving bulldozers over draw cones. However, if a void could be detected early on, operators could be warned to stay far away from feeder areas until the bridge over a void collapses.

While the risk of being drawn into a cone during drawdown operations is significant, once personnel or equipment are engulfed, rescue operations may be even more hazardous. Rescue operations involve sending a worker down into the cone in a suspended basket or cherry picker or cutting a path into the cone from the side, both processes that send a second equipment operator beneath hazardous slopes or cut walls.

2 SOLUTION TO PROBLEM

In this investigation, we examined the concept of detecting voids through the use of an overhead scanner to measure a profile of the top surface, then calculating the pile volume beneath that surface and measuring the volume of material drawn onto the exit conveyor, all on a real-time basis. This was an investigation of the concept only and not an investigation of instruments that might be used to put the concept into practice.

The method would require scanning the surface of the surge pile only in the area surrounding the draw cone and calculating the volume beneath that surface. The calculated volume would be plotted in real time. A similar curve would be determined by subtracting the volume of material withdrawn by the conveyor from the initially calculated volume. By comparing these curves, voids can be indicated by different slopes of the curves and different volumes. Adjustments would need to be made for material added to the pile.

3 CONCEPT TESTING WITH PARTICLE FLOW CODE

The volume profiling concept was tested with numerical simulation using the computer program Particle Flow Code in Two Dimensions (PFC2D) from Itasca Consulting Group, Minneapolis, MN (1999). PFC2D models a system of circular balls and walls using the distinct-element method, as described by Cundall & Strack (1979). PFC2D was chosen because of its versatility with the embedded FISH computer language, which permits use of a scanner over a pile of particles to be simulated. The two-dimensional version was selected over the three-dimensional version to reduce the size of the problem. A vertical cross section of a draw cone should be almost identical in any orientation, and therefore adding a third dimension would not provide enough benefit to justify the significantly larger problem size.

Figure 1 shows the initial state of all problems. The size of the model was chosen small to limit problem size, that is, vertical walls were placed at ±9 m (±30 ft) from the origin, and the vertical walls were only 12 m (40 ft) high. The number of particles used was 4,200. Diameters were selected from a Gaussian distribution instead of a random distribution to increase the number of particles in the mid-size range. Average diameter was 17 cm (6.5 in), standard deviation was 14 cm (5.5 in), and minimum diameter was 2.5 cm (1 in). There was a 1.5-m (5-ft) opening in the center of the base wall to allow particles to be drawn into a chute. The lower wall of the chute was vibrated in a sine wave to draw particles from the surge pile. Table 1 shows properties of the particles and walls.

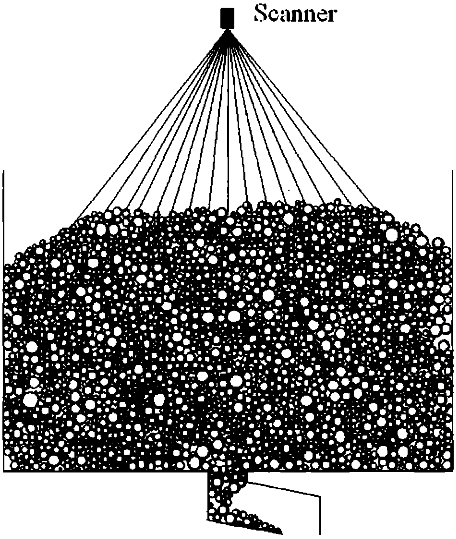

Figure 1.—Surge pile at equilibrium at the start of each case. Profile scanning concept indicated.

A mathematical scanner was hypothetically positioned at 15 m (50 ft) above the base of the pile (Figure 1) to simulate surface profiling. A series of points with x and y coordinates were scanned along the surface of the pile ±6 m (±20 ft) horizontally from the center of the pile. This was done by first scanning the point directly below the scanner. The distance was determined from the point where the line of the scan intersected the surface of the nearest particle. For the next scan to the left or right, an initial scan angle of 3° was used, that is, the angle of the line of the scan was 3° from vertical. The horizontal interval between scans at 5 m (17 ft) vertically below the scanner was used to determine subsequent scan angle intervals so that horizontal intervals were kept constant.

Differential density scaling of the particles was used. That is, in the motion calculation, the mass for each particle was multiplied by a factor so that the time step was 1. For gravity force calculations, the mass of each particle remained unchanged. This had the disadvantage of causing unrealistic forces in a dynamic situation and hence some unrealistic

Table 1.—Properties of particles and walls

Items	Normal stiffness		Shear stiffness		Friction coefficient
	MN/m	lb/in	N/m	lb/in	
Particles	403	2.3×10^6	403	2.3×10^6	0.7
Walls	1664	9.5×10^6	438	2.5×10^6	0.7

movement. However, the uniform time step provided an easy method to vibrate the chute wall uniformly and to compare profile with solution time. Also, the run time is faster than without differential density scaling, although the time savings tends to be small.

A default damping constant of 0.7 was used. The odd sizes and points of real coal particles provide additional friction and stability, whereas circular particles have the tendency to roll down the slope of the draw cone. Over damping removes some particle inertia so that static friction between particles can stop drawdown in the event that feeder vibrations stop.

4 CASE STUDIES

Models of six case studies were constructed and run. Table 2 summarizes the case studies and the purpose of each. Case study 1 served as a base case with no void formation. In case studies 2 through 4, a void was formed, but void detection was rather simple because no particles were added to the pile. Cases 5 and 6 were more complicated because material was added from outside the scanned volume.

5 RESULTS

Figure 2 is a plot of time step versus pile volume for the first case study. One curve reflects the scanned volume versus time step. The lighter curve represents the initial scanned volume less the volume of particles that exited the chute. Before subtracting the volume of each particle exiting the chute from the initial volume, each ball's volume was multiplied by a factor to account for the pile's void ratio. That void ratio was calculated from a representative volume in the surge pile.

In the first 1.5 million time steps, the two curves began to deviate from each other. Such deviation reflects the increase in the amount of void space that naturally occurs in the draw process. After 1.5 million time steps, the lower chute wall ceased to vibrate. Draw from the pile came to a stop shortly thereafter with the aid of a "quiet" FISH function, that is, particle velocities were set to zero periodically to dampen inertia more quickly. When drawdown ceased, the pile settled so that the increased void space was eliminated. Thus, the two curves began to coincide.

Chute vibrations resumed at 3 million time steps, and drawdown of the pile resumed. Thus, the void ratio increased in the pile and the two curves departed until their slopes became relatively constant with a relatively constant offset. Figure 3 shows the appearance of the pile at the end of 6 million time steps. A draw cone had definitely formed.

Figure 4 shows time step versus pile volume for the second case study. Here, a small cohesive arch formed at the start of drawdown, as indicated by the initial difference in curve slopes. At 1.5 million time steps, the bonds in the cohesive arch were deleted, and the pile resumed drawing. Figure 5 shows the location of contact bonds in the pile that formed the cohesive arch over the draw point.

Figure 6 shows time step versus pile volume in the third case study. For this case, a larger cohesive arch was formed by contact bonds after 1.5 million time steps. The slopes then drastically departed until particles under the cohesive arch had been drawn. At 3 million time steps, the contact bonds were deleted and the pile resumed drawing. Figure 7 shows loca-

Table 2.—Surge pile case studies

Case study	Run description	Purpose
1	Drawdown, stop draw, resume drawdown	Establish a base case showing typical response to drawing down, stopping, and resuming drawdown.
2	Small cohesive arch forms before drawdown	Show response to a small cohesive arch forming over draw chute.
3	Larger arch forms after initial drawdown, then arch bonds break.	Show response to a larger cohesive arch forming over draw chute.
4	Cohesive layer forms before drawdown. Bonds break after initial drawdown.	Show profiling response in the event of a cohesive layer forming in surge pile.
5	Stacker tube feeds the pile	Show profiling response for relatively constant inflow from stacker tube.
6	Left and right bulldozers feed the pile	Determine if addition of bulldozed material can be detected.

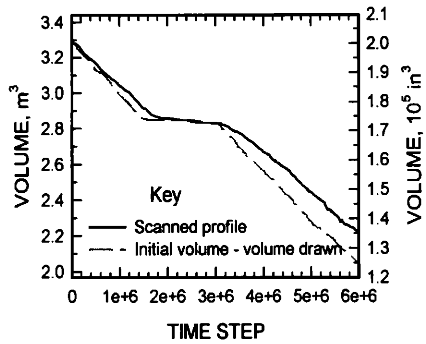

Figure 2.—Time step versus pile volume for case 1.

