Application of physical modelling and particle flow analysis to evaluate ore-pass design

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Synopsis

U.S. Mine Safety and Health Administration (MSHA) accident statistics have identified ore-pass hazards as a significant safety problem in U.S. underground metal mines. The statistics show that nearly 75% of injuries are directly or indirectly related to pulling or freeing of ore-pass chutes, the use of hand tools in ore passes, falls of broken rock in ore passes and structural failures of chutes or gates and ore-pass walls.

Researchers at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) are investigating hazards in and around ore passes in hard rock mines. Risk assessment methods, such as fault-tree analysis, have been employed to identify the most probable causes of ore-pass failures, define research priorities and analyse the factors that result in malfunctioning and unsafe ore passes. Static and dynamic loads are being measured in a laboratory setting with the use of a reduced-scale ore-pass mock-up. Field tests are being initiated in mine ore passes to determine static and dynamic loads. Data from the test ore passes are being compared with data from the mine to characterize true system behaviour. Computer modelling with the use of closed-form solutions, finite-element analyses and a newly developed particle flow code predicts static and dynamic loads from the flow and the impact of ore and waste in the ore pass.

Preliminary results indicate that dynamic impacts from ore and waste rock might be considerably greater than expected. The total static load is substantially less than is typically used for the structural design of chute and gate support members. It is suggested that damping factors, normal and shear stiffness and mass frictional characteristics have a significant effect on particle flow and resulting impact loads. This is being verified with the use of results from laboratory tests, field tests and particle flow analyses.

Ore passes are vertical or steeply inclined openings in a rock mass through which ore and waste are transported and where they may also be stored. A typical underground mining system is shown in Fig. 1. The arrows indicate the locations of ore passes and loading pockets and their relative configurations.

The control of material flow is potentially one of the most hazardous operations in underground mining. According to MSHA data, most of the ore pass-related accidents in the U.S.A. are associated with the loading–unloading cycle and removal of blockages from ore passes. In particular, attempts to free ore hang-ups have resulted in multiple fatalities. The hazards are obvious; there is uncertainty as to when the ore will break loose and miners are unable to escape falling rock to a safe location. Although ore passes and chutes and gate systems for underground metal and non-metal mines must meet the requirements specified in the U.S. Code of Federal Regulations (CFR), Parts 57 and 75, recent structural failures of ore-pass linings and gates have underlined the lack of adequate ore-pass design standards available to both MSHA enforcement staff and mine engineers. Because of the importance of an ore pass to the safe operation of a mine design criteria need to be assessed and new guidelines developed.

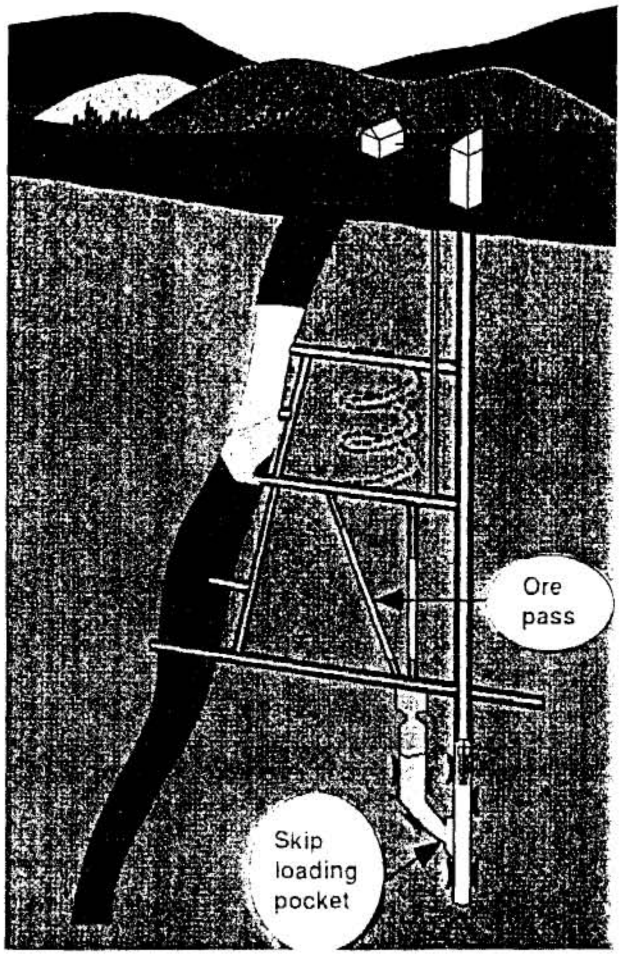

Fig. 1 Typical mine ore-pass system

Researchers at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) are investigating hazards in and around ore passes in hard rock mines and studying design criteria for ore passes. The near-term goal is to conduct laboratory and field experiments and computer modelling to evaluate the ore-pass design criteria currently used. Literature searches, field site

