Safety considerations for transport of ore and waste in underground ore passes

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Abstract

Recent ore pass failures have underlined the need for improved designs, standards, structural monitoring methods and better hang-up prevention and removal techniques. Researchers at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) are investigating methods to improve safety during the transport of ore in ore passes. Design criteria and hang-up prevention and remediation strategies involve studies of the effects of static and dynamic ore and waste-rock loads on chutes, walls, gates and support structures. Particle-flow analysis methods were used to simulate the response of various ore pass designs to a wide range of ore loading conditions. A full-scale mockup of actual ore pass and chute assemblies was duplicated and tested for load response. Data from a particle flow code and the mock-ups were compared. Loads on an active ore pass chute were measured.

Introduction

Production in most deep underground mines depends on the ore pass system. If the primary ore pass becomes inoperable because of structural failure, plugging, chute and gate problems, or for other reasons, the production of the mine comes to a halt. For example, one mine took 14 months to remove a hang-up that was about 18-m (60-ft) long (Hambley et al., 1983). The hang-up cost the company thousands of dollars.

Miners are exposed to numerous hazards during the process of moving underground ore and waste rock to the surface. This is especially true when miners are removing material from ore passes that become blocked or when equipment fails. For example, in a recent accident (Tanner and Okuniewicz, 1995), two miners, after several unsuccessful attempts to remove ore hung up in the chute, were caught when the ore suddenly and unexpectedly broke loose, striking the chute and gate assembly and causing the bottom of the assembly to break away from its support structure. One of the miners was fatally injured. The cause of the accident was given as "failure of the ore chute mounting assembly, which did not provide support for loads imposed during mining operations." A contributing factor to the accident was "allowing ore, saturated with mine water, to set for days in the ore raise."

Other hazards include structural failures, blocked gates and excessive water pressure. Undetected excessive loads can cause progressive structural failure, and blocked gates can result in spillage of large volumes of fine material. Water flowing into the ore pass can result in catastrophic muck flows and inundation.

Chute design and hang-up removal methods are often based on experience, i.e., on what has worked in the past. However, because of different rock types and geologic structures, ore pass designs and hang-up removal methods that work in one mine may not work in another, or they may even not work in a different area of the same mine.

Guidelines for open-pit ore pass design (Hambley et al., 1983) and for underground ore pass design (Hambley, 1987; Ferguson, 1991) include extensive information on proper ore pass construction and numerous factors that need to be considered by design engineers. However, despite the existence of excellent guidelines, hang-ups, failures and other ore pass problems still occur frequently in underground mines. Loads approaching maximum design loads will affect an ore chute and/or gate and eventually, if undetected, may result in chute and gate failure. This paper describes relatively easy and inexpensive methods for measuring loads on ore pass chutes and gates and for predicting loads using particle flow codes.

Mine visits

At the beginning of the project, five underground mines in Arizona, Montana, South Dakota, and Idaho were visited. Each mine has an ore pass system, and each had experienced ore pass problems, particularly hang-up problems.

Three mines were concerned about load-out chute design and support. While most mines designed deflection points into the ore pass above the load-out chutes, direct or secondary impacts by ore caused chute damage because deflection angles were inadequate. Muck would pile up or stick at the deflection point, resulting in the ore striking the chute itself. If hang-ups were blasted free, percussion waves would reduce the structural integrity of the chute and ore pass. Based on the calculation of loads, all mine operators felt that their ore pass chute supports were

FIGURE 1

Full-scale laboratory mockup of top assembly of ore pass discharge and support structure.

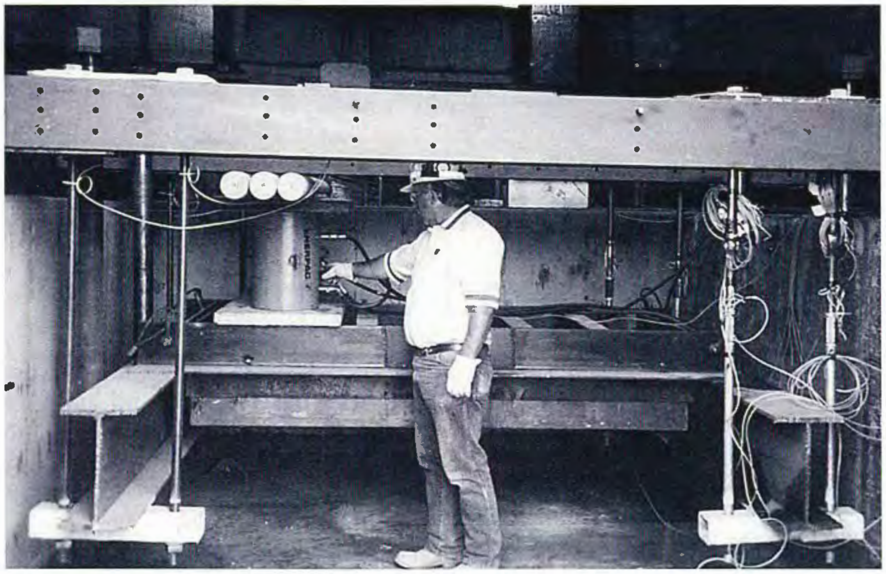
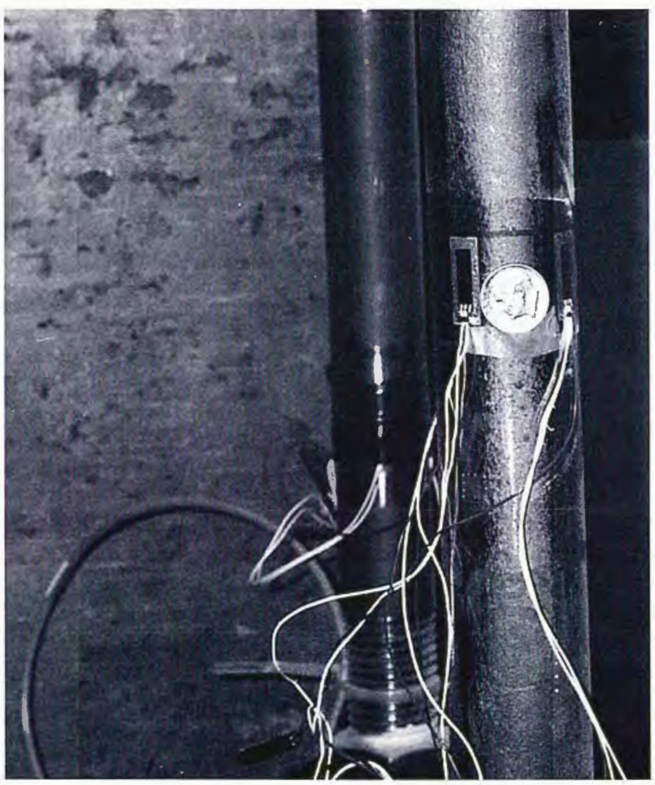