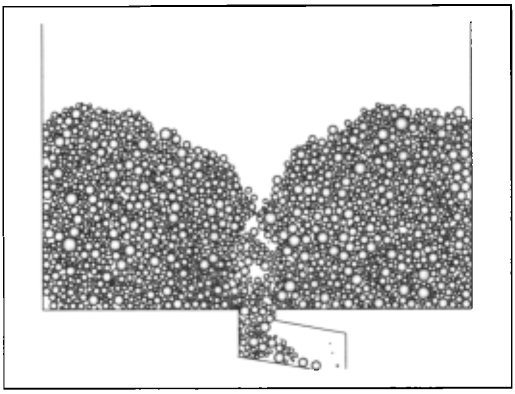

Figure 3.—Surge pile at completion of case 1 run.

tion of contact bonds that formed the cohesive arch over the drawpoint.

Time step versus pile volume for the fourth case study is shown in figure 8. A cohesive layer was formed initially, and contact bonds were deleted at 2 million time steps. Figure 9 shows the state of the cohesive layer just before the bonds were deleted. The layer sagged a great distance without breaking up much, which may not be realistic but does not invalidate the usefulness of the curves in figure 8. The initial difference in slopes of those curves indicates the formation of a void The distance between curves over time probably is indicative of an increase in void space as the pile is drawn and a scan grid interval that is too large over the draw cone.

For the fifth case study, a stacker tube was simulated with walls on the right-hand side of the pile. Three 2-m (7-ft) openings were spaced every 4.3 m (14 ft) to allow particles to flow into the surge pile. Initially, 150 particles were created to fill partially the stacker tube. Every 50,000 cycles through step 3.15 million, 15 particles were created near the top of the stacker tube, and each was given an initial downward velocity as if it had fallen from the top of the tube. Figure 10 shows the volume curves (scanned profile and initial minus drawn material) with time step. The scanned profile curve is noisy

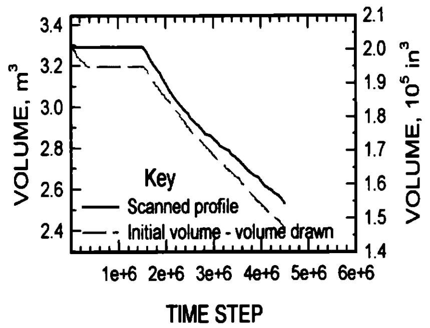

Figure 4.—Time step versus pile volume for case 2 in which an initial cohesive arch causes formation of a void.

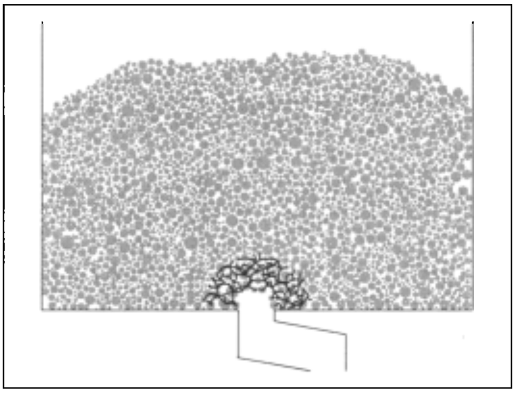

Figure 5.—Case 2 pile in which a void formed because a cohesive arch existed when the feeder started up. Contact bonds are shown with black lines between particles. Time step is 1.5 million.

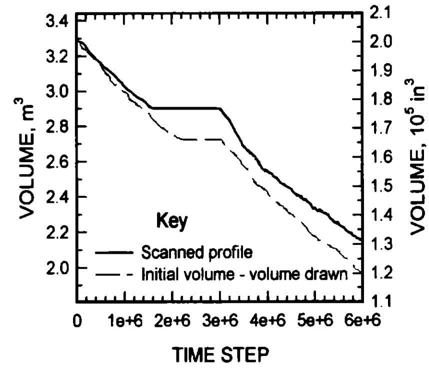

Figure 6.—Time step versus pile volume for case 3 in which a cohesive arch forms after some drawdown.

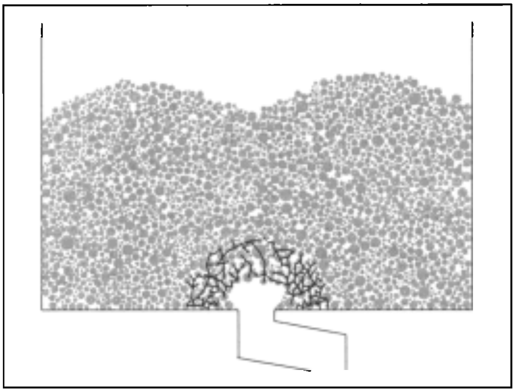

Figure 7.—Case 3 pile in which a void formed because a cohesive arch formed after some drawdown. Contact bonds are shown with black lines between particles. Time step is 3 million.

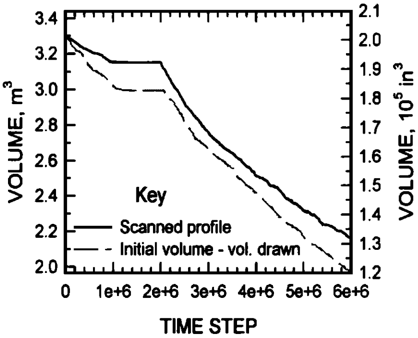

Figure 8.—Time step versus pile volume in case 4 in which a cohesive layer caused void formation.

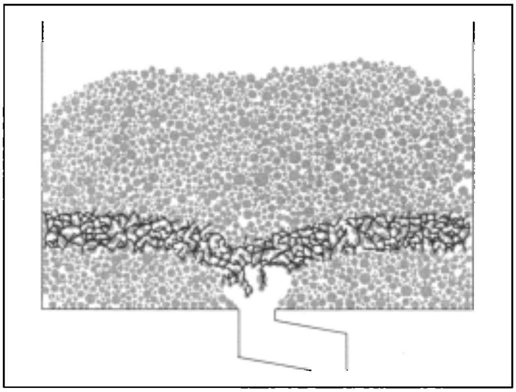

Figure 9.—Case 4 pile in which a void formed because a cohesive layer existed when the feeder started up. Contact bonds are shown as black lines between particles. Time step is 2 million.

because of stray particles. Most of the noise is the direct result of using differential density scaling and, therefore, should be ignored here. Some filtering yields a better curve. Figure 11 shows the state of the pile at 2 million time steps. The curves in figure 10 have an elbow at time step 2.8 million because the damping constant was lowered from 0.7 to 0.4 so that flow from the tube would increase and the potential for friction hangups in the tube would decrease. The curves continue to diverge throughout the simulation because of the nearly constant influx of particles.

For the sixth case study, bulldozer runs from the left and right were simulated with 2-m (7-ft) walls. Particles were pushed from the 8.6-m (28-ft) x-

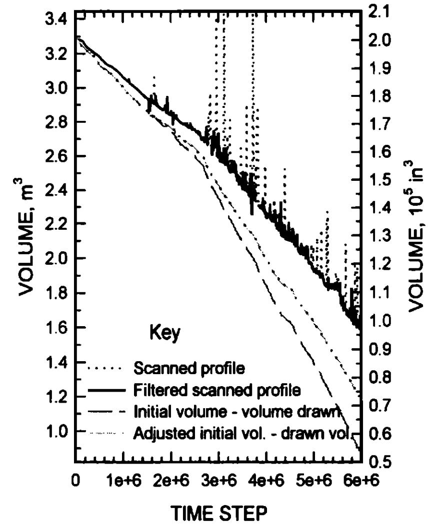

Figure 10.—Time step versus pile volume for case 5 in which a stacker tube fed the draw cone.

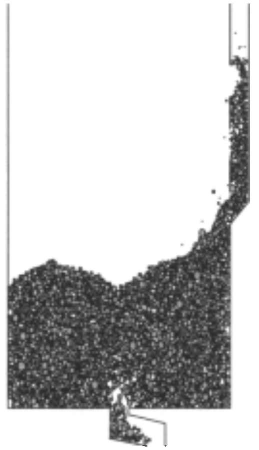

Figure 11.—Case 5 run with stacker tube feeding the draw cone. Time is at 2 million time steps. Many "airborne" particles over the pile are too small and do not show up in the figure.

coordinate to the 2.3-m (7.5-ft) x-coordinate on the left and right sides of the pile. With each successive run, the blade was lowered 0.6 m (2 ft). Figure 12 shows time step versus volume and identifies when a bulldozer was pushing material from the left and from the right. The initial bulldozer runs from the left and right did not affect the curves much because the number of particles pushed was small. Larger deviations in the curves were present with subsequent bulldozer runs. Figure 13 shows a bulldozer run in progress.

6 BASIS FOR ALGORITHM

Results of the first four case studies show that when no additional material is added to the pile, a simple algorithm can detect significant voids. Void space increases naturally as the pile is drawn. However, a combination of monitoring scanned slopes and a threshold error can be used to detect the voids that form. The initial-minus-drawn volume curve must be reset periodically so that the threshold error is not exceeded. Otherwise, the error threshold should be a function dependent on time since reset.

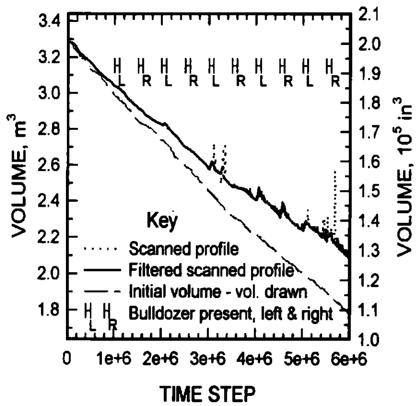

Figure 12.—Time step versus pile volume for case 6 in which bulldozers push particles into the draw down from the left and the right

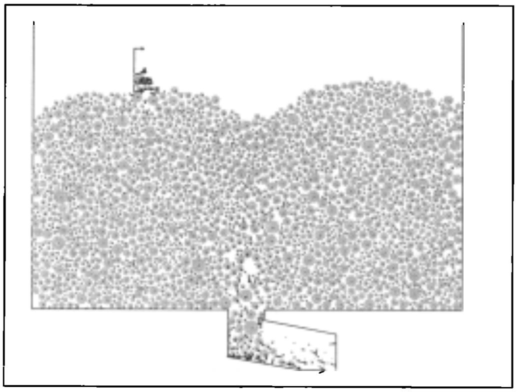

Figure 13.—Wall simulating bulldozer pushing particles toward the draw cone. Particle velocities shown as vectors.

The addition of particles from a stacker tube or bulldozer presents significant difficulty. However, by monitoring the slope of the initial-minus-drawn curve before additional particles enter the scanned area, a characteristic slope is established. The adjusted curve in figure 10 takes that initial slope into account to offer a running correction to the initial volume. The adjusted curve is corrected for the change in damping constants. The result is a curve that does not differ as much from the filtered scanned profile curve with time. Practically, to make this compensation, the algorithm must include input of the start and stop times of material inflow into the scanned area. Such information is difficult to input because, even though it is not difficult to determine when material is flowing into the tube and the rate, it is difficult to determine when material is actually flowing into the scanned area. A thorough study of flow and delay times would be necessary to develop a useful algorithm.

Additional material pushed in by a bulldozer is not as difficult to determine as long as there is a way for the bulldozer to be sensed in the scanned area, such as by the use of global positioning equipment equipment. When the bulldozer leaves the scanned area, the current initial-minus-drawn amount may be reset to the scanned volume amount, as shown in figure 14. Careful monitoring of slopes and errors before and after resetting the curve will allow detection of voids formed.

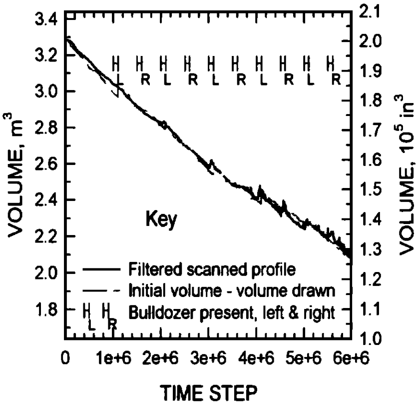

Figure 14.—Time step versus pile volume for case 6 in which the initial-minus-drawn curve is reset to the scanned volume when the bulldozer leaves the scanned area.

7 DISCUSSION

The numerical experiments described in this report show that the concept of real-time monitoring of pile volume near drawpoints can be successful if implemented under certain conditions. By limiting complications created by material added to the monitored area, the concept could be used to detect a void when a feeder is started. This would require that a scanner be positioned overhead and that some measuring device be placed on the conveyor under the feeder to sense the volume drawn. The system could be automated so that visual and/or audio warnings could alert workers to the formation of a void. A system operator would be required to monitor the system continually and change threshold values of slope differences and errors according to conditions so that false positives are minimized.

Ongoing detection of voids requires information about adding material. Automation of resets performed when a bulldozer left the scanned area is not difficult if a method of detecting the location of the bulldozer is in place. Automation of void detection when material is flowing from a stacker tube is possible, but would require more development. Once developed, the system would require ongoing monitoring and continual verification.

8 CONCLUSIONS AND RECOMMENDATION

Real-time monitoring of pile volume near feeders could be useful in detecting voids in surge piles if used when feeders are started. Continued monitoring to detect voids may also be useful, but interpretation of the measurements is difficult when material is added to the scanned area by a stacker tube or bulldozer. Automation may not be too difficult in the case of material added by bulldozer, but the problem is more challenging if material is flowing from a stacker tube.

The case with the stacker tube should be rerun without differential density scaling. Such results would produce more realistic flow calculations, but probably would not affect the main conclusion.

Technology for profiling pile volumes and monitoring drawn volumes should be explored.

9 ACKNOWLEDGMENTS

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