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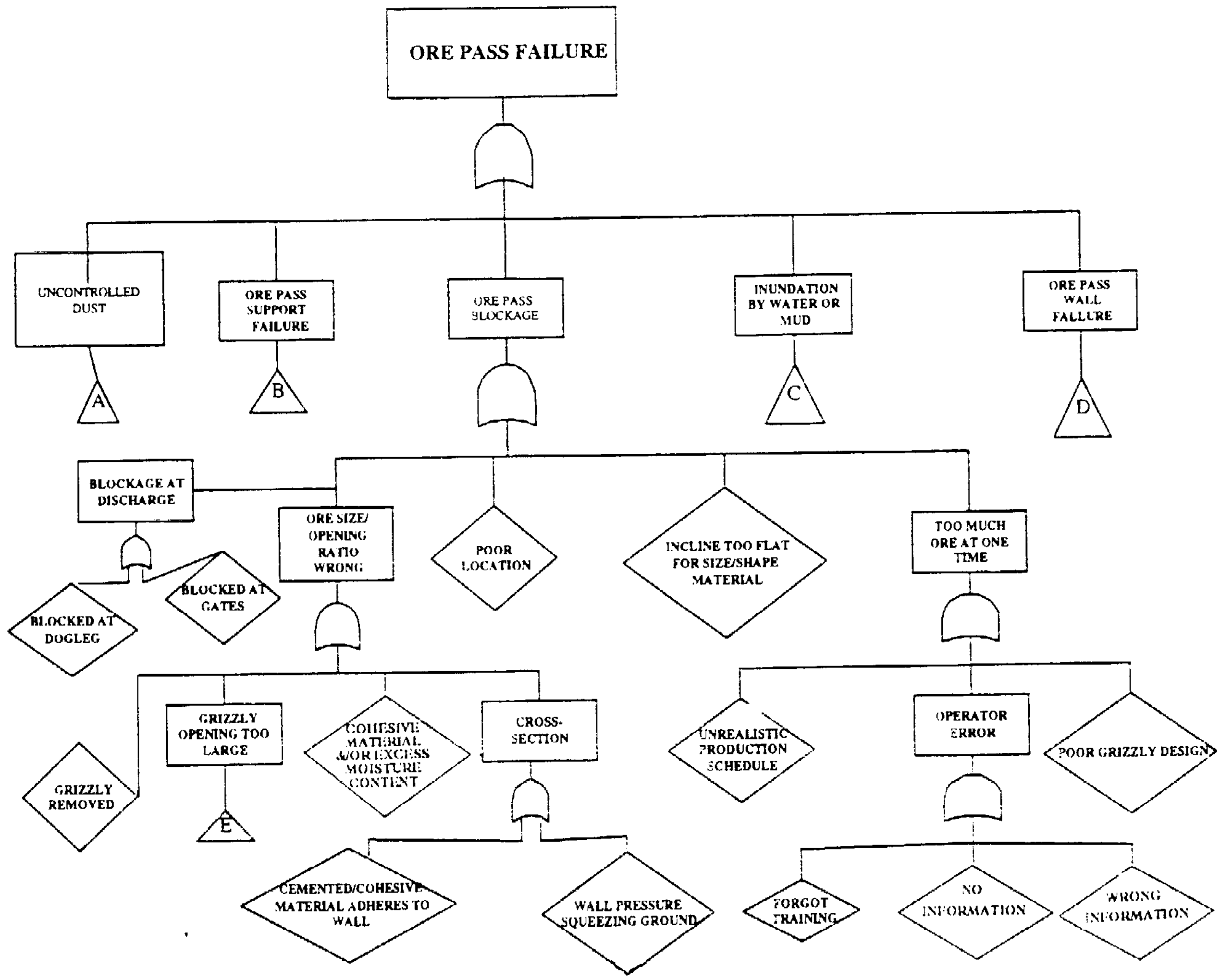

Fig. 2 Partial fault-tree diagram of elements leading to ore-pass failure

visits and a formal hazard assessment have been completed to focus research and define currently accepted design practices. The overall goal of this project is to prevent injuries and fatalities through an assessment of ore-pass hazards, experimental and computer analyses of current designs, measurements of loads and structural responses to loading in ore passes in laboratory test facilities and in the field, and identification and testing of hang-up prevention and removal strategies.

Background

Hazard assessment

Evaluation of statistics related to ore passes, formal hazard assessments and mine visits to obtain mine-specific information on ore-pass problems are being used to define problem areas for research. These data indicate that for the 20-year period between 1975 and 1995 75% of the injuries that occurred during pulling or freeing of ore-pass chutes were related to falls of broken rock and the use of hand tools. The following is a list of accounts of some typical accidents.

Fatality The employee was pulling muck into the grizzly with his partner. He was hooking a rock, lost his footing and fell forward. A *large boulder* came out of one drawpoint, breaking the control board (burying the victim).

Fatality The victim was loading an ore train using a pneumatically operated chute door when *very wet ore* broke the chute structure, burying the victim.

Fatality While the skip tender was loading a muck skip the heavy muck came loose (in the ore pass), causing an *overflow of water*. The overflow washed the miner over and through the shaft guards.

Fatality The employee was fatally injured when a chute filled with *ore blew out*, covering him with approximately 1.5 m of ore.

Permanent disability The employee was loading a car when one of the control boards was knocked out. When he was putting the control board back in *a rock* hit the control board, causing his right thumb to be caught between the two control boards.

Days-off injury The employee was bringing down a hang-up and *a rock* hit his left foot.

Days-off injury The employee fractured his right little finger when loose *muck fell* from a raise and struck his left hand and right hand.

Preliminary assessment of the accident statistics and field visits to characterize and quantify ore-pass design problems resulted in the identification of numerous cause-and-effect relationships. For example, hang-ups and structural problems may continue as mining progresses because of changes in ore material properties during the life of the mine (unsaturated to saturated environments, high-grade to low-grade ore) or changes in ore-pass shapes as a result of stresses in ore-pass walls, erosion and blasting and fracturing.

Because of the complexity of the problem and the need to focus research on the most productive ideas a formal risk and hazard assessment method was employed. Fault-tree analysis was used to analyse hazards and the causes of ore-pass failure. This method, employed extensively by the nuclear power and airline industries as well as by the MSHA.[1] provides a systematic description leading to the identification of hazardous conditions. Various combinations of failures that could result in some overall undesired event are modelled. In the partial flow diagram illustrated in Fig. 2, for example, the major failure element of an ore-pass blockage is shown and events leading to this failure are developed in the flow logic diagram. Other major elements of ore-pass failure, such as structural failure of chutes, gates and supports (ore-pass support failure), are similarly developed; current research is focused on this failure element and the logical events (B) leading up to it.

Analytical solutions

Existing design standards for ore passes are essentially rules of thumb based on simplified equilibrium analyses, model experiments, empirical observations and experience. The indications from accident statistics and preliminary analysis are that the current guidelines are not sufficient or ore-pass design engineers and miners do not follow the guidelines, or both. Current analytical approaches tend to assign high safety factors to the chute and gate structure, so that it will withstand excessive static and dynamic loads, and to maintain ore-pass opening and material size relationships to prevent hang-ups. Ore-pass design has structural and functional components that affect each other. The structural components are associated mainly with the stability of ore-pass walls, liner or timber lagging and chutes and gates. The functional design is concerned with the flow, or lack thereof (hang-ups), of ore and waste.

Important structural design factors are the static and dynamic loads that ore-pass chutes and gates must withstand. Blight and Haak[2] conducted tests on model ore passes to determine static gate pressures and dynamic load factors. The effects of ore-pass length and inclination and the capability of doglegs to absorb impacts from rock released from hang-ups were determined. Their results indicated that there was a minimal change in static load when the material column exceeded a depth of about 1 m above the gate; that total static load and dynamic load factors decreased significantly when the inclination was less than 70°; that the presence of a dogleg had little effect on static gate load; and that peak impact load exceeded static load in vertical or near-vertical ore passes by a factor of four. Their conclusions were that the static load on the gate of an ore pass could be predicted accurately using equations developed by Janssen[3] for vertical or inclined silos.

Simplified versions of the Janssen equations for determining static pressure normal to the control gate of a vertical or inclined silo are

$$\sigma_N = \sigma_{N\max}[1 - e^{\gamma z/\sigma_{N\max}}] \qquad (1)$$

and

$$\sigma_{N\max} = \gamma R \sin\beta / K \tan\delta \qquad (2)$$

where σ_N is normal pressure on the chute gate of the silo or ore pass, $\sigma_{N\max}$ is maximum pressure normal to the gate, R is hydraulic radius (cross-sectional area over perimeter), K is ratio of lateral to normal pressure, γ is unit weight of rock in the ore pass and z is height of ore above the chute gate.

Solutions to determine dynamic load factors are typically based on those derived by Timoshenko[4] and found in most engineering handbooks. For example, it can be shown that the impact stress, σ_i, produced in a structural member as a resulti of the impact of a body falling from height h is greater than the stress, σ, and deformation, δ, produced by the same body applied as a static load in the ratio of

$$\frac{\sigma_i}{\sigma} = 1 + \left(\frac{1 + 2h}{\delta}\right)^{-2} \qquad (3)$$

It is generally assumed that the energy losses of material falling down an ore pass are very high and that the dynamic load factor can be approximated by a case of sudden loading ($h = 0$), which results in a dynamic load factor of 2.

Functional design factors minimize malfunctions in material flow, such as hang-ups, piping and water inundation. Guidelines have been developed for dimensional relationships between ore-pass openings and ore size, proper sizing of drawpoints, chutes and feeders, inclined versus vertical passes, proper branch and bend angles and ore-pass ground support and siting criteria.[5]

The probability that a hang-up in non-cohesive ores is directly related to ore-pass diameter, ore particle size and height of ore has also been discussed.[6] In cohesive ores additional properties, such as cohesion, density and internal angle of friction, have to be considered.[7] Two distinct types of hang-ups have been recognized: those caused by interlocking of large boulders that become wedged in the ore pass and those caused by cementing of cohesive fines. Some of these design relationships are summarized in Table 1.

Table 1 Ore dimensions and hang-up prevention (from Hambley and co-workers[5])

Dimensional requirements	Types of hang-ups prevented
$D/d > 5$	Interlocking arches
$D > (2k/\gamma)(1 + 1/r)(1 + \sin\phi)$	Cohesive arches
$D_o \geq 3d$	Interlocking arches (drawpoints)
$H \geq 0.8D_o$	Hang-ups in transfer chutes

D, ore-pass dimensions; d, diameter of largest particle; k, cohesion of fines; γ, density of fines; r, ratio of opening length to width; ϕ, internal friction angle; H, chute height; D_o, chute width divided by width of outlet.

In the present study it is assumed that current design guidelines are not all-embracing and may not take some important factors into consideration. Factors that may require additional research include: dynamic loads on chutes and control gates from falling ore and rock; changes in material properties and particle sizes and redistribution of particles during free fall and on impact; accumulated structural damage to ore-pass walls, chutes and gates caused by material movement, blasting (to remove a hang-up) and *in-situ* stress changes (borehole breakout); ground-control methods around ore passes; and fundamental behaviour of flowing granular materials and how these materials interact with larger blocks.

Current research

Research currently being conducted will attempt to address the concerns over, and apparent deficiencies in, the methods now used to design mine ore passes. Research is being focused on the development of more accurate behavioural models in a laboratory setting and validating computer models that analyse particle flow and impact loads on ore-pass control gates. Field tests are being initiated at several mine sites where ore-pass hang-ups and flow control problems are experienced.

Laboratory testing

The purpose of the laboratory tests is to evaluate the response

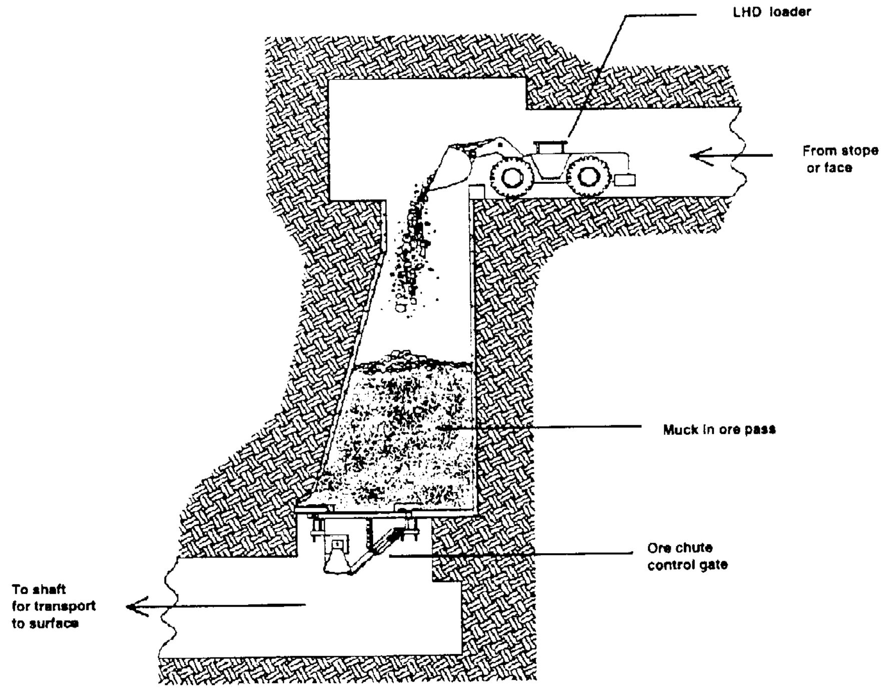

Fig. 3 Full-scale mock-up of mine ore chute and support structure based on actual 'as-built' design

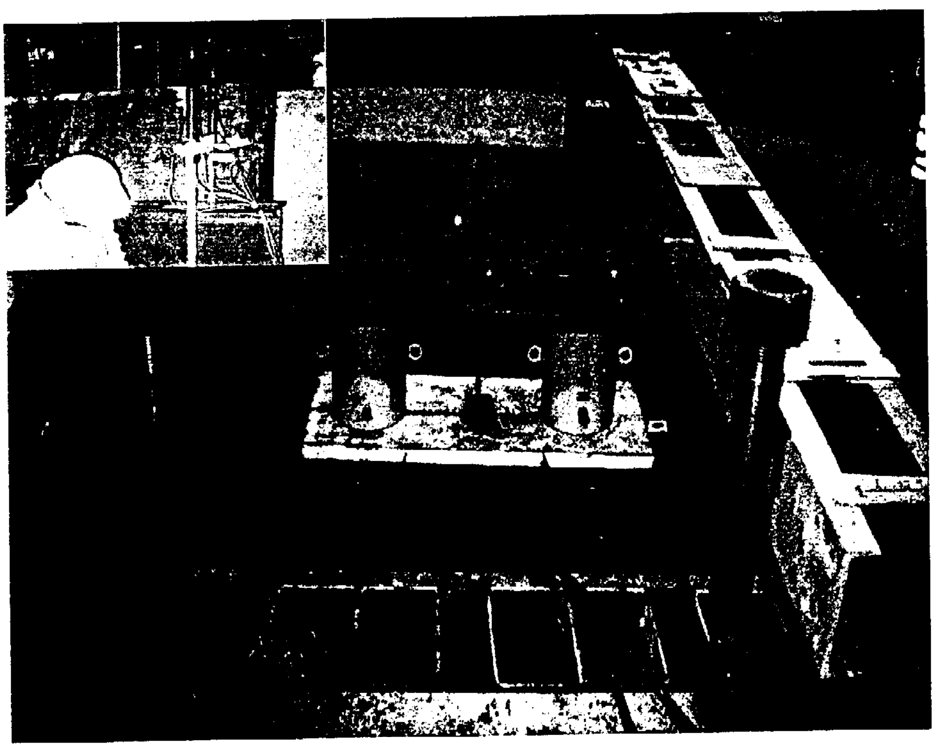

Fig. 4 Full-scale mock-up of mine ore chute and gate (see Fig. 3). Inset shows strain gauges on support hanger bolts to measure control gate loads

of a typical chute support structure to a given loading condition and, thus, the gate forces. Since muck-control gates are the most important structural element subjected to the excessive loads that cause overall ore-pass failure, analysis of the maximum static and dynamic gate forces is an important goal.

A full-scale mock-up typical of a mine ore chute and support structure was constructed (Fig. 3). The actual chute support structure and gate assembly are suspended on steel beams, which rest on saddles attached to bolts. Eight 3.8-cm diameter, high-tensile steel bolts are anchored into the rock mass in the back of the drift cut-out. In the mock-up, shown in Fig. 4, the support bolts are suspended on steel beams that span steel and reinforced-concrete abutments. The chute and gate assembly is simulated with rigid I-beams welded to the chute support frame. The chute support frame, I-beams, hanger bolts and saddles are identical to those in the actual structure. Loads are applied by two 180-t hydraulic jacks.

The purpose of the mock-up tests was to develop an instrumentation scheme for the determination of static and dynamic muck loads that could be implemented easily and cheaply in the field. The assumption was that measurements of tensile strain on the support bolts could provide an accurate representation of muck loading forces, subject to certain energy losses. In the mock-up four 350-Ω strain gauges spaced 90° apart were installed longitudinally on eight support bolts and wired in series (see inset in Fig. 4). This results in an electronically averaged output signal through a 1400-Ω 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 through a three-wire hook-up (to minimize temperature effects) into a full bridge configuration at the data-logger. Strain was measured at a maximum scan rate of 100 samples per second with Windows 95-based data acquisition software and hardware.

Tests on the full-scale mock-up consisted of applying load through a load distribution plate, which approximated the cross-sectional area of the actual chute gate. The maximum static normal load used in the structural design of the chute gate was estimated to be approximately 9 t. The support framework was designed to accommodate a total maximum load of 45 t. Load was applied at various points and magnitudes across the top of the structure to simulate various muck column heights and distributions. Fig. 5 is a plot of total load calculated from a summation of individual bolt strains compared with actual load applied with the hydraulic jacks as logged by the pressure transducer. A regression analysis related actual load to computed load. The load calibration equation is $y = 1.093x$, where y is actual load being applied, N, and x is computed load determined by the average summation of strain on 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 bolt strain will effectively act as a calibrated 'load cell' to determine normal loads acting on the chute control gate. A faster measurement system has been acquired and interfaced with the existing bridge circuitry to capture dynamic load response when field testing is initiated.

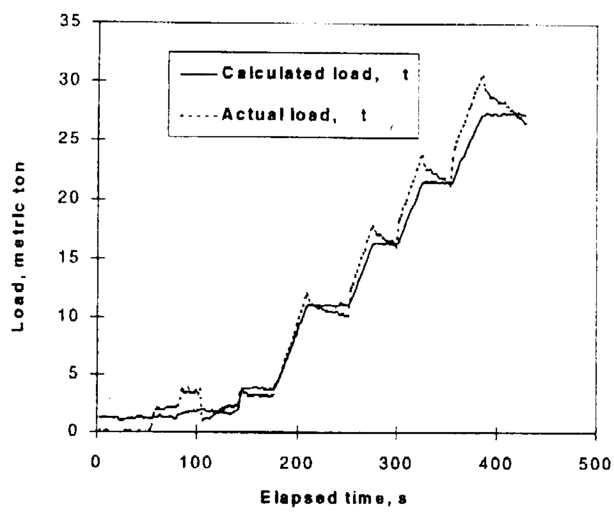

Fig. 5 Plot of actual load and calculated load from bolt strains

To allow for dynamic loading that reflects the effect of muck being released from a hang-up a reduced-scale test facility was constructed. Mine shaft and hoisting research as well as investigation of ore passes can now take place in a controlled setting.[8] It comprises an 18.3 m high hoist tower to simulate the headframe and shaft, a 5.5 m deep underground 'shaft' lined with concrete sections, a sheave wheel assembly and a 0.45-t capacity skip (Fig. 6). The hoist-room components include a winding drum, a gear reducer, a braking system and a 37-kW dc motor with digital control. The hoist drum has a capacity of 5 m of 9.5-mm diameter wire rope.

The chute and ore-pass system is simulated by a 3.3-m diameter corrugated culvert. Ore is initially loaded through a ground-level grizzly into a gated below-ground discharge chute and loading cartridge and then into the skip for hoisting. The skip hoists the ore to the top of the headframe, where it is dumped into a hopper and return chute connected to the top of the ore pass. The ore is gravity-fed into the simulated ore pass and the chute and gate assembly and then

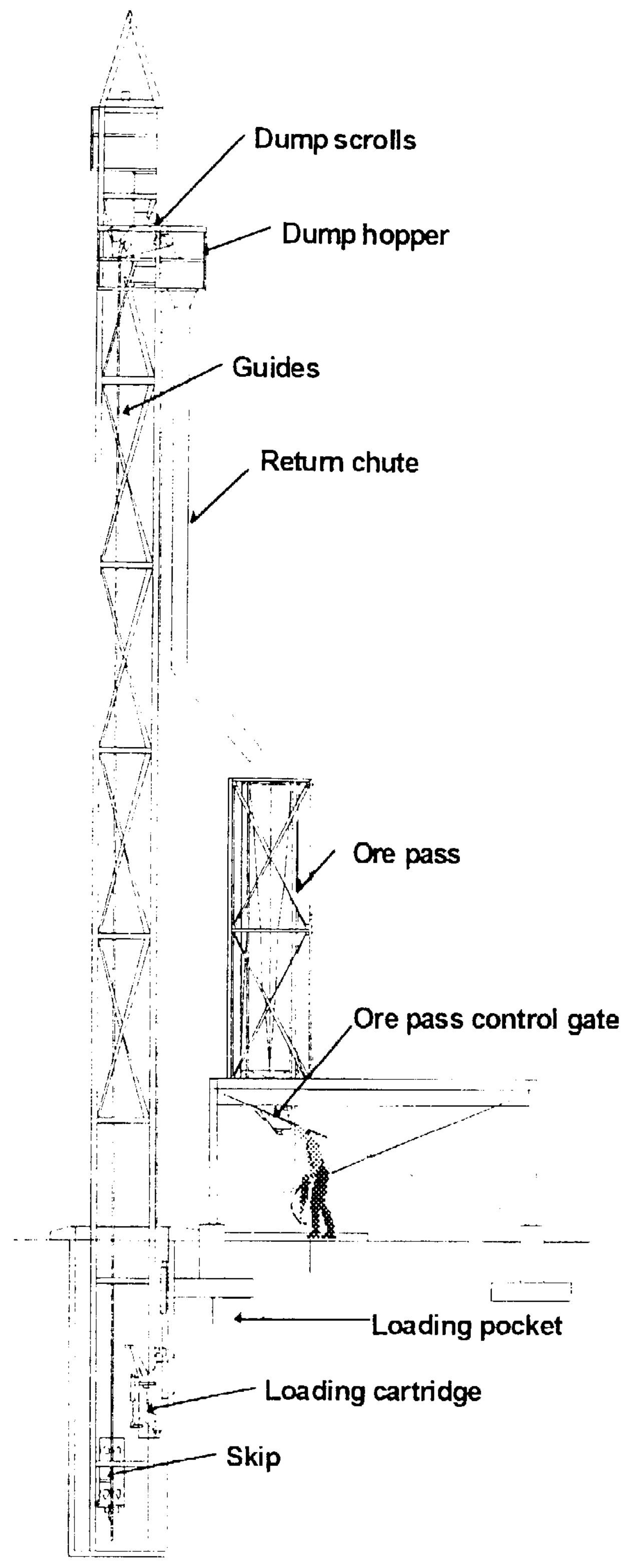

Fig. 6 Layout of one-third-scale hoist and ore-pass test facility

dumped into the below-ground loading pocket, completing the closed loop. Static and dynamic forces are measured on the chute gate.

Computer modelling and simulation

Re-examination of existing experimental data with the application of granular media physics[9] and physical experiments backed by appropriate analyses are important. Although fundamental physical laws apply regardless of scale, new analytical tools are needed. Numerical simulations are being conducted to evaluate particle flow phenomena, hang-up potential and dynamic and static forces on the chute gate using two- and three-dimensional particle flow codes (PFC^{2d} and PFC^{3d}).[10]

The fundamental geometric shape for the PFC model is a ball. The balls are assigned density and gravitational forces. They are assumed to be rigid except at points where one ball makes contact with another and the balls deform. Overlapping areas of contact correspond to physical deformation. Balls can be packed together into bonded clusters that resemble angular shapes or blocks to approximate the behaviour of a relative continuum, such as large rock blocks, timbered support within an ore pass, wallrock or the chute and gate structure.

Of particular interest are: simulations of particle-size redistribution as material falls through an ore pass; ore-pass hang-up phenomena; the effects of large boulders or clumps of material on an empty chute and control gates; and evaluations of the validity of currently used closed-form solutions of static and dynamic load factors for chute and gate structural designs.

Various contact models are available. In the linear contact stiffness model forces and relative displacement are related linearly by the constant contact stiffness, a function of the intrinsic stiffness of the two contacting entities. In the simplified Hertz contact stiffness model[11] forces and relative displacements are related non-linearly by non-constant contact stiffness, which is a function of the geometric and material properties of the two contacting entities and the current value of the normal force. A slip model allows two entities in contact to slide relative to each other and to separate if they do not bond. Bonding models are used that correspond to two physical possibilities: contact bonds reproduce the effect of adhesion at the contact point; and parallel bonds reproduce the effect of cementation, described as additional material being deposited around the particles once they are in or near contact.

Particles contained in an ore pass are a combination of solid particles amenable to analysis by continuum mechanics and soil-like material with a composition not unlike very fine sand. Analysis of the resulting muck requires identification of individual rock fragments as well as consideration of the collective behaviour of fines and interaction between particles. Hang-ups caused by fine particle cohesion, cementation and bridging of oversized particles can be simulated for various ore-pass dimensions and inclinations. Fig. 7 illustrates a PFC^{2d} simulation of a simple hang-up caused by oversize particles based on the geometry of the ore pass shown in Fig. 3. The relative magnitudes of contact forces between the particles are indicated by the thickness of the solid line.

Another PFC^{2d} test problem involved dropping a large lead ore block about 33 cm in diameter and weighing 275 kg to simulate a worst-case condition in terms of dynamic loads on the chute gate. The block was dropped from the top of the ore pass—about 20 m—after four loads of smaller particles had been loaded and dumped, as shown in Fig. 8. Some balls remained in the chute after the gate was closed. Physical properties, such as density and rock and wall stiffness, were based on typical values of hard intact lead ore. A default damping factor of 0.7 was used.

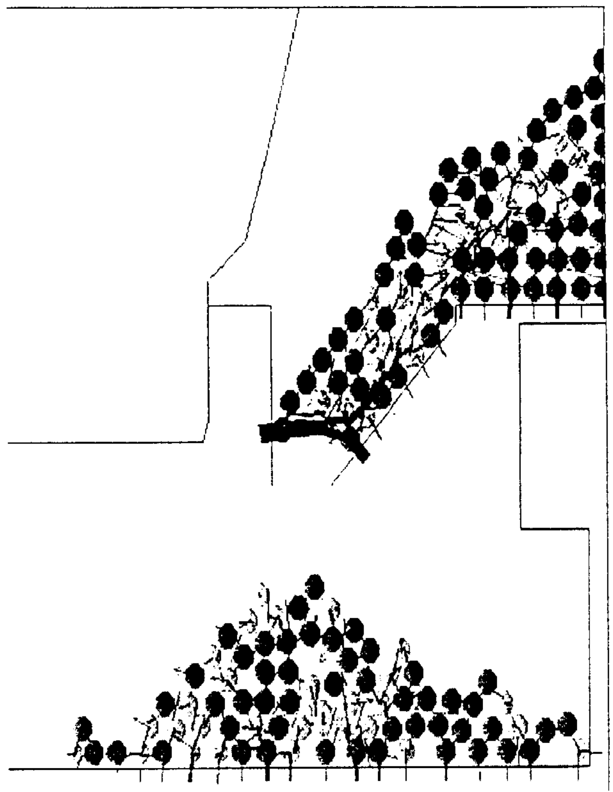

Fig. 7 Simulation of hang-up at control gate

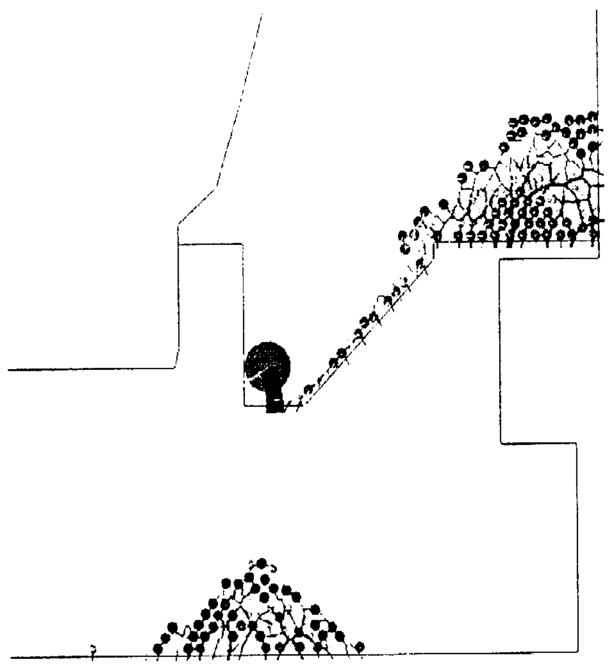

Fig. 8 Simulation of effects of dropping large rock block after several loads have been dumped

Fig. 9 shows the total gate forces over an interval of 192 s—the time that it took the boulder to fall, strike the chute gate and reach equilibrium. The final static load on the gate was about 2858 N. The maximum dynamic load from the impact of the boulder was significantly higher than theory might predict. However, the block was dropped directly on to the gate, which was modelled as a very stiff system. This analysis ignores energy losses, damping factors and inter-particle, intra-particle and particle-wall stiffness that occur as large boulders fall down an actual ore pass.

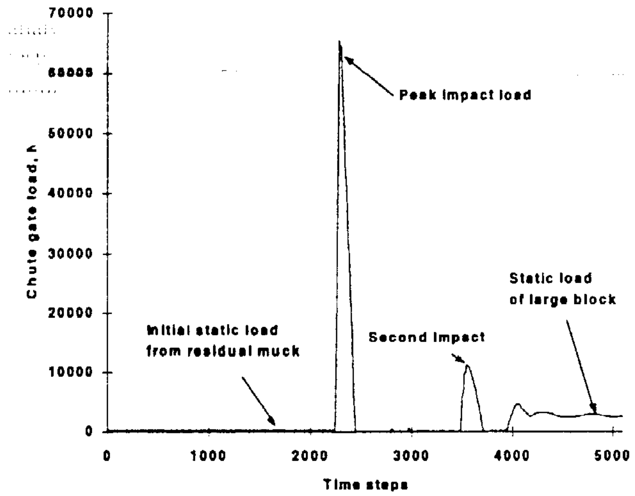

Fig. 9 Force-time plot showing effects of dropping large boulder on chute gate after chute is emptied

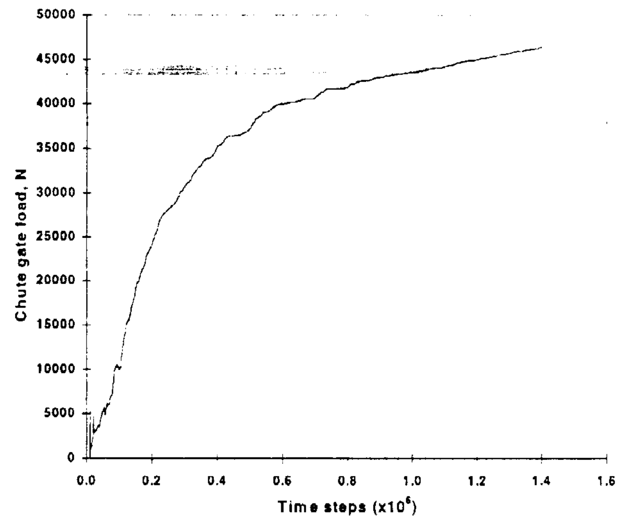

Fig. 11 Plot of normal forces on chute gate after 40 LHD loads have been dumped into ore pass

Three-dimensional modelling can provide a more accurate representation of the geometric configuration of the ore-pass system, including the contained muck. Fig. 10 shows a PFC^{3d} representation of the ore pass and truck chute shown in Fig. 3. The physical properties are the same as those used for the two-dimensional model. This model was used to analyse dynamic and static load build-up and the evolving shape of the muckpile. The simulation analysed 40 loads from load–haul–dump (LHD) units containing about 7 t of material each. The problem took about 1 500 000 time steps and 14 days' run time on a 200-MHz Pentium computer.

The accumulated control-gate forces resulting from 40 loads are shown in Fig. 11. The increase in gate load drops dramatically after about one-third (10–15) of the LHD loads have been delivered. The total static load approximated the loads used in the structural design, being based on a volumetric–density calculation for a full muck chute considering just the gate area exposed to the muck. Analysis of the initial time steps indicated that dynamic loads were a factor on the control gate only during the first dumps. The intial dump on the empty control gate indicates a peak dynamic load from the leading edge of the muck column of about seven times the static load. By the fourth dump impact loads are sufficiently damped by the muck already in the chute that no impact forces are seen.

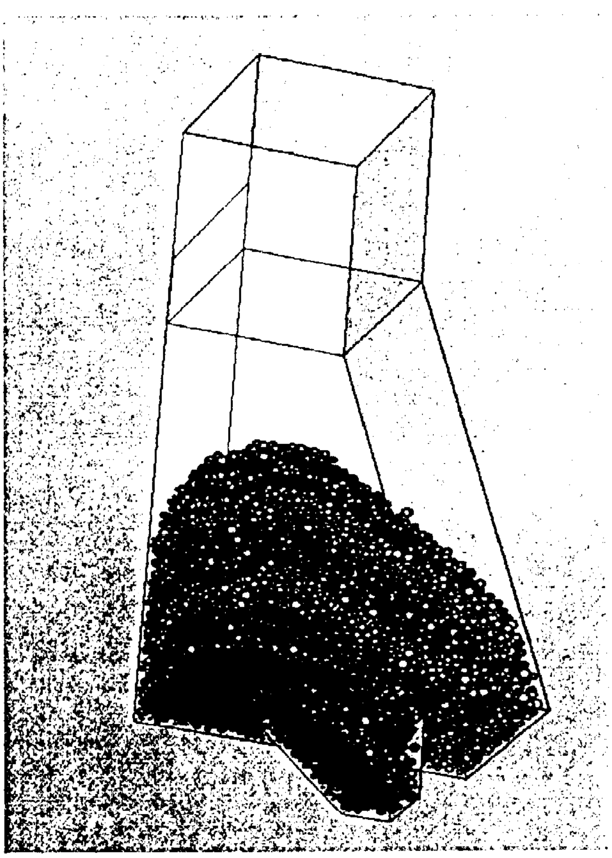

Fig. 10 Three-dimensional layout from PFC^{3d} showing geometry after 40 LHD loads have been dumped into ore pass

Detailed analysis of this problem will continue with refinement of the physical properties. Material property testing will determine grain-size distribution, moisture content, the cohesion of fines and the angle of internal friction of the fines. Representative bulk samples are being collected and stored for materials testing and for use in the ore-pass test facility. The moisture content will be determined at the mine with a field moisture scale and drying device. Cohesion and friction properties will be determined from prepared samples at the Spokane Research Laboratory's soils testing laboratory with a large-diameter, direct-shear machine capable of testing 33-cm^2 samples. The physical properties of the material will also be characterized before and after ore-pass dumping to determine changes in grain size and moisture content resulting from hoisting and dumping.

Field testing

The purpose of field testing is to validate numerical modelling approaches to the prediction of structural stability and hang-up potential and location. An ore pass and chute and gate system (Fig. 3) is currently being instrumented in a deep metal mine in northern Idaho. The approach to field testing is based on the results from tests on the full-scale mock-up. The instruments and data acquisition system developed and tested to measure static and dynamic loads are now being installed on the support bolts. An LHD will dump successive loads into the emptied ore pass, and the dynamic and accumulated static loads will be measured. These results will be compared with predictions generated by the PFC^{3d} code.

Summary

Design and construction of reduced- and full-scale mock-ups of ore-pass and chute and gate systems have been completed. A new load-monitoring system and method of computer analysis to assess the design have been evaluated. Full-scale tests at the laboratory facility validated strategies for field monitoring. The approach is now being duplicated at a field site to obtain actual static and dynamic responses to varying loads in an ore pass.

The combination of numerical modelling and simulation, scaled experiments and full-scale testing is providing important new insights into rock flow characteristics in ore passes and the static and dynamic loads involved in gate failures and the clearance of blockages.

The major benefit arising from this research will be the prevention of injuries and fatalities during ore-pass operations. Work is continuing to evaluate methods to increase awareness of the proper functioning of mine ore passes, warn of potentially dangerous situations and improve hang-up removal methods. With improved monitoring, engineering control technology and safer procedures miners will be less likely to be exposed to hazardous locations within an ore-pass infrastructure.

Acknowledgement

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