Design Analysis of Underground Mine Ore Passes: Current Research Approaches

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ABSTRACT

The U.S. Mine Safety and Health Administration (MSHA) has identified ore pass hazards as a significant safety problem in underground metal mines in the United States. Injury and fatality data show that many injuries are related to pulling or freeing ore pass chutes and structural failures of control gates and ore pass walls. Researchers at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health are investigating these hazards and developing methods to improve safety during transport of ore and waste. Particle flow analysis methods were used to simulate chute and control gate response to various material loading scenarios. Results from computer models indicate that dynamic impacts from ore and waste rock might be considerably greater than theory predicts. Static and dynamic loads were measured in a laboratory setting using scaled ore pass mock-ups. Field tests were initiated in an active ore pass to determine actual static and dynamic loads. Field data were compared to computer results and indicated that impact and total static loads were substantially less than the computer model results suggested. Damping factors, normal and shear stiffness, and mass frictional characteristics have a significant effect on particle flow and resulting impact loads.

INTRODUCTION

The control of material flow in ore passes and loading pockets is potentially one of the most hazardous operations in underground mining. According to MSHA data, most of the ore-pass-related accidents in the United States are associated with the loading-unloading cycle and removal of blockages, and attempts to free hang-ups have resulted in multiple fatalities. Other hazards include structural failures, blocked gates, and excessive water. Excessive loads can cause progressive structural failure. Blocked gates can result in spillage of large volumes of fine material, resulting in gate damage. Falling muck from a released hang-up can cause further damage from an air blast. Water flowing into an ore pass can result in catastrophic muck flows and inundation.

Researchers at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) are investigating these hazards and studying existing design criteria. Literature searches, field site visits, and a formal hazard assessment have been completed to focus research and define currently accepted design practices. Computer modeling and laboratory and field testing are underway. The goal 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

Evaluation of hazards related to ore passes consisted of a review of MSHA accident reports, mine visits to obtain mine-specific information on ore pass problems, and a formal hazard assessment. MSHA 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. Assessment of the accident statistics and field visits further identified the character and extent of ore pass design problems and identified numerous cause-and-effect relationships.

Design Guidelines

Ore passes and chutes and gate systems for underground metal/nonmetal mines must meet the requirements specified in the U.S. Code of Federal Regulations (CFR), Parts 57 and 75. Guidelines for underground ore pass design, such as those proposed by Hambley (1987) include extensive information on proper ore pass construction and numerous factors that need to be considered by design engineers. However, based on information from mine personnel during visits to five underground mines in Arizona, Montana, South Dakota, and Idaho by the authors, and from recent MSHA accident reports, safety issues regarding material transport in ore passes are considerable, and hang-ups still occur frequently.

Existing design standards for ore passes are essentially rules of thumb based on simplified equilibrium analyses, model experiments, empirical observations, and experience. Current analytical approaches tend to assign high safety factors to the chute and gate structure so it will withstand excessive static and dynamic loads, as well as maintain ore pass opening and material size relationships to prevent hang-ups. Ore pass design has *structural* and *functional* components, both affecting the other. The structural components are associated mainly with the stability of ore pass walls, liner or timber lagging, and chutes and gates. The functional component is concerned with the flow 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 (1994) conducted tests on model ore passes to determine static gate pressures and dynamic load factors. The effects of ore pass length, 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 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 4. Their conclusions were that the static load on the gate of an ore pass could be predicted accurately using equations developed by Janssen (1895) 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—

$$\sigma_N = \sigma_{Nmax}[1-e^{\gamma z/\sigma Nmax}] \quad (1)$$

and

$$\sigma_{Nmax} = \gamma R \sin\beta / K \tan\delta, \quad (2)$$

where σ_N = normal pressure on chute gate of silo or ore pass,
σ_{Nmax} = maximum pressure normal to gate,
R = hydraulic radius (cross-sectional area over perimeter),
K = ratio between lateral-to-normal pressure,
γ = unit weight of rock in ore pass,
and z = height of ore above chute gate.

Solutions to determine dynamic load factors are typically based on solutions derived by Timeshenko (1934) and found in most engineering handbooks. It can be shown that impact stress (σ_i) produced in a structural member resulting from the impact of a falling body from a 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—

$$\sigma_i/\sigma = 1 + (1 + 2h/\delta)^{-2}. \quad (3)$$

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 feeder; inclined versus vertical passes; proper branch and bend angles; and ore pass ground support and siting criteria. The probability that a hang-up in noncohesive ores is directly related to ore pass diameter, ore particle size, and height of ore has also been discussed (Aytaman, 1960). In cohesive ores, additional properties, such as cohesion, density, and internal friction angle, have to be considered (Hambley, 1987). 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

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

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.

The present study assumes that current design guidelines may not consider some important factors, including (1) actual dynamic loads on chutes and control gates from falling ore and rock, (2) changes in material properties and particle sizes and redistribution of particles during freefall and upon impact, and (3) accumulated structural damage to ore pass walls, chutes, and gates caused by falling material, blasting (to remove a hang-up), and in situ stress changes (borehole breakout).

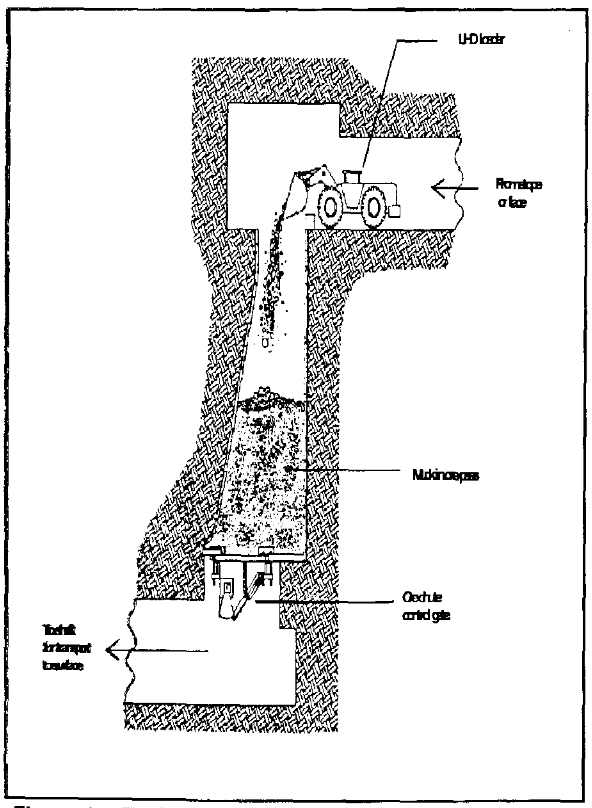

Figure 1.—Typical mine ore chute and support structure

LABORATORY TESTING

Laboratory research is being conducted to (1) validate the results of computer modeling of rock particles for evaluating impact and static loads on ore pass control gates, (2) develop ore pass load measurement schemes, (3) evaluate the effects of various ore pass designs on maximum impact loads, (4) test the effectiveness of hang-up detection and removal methods, and (5) determine the physical properties of ore and waste to evaluate hang-up potential.

Since muck-control gates are the most important structural element subjected to the excessive loads that cause overall ore pass failure, determining maximum static and dynamic gate forces is an important goal. Initial laboratory studies have focused on evaluating methods to measure control gate loads and using ore pass load monitoring as an aid in preventing unexpected failure.

Full-Scale Laboratory Mock-Up

The purpose of the full-scale laboratory mock-up is to evaluate the response of a typical chute support structure and gate forces to a known loading condition. In addition, the mock-up tests were used to develop and evaluate an instrumentation scheme for determining static and dynamic muck loads on ore pass chutes and gates that could be easily and cheaply implemented in the field. Measurement of tensile strain on the support bolts provided an accurate representation of muck loading forces. A typical mine ore chute and support structure is shown in figure 1. A full-scale mock-up of this assembly was constructed with support bolts suspended on steel beams that spanned steel and reinforced concrete abutments. The chute and gate were simulated with a rigid I-beam welded to the chute support frame. The chute support frame, I-beams, hanger bolts, and saddles are identical to those in an actual structure in a mine. Loads are applied using two 180-mt hydraulic jacks.

In the mock-up, 4,350-ohm strain gages spaced 90° apart were installed longitudinally on the eight support bolts and wired in series. The result is an electrically averaged output signal through a 1,400-ohm effective resistance. In calibration tests, this configuration was shown to minimize the effects of bending and torsional strains in the bolt and produce a true measurement of axial strain. Long-term static load trends are measured at a scanning rate of up to 100 samples per second with Windows 95-based data acquisition software and hardware. Data are processed and stored in a removable memory card or downloaded via a modem to a laptop computer. Based on laboratory drop tests, a sampling rate of about 1,500 samples per second is required to capture dynamic impact forces. A supplementary high speed system was thus acquired and interfaced with the bridge circuitry to capture dynamic load response.

Static load tests on the full-scale mock-up consisted of applying load through a load distribution plate to approximate 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. The support framework was designed to accommodate a total maximum load of 45,360 kg. A regression analysis relating actual load measured on a test machine to computed load based on a summation of strain from the eight bolts yielded a correlation coefficient (R^2) of 0.995 and validated the measurement approach. After completion of the static tests, the hydraulic cylinders and load distribution plate were removed. Dynamic tests consisted of dropping a load of mine waste rock having a bulk density of 1.7 g/cm^3 from a height of 1.8 m into a 2.4-m-wide, steel-reinforced container sitting on the mock-up chute assembly. 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, 1,000 kg, and 1,238 kg. Results of test 3 (1,238 kg) indicated a static load of 1,410 kg and a peak impact load of 3,136 kg.

One-Third-Scale Test Facility

Laboratory tests are also being done using a recently completed hoist and ore pass testing facility (Beus and Ruff, 1997). This closed-loop, fully automated hoisting facility utilizes a 18.3-m hoist tower to simulate the headframe and shaft. A 5.5-m-deep underground "shaft" lined with concrete sections houses a loading pocket and measuring cartridge (figure 2). The hoist room includes a winding drum, a motor-gearbox interface, 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-diam wire rope and 0.4536-mt-capacity skip.

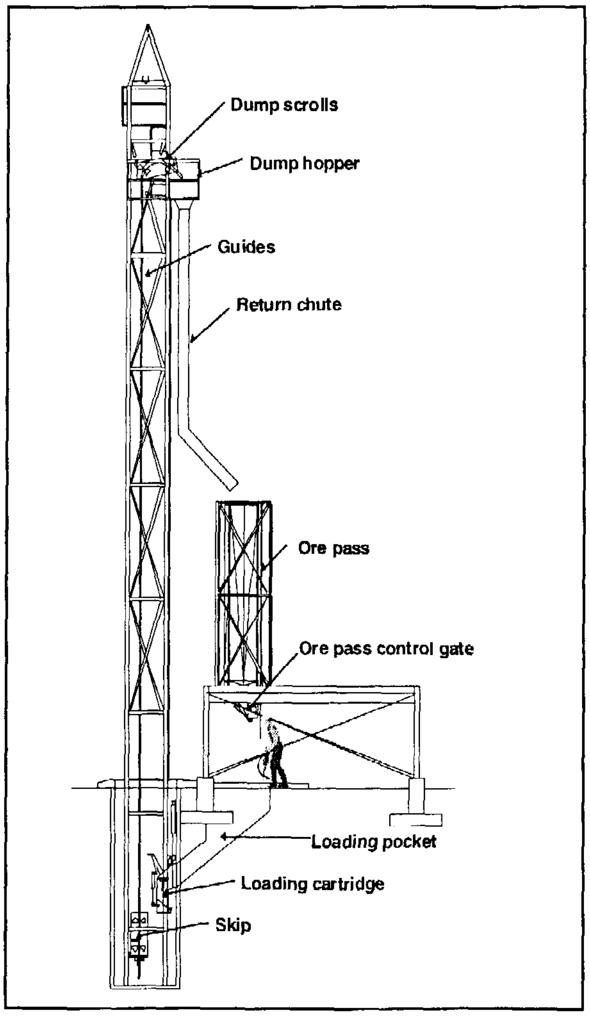

Figure 2.—Layout of one-third-scale hoist and ore pass test facility

The chute and ore pass system is simulated by a 3.3-m-diam 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 dumped into the below-ground loading pocket, completing the closed loop. Current testing involves measurement of static and dynamic forces on the chute gate. Methods for hang-up detection and removal and measurement of ore pass and loading pocket muck levels will also be tested.

FIELD TESTS

The purpose of field testing is to validate laboratory results and computer modeling. The approach is based on the system developed and tested on the full-scale mock-up. The instrumented chute and gate system (see figure 1) includes top brackets anchored by 244-cm-long Dywidag rock bolts installed at 45° to 60° angles into the rock mass at the back of the drift cutout. The centerline of the gate assembly was offset 2.4 m from the longitudinal axis of the ore pass so that falling ore did not directly hit it.

Thirty-two weldable strain gages were installed on the eight support bolts (four gages per bolt spaced 90° apart). Tensile strains produced a measurement of the total vertical force acting on the structure as material was dumped into the ore pass. Fourteen loads of damp waste rock from load-haul-dump (LHD) units at 1.53 m^3 per load were dumped into an empty ore pass. Twelve of the dumps averaged from 2,270 to 2,730 kg of material; two of the dumps (8 and 9) were material from cleaning up the drift and weighed about 270 kg each.

Preliminary analysis of the results indicated that static and dynamic loads on the control gate assembly were significantly less than anticipated. The total weight of material dumped in the ore pass was in excess of 27,300 kg; however, a maximum static load of only 6,800 kg was measured. This load was approximately the weight of waste material required to fill the chute. The rest of the static load was carried by timber adjacent to the chute assembly and the ore pass walls. An offset chute design allowed 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 3 shows a typical static and dynamic load pattern after an LHD dump.

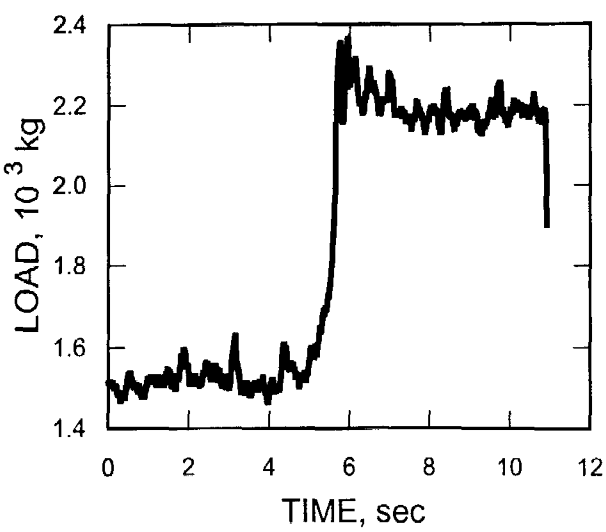

Figure 3.—Typical load pattern after LHD dump

Dynamic load factors ranged from 1.06 to 1.33 on the chute and gate assembly. An average load factor of 4.09 was reported by Blight and Haak (1994) in tests in a vertical ore pass where material struck the chute directly. Monitoring and interpretation of long-term loading data are being enhanced by installation of a motion-activated camera and video recording system at the top and bottom of the ore pass. This system will time and date-stamp the video each time material is added to or dumped from the ore pass.

COMPUTER MODELING

Computer modeling is being conducted to evaluate rock-particle flow phenomena, hang-up potential, and dynamic and static forces on the chute gate. Of particular interest are (1) simulations of the redistribution of rock particles of different sizes as material falls through an ore pass, (2) ore pass hang-up phenomena, (3) the dynamic effects of large boulders or chunks of material in an empty chute, and (4) evaluation of currently used closed-form solutions of static and dynamic load factors for chute and gate structural designs.

Recent advances in modeling the flow of particles provide important building blocks for analysis of underground transport of broken ore and waste rock via inclined and vertical ore passes. SRL has applied Itasca Consulting's (1995)

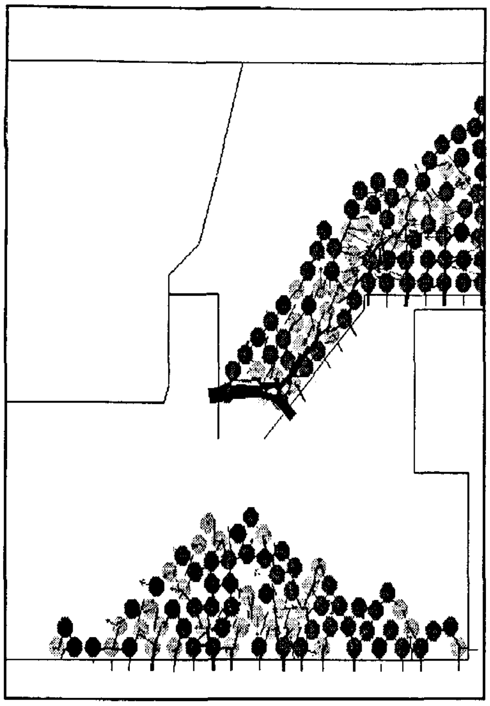

Figure 4.—Simulation of hang-up at control gate

two- and three-dimensional particle flow codes (PFC^{2d} and PFC^{3d}) for various purposes, such as the analysis of ground control problems. The fundamental geometric shapes in the PFC program are balls to simulate ore and waste particles and walls to simulate containment structures such as bored raises and chutes. The balls are assigned mass, radius, friction coefficient, and normal and shear contact stiffness. 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 velocity, and interact with other balls and the ore pass walls and gates.

Several test problems were formulated to evaluate overall application of the code to simulate ore pass material behavior. These problems included simulation of a hang-up and modeling of a large rock block striking an empty control gate.

Hang-ups are caused by fine particle cohesion, cementation, and bridging of oversized particles. Figure 4 illustrates a PFC^{2d} simulation of a simple hang-up caused by oversized particles. The relative magnitudes of contact forces between the particles are indicated by the thickness of a solid line between the particles.

Oversize rock blocks spalling from the walls of the ore pass or getting through the grizzly can frequently be a problem. This test problem involved dropping a large rock 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 20 m from the top of the ore pass after four loads of smaller particles had been loaded and dumped (figure 5). Some particles 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 quartzites. A default damping factor of 0.7 was used. The final static total gate load was about 2,858 N. The maximum dynamic load from the impact of the boulder was about 65,772 N, which is roughly 24 times the mass of the block.

Three-dimensional modeling can provide a more accurate representation of the geometric configuration of the ore pass. In modeling dynamic loads on the full-scale mock-up, four walls represented a loader bucket. The load consisted of 260 particles weighing 1,238 kg. The particles 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 an actual loader bucket dumps material. The particles were dropped 2 m onto a horizontal wall. A particle stiffness of 149,000 kg/cm and a plate stiffness of 82 kg/cm were used. An average particle diameter of 15 cm was selected, and attempts were made to approximate size distribution as determined by laboratory tests. The damping constant was fixed at 0.7. Figure 6 compares force versus time from PFC^{3d} to results from the mock-up drop test. The maximum dynamic force was 3,182 kg. The interval between impact and final static load equilibrium was greater than 3 sec, which was longer than the actual test. The leading edge of the muck column reached maximum dynamic load, but the peak could not be sustained over the impact time as in the actual test.

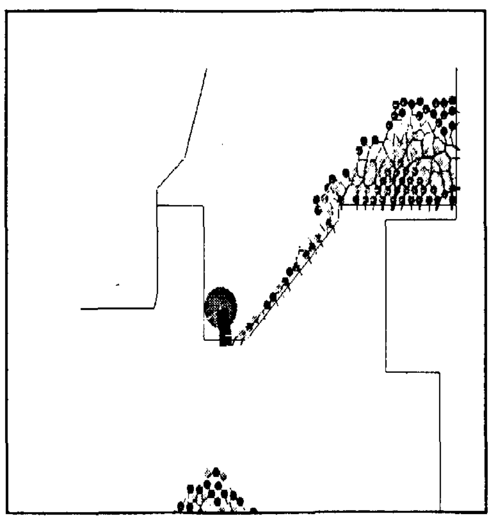

Figure 5.—Simulation of effects of dropping a large rock block after several loads have been dumped

Another PFC^{3d} model simulated the ore pass and truck chute shown in figure 1 and demonstrated dynamic and static load buildup and the evolving shape of the muck pile. The simulation computed results from 40 loads dumped from an LHD containing about 7 mt of material each for a total weight of about 280 mt. The problem took about 1.5 $\times 10^6$ time steps and 14 days run-time on a 200-MHZ Pentium computer. The rate of increase in gate loads dropped dramatically after about one-third (10 to 15) of the LHD loads had been delivered.

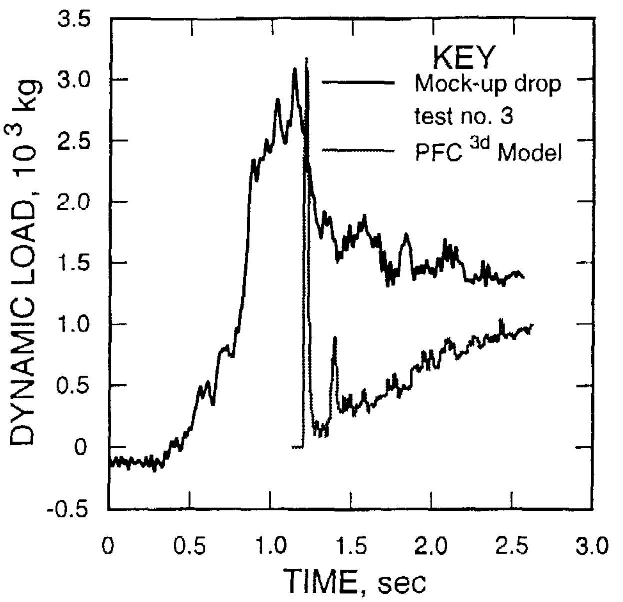

Figure 6.—Plots of force versus time for PFC3d and drop test

The accumulated control gate forces resulting from the first 14 loads are compared to the actual results from the field test in figure 7. Total calculated static load exceeds actual load for a full muck chute by about 4 times when considering just the cross-sectional area exposed to the muck carried by the support bolts. Analysis indicates that dynamic loads were a factor on the control gate only during the first three to five dumps.

Several difficulties remain in realistic modeling of rock particle flow, such as determining shape functions, damping factors, and the relative stiffness characteristics of the rock particles and the confining walls. The shape, rotation, and durability of each rock affects rebound characteristics. Incorporating more realistic rock particle shape and durability features would improve rocklike characteristics during impact. A variety of particle shapes can be developed by modeling as an assemblage of balls. The balls within the assemblage may be connected using PFC^{3d} contact and parallel bonds. A modeled particle assemblage such as this would rebound more realistically or break into smaller pieces when striking a wall or another particle in the model.

Another difficulty is the selection of a damping constant. Without damping, a particle will bounce indefinitely. In actual rock flow, energy losses occur when balls collide with each other or with the walls of the ore pass. Using an appropriate damping constant, the energy lost during collisions can be modeled and rebound height controlled.

Various contact models are available to simulate relative stiffness. In the linear contact stiffness model, forces and relative displacement are linearly related by the constant contact stiffness, a function of the intrinsic stiffness of the two contacting entities. A slip model allows two entities in contact to slide relative to one another and to separate if they do not bond. Bonding models are used to correspond to two physical possibilities. (1) Contact bonds reproduce the effect of adhesion at the contact point. (2) Parallel bonds reproduce the effect of cementation, described as additional material being deposited around the particles after they are in or near contact.

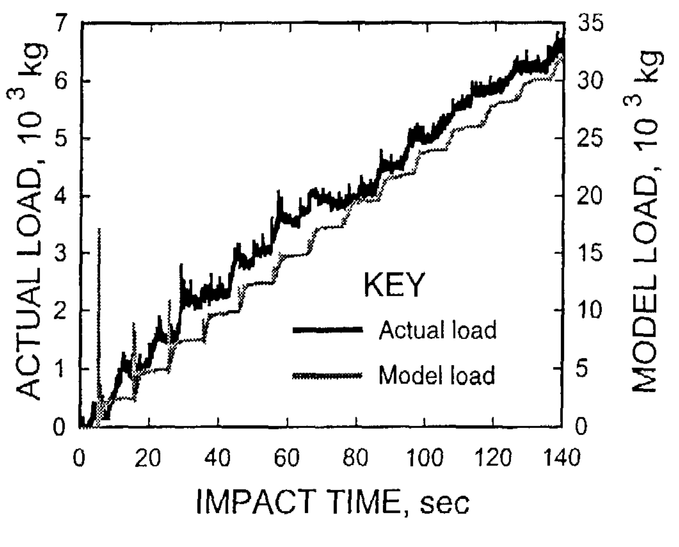

Figure 7.—Modeled and actual forces on control gate

Particles contained in an ore pass are a combination of solid particles amenable to analysis using continuum mechanics and soil-like material composed of very fine sandlike material. Analyses of the resulting muck requires identification of individual rock fragments as well as consideration of the collective behavior of fines and interaction between particles. Analysis of particle flow problems will be refined with determination of the physical properties. Material property testing will determine grain-size distribution, moisture content, cohesion, and angle of internal friction of fines. Representative bulk samples are being collected for materials testing and for use with the ore pass test facility. Moisture content will be determined at the mine using a field moisture scale and drying device. Cohesion and friction properties will be determined from prepared samples at SRL's soils testing laboratory using a large-diameter, direct-shear machine capable of testing 33-cm^2 samples. 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.

SUMMARY

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. Design and construction of one-third-scale and full-scale mock-ups of ore pass and chute and gate systems have provided realistic static and dynamic loading test platforms. A new load-monitoring system and computer analysis method to assess the design have been evaluated. Full-scale tests at the laboratory test facility will validate strategies for field monitoring.

The combination of numerical modeling and simulation, scaled experiments, and full-scale testing are providing important new insights into rock flow characteristics in ore passes and the static and dynamic loads involved in gate failures and clearance of blockages. The major benefit arising from this research will be the prevention of injuries and fatalities during ore pass operations. This research will continue 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.

ACKNOWLEDGMENTS

The authors express their appreciation to NIOSH researchers Art Miller, mechanical engineer, Charles Kerkering, mathematician, Todd Ruff, electrical engineer, Dave Denton and Ted Williams, mining engineers, and Hecla Mining Co., Coeur d'Alene, ID, for their help in providing test sites and other assistance.

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