FIGURE 2

Strain gages used to measure static and dynamic loads.



adequately designed, or even over-designed. However, none of the mines had installed instruments to measure static loads due to muck weight or dynamic loads due to blasting or release of hang ups.

The causes of the hang-ups varied. Daily hang-ups occurred at one mine because the ore pass walls were sloughing; this mine had a major hang-up every three to six months. The hang-ups were then blasted loose. At another mine, several hang-ups were occurring each day, immediately above the load-out chute because of what appeared to be too much cohesive sand in the muck, which had just enough moisture to cause the sand to stick. A high-pressure air-injection system was used to remove the hang-ups. A third mine experienced hang-ups in both the ore and waste rock passes. The ore contained a large amount of cohesive fines that caused arching-type hang-ups, while the waste rock contained oversized boulders that caused block-type hang-ups. Blasting was generally used to remove both types of hang-up.

Very little information on the physical properties of the ore or waste rock exists at these mines. This is unfortunate, because size distribution, amount of fines, cohesiveness of fines, moisture content, density and angle of internal friction are all physical properties that relate to material flow.

Grizzlies are important in preventing block-type hang-ups, because they control maximum particle size in the material dumped into an ore pass. However, at some of the ore pass dump points in these mines, grizzlies had been removed or were damaged.

Chute load analyses

Full-scale laboratory mock-up. Long-term chute load monitoring can aid in preventing unexpected chute failure. Actual loads can be compared to calculated loads, allowing an engineer to check the design. Previously undetected high load events (loads that approach or exceed maximum design loads) and the frequency of these events can be determined by analyzing stored strain-gage data. By knowing when high loads occur, inspections of chute and gate structures can be scheduled in a timely manner. Because muck-control gates are the most important structural element subjected to the types of excessive loads that cause overall ore pass failure, detecting maximum static and dynamic gate forces is an important goal.

Prior to testing chute loads in an actual mine, a full-scale mockup of a chute frame was constructed at the Spokane Research Laboratory's test facility using a suspended chute in a mine in northern Idaho as the prototype. The objective was to develop a scheme for determining muck loads on ore pass chutes and gates that could be easily and cheaply implemented in the field and to test the load measuring method in the laboratory prior to underground mine tests. In the mockup (Fig. 1), eight 38-mm- (1.5-in.-) diam, 1.07-m (3.5-ft) long supporting bolts were attached at the top to steel beams that spanned reinforced concrete abutments lined with steel plate. The chute frame was welded to two I beams that rested on suspended saddle beams. The support bolts were attached at the bottom to the saddle beams. The chute frame, I beams, support bolts and saddle beams are identical to those in the mine. Loads were applied using two 180-t (200-st) hydraulic jacks.

In the mock-up, four 350-ohm strain gages (Fig. 2) spaced 90° apart were spot-welded to each of the support bolts to measure the load on the bearing support structures of the ore pass chute. The assumption was that measurements of tensile strain on the support bolts accurately represent muck loading forces (minus certain energy losses). Four strain gages (one set) were installed on each bolt (a total of 32 gages) and were wired in series to produce an electronically averaged output signal through a 1,400-ohm effective resistance. In calibration tests in a load test machine, this configuration was shown to minimize the effects of bending and torsional strains in the bolt and produced a true measurement of axial strain. The resulting "active leg" was completed into a full bridge configuration at the datalogger using a three-wire hookup to minimize variations in signal caused by temperature changes. Strain was measured at a maximum scan rate of 100 samples per second with a Windows 95-based data-acquisition software and hardware. Data could be processed and stored in a removable memory card; or it could be downloaded via a modem to a Pentium 133 MHZ laptop computer.

Static tests: Static tests on the full-scale mockup consisted of applying load through a load-distribution plate. This configuration approximated the cross-sectional area of the actual chute gate. The maximum static normal load used for the structural design of the chute gate was estimated to be approximately 9,072 kg (20,000 lb). The support framework was designed to accommodate a total maximum load of 45,360 kg (100,000 lb). Two types of static tests were performed: ramp tests, in which the load was steadily increased; and incremental tests, in which a load was applied, maintained for a period of time, increased again, maintained, and so forth, five times, with the load being increased each time.

FIGURE 3

Ramp load test results on full-scale mockup.

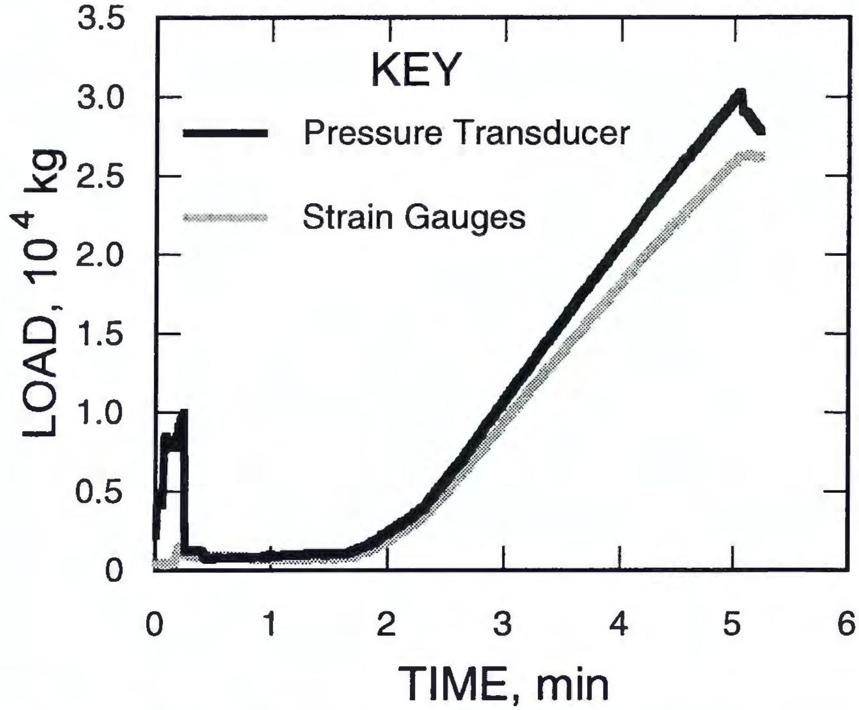


FIGURE 4

Incremental load test results on full-scale mockup.

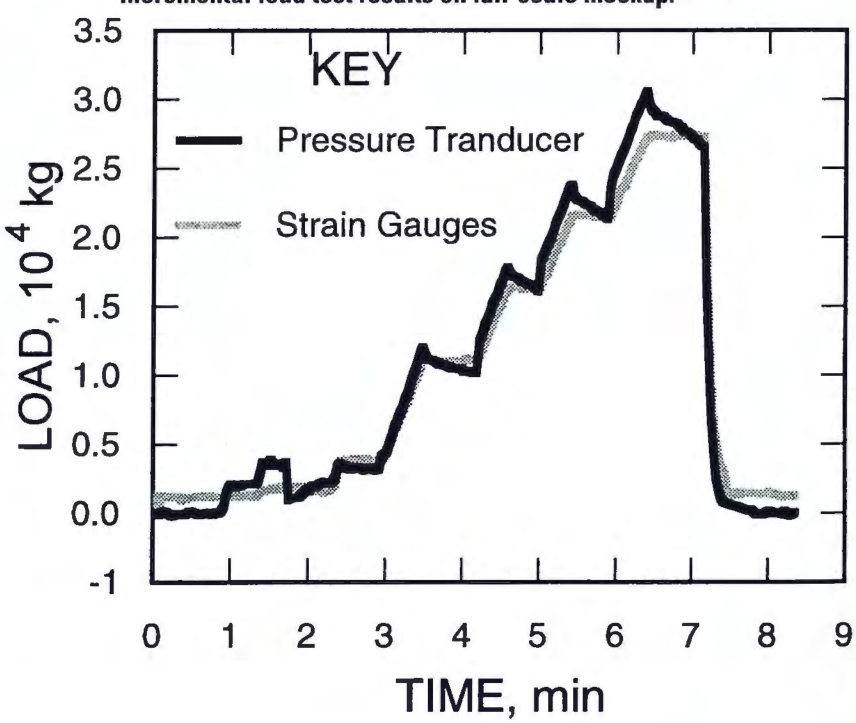


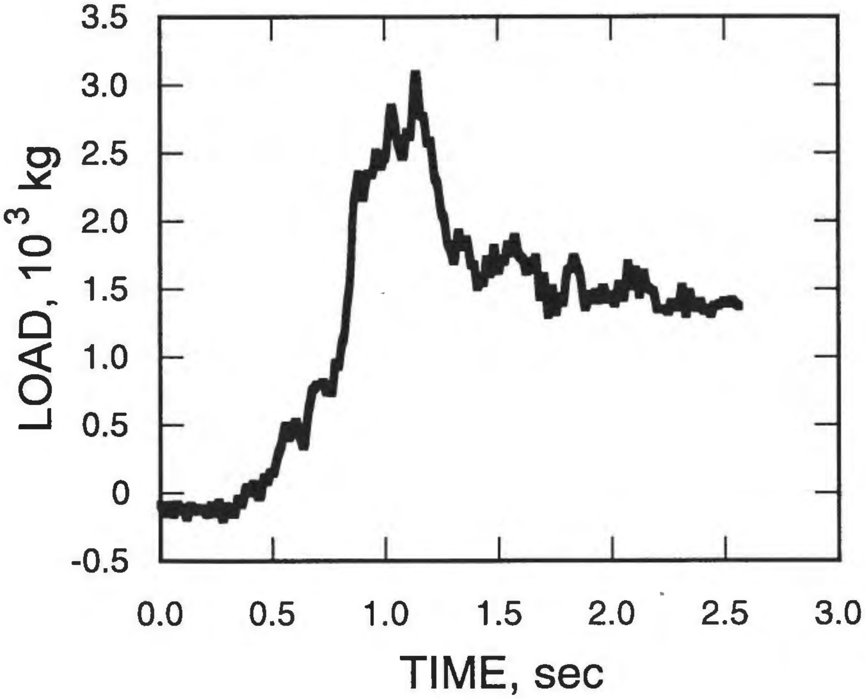
Figure 3 is a plot of one of the ramp tests. In each of the tests, loads on the hydraulic jacks determined by measuring fluid pressure with a transducer were higher than the loads measured by summing the loads on the strain gages attached to the bolts. This could be a result of errors in strain-gage calibration or errors from the pressure transducer signal.

Figure 4 shows a plot of an incremental test. Again, loads on the hydraulic jacks were higher than loads on the strain gages. When the loads were held constant, the pressure transducer loads decreased while the strain gage loads remained constant. This would indicate a potential signal error in the pressure transducer and not a "leaky" hydraulic jack.

A regression analysis was performed relating actual load measured on a test machine in the laboratory to computed load based on a summation of strain from the

FIGURE 5

Dynamic load tests on full-scale mockup.



eight bolts. The load calibration equation is

$$y = 1.093\ x \qquad (1)$$

where
y is the actual load being applied and
x is the computed load, in pascals, from the average strain summation from the eight bolts.

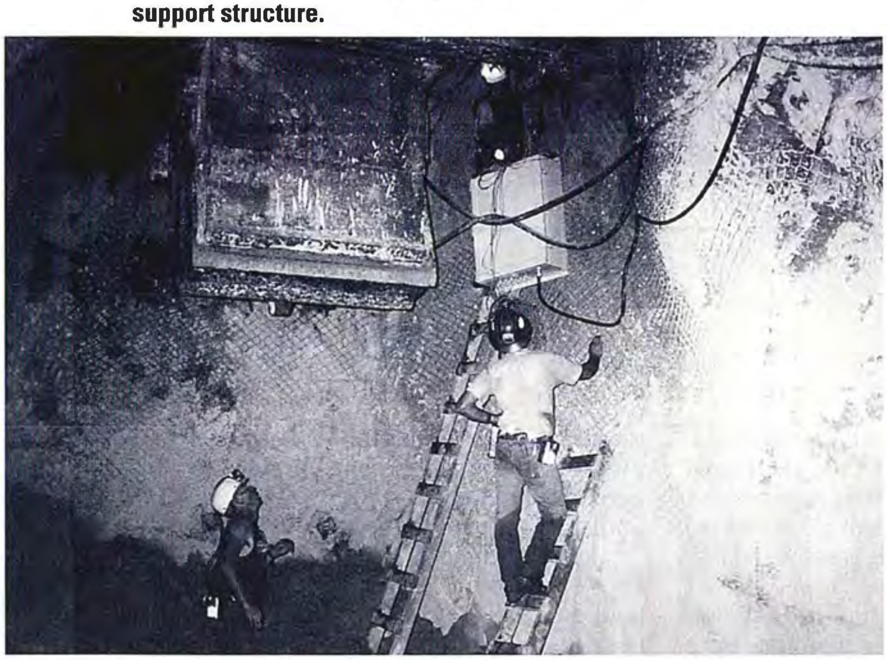
The results from the best-fit straight line yielded a correlation coefficient (R^2) of 0.995. It was thus shown that strain gages could effectively act as calibrated "load cells" to determine static loads acting on a chute and gate system.

Dynamic tests: After completion of the static tests, the hydraulic cylinders and load-distribution plate were removed for the dynamic tests. These tests consisted of dropping a load of mine waste rock having a bulk density of 1.7 g/cm^3 (104.9 lb per cu ft) from a height of 208 cm (82 in.) into a 2.4-m- (8-ft-) wide, steel-reinforced container sitting on the mockup chute assembly. Plywood was placed in the bottom of the container. A front-end loader with a clam shell bucket was used to drop the material into the container. After each drop, the container and material were lifted and weighed. Three tests were completed with material weighing 808 kg (1,778 lb), 1,000 kg (2,200 lb) and 1,238 kg (2,724 lb). Figure 5 shows a plot of results of Test 3, in which the static load measured 1,410 kg (3,100 lb) and the peak load 3,136 kg (6,900 lb). The difference between the measured static load and the weight of the material was the weight of the container (356 lb) and spilled material that struck the chute assembly but was not weighed. The laboratory tests showed that the strain gages could measure small dynamic and static loads within an acceptable range (R^2 = 0.995). The next step was to test the response of the strain gages to large dynamic loads similar to those in mine ore passes.

In-mine tests. The in-mine field test was conducted on an ore pass chute and gate system at an active mine (Fig. 6). The purpose of the test was to determine if the strain-gage system could feasibly measure large static and dynamic loads on chutes and control gates under actual conditions of high humidity and high temperatures in a mine environment.

FIGURE 6

Placing instruments on ore pass load-out chute support structure.



The mine-chute support structure and gate assembly were welded to two steel beams resting on saddle beams suspended from eight 38-cm- (1.5-in.-) diam, high-tensile-steel support bolts. Thirty-two strain gages in sets of four each were welded on the eight bolts. Each strain gage cost about $50 and took approximately 45 min to position, weld, waterproof and wire into the datalogger. The eight bolts were attached to brackets at their tops and to the saddle beams at their bottoms. The top brackets were anchored by 2.44-m- (8-ft-) long Dywidag rock bolts installed at 45° to 60° angles into the rock mass at the back of the drift cutout. The center of the gate assembly was offset 2.4 m (8 ft) from the longitudinal axis of the ore pass so that falling ore did not directly hit it.

Fourteen loads of moist waste rock from load-haul- dump (LHD) units, at 1.53 m^3 (54 cu ft) per load, were dumped. Twelve of the dumps each averaged from 2,270 to 2,730 kg (5,000 to 6,000 lb) of material; two of the dumps were material from cleaning up the drift and weighed about 270 kg (600 lb) each. Data from the strain gages were transmitted to the same portable datalogger used in the laboratory tests. Tensile strains were averaged to produce a measurement of the total vertical force acting on the structure as material was dumped into the ore pass.

Preliminary analysis of the data showed that two sets of strain gages were not working. Examination of the problem indicated that two strain gages on different support bolts were damaged during installation. Because each set of gages was wired in series, no data could be obtained from these two support bolts. The loads on the two nonworking bolts were assumed to be the same as on their companion working bolts. This assumption is reasonable because in the laboratory tests, companion bolts gave similar load readings.

Results indicated that static and dynamic loads on the chute and gate assembly in the mine were significantly less than anticipated. The weight of material dumped in the ore pass was in excess of 27,300 kg (60,000 lb); however, a maximum static load of only 6,800 kg (15,000 lb) was measured. This static load was approximately the weight of waste material required to fill the chute. The rest of the static load was being carried by other members, such as the wedged timber set adjacent to the chute assembly and the ore pass walls.

Dynamic loads on the chute and gate assembly were reduced significantly because the chute was offset from the ore pass. Impact values (peak value of strain-gage output divided by steady output after fallen ore has come to rest) ranged from 1.06 to 1.33. This compared to an average impact value of 4.09 reported by Blight and Haak (1994) in tests in a vertical ore pass where material struck the chute directly. An offset chute design allows a cushion of material to pile up at the base of the ore pass to absorb the initial impacts from the leading edge of the falling column of ore or waste. Figure 7 shows the increase in the strain gage load after the fourth LHD dump, and Fig. 8 shows the load response from all 14 dumps combined. After the initial dump test,

FIGURE 7

The load on the strain gages in the ore pass load-out chute while dumping 0.34 m^3 (12 cu ft) of waste rock from the top of the ore pass.

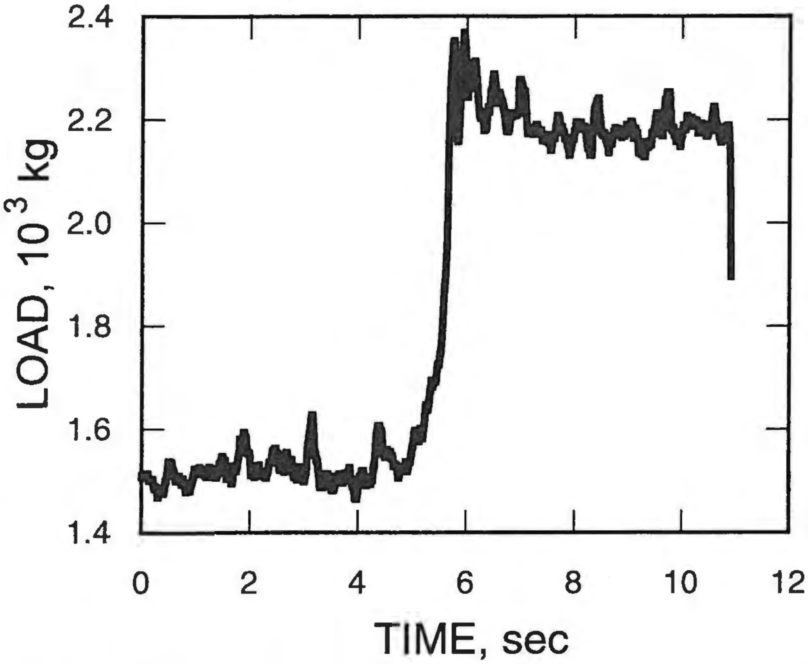


FIGURE 8

Cumulative load on strain gages in ore pass load-out chute from dumping 14 LHD loads of waste rock.

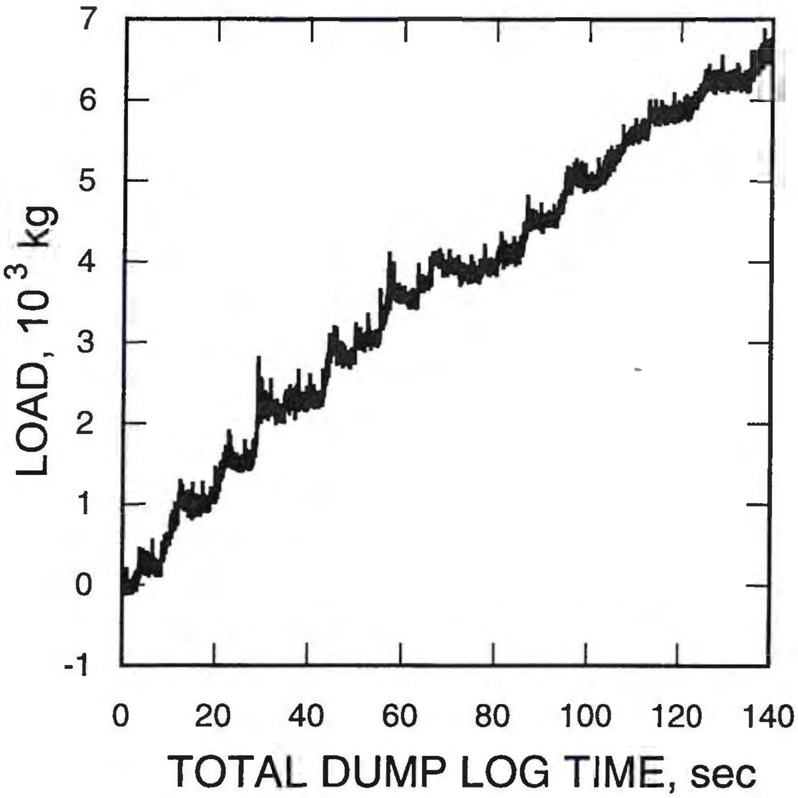
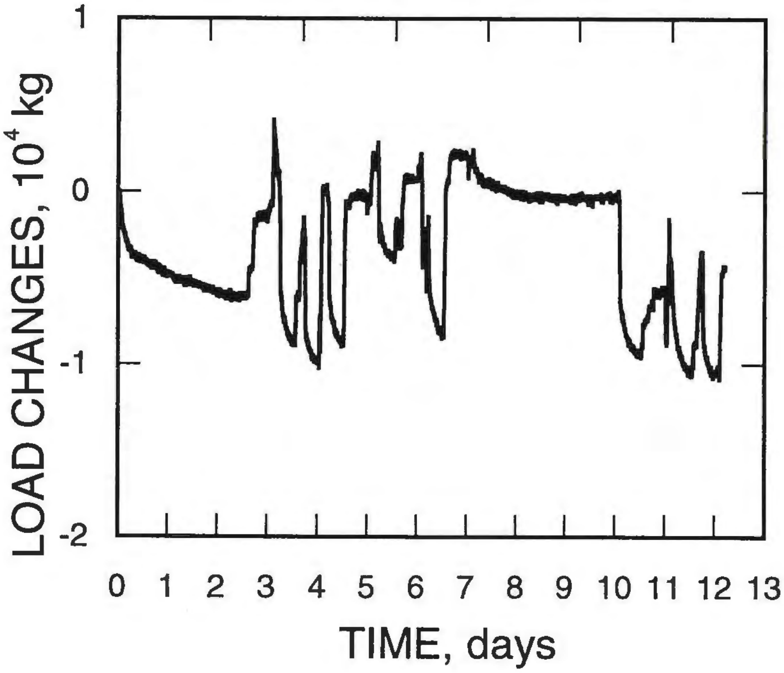


FIGURE 9

Twelve-day record of load changes on ore pass load-out chute.



the datalogger was set to record every two minutes. A 12-day record of the ore pass loading and dumping cycle is shown in Fig. 9. The flat parts of the curve (Days 1 and 2 and Days 7, 8 and 9) indicate no loading or dumping cycles. These times corresponded to the weekends, during which no ore was loaded or unloaded. Accurate interpretation of the data would be enhanced by loading and dumping logs or direct observations.

Installation of the gages on the bolts would be easier and less time-consuming if they were installed before the bolts were placed in the mine. This would be especially true in hanging chutes. Although not tested, strain gages attached with epoxy may be just as effective, reducing the cost of gage welding equipment. The high humidity (80%) and temperature 35°C (95°F) in the mine did not appear to affect either the strain gages or the datalogger.

Numerical modeling

Itasca Consulting Inc. is a leader in the development of finite-element and distinct-element modeling codes. SRL has utilized Itasca's codes for various purposes, such as the analysis of rock mechanics problems. Advances have been made in recent years in modeling the flow of particles. The program Particle Flow Code in Three Dimensions (PFC3d) by Itasca provides the building blocks for modeling distinct particles. The underground transport of broken ore and waste rock via inclined and vertical passes can be modeled using PFC3d.

PFC3d utilizes balls and walls in three-dimensional space. The measured characteristics of the balls include mass, radius, friction coefficient and contact stiffness in both normal and shear. Walls do not have mass, but do have length and width, friction coefficient and contact stiffness in both normal and shear. With the application of gravity to the model, the balls will accelerate, reach a certain velocity and then collide with other balls and the walls included in the model.

Using the assumptions of this numerical modeling tool is simplistic compared to what actually occurs during the flow of real particles in an ore pass. A simple PFC3d model can be likened to dropping golf balls down a pipe and comparing the result to rocks being dropped down an ore pass. It is easy enough to model the walls of an ore pass and the details of the chute structure below. The difficulty is in determining the stiffness characteristics of the balls and walls. Stiffness units in PFC3d are force per unit length. Young's modulus can be used to help determine stiffness of the individual balls but cannot be used directly because the relation is length squared force per unit. Furthermore, the stiffness of a ball having a large radius may be greater than the stiffness of a ball having a small radius, given that the balls represent the same rock type.

Rock particle shape and durability need to be included in a PFC3d model to improve rocklike characteristics during impact. Rocks do bounce because of the stiffness of the interacting bodies, but more importantly, the shape, rotation, and durability of each rock affects rebound characteristics. An improvement over a single ball in representing a rock particle is an assemblage of balls. A variety of shapes can be developed. The balls within the assemblage would be connected using PFC3d's contact and parallel bonds. A modeled particle assemblage such as this would break into smaller pieces when striking a wall or another particle in the model.

Another difficulty in modeling using PFC3d is the selection of the damping constant. The model will come to rest or be solved in a shorter time using the damping constant. Without damping, a ball will bounce indefinitely. In actual rock flow, energy losses occur when balls collide with each other or, in an ore pass, with the walls. Using a damping constant, the energy lost during collisions can be modeled and rebound height controlled. This is accomplished by damping the resultant force during collisions, but then applying the opposing damping force opposite of the resultant velocity. Actually, by default, damping is applied even when collisions are not occurring, which impedes proper acceleration during free fall of particles.

In spite of the difficulties yet to be overcome in modeling rock flow in mine ore passes, some success has been made in predicting forces applied by rock impacts at the bottom of ore passes at the chute and gate assembly.

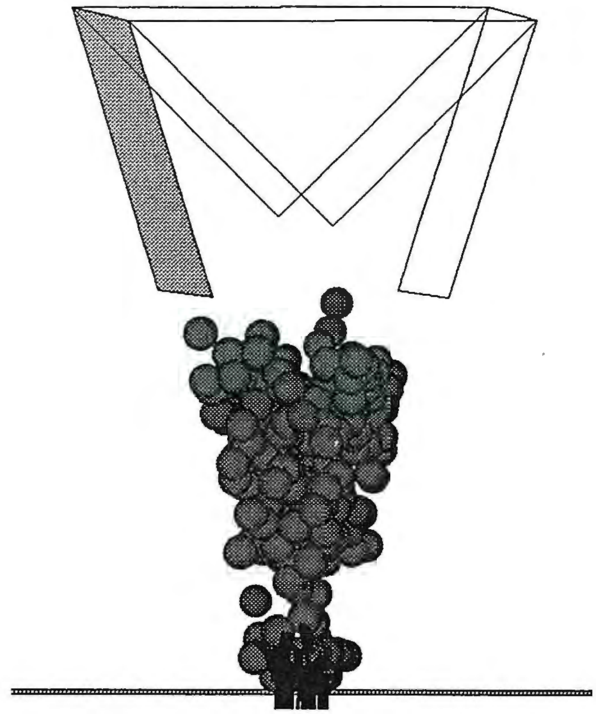
In modeling dynamic loads on the full-scale mockup, four walls represented a loader bucket. The load consisted of 260 balls weighing 1,238 kg (2,724 lb). Attempts were made to match particle-size distribution in the model to the rock used in the test. The number of balls required was beyond the capabilities of PFC3d. The balls were generated above the bucket and allowed to settle. Two angled walls of the bucket were rotated in a manner similar to that resulting when a real loader bucket moves. The balls were dropped to a horizontal wall below, a distance of 208 cm (82 in). The lower wall represented the chute assembly (Fig. 10).

The physical properties of the wall and balls were selected using the assumptions that the rock being modeled had a very high stiffness and the wall representing the chute assembly had a very low stiffness. The steel beams, the plywood and the steel of the chute assembly made the assembly very flexible. A ball stiffness of 149,000 kg/cm (10,000,000 lb per ft) and a chute wall stiffness of 82 kg/cm (5,500 lb per ft) were used. A ball diameter of 15 cm (0.5 ft) was selected primarily to speed up calculation time. The damping constant was fixed at 0.7.

The goal of this model was to match the force-vs.-time graph in the PFC3d to the actual force-vs.-time graph from the mock-up test (Fig. 5). A comparison of Figs. 11 and 5 shows that the graphs for the modeled chute wall matched fairly well. The maximum dynamic force was 3,182 kg (7,000 lb). The interval between impact and final static load was greater than three seconds, which was much longer than the actual test. The first arrivals of the balls reached maximum dynamic load, but the peak could not be sustained over the impact time as in the actual test.

FIGURE 10

Full-scale mockup modeled in PFC3d showing loader bucket dumping balls onto lower chute wall.



Future research

Additional laboratory and in-mine tests will refine the load measurement approach and validate particle-flow computer models. A one-third-scale ore pass model is being constructed. This model will allow analyses of static and dynamic loads on alternative chute designs and will provide a means of testing of hang-up removal methods. Additional in-mine chutes and gates load monitoring will include longer ore passes with potentially much higher static and dynamic loads.

Because of hazards associated with hang-up removal, research will focus on preventing ore pass hang-ups. Emphasis will be placed on the physical properties (moisture content, thixotrophic properties and grain-size distribution) of ore pass material and operational functions that influence flow behavior. After blasting and prior to ore pass transport, moisture is often added to the muck pile to control dust. Generally, the amount of moisture is not measured. Most sands are cohesionless aggregates; however, in a moist state, they have a certain amount of apparent cohesion. This cohesion disappears in the presence of large amounts of water, but adding large amounts of water may result in dangerous mud flows down the ore pass. The very fine soil fraction is also influenced by moisture. If the water content of a very fine-grained saturated soil is reduced by consolidation, cohesion increases (Terzaghi and Peck, 1964). Consolidation and moisture reduction occur in ore passes when muck flow stops. Moisture control and muck movement may be the keys to preventing cohesion-type hang-ups.

Once flow is stopped in an ore pass, the consolidation-moisture reduction-cohesion increase process begins. This process, known as thixotropy, is basically an increase in cohesive strength when material is allowed to stand, a considerable decrease in cohesive strength when the material is moved (at unaltered water content), and a complete regaining of cohesive strength if the material is allowed to stand again (Terzaghi and Peck, 1964). How long does this process take in an ore pass before a hang-up occurs? Determining the time factor for cohesive arching as a function of cohesive strength will help mine operators determine the maximum time that the ore should be left standing in an ore pass to prevent the possibility of cohesive arching.

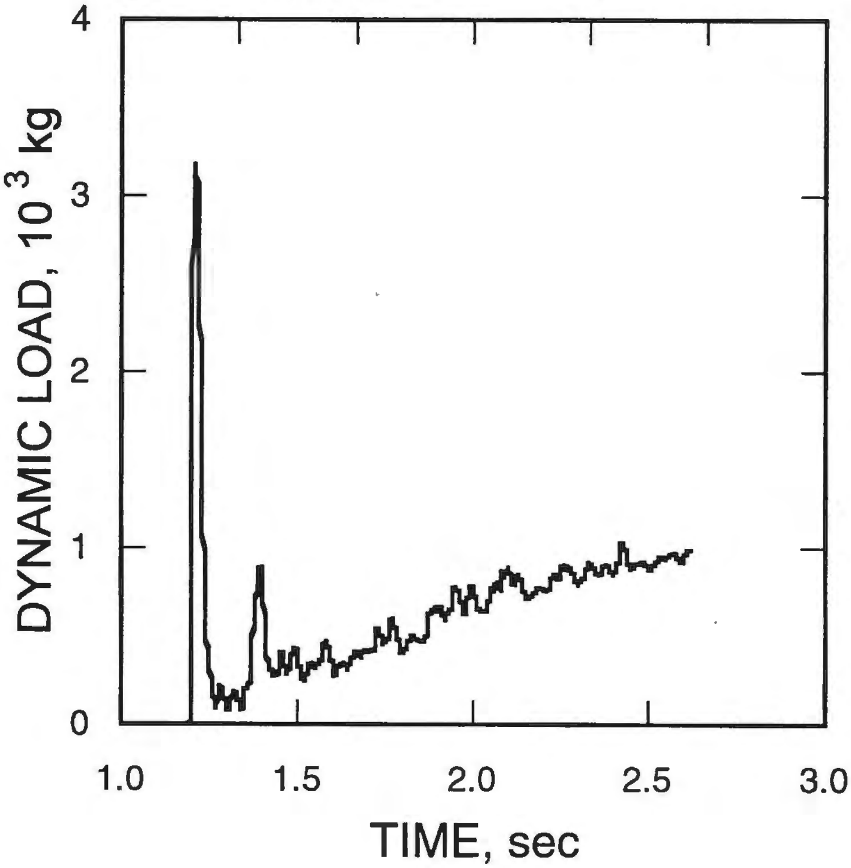
Because of the influence on cohesion and internal friction angle, the amount of fines in ore pass material plays an important role in ore pass hang-ups. In a study of the physical properties of coal waste (Stewart and Atkins, 1982), a sample with 100% +No. 4 (4.76 mm) US Standard Sieve size had an angle of internal friction of 29.2° and cohesion of 197 g/cm^2. On the same sample screened to 100% –No. 4 mesh, the angle of internal friction was 39.3° and cohesion was 1,118 g/cm^2. Based on existing design criteria (Hambley, 1987), the 100% –No. 4 material would require ore pass dimensions five times larger than the 100% +No. 4 material to prevent cohesive hang-ups. Even if the original fine fraction is small, fines can be generated by breakage of ore during transport. Research will determine different amounts of high- and low-cohesion fines necessary to cause hang-ups. In mines where enough cohesive fines are being generated to cause constant hang-up problems, it may be cost effective to add a material-screening system to separate the fines from the course material before dumping the material into the ore pass. Research will focus on cohesion-reducing methods for fine ore or waste-rock particles.

Conclusions

Strain gages spot-welded to ore-chute support struc-

FIGURE 11

Dynamic loads on modeled full-scale mockup.



tures were found to be effective for measuring high static and dynamic chute loads. Static and dynamic loads in the mine test were considerably less than expected because of the offset design of the chute and timber supports adjacent to the chute assembly. Interpreting long-term strain-gage data would be enhanced by comparing the data with dumping logs. Dumping logs include such information as the number of dumps, the types of material dumped (ore, waste rock, slimes, etc.), the quantity of each type of material and the moisture contents of the dumped materials (saturated, dry, etc.).

Ore-chute load monitoring improves ore pass safety by indicating if actual loads are within design criteria. In addition, continuous load monitoring will flag unusually high-load events. Once high-load events are detected, visual inspections can be made and damages repaired prior to the next high-load event.

The numerical-modeling results from the full-scale mockup successfully matched measured peak dynamic load. By adjusting the stiffnesses of the ball and wall, accurate peak dynamic loads were modeled using PFC3d. One problem with the model was that the particle size selected was too large. Smaller balls and a number closer to the actual number of rock particles modeled would improve results. Another problem was that, because rock particles are not perfect spheres, they do not interact with one another and rebound the same way balls do. The duration of dynamic loading was less accurately modeled, possibly because of the particle size and shape selected. ■

Acknowledgments

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