Static and dynamic loads in ore and waste rock passes in underground mines

M. Beus & S. R. Iverson
Spokane Research Laboratory, National Institute for Occupational Safety and Health, Wash., USA

A. Dreschler & V. Scott
Department of Civil Engineering, University of Minnesota, Minneapolis, Minn., USA

ABSTRACT: This paper describes research to improve safety during transport of ore and waste in underground mines. Field tests are underway in mines in Idaho and Montana. Strains measured on structural support members in an ore pass provided information about total forces acting on the structure as material was dumped into it. Results show that measured static loads were considerably less than actual total weight of the material dumped and that dynamic loads were subject to many factors, such as effects of blasting to remove hang-ups.

Comparisons of measurements and computer results using a particle flow code indicated that several difficulties remain before achieving realistic determinations and models of the dynamic effects of particle flow in ore passes and impact loads on the gates. Impact loads were overestimated in computer analyses as compared to loads measured in field tests. An alternative design approach based on softening the chute and control gate assembly is being proposed.

1 INTRODUCTION

Hazards related to the operation of ore and waste rock passes have been identified as a significant safety problem in underground metal mines in the United States. Such hazards include structural failures, blocked gates, and water flow. Specifically, ore or waste rock hang-ups can collapse spontaneously or during freeing operations; the sudden release of hang-ups is the single most important cause of serious accidents. The dynamic loads induced by large falling blocks of ore or waste rock can weaken the chute and gate structure. Blocked gates can result in spillage of large volumes of material. Damage can also be caused from an air blast as material is released. Water flowing into an ore pass can result in catastrophic muck flows and inundation.

Existing design standards for ore passes are essentially rules-of-thumb based on simplified equilibrium analyses, model experiments, empirical observations and experience. This approach tends to assign high safety factors to the chute and gate structure so it can withstand excessive static and dynamic loads.

Ore pass design has structural and functional components, with one affecting the other and vice versa. The structural components are ore pass walls, liners, timber lagging, and chutes and gates, which control the flow of material. The functional component 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 et al. (1994) conducted tests on model underground ore passes to determine factors associated with static gate pressure and dynamic loads. The effects of ore pass length, inclination, and the presence or absence of doglegs, which absorb impacts from the release of hang-ups, were determined. The results indicated minimal change in static load when the material column exceeded a depth about 1 m above the gate, and that total static load and dynamic load factors decreased significantly when the inclination was less than 70°. They also found that the presence of a dogleg had little effect on the static gate, and that peak impact loads could exceed four times the static load in vertical or near-vertical ore passes. Their conclusions were that static loads 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

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

where σ_N = vertical pressure on chute gate of silo or ore pass,
σ_{Nmax} = maximum vertical pressure,
R = hydraulic radius (cross-sectional area over perimeter),
K = ratio between lateral and vertical pressure,
γ = unit weight of rock in ore pass,
δ = wall friction angle,
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_d) produced in a structural member resulting from the impact of a falling body from a height (h) is greater than the stress (σ_{st}) and deformation (δ_{st}) produced by the same body applied as a static load in the ratio of—

$$\frac{\sigma_d}{\sigma_{st}} \quad 1+\left(1+2h/\delta_{st}\right)^{1/2} \quad (3)$$

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 and were extensively reported (Hambley & Pariseau, 1983). This research developed guidelines for dimensional relationships between ore pass openings and ore size to prevent hang-ups; proper sizing of drawpoints, chutes, and feeders; inclined versus vertical passes; proper branch and bend angles; ore pass that a hang up in noncohesive ores is directly related to ore pass diameter, ore particle size, and height of ore has also been described (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 were 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.

2 RESEARCH APPROACH

Research at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) to investigate ore pass hazards and develop methods to improve safety has evolved into three approaches: (1) reduced-scale laboratory tests, (2) full-scale field tests, and (3) computer modeling of particle flow. Current research concentrates on determining the static and dynamic forces acting on the chute and control gate assembly (Beus et al., 1998).

2.1 *Experimental test facilities*

The laboratory facilities for ore pass research consist of both reduced-scale and full-scale ore pass and chute components. The reduced-scale hoist and ore pass testing facility has recently been constructed to facilitate testing and to validate computer models in a controlled setting (Beus & Ruff, 1997). This fully automated facility utilizes a 18.3-m-high hoist tower to simulate the headframe and shaft (Fig. 1). A 5.5-m-deep underground "shaft" lined with concrete sections houses a loading pocket and measuring cartridge. The hoist drum is operated by a digitally controlled 37-kW dc motor. The skip has the capacity of 0.453 mt. The ore pass system is simulated by a

Table 1. Ore dimensions and hangup prevention (from Hambley et al., 1984)

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

D = ore pass dimensions.
d = diameter of largest particle.
c = 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.

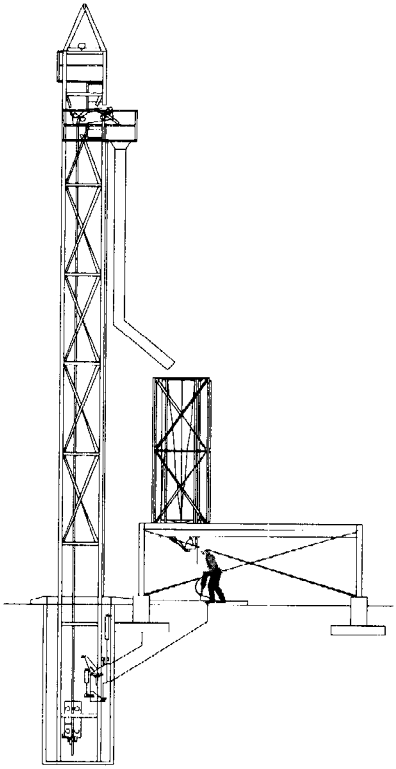

Figure 1. Reduced-scale hoist and ore pass test facility.

3.3 m in diameter corrugated culvert and an instrumented control gate. The "ore pass" can be inclined up to 25° off vertical in 5° increments to study the effects of ore pass inclination. Ore and waste material is loaded through a grizzly and loading pocket system into the skip for hoisting. The skip hoists the ore to the top of the headframe where it is discharged into a hopper and a chute directed to the top of the ore pass. The ore falls through the ore pass into the chute and gate assembly and impact and static load levels are acquired. The material is then is dumped into the ground level grizzly and recycled through the hoisting loop. Design of the ore pass, chute, and control gate assembly is based on that currently used in several mines.

In addition, to obtain accurate field data, full-scale mockups are fabricated in which the actual structure used at the field site is duplicated and calibrated in a loading frame. The full-scale laboratory mock-up using known loading conditions thus reproduces the expected response of chute support structure and gate forces in a mine, providing a calibrated system. These mockup tests are also used to develop and evaluate instruments schemes that can be easily and cheaply implemented in the field.

In preparation for the initial field test, a full-scale mockup of the support bolt assembly was constructed. The support bolts were 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 used in the mine. Loads are applied using two 180-mt hydraulic jacks. In the *initial* mockup, four 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 were measured with Windows 95-based data acquisition software and hardware at a scanning rate of up to 100 samples per second.

Static load tests on the full-scale mockup consisted of applying load through a load distribution plate to approximate the cross-sectional area of the actual chute gate. The maximum force used for the structural design of the chute gate was estimated to be 90 kN. The support framework was designed to accommodate a total maximum force of 453 kN. 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 183 cm 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, 1,000, and 1,238 kg. Results of test 3 indicated a force at equilibrium of 14 kN and a peak impact load of 31 kN. Figure 2 shows these results compared to a particle-flow computer model (section 2.3). Peak impact forces were similar; however, static forces were somewhat less than actually measured.

In preparation for the second field test, strain gages were installed on identical sections of support beams. The beam sections were then end-loaded in a test load machine to yield axial load on the beam. Two 350-

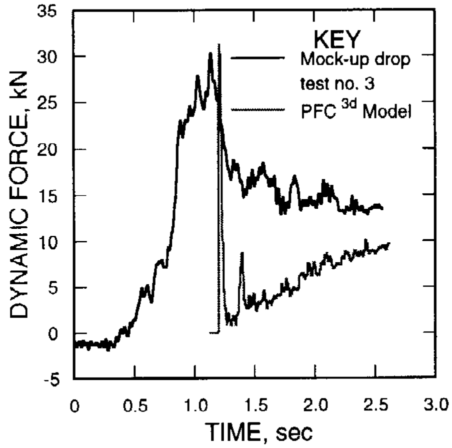

Figure 2. Results of mockup drop tests compared to particle flow code data.

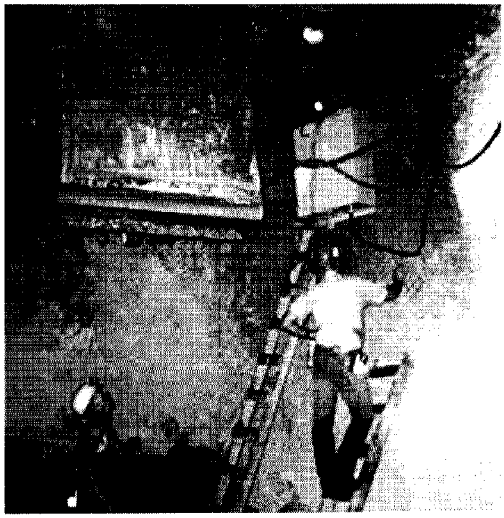

Figure 3. Instrumenting support bolts at truck loadout chute.

ohm strain gages were positioned in a T-configuration on each beam.

2.2 *Field tests*

Field tests are underway in mines in Idaho and Montana. The goal of these tests is to determine actual static and dynamic loads and validate reduced-scale tests results and computer models. The initial field test was in a deep silver mine in northern Idaho. The ore pass and chute and gate systems in this mine contain offset boreholes and doglegs that direct falling material to the floor of the ore pass and absorb the initial impacts from the falling column of ore or waste. 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 strain gages were welded on eight 3.8-cm bolts that were supported by brackets fastened to the rock mass to support the assembly. Figure 3 shows the truck loadout chute during instrumentation of the bolts. Four gages were mounted on each bolt at 90° angles, as in the mockup. Measurements of tensile strain produced total vertical force on the structure as material was dumped into the ore pass.

The test series consisted of 14 loads of damp waste rock from load-haul-dump (LHD) units at 1.53 m^3 per load. Twelve of the dumps ranged 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. The total weight of material dumped in the ore pass was in excess of 27,300 kg.

Preliminary analysis of the results indicated that the dynamic forces on the control gate assembly were significantly less than anticipated. Figure 4 shows typical impact forces measured on the chute support structure during the third LHD dump. Impact forces ranged from 1.06 to 1.33 of the static load on the chute and gate assembly and were reduced significantly because the chute was offset from the ore pass. This compared to an average impact value of 4.09 reported by Blight & 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 initial impacts from the leading edge of the falling column of ore or waste. The load response from all 14 dumps is shown in Figure 5.

The second field test involved mounting weldable strain gages on a chute and gate support structure at a large underground platinum mine in south-central Montana to determine axial strain. These strain gages were welded on eight support beams identical to those used in the laboratory experiment. Eight load-cell washers were installed to determine total force on the gate assembly (Fig. 6).

Both the strain gages and load washers were precalibrated in the laboratory on duplicate structural members to yield direct axial force on the member. A prototype single-channel data acquisition board was developed to minimize the difficulties experienced in the first field test and improve the capture of the wide range of strain response from the ore pass structure. During the experiment, the ore pass was consistently hung up, and it was necessary to blast the chute at the bottom of the ore pass to free the material. This

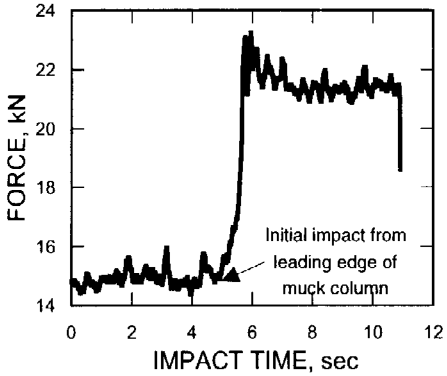

Figure 4. Impact forces on chute support structure.

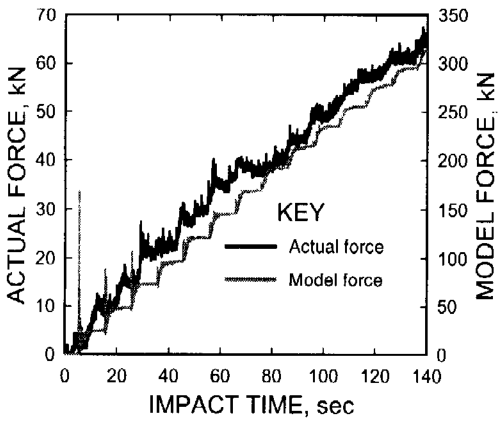

Figure 5. Comparison of actual and computer-generated loads from 14 dumps of material.

situation made it extremely difficult to maintain the instruments, but valid field data are being obtained and evaluated nonetheless. In addition, a mine-ready data collection system has been proven in an extremely harsh environment. This system will accommodate the anticipated wide range of strain levels to a high degree of accuracy.

2.3 Computer modeling

Computer modeling aims at simulating dynamic and static forces measured in the field on the chute gate, as well as overall particle flow phenomena and the potential for hang-ups. Of particular interest are the dynamic effects of large boulders or chunks of material falling through an empty ore pass. The modeling research will also evaluate adequacy of existing closed-form solutions of static and dynamic load factors for chute and gate structural designs, as

Figure 6. Load-cell washers installed on one side of control gate support bolts.

discussed in the introduction.

Computer modeling involves the application of the two- and three-dimensional particle flow codes PFC^{2D} and PFC^{2D} (Itasca Consulting Group, Inc., 1995a, 1995b). PFC^{3D} was used to simulate flow through the ore pass and truck chute instrumented in the initial field test. 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 rate of increase in gate loads dropped dramatically after about one-third (10 to 15) of the LHD loads had been delivered. The accumulated control gate forces resulting from the first 14 loads are compared to the actual results from the field test in Figure 5. Analysis indicates that dynamic loads were a factor on the control gate only during the first three to five dumps, both in the computer model and in the field test. However, the magnitude of force varied by a factor of about 5 times. This discrepancy may be associated with uncertainty in selecting the stiffness characteristics of the particles and walls, as well as the shape of particles (clusters). Another factor difficult to model are rock durability features and rebound during impact (Larson et al., 1998).

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

An alternative design approach, which may accommodate the dynamic loading uncertainties experienced in the field, is currently under investigation. The concept is based on "softening" the chute and control gate assembly and/or the supporting structure with the overall stiffness k_a, by means of springs or other components with the stiffness k_s to dampen the dynamic load. The resulting stresses in the bearing members of the softened assembly with respect to static stresses can then be expressed as

$$\frac{\sigma_{ds}}{\sigma_{st}} \; 1+\left(1+2h/\delta_{st}K\right)^{1/2} \qquad (4)$$

where $K = 1 + k_a/k_s$. Comparisons of equation 4 with equation 3, where h>0, indicates a reduction in stresses in the bearing members when the stiffness of the softening components k_s decreases.

3 SUMMARY

A state-of-the-art ore pass test facility has been completed and is available to test various aspects of ore pass design and particle flow characteristics. A field-proven method of measuring and collecting data has been developed that will accommodate the wide range of structural responses to dynamic forces caused by blasting during release of hang-ups. Comparisons of field measurements and computer models indicates that several difficulties remain before the dynamic effects of material flow in ore passes and impact loads on the gates can be accurately predicted. It has been found that computer analyses significantly overestimate dynamic impacts when the results of these analyses are compared to impact loads measured in field tests. Structural modifications using springs or other stiffness-reducing methods should result in a significant economy of design, reduction in material costs, and increased safety of the control gate assembly in ore passes.

REFERENCES

Aytaman, V. 1960. Causes of Hanging in Ore Chutes and Its Solution. *Can. Min. J.* 81:77-81.

Beus, M., & T.M. Ruff 1997. Development of a Mine Shaft and Ore Pass Research Facility. NIOSH Rep. Invest. 9637, 12 pp.

Blight, G.E., & B.G. Haak 1994. A Test on Model Underground Ore Passees. *Bulk Solids Handling* 14(1):77-81.

Ferguson, G. 1991. Orepass Design Guidelines. Report to Mining Research Directorate, Sudbury, Ontario. Sudbury, ON: Bharti Engineering Asso.

Hambley, D.F. 1987. Design of Ore Pass Systems for Underground Mines. *CIM Bull.* 80:25-30.

Itasca Consulting Group, Inc. (Minneapolis, MN), 1995a. PFC^{2D} (Particle Flow Code in 2 Dimensions), Version 1.1 .

Itasca Consulting Group, Inc. (Minneapolis, MN), 1995b. PFC^{3D} (Particle Flow Code in 3 Dimensions), Version 1.1.

Janssen, H.A. 1895. Versuche uber Getreidedruck in Silozellen. Zet. Ver. Deutsch. Ing. 39:1045-1049.

Larson, M.K., S.R. Iverson, B.M. Stewart, & K. Walker 1998. Preliminary Assessment of Particle Flow Code as a Tool to Assess Ore Pass Safety. Presentation, Rock Mechanics in Mining, Petroleum, and Civil Works: 3rd N. American Rock Mechanics Symp., Cancun, Quintana Roo, Mexico, June 3-5. Paper 92. Ext. abs. in *Intern. J. Rock Mech. & Min. Sci.* 35(4-5):533. Available on CD-ROM from Elsevier, New York.

Rankin, J., & G. Tolley 1978. *Fault Tree Analysis*. Mine Safety and Health Admin., 32 pp.

Timoshenko, S. 1934. *Theory of Elasticity*. Eng. Soc. Monograph. New York: McGraw-Hill.