COMPARISON OF ORE PASS COMPUTER SIMULATIONS FOR DESIGNS AGAINST DYNAMIC LOAD

S. Iverson
Spokane Research Laboratory, National Institute for Occupational Safety and Health, Spokane, WA

S.J. Jung and K. Biswas
University of Idaho, Moscow, ID

ABSTRACT

Computer modeling of rock flow in ore passes is being investigated and compared using MSC Software's Working Model 2D[1] (WM2D) and Itasca Corp.'s Particle Flow Code in Two Dimensions (PFC2D). This work is being carried out by the Spokane Research Laboratory of the National Institute for Occupational Safety and Health to determine the usefulness of computer modeling to improve ore pass design. The types of tests included pendulum tests to validate WM2D simulations and simulated single-rock drop tests in both WM2D and PFC2D to understand their contact models. Simulated rock impacts at the ore pass chute and the use of inclined ore passes and doglegs were investigated in both programs. A PFC2D simulation showed that dynamic loads at the chute gate were reduced significantly when a dogleg transition was used, and simulations in which the ore pass was inclined showed significant reductions in chute impact loads compared to simulations of a vertical ore pass. A released hang-up was simulated using PFC2D.

INTRODUCTION

Ore passes are a common means of moving ore and waste downward in underground mines, as well as at some surface mines where under-ground haulage methods are used. However, the hazards related to the operation of ore and waste rock passes have been identified as a significant safety problem in the United States. Dynamic loads induced by falling masses of ore and the spontaneous collapse of hang-ups can cause structural failure of control gates, chutes, and ore pass walls with consequent threats to personnel safety. The purpose of this paper is evaluate the usefulness of computer modeling in improving ore pass design and thereby reduce the threat of structural damage and improve miner safety.

Gravity-induced rock flow is a simple process, but can pose design challenges if damage from rock impacts and abrasions are to be prevented. Understanding rock trajectories during a dump cycle, the degree of ore pass inclination, and the effects of rock impacts on the ore pass structure are important for extending the life of an ore pass. That is, an ore pass designed to decrease rock impact loads can save on repair costs or prevent hidden structural damage that could result in a catastrophic failure. MSC Software's Working Model 2D (WM2D) and Itasca Corp.'s Particle Flow Code in Two Dimensions (PFC2D) computer programs were studied to better understand material flow by addressing rock particle interaction in an ore pass and impact forces at the ore pass bottom end structure.

In an ore pass, rock is likely to be fractured into smaller pieces when it strikes a surface or is struck by another rock. The surfaces of structural steel plates used in an ore pass chute can deform elastically, but may also deform plastically when struck. Although rock will break down in an ore pass, it will also deform elastically when struck (see Pariseau 1998). In double-pendulum tests, Larson et al. (1998) demonstrated that deformation of rock spheres 38 mm (1.5 in) in diameter was nearly perfectly elastic during collisions.

The authors envisioned three important scenarios.

- A single falling boulder within a mix of large rock and fines dumped at the top end of an ore pass or a large boulder that has broken free from the ore pass walls striking the walls or the bottom end structure.

---

[1] The mention of specific products and manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health.

- A stream of rock striking the bottom end of an ore pass. In this scenario, flow rate becomes important. The rate of dumping into the ore pass, how the rock interacts with a grizzly, and the dispersion of the rock material as it falls down the ore pass will affect the impact stream at the bottom end.
- A large mass of material released instantaneously and falling onto the bottom end structure. This type of event may follow after a hang-up is blasted or another method of hang-up release is employed. The mass of rock released may strike the bottom end with a force greater than a single boulder or a stream of rock. The air compressed during the fall of this mass of rock can cause air blast damage as well.

Single-particle impacts were modeled using WM2D, while all three scenarios were investigated using PFC2D.

WM2D

WM2D employs an impulse-based collision model in which the coefficient of restitution *e* is used to control the elasticity of the collisions. Collisions occur in discrete time, and the forces arising from the collision are affected by the time step. WM2D calculates collision force f_1 acting on mass m_1 using the formula $f_1 = m_1 ((v_1' - v_1)/\Delta t)$, where v_1' = velocity before collision, v_1 = velocity after collision, and Δt = animation time step.

When two bodies collide, there is a moment when the forces oppose the collision. If graphed over time, the force of a real particle during the impact period may be a bell-shaped curve. The force calculated by WM2D using the integration time step is a constant if graphed over a given time period. According to WM2D literature, “When the contact force between two bodies is measured, WM2D reports the impulse of the collision divided by the animation time step.”

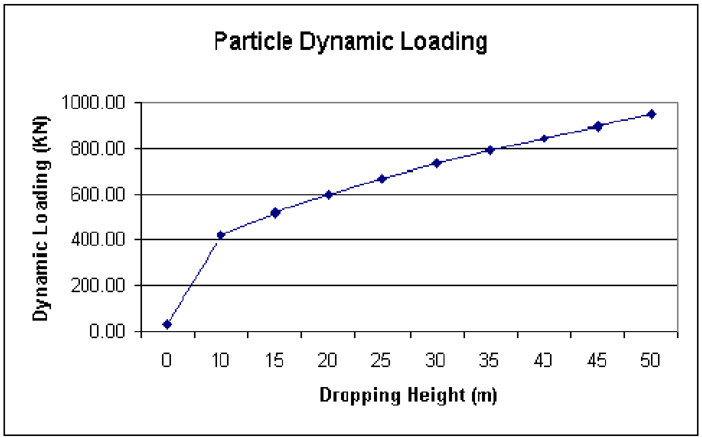


Figure 1.—Data from WM2D single-particle drop-test simulation

Table 1.—Results of WM2D single-particle drop test

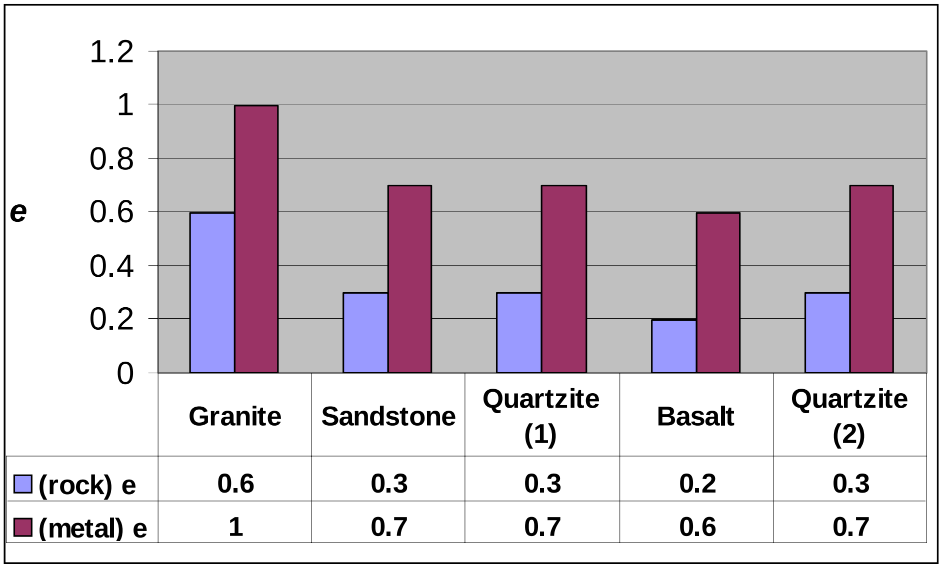
Height, m	Dynamic loading	
	kN	lb-force
0	30.81	6,927
10	422.90	95,080
15	517.60	116,400
20	598.00	132,000
25	668.40	150,300
30	732.60	164,700
35	790.90	177,800
40	845.80	190,200
45	896.60	201,600
50	945.20	212,500

Drop Test Simulation

Simulating collisions between particles is the key to creating an accurate simulation of an ore pass for studying material flow. As two particles collide, they lose energy if the collision is not perfectly elastic. The elasticity of particles in WM2D is controlled by the coefficient of restitution input. Simple drop test simulations were conducted using a circular disk and a horizontal wall. A 1-m- (3-ft) in diameter disk with a mass of 3,142 kg (6,927 lb-mass) and *e* of 0.2 was simulated and dropped from different heights to compare dynamic loads on the wall. *e* was assigned for each object. When a collision occurred, the smaller of the two *e* values was used to calculate the collision. In this case, the wall was assigned the same density and elasticity as the rock. Table 1 and figure 1 show the increase in dynamic loads for increasing drop heights.

Physical Model Pendulum Test

A physical model pendulum test was used to determine *e* for rock. A metal plate and a rock slab were used as objects onto which rock specimens were dropped five times to get the best estimate possible Using a background marked off in 1-1/2-in increments, we were able to estimate the different heights the rocks "bounced." Figure 2 shows the results of the physical pendulum tests. *e* varied greatly, depending on the rock specimen. We concluded that even if rock appeared to be the same, but came from different



	Granite	Sandstone	Quartzite (1)	Basalt	Quartzite (2)
🟦 (rock) e	0.6	0.3	0.3	0.2	0.3
🟥 (metal) e	1	0.7	0.7	0.6	0.7

Figure 2.—Coefficient of restitution as determined from pendulum test of rock against steel and rock

localities, *e* values were very different. *e* was found to be dependant on impact velocity, mass, and shape of the colliding bodies.

Ore Pass Simulations

In WM2D, disks can be used to represent rock particles. However, we used particles created in odd shapes to best reproduce the closest simulation of rock flow possible. Particles can be viewed flowing down the ore pass during the simulation. When first dumped, they spread out, resulting in different velocity profiles. Initial potential energies are slowed because of friction values assigned to the particles and the ore pass walls. The flow profile of the particles being dumped into the ore pass can be seen in the sequential representations created in figure 3.

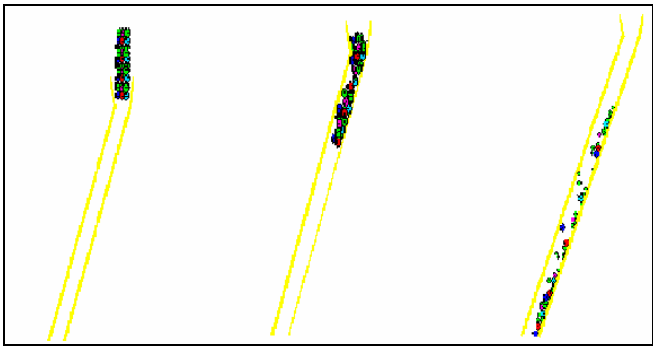


Figure 3.—WM2D simulations of flow in ore pass. Left: Particles just entering an inclined ore pass; middle: particles after being dumped into ore pass; right: particles have fallen a certain distance.

Various ore pass inclinations were simulated, and the impact force on the bottom end was measured for a single particle. Figure 4 compares impact force for a 90° (vertical) ore pass to other inclinations simulated. These ratios show that a force reduction of up to 60% occurs when a 60° inclination is used. Stream impact and hang-up release loads were not attempted in WM2D.

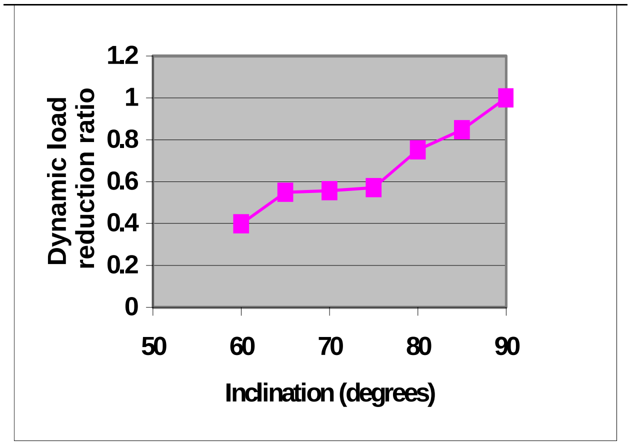


Figure 4.—Impact loads at various inclinations normal-ized to vertical load for a single-particle drop in ore pass simulation using WM2D

PFC2D

PFC2D is a distinct-element code designed to model complicated problems in solid mechanics and granular flow and is one product from a suite of geomechanics software tools from Itasca Corp. The calculation method in this code is a time-stepping, explicit scheme that is also called the "molecular dynamics" method (Luding et al., 1995). Contact laws using spring stiffness and damping are employed. The difference between WM2D's event-driven method and PFC2D's molecular dynamics method is the amount of contact time during particle collisions. In the event-driven method, the time during contact is ideally zero (Luding et al., 1995), although WM2D utilizes the integration time-step that is set arbitrarily by the user to aid in calculating forces. In molecular dynamics simulations, contact time is dependent on initial velocities, spring stiffness, and damping. Impact calculations occur during a time period of elastic compression and release.

The standard particle shape in PFC2D is a circular disk or a sphere. Complex particle shapes can be built using a clumping technique. The perimeter of individual particles are defined by identifying polygon line segments around a group of tightly packed disks or spheres.

Rock Properties and Simulation Inputs

Both rock and soil-like properties have implications for flow when simulating rock flow. A sample from a U.S. mine was tested to evaluate these properties and to provide input into the simulations.

Blasted mine rock, whether it is ore or waste, contains a wide distribution of particle sizes. The largest sizes may become a handling challenge at an ore pass grizzly because, if allowed into the ore pass, boulders may cause a blocky hang-up somewhere along the flow route. The weight of a boulder is important to consider also, because it may affect impact loads. Particle size distribution and specific gravity of rock were considered in the ore pass simulations.

The fine fraction of the particle-size distribution curve has cohesive strength when water is added. Depending on the water content of the fines and the amount of compaction in the ore pass during filling, the fines could cause a hang-up. The fines also act as a binder around coarse particles, locking the bulk material together into one large mass. Knowing the amount of fines, the water content in the bulk material, and the strength of the fines will provide enough information to predict whether a hang-up will occur in an ore pass with a given design. The rock properties of interest are size, shape, weight, and elasticity (table 2). Figure 5 shows the size distribution of the rock from the sample. An ore pass simulation should match the actual size distribution at the mine as closely as possible.

Table 2.—Rock properties of interest for simulations

Rock properties:	
Modulus of elasticity	5.5e4 MPa (8.0 × 10^6 psi)
Specific gravity	3.0
Particle size distribution	(see figure 5)
Particle shape	(see figure 6)
Soil-like properties:	
Internal friction angle (fines only), deg	35 to 39[1]
Angle of repose at the mine, deg	35.5 to 41
Angle of repose, dry (fines only), deg	36 to 41
Sliding friction, static (fines only), deg	25.4 dry, 40.0 wet
Sliding friction, constant velocity (fines only), deg	22.6 dry, 34.5 wet
Percent fines	16.0
Uncompressive strength (fines only)[1]	4,700 to 13,000 Pa (0.68 to 1.9 psi)
Water content (fines only), pct	14.0

[1] Iverson (2002)

Particle shape was determined for the PFC2D simulations using a three-view shadow. Front, side, and top views were shadowed for each particle sampled, and lines were drawn to that shadowed shape. Three outline views of a typical ore particle are drawn in figure 6 showing normal vectors from each side to the centroid from which angle and distance were modeled. A suite of 31 particles from three size fractions was sampled for shape. The number of sides was determined from 93 views of the 31 particles. Normal angles were determined from 33 views of the 11 sized particles.

Data from these shape measurements are shown in tables 3 and 4 and were input into the ore pass simulations (figure 7).

Due to the limits of computer processing, the shape of the smallest rocks could not be simulated. A compromise was to pick a cutoff size for a shape simulation. The sizes below the cutoff value are represented by uniform sized spheres or disks. Particles at the cutoff size are considered the fine fraction.

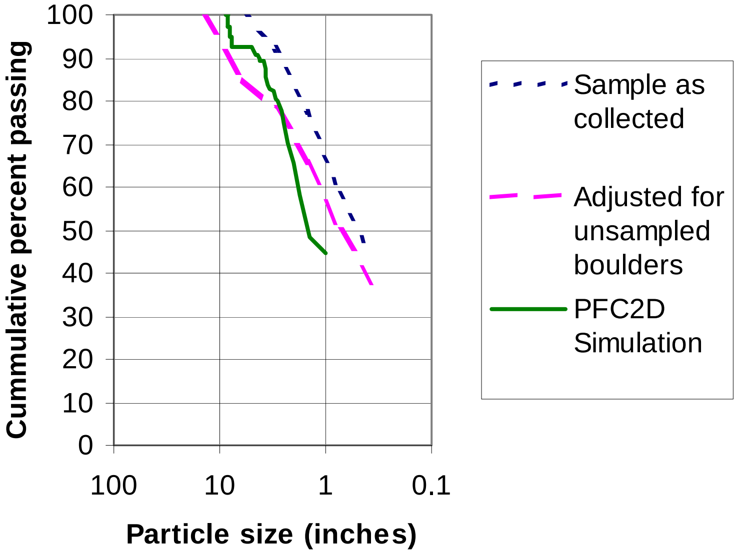


Figure 5.—Mine-run ore size distribution compared to simulated distribution

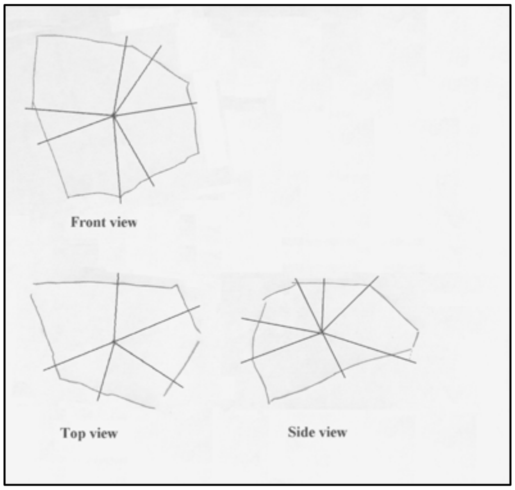


Figure 6.—Outline of typical ore particle showing top, front, and side views with normal vectors to each side for angle and distance measurements from the particle centroid

Soil-like properties are critical to understanding cohesive strength and hang-ups. The percentage of fines is a good indicator of potential problems. Beus et al. (2001) stated that 20% fines in the rock material will form a continuous matrix, and the greater the fine fraction, the greater is the potential for cohesive arch formation. Fines are considered to be particles less than 0.074 mm (0.0029 in) in diameter or U.S. Standard 200 mesh (Beus et al., 2001). Water content and the amount of compaction of the wetted fines will determine cohesive strength. It is the authors' contention that a combination of cohesive fines and interlocking of boulders can exacerbate a hang-up problem.

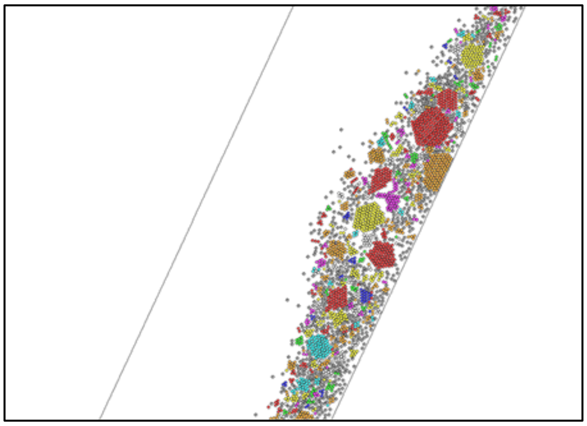


Figure 7.—Simulated falling ore particles with clumps based on shape and size distribution analysis

Table 3.—Variation in the number of sides for each size of rock measured

	Large rock	Medium rock	Small rock	All sizes
No. of rocks measured	11	10	10	31
Average no. of sides	6.1	8.5	8.9	7.8
Standard deviation	1.27	2.9	2.6	2.6
Average radius	0.0419 m (1.65 in)	NM	NM	
Standard deviation	0.56	NM	NM	

NM. Not measured

Table 4.—Variations in angle between sides for large and medium rocks

Sides, no.	Views measured, no.	Average angle between normal vectors, degrees	Standard deviation
3	1	120	9.2
4	1	90	9.1
5	11	72	22.3
6	9	60	25.4
7	6	51.4	21.0
8	4	45	21.1
9	1	40	24.1

For simulation purposes, friction of the rock and the soil-like material is important. Friction properties (internal angle of friction, angle of repose of piles, angle of repose of fines, and sliding friction angle of dry and wetted fines) were obtained from laboratory experiments. Internal friction angle was used for friction coefficient of the particles in the simulation. The repose and sliding angles can be compared with sliding material simulations in PFC2D. Wall friction coefficients and particle friction coefficients can be adjusted.

In simulating the fine fraction in PFC2D, bonding between particles was used to represent the cohesive strength of the material. Two-dimensional unconfined compressive strength tests were simulated based on laboratory tests of the fine fraction (Iverson, 2002).

PFC2D simulation inputs used are shown in table 5. Particle stiffness was determined from the modulus of elasticity value. Larson et al. (1998) provides a conversion to particle stiffness using the following equation:

$$Kn = ArE$$

where Kn = particle stiffness, N/m,
A = dimensionless constant (determined to be 0.19052),
r = particle radius, m,
and E = modulus of elasticity, Pa.

Table 5.—PFC2D simulation inputs

Particle density	3000 kg/ m^3
Cutoff particle radius	0.0127 m
Particle type (disk or ball)	ball
Cohesion bond strength	5000 Pa (0.7 psi)
Particle stiffness (normal and shear)	1.3e8 N/m (8.9e6 lb/ft)
Bond stiffness (normal and shear)	1e8 N/m (6.9e6 lb/ft)
Steel chute stiffness	4.8e8 N/m (3.3e7 lb/ft)
Particle friction coefficient	0.73
Wall friction coefficient	0.73 wall rock, 0.17 steel chute
Grizzly spacing	0.381 m (1.25 ft)
Ore pass width	3.0 m (9.8 ft)
Ore pass angle	Variable
Chute angle	45 degrees
Chute gate opening height	0.91 m (3 ft)
Ore pass height	91.4 m (300 ft)

Larson et al. (1998) also indicate that the angle of repose is reasonable for use as a friction coefficient in PFC2D.

Simulated Single-Particle Drop Test

A single-particle drop test was run in PFC2D using the same parameters as in the WM2D test. Since there is no input in PFC2D for *e*, the elasticity of the impact had to be obtained by using a special contact model. The stiffness of the impact was decreased during the second half of the collision. By adjusting rebound stiffness, a comparable *e* was accomplished. Dynamic loads produced in PFC2D were much higher than in WM2D. The impact period or integration time-step used in WM2D was 0.196 sec, much longer than in PFC2D. Particle and wall stiffness affect dynamic load significantly in PFC2D. When drop height was zero, PFC2D produced a dynamic peak load twice the final static load. Data from the drop test are shown in table 6 and figure 8. Dynamic loads were large compared to the later ore pass simulations because particle size in the single-particle drop test was large compared to individual particle sizes in the ore pass simulations.

Table 6.—Single-particle drop test data from PFC2D

Drop height		Rebound		*e*	Dynamic load	
m	ft	m	ft		kN	lb-force
0	0	0	0	0	60	1.0e4
10	30	0.8	2.6	0.283	45,710	1.02e7
15	49	1.05	3.4	0.265	57,800	1.30e7
20	66	1.1	3.6	0.235	66,910	1.504e7
25	82	1.5	4.9	0.245	75,120	1.689e7
30	98	1.85	6.1	0.248	82,430	1.853e7
35	115	2	6.6	0.239	87,910	1.976e7
40	131	2.2	7.2	0.235	94,440	2.123e7
45	148	2.4	7.9	0.231	97,510	2.192e7
50	164	2.6	8.5	0.228	104,200	2.343e7

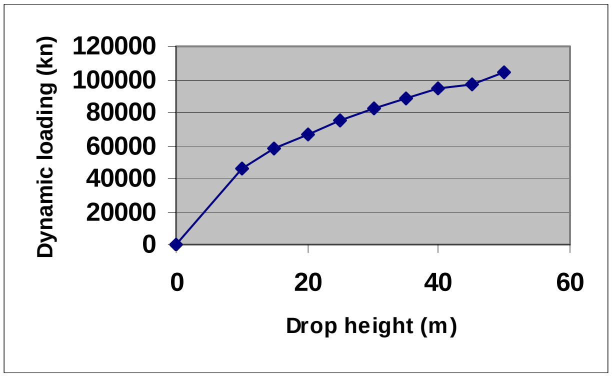


Figure 8.—Peak dynamic loads from PFC2D single-particle drop test simulations

Table 7.—PFC2D simulation results showing peak dynamic load and inclination

Ore pass inclination, degrees	Peak dynamic load	
	N	lb-force
90	125,000	2.81e4
80	92,140	2.07e4
70	86,300	1.88e4
60	67,500	1.52e4
50	58,900	1.32e4

Inclined Ore Pass Simulations

To simulate the effects of ore pass inclination, rock particles were dumped into the ore pass at various angles of inclination, and dynamic loads were measured at the bottom end (table 7). Figure 9 illustrates the setup for an inclination of 65° with a grizzly at the top end and a chute at the bottom.

The material was generated at the top of the simulated ore pass just above the grizzly (figure 10). Figure 10 is a close-up view of an ore pass setup similar to that shown in figure 9, but at 80° inclination. The small rectangles represent the bars of a grizzly. Material passing through the grizzly was "metered," much like what occurs at the top end of an ore pass in a real mine environment. The PFC2D dynamic loads at the ore pass bottom are shown graphically in figure 11. Observations during peak impacts indicate single-particle impacts represent peak dynamic loads.

Dogleg Simulation

The inclined ore pass with a short dogleg transition into the chute was used to compare forces at the dogleg with forces at the chute gate (figure 9). Figure 12 provides a close-up view of the PFC2D simulation and shows rock striking the chute slide, followed by impacts to the chute gate. Figure 13 is a graph of dynamic force over time acting normal to the chute slide and the chute gate. A comparison of both graphs in figure 13 shows that the chute slide was subjected to greater impulsive force from the stream of rock. Peak forces were 58,630 and 13,490 N (13,180 and 3,033 lb-force) on the chute slide and gate, respectively.

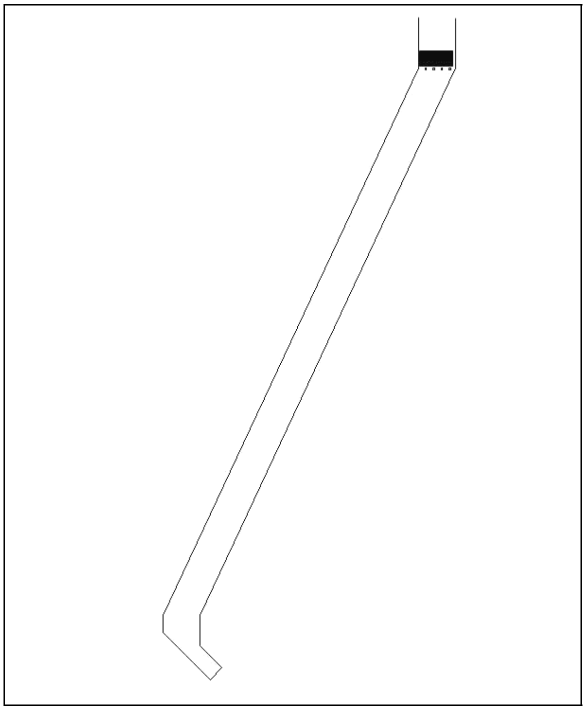


Figure 9.—PFC2D ore pass simulation setup for a 65° inclination

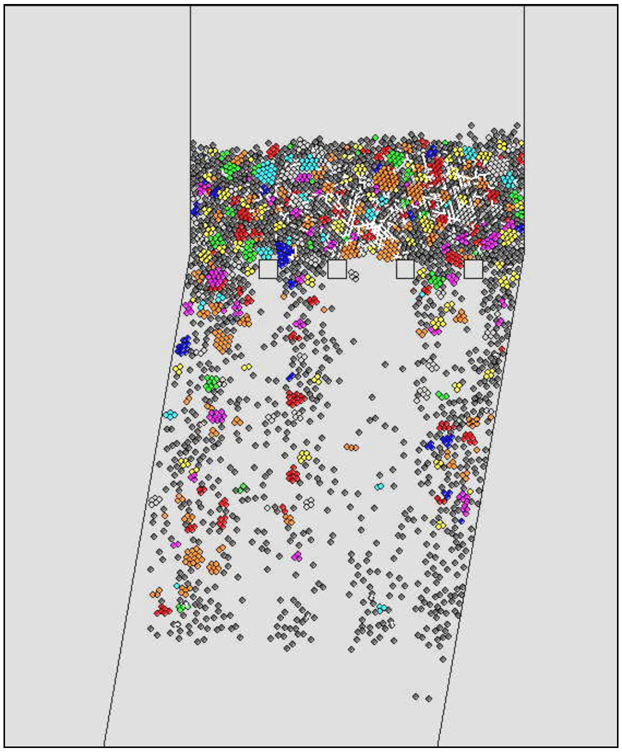


Figure 10.—PFC2D grizzly dump simulation using angular clumped particles and cohesive bonding for fine material

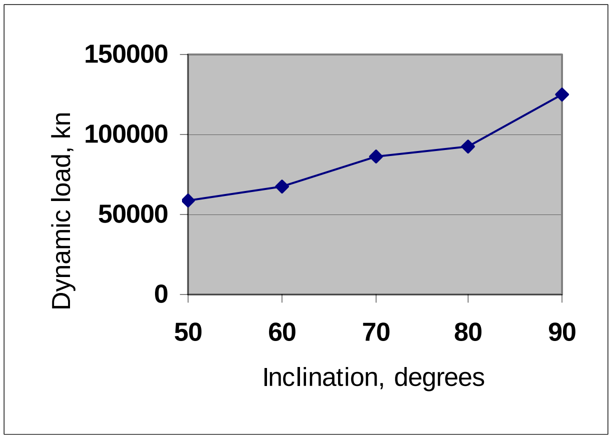


Figure 11.—Ore pass inclinations and peak impact load from PFC2D simulation

Final static loads on the chute slide and gate were 600 and 425 N (135 and 95.5 lb-force), respectively. The duration of impacts for the chute slide and gate were 1.6 and 1.2 sec, respectively. The total mass of the dump was 84.3 kg (5.78 slugs), providing a static weight of 827 N (186 lb-force).

Hang-Up Release Simulation

A hang-up release simulation was run for a 91.4-m (300-ft) vertical ore pass without a grizzly. In this simulation, particles remained tightly packed until they struck the chute slide below. This impact simulated the sudden release of a hang-up in which a large mass of rock fell as a unit onto the bottom end chute. Peak dynamic force normal to the chute slide wall in this test was 6.7 times the peak force measured in the vertical ore pass simulation with a grizzly (figure 14). Peak impact forces for the slide and gate were 390,800 and 191,800 N (87,860 and 43120 lb-force), respectively. Final static loads on the slide and gate were 800 and 550 N (180 and 124 lb-force), respectively. Duration of impacts for the slide and gate was short, about 0.2 sec combined. The total mass of the dump was 75.3 kg (5.16 slugs), providing a static weight of 739 N (166 lb-force). Packing into the chute area was greater in this simulation than in the simulation in which a grizzly was used over the ore pass, which resulted in greater static forces.

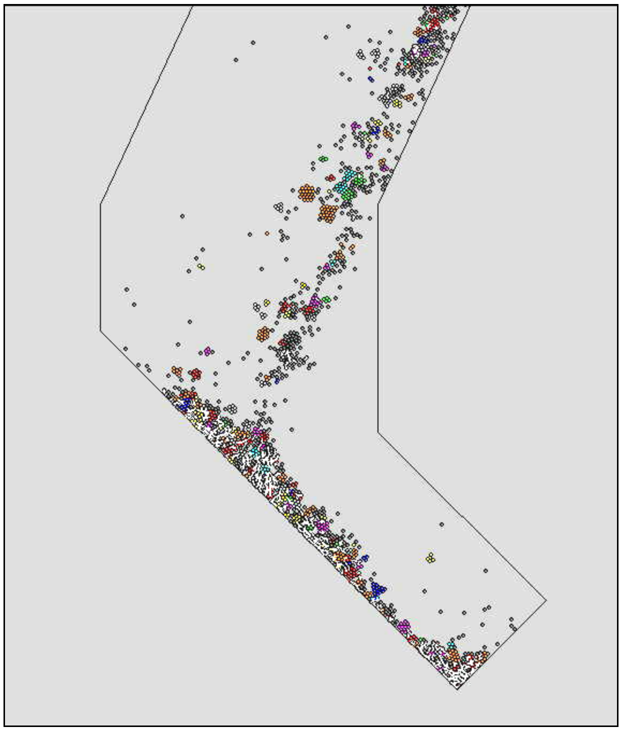


Figure 12.—PFC2D simulation of angular rock particles striking chute slide and gate

DISCUSSION AND CONCLUSIONS

PFC2D can be made user friendly by programming specific dimensions or features into the simulation. Ore pass angle, chute slide angle, chute opening angle, chute length, and grizzly spacing are some of the variables worth manipulating in the design of an ore pass. With some additional effort, grain-size distribution and particle shape can also be simulated.

PFC2D was used to compare dynamic forces at the bottom end of a chute with various ore pass angles. Forces on chute slide and gate components were also compared. As a two-dimensional simulation, forces on the bottom at the dogleg or at the chute were much less than what would be expected in a three-dimensional simulation or in a real-case ore pass scenario. Individual unclumped spherical particles simulated in two dimensions are comparable to a three-dimension situation.

The cohesive nature of fine particles can be modeled using PFC2D bonds. There is a limit to the number of particles that can be simulated because of limitations in the capabilities of personal computers. This can be remedied by using a cutoff particle size and model that fraction as cohesive fines. Single rock impacts, rock streams, and released hang-ups were all simulated using PFC2D. The force of individual impacts measured in the simulations were high, but represent the elasticity of the materials simulated. These forces may be slightly overestimated, considering that rock will fracture during impact and absorb some of the collision energy over a longer impact period. Also these simulated collisions do not account for flexure of an impact surface, such as a steel plate that is part of a chute assembly.

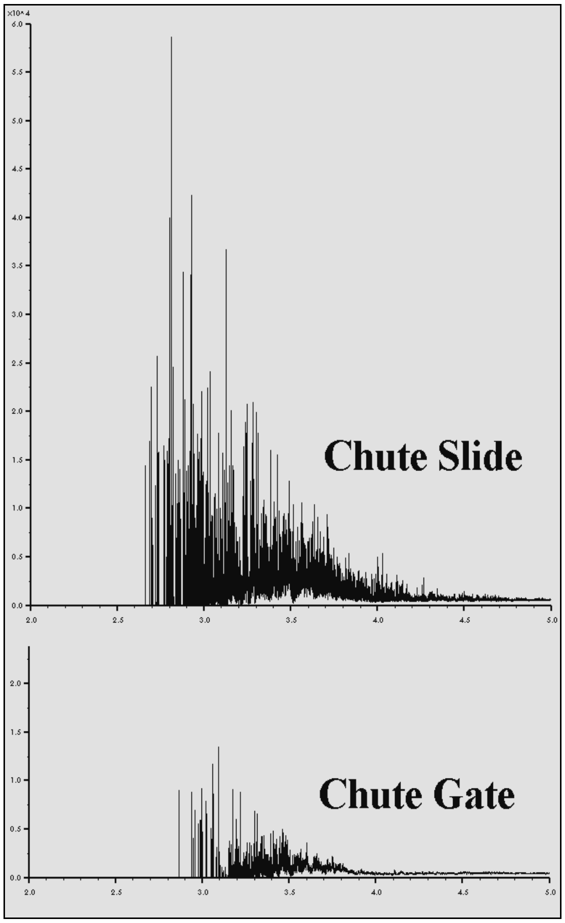


Figure 13.—Dynamic force on chute slide and gate from one dump event analyzed with PFC2D

WM2D was also useful in measuring dynamic forces and testing flow designs. Dynamic load values are suspect because of the arbitrary use of the integration time-step and its effect on normal force. With such a large time-step used, force values may be severely underestimated. Design considerations can be tested using various inclinations, doglegs, and chute configurations in WM2D.

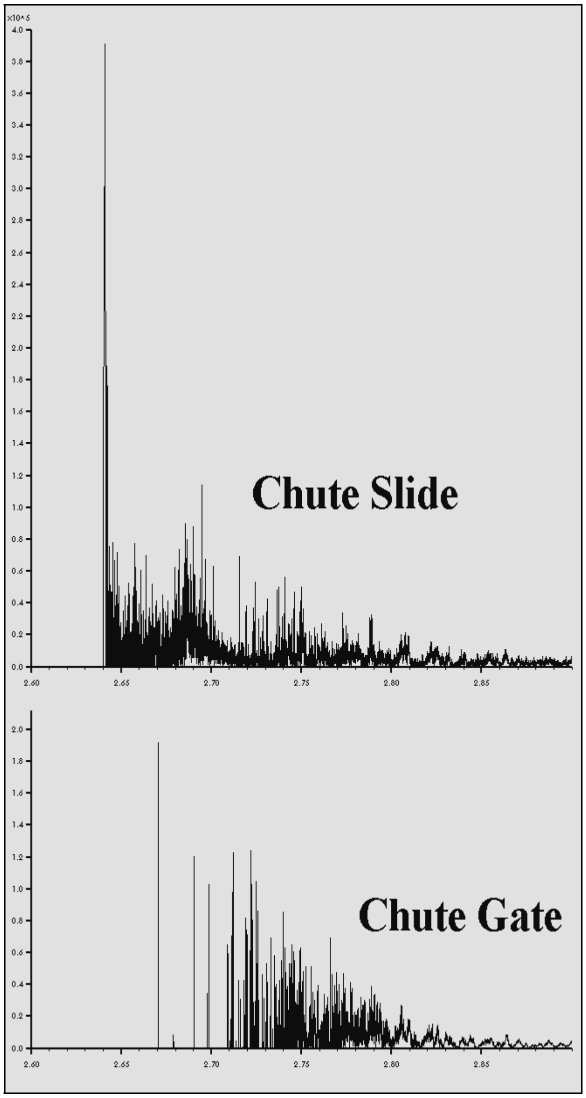


Figure 14.—Impact forces on chute slide and gate following a hang-up release analyzed using PFC2D

Testing ore pass designs using either program takes computer simulation time and computer resources. Which type of simulation is best was not determined. The event-driven simulation using WM2D may have advantages in processing time due to the nature of its calculation cycle. PFC2D requires time-stepping during compression and relaxation of each particle collision whereas WM2D does not. Higher particle velocity requires a smaller time-step during cycling in both PFC2D and in WM2D. PFC2D has the capability of modeling cohesion using bonds whereas WM2D does not.

Although the impact forces are somewhat suspect, the use of inclined ore passes and doglegs to reduce impact force on the chute was demonstrated using PFC2D and WM2D.

REFERENCES

Beus, M.J., W.G. Pariseau, B.M. Stewart, and S.R. Iverson. 2001. Design of Ore Passes. Ch. 71 in *Underground Mining Methods: Engineering Fundamentals and International Case Studies*, Hustrulid and Bullock, eds. Society for Mining, Metallurgy, and Exploration, Inc., pp. 627-634.

Itasca Consulting Group, Inc. (Minneapolis, MN). 1995 PFC2D (Particle Flow Code in 2 Dimensions), Version 2.0.

Iverson, S.R. 2002. Investigation of Bulk Solids Engineering Properties and Application of PFC2D to Ore Pass Flow Problems. In *Numerical Modeling in Micromechanics via Particle Methods. Proceedings of the 1st International PFC Symposium*, ed. by H. Konietzky (Gelsenkirchen Germany, Nov. 6-8, 2002). Balkema, Rotterdam, Netherlands, pp. 252-258.

Larson, M.K., S.R. Iverson, B.M. Stewart, and K. Walker. 1998. Preliminary Assessment of Particle Flow Code as a Tool To Assess Ore Pass Safety. Presentation at Rock Mechanics in Mining, Petroleum, and Civil Works: 3rd N. American Rock Mechanics Symp. (Cancun, Quintana Roo, Mexico, June 3-5, 1998), paper 92. Extended abstract in *International Journal of Rock Mechanics & Mining Science*, vol. 35, nos. 4-5, p. 533, 1998. (Available on CD-ROM from Elsevier, New York, NY)

Luding, S., E. Clement, A. Blumen, J. Rajchenbach, and J. Duran. 1995. Interaction Laws and the Detachment Effect in Granular Media. Symposium Proceedings, Materials Research Society, Pittsburgh, PA, vol. 367, p. 495.

MSC Software Corp. (Santa Ana, CA). 2002. Working Model 2D.

Pariseau, W. G. 1996. Role of Material Properties in Ore Pass Design. Unpublished contract report to NIOSH, 23 pp.

COMPARISON OF ORE PASS COMPUTER SIMULATIONS FOR DESIGNS AGAINST DYNAMIC LOAD

S. Iverson
Spokane Research Laboratory, National Institute for Occupational Safety and Health, Spokane, WA
siverson@cdc.gov

S.J. Jung and K. Biswas
University of Idaho, Moscow, ID