Submitted to the International Journal of Rock Mechanics & Mining Sciences, February 17, 2006

Forecasting potential slope failure in open pit mines – contingency planning and remediation

Nick D. Rose[a] and Oldrich Hungr[b]

[a]*Piteau Associates Engineering Limited, 215-260 West Esplanade, North Vancouver, B.C., Canada V7M 3G7*
[b]*Department of Earth and Ocean Sciences, University of British Columbia, 6339 Stores Rd., Vancouver, B.C., Canada V6T 1Z4*

Abstract

Forecasting potential slope failure in open pit mines is integral to maintaining safety and mine productivity. Laboratory testing of rain induced landslides in Japan 20 years ago led to an inverse-velocity approach for estimating the time of slope failure. This approach appears to have been largely overlooked in mining, but has been successfully applied in the prediction of three large slope failures ranging in size from 1 to 18 million cubic metres. These predictions were forecasted two weeks to three months in advance of failure. This paper provides an overview of the development of inverse-velocity as a tool for failure prediction and presents four case examples of successful application of this approach. A methodology is also presented and illustrated by an example, that facilitates contingency planning and remediation based on slope movement rate predictions and selection of operational threshold movement rate criteria.

Keywords: Inverse-velocity; Slope failure prediction; Failure remediation; Failure mitigation; Contingency planning

1. Introduction

Assessment of rock slope failure mechanisms requires an understanding of structural geology, groundwater, rock mass strength and insitu stress conditions. Stress relief associated with mining excavation leads to elastic rebound and ground relaxation displacements that dissipate with time, a process that is often referred to as time-dependent deformation [1,2]. With continuing excavation, regressive slope displacements may occur in a cyclical decelerating fashion, but may not lead to slope failure. As strain levels increase, or in the case of weak or altered rock masses, strain softening may lead to plastic (non-recoverable) deformation and progressive failure development.

The inverse-velocity method, developed by Fukuzono [3] in 1985, provides a useful tool for predicting slope failure time. Astonishingly, even though this approach was developed based on laboratory tests more than 20 years ago, it does not appear to have been applied for real-time slope failure prediction in the mining industry until 2001, when it was used to predict the first of three large-scale slope failures presented in this paper. Application of the inverse-velocity approach for large-scale slope movements in poor and fair quality rock masses, has led to accurate prediction of three large failures ranging in size from 1 to 18 million cubic metres (m^3). Back analysis of data from other slope failures has also provided reasonable calibration using inverse-velocity. This paper provides a background of the development of inverse-velocity as a tool for predicting failure time and presents case examples demonstrating the successful use of this method. Empirical and analytical approaches are also discussed that provide estimates of possible impact zones for hazard zoning and design of protective remedial measures.

2. Background

The concept of inverse-velocity for predicting slope failure time was developed by Fukuzono [3] based on large-scale laboratory tests that simulated rain-induced landslide potential in soil masses at various slope angles. The conditions simulated in the laboratory were considered to be characteristic of accelerating creep conditions (i.e., slow continuous deformation) under gravity loading. Assessment of the laboratory data led to the recognition that the logarithm of surface displacement acceleration increased in proportion to the logarithm of surface velocity, resulting in approximately linear correlations in some cases. When inverse-velocity was plotted versus time, the values of inverse-velocity approached zero as velocity increased asymptotically towards failure. Plotted graphically, a trend-line through values of inverse-velocity versus time was found to project to the x-axis (zero value of inverse velocity), predicting the approximate time of failure, as shown on Fig. 1. Fukuzono presented three types of plots to the laboratory data (i.e., concave, convex or linear) based on the following equation:

$$\frac{1}{V} = [A(\alpha - 1)]^{\frac{1}{\alpha-1}} \cdot (t_f - t)^{\frac{1}{\alpha-1}} \qquad (1)$$

where A and α are constants and t_f is the time of failure. In the laboratory experiments, α was found to range between 1.5 to 2.2. As shown on Fig. 1, the curve of inverse-velocity is linear when α =2, concave when α <2 and convex when α >2. Based on the results of laboratory testing, Fukuzono concluded that a linear trend fit through inverse-velocity data provided a reasonable estimate of failure time, shortly before failure. By substituting a value of α =2 in Eq. 1, the estimation of the time of failure can be simplified to Eq. 2 in Section 3.3.

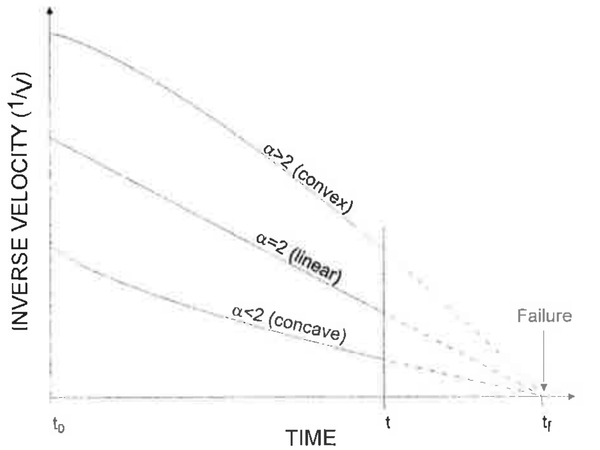

Figure 1: Inverse-velocity versus time relationships preceding slope failure - after Fukuzono [3].

3. Methodology

Assuming that accelerating creep-type conditions may be characteristic of the slope failure mechanism under investigation (i.e., little potential for rapid brittle failure), the inverse-velocity approach is a useful tool to assess the potential time of failure. In the early stages of failure development, when slope accelerations may be relatively low, inverse-velocity trends can be used to forecast potential failure time, allowing appropriate threshold movement rates to be selected for safe operation. A major advantage of this approach is that threshold movement rates can be selected based on consideration of the duration of time preceding failure, rather than based on empirical estimates alone. However, a cautionary approach should be used in the application of this method, such that complacency does not develop based on assumed accuracy in slope failure time predictions. As is the case with any failure prediction method, the accuracy of the monitoring system and data filtering approach can significantly influence predicted trends. Potential for changes in slope behaviour also needs to be taken into account. As such, specialist expertise should be employed whenever the potential consequences of slope failure could adversely impact mine personnel, equipment or infrastructure.

3.1 Slope Movement Monitoring

Slope movement monitoring, even in its simplest form, should be carried out in all mining situations. Regular visual inspection for signs of tension cracking, rock fall activity, slope raveling, bulging in the slope face or heaving at the toe of a slope can provide advanced warning of potential instability. Depending on the duration of mining and the heights of the proposed mine slopes, an array of reflective survey prisms located near the pit crest provides a baseline of slope displacements, from which potential changes in slope behaviour can be assessed. In potentially unstable areas where tension cracks or slope movements are detected, survey prisms, wireline extensometers or crack monitors should be deployed to monitor surface displacements. Subsurface monitoring of potential shearing can be achieved with "poor-boy" casings, slope inclinometers, or time domain reflectometry (TDR) cables. The data from these installations should be recorded, plotted and interpreted regularly with respect to relative displacement, velocity and acceleration. For total station surveys of reflective prisms, vector directions, magnitudes and plunges can be calculated to assist in interpretations of potential failure mechanisms. Comprehensive descriptions of surface and subsurface monitoring, data collection and assessment methods are included in Dunnicliff [4], Turner and Shuster [5] and Wyllie and Mah [6].

3.2 Data Filtering

Depending on the accuracy of the monitoring system, data smoothing may be required to filter out the effects of instrument error as well as "noise", such as apparent movements caused by temperature changes or by periodic blasting vibration episodes. In large open pits, considerable distances may be required to survey prisms in the direction opposing slope movement. At large distances, optical refraction and diurnal temperature and pressure effects can result in appreciable error, even with the most accurate monitoring systems. Future advances in Global Positioning System (GPS) monitoring methods may help overcome these problems. The magnitude of instrument error in survey readings can be estimated by plotting data for stable reference points located at similar distances and elevations from the instrument. The relative scatter in the survey data can be assessed to determine the magnitude of error.

For short durations between survey measurements, instrument error can have a significant effect on the ability to detect low level movement rates (velocity), due to the ratio of error to the detected movement. A number of approaches can be used to filter data and reduce the effect of instrument error, including:

- measurement of slope movements at approximately the same time of day to reduce diurnal effects;
- minimizing the number of surveyors to reduce the influence of operator error;
- calculating running average velocities based on a time increment that incorporates sufficient movement to reduce the ratio of error to detected movement; and
- calculating velocity based on the line of sight or "slope distance", thereby reducing the influence of horizontal and vertical angular error.

The appropriate level of filtering or smoothing is generally determined on a trial basis and may require consideration of different time durations between surveyed values, such as: one-day, seven-days, 15-days or 30-days. Data filtering should incorporate the shortest time increment that provides the best resolution of velocity without significant effects from error.

3.3 Assessment of Inverse-Velocity Data and Predicted Velocity and Displacement Curves

Once accelerations have been identified in slope movement data, linear trends can be fitted through inverse-velocity values, either by hand, or with a graphing utility package. Early assessment of possible failure trends is typically best achieved visually. Once linear trends are identified in slope movement data, equations and R^2 linear regression coefficients can be determined for best-fit trend-lines. A prediction of failure time can be achieved either visually at the date where the trend-line intersects the x-axis or by setting inverse-velocity equal to zero in the following equation (based on the assumption of a linear trend, i.e.,a =2):

$$\frac{1}{V} = \frac{1}{V_0} - A(t - t_0) \quad (2)$$

where t_0 is the date time value in days at the start of the graphical plot (at which point the velocity is V_0), as shown on Fig. 1. Predicted failure time can then be calculated as follows:

$$t_f = \frac{1}{AV_0} + t_0 \quad (3)$$

Once the slope of the line (A) and the y-intercept ($1/V_0$) are known, predicted velocities can be plotted versus time by taking the inverse of Eq. 2, such that:

$$V_{Predicted} = [\frac{1}{V_0} - A(t - t_0)]^{-1} \quad (4)$$

By integrating the above equation, predicted relative displacements can be calculated as follows:

$$x_{Predicted} = \frac{1}{A}\{\ln(\frac{1}{V_0}) - \ln[\frac{1}{V_0} - A(t - t_0)]\} \quad (5)$$

Predicted velocity and relative displacement curves can be compared to the actual slope monitoring data to determine whether the predicted trends approximate actual values on an ongoing basis, or whether potential changes in slope behaviour may be occurring with time.

3.4 Selection of Threshold Movement Rates

Selection of appropriate threshold movement rates for safe operation and closure of mining areas based on slope movement rates should take into account a number of factors including:

- the accuracy of the slope monitoring system;
- the level of understanding of the slope failure mechanism;
- the potential behaviour of a slope failure if it were to occur (i.e., creep-type displacement versus potential for rapid brittle failure);
- the potential to mitigate slope movements with remedial measures (e.g., buttressing, offloading, installing horizontal drain holes or wells, etc.);
- the time required to implement remedial measures;
- availability of alternate mining faces or accesses; and
- the time required to safely evacuate personnel and remove equipment or infrastructure.

The greatest long-term flexibility is achieved with threshold movement rates that are low enough to allow remedial measures to be implemented safely, prior to significant deterioration of slope conditions. Delays in the mining schedule can be implemented to determine whether slope displacements are regressive (exhibiting post-mining deceleration) or are progressive towards failure. Stability analyses can be carried out to determine the most effective form, or combination of remedial measures (i.e., crest offloading versus buttressing, and/or groundwater depressurization) that may be required to mitigate possible slope failure. Estimates of the required time to implement remedial measures should be developed to determine the appropriate slope movement rate thresholds. A margin of safety should be included to reflect uncertainties in potential slope behaviour.

If possible, remedial measures should be considered at least one-month in advance of a potential failure, to provide maximum flexibility and safety. At that point, slope monitoring should be carried out at least daily. Prior to implementing remedial measures, delays in mining activities should be considered to test whether regressive response is achieved, or whether slope movements continue to accelerate. Potential influences of precipitation, groundwater recharge (e.g., from spring thaw) and blasting should be included in these assessments. Mining and remediation activities should be discontinued at least one week prior to failure. If other potential hazards, such as increased rockfalls, bench-scale failures etc., could occur as a result of increasing slope movements, these thresholds should be implemented earlier at lower movement rates.

3.5 Estimation of Failure Runout Potential and Impact Zones

Assessment of debris runout potential can be made using an empirical relationship known as the Fahrböschung or runout angle (defined as the angle between the post-failure crest and the ultimate toe of the slide debris) for estimation of possible impact zones and keep-out areas. The Fahrböschung angle relationship inherently recognizes that the mobility or travel distance of rock avalanches increases with increasing volume. Based on an empirical chart of documented landslides of varying volumes developed by Scheidegger [7] and from a database of 76 European landslides by Li [8], the runout angle of a potential debris avalanche can be estimated. Empirical charts relating failure volume to the tangent of the runout angle, or ratio of slope height to runout length (H/L), can be used to estimate possible runout distances. More sophisticated analysis tools can be utilized such as the Dynamic Analysis code DAN, described by Hungr [9]. This code is best suited for assessment of failures that are relatively shallow, compared with their areal extent, rather than deep-seated, moderately mobile failures in bedrock. It is useful in analyzing and designing protective measures (e.g., impact berms) for control of mobile debris slides or rock avalanches associated with post failure conditions. Design of these measures should incorporate modeling of potential rockfall hazards with computer codes such as the Colorado Rockfall Simulation Program (CRSP), among others.

4. Case Examples of Predicted Failure Time Using Inverse-Velocity

Three case examples are presented from two large open pit mines that illustrate the use of inverse-velocity for predicting failure time. Examples 1 and 3 occurred in 2001 and 2005 at Barrick Gold's Betze-Post open pit mine located in the Carlin Trend, northeastern Nevada. Case Example 2 occurred at another large mining operation. Each of these case examples involved instabilities that were monitored using manual and robotic total station survey of reflective prisms, and wireline extensometers. In each case, failure predictions approximated the failure time to the day of the actual failure. Predictions of failure time for the 1, 2 and 18 million m^3 failures were forecasted two-weeks, five-days and three-months prior to failure, respectively.

At both mining operations, survey distances of greater than 1km resulted in accuracies in survey measurements of about ± 10 to 15 mm, or greater. As a result, different methods of data smoothing were required to provide reasonable resolution of slope movement trends.

4.1 Case Example 1

Case Example 1 involves a 550m high slope failure that occurred on the southeast wall of the Betze-Post open pit in August 2001. The southeast wall is situated in Jurassic granodiorite intrusive rocks that are argillically (clay) altered along major gouge-filled faults and shear zones. As a result, groundwater is highly compartmentalized and has a significant influence on slope stability. A description of the structural geology and hydrogeology of the southeast wall is included in Rose and Sharon [10].

Complex wedge deformations on the upper southeast wall began as early as 1993. The failure mechanism involved shearing along deep wedge intersections that plunged shallowly towards the open pit, causing upward heaving along shallow in-slope dipping faults that were oriented obliquely to the slope face. Stability analyses were carried out to define the required slope geometry to maintain a minimum factor of safety (FOS) of 1.2 under partially depressurized conditions. Between 1993 and 1998, slope stability was managed on the 1st and 2nd East Laybacks with a combination of engineered waste rock buttresses, offload cuts, stepouts, horizontal drain holes and vertical wells.

In 1998, a re-design of the southeast wall was required due to instability that had occurred in two adjacent slope areas, as described by Rose and Sharon [10]. As part of the 2SE Layback design, twelve nested complex wedges ranging in size from approximately 1 to 10 million m^3 were analyzed using the three-dimensional limit equilibrium program CLARA-W [11] to satisfy a minimum FOS of 1.2 for the ultimate slope.

Approximately six months after the start of the 2SE Layback, slope deformations began to develop in the mid to upper slope and ensued for another two years, through to completion of the ultimate wall. Ten survey prisms were used to monitor the main complex wedge area with locations shown on Fig. 2. Total displacements of up to one metre were encountered in the upper slope over the course of mining, defining an average movement rate of about 2 mm/day. Slope deformations responded cyclically to mining and seasonal precipitation, but remained regressive throughout mining. No remedial changes were required to the 2SE Layback mine plan and ore recovery was successfully completed in January 2001 to one additional bench below the final bottom target elevation.

Approximately five months after mining was completed, the southeast wall began to exhibit signs of progressive failure development, as was recognized from weak accelerations in the slope monitoring data. Inverse-velocity graphs were developed to predict the potential slope failure time, which was initially estimated to occur approximately two to three months later. As displacement rates increased, inverse-velocity trends exhibited greater linearity and began to converge on a common failure time of August 29, 2001. Figure 3 is a plot of inverse-velocity versus time showing the predicted trends of nine survey prisms located at various elevations on the slope (Fig. 2) over the last six weeks of data leading up to failure. Data-smoothing was achieved by calculating six-day average slope distance velocities to reduce the effects of instrument error in low-level velocity values. Linear regression coefficients (R^2) were 99% for all nine prisms. Six-day incremental velocities were calculated and plotted up to two days prior to failure. Although the six-day average data began to diverge from the best-fit lines closer to the failure time (Fig. 3), it was previously recognized that six-day averages could result in a delayed failure prediction of up to one to two days. To accommodate this, the best-fit trends were projected back through two to four weeks of data rather than adjusting predictions based on short-term trends.

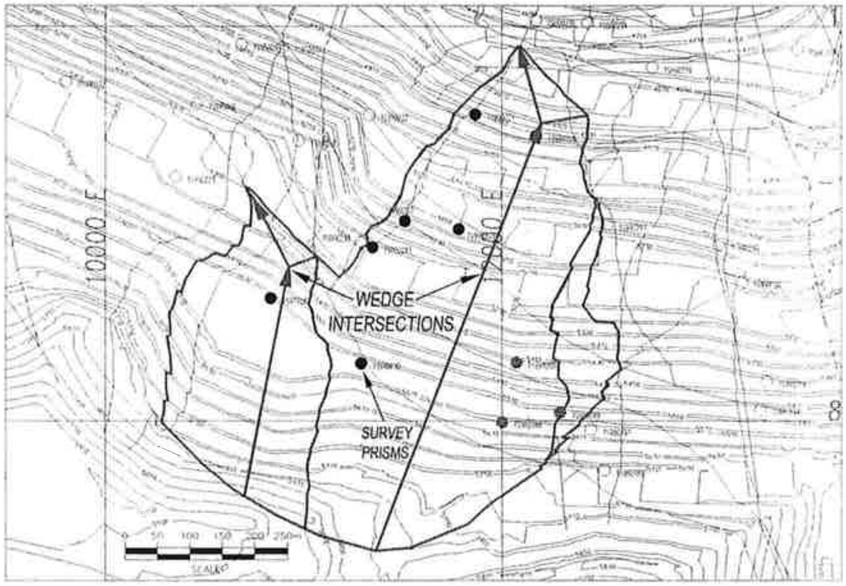

Figure 2: Map of southeast wall showing complex wedge geometries, prism locations (solid dots) and sliding directions (arrows).

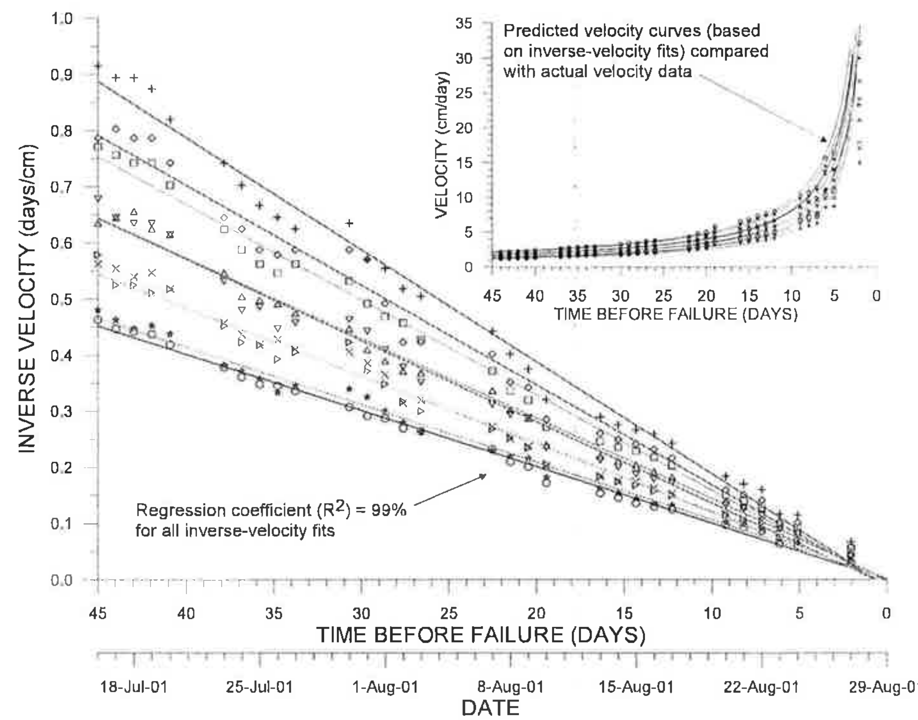

Figure 3: Case Example 1 - Plot of six-day average inverse-velocity and velocity (predicted curves versus actual values on inset graph) versus time for nine prisms (time 0 was the observed time of failure).

An 18 million m^3 (47 million tonne) failure occurred on the southeast wall of the Betze-Post pit on August 29, 2001. The failure initiated in a 345m high section of the upper bedrock slope. Prior to failure, the maximum overall slope angle (crest-to-toe) was 27° over a slope height of 450m. The failure encompassed an overall slope height of 550m. The angle defined from the original crest to the toe of the failure debris was 24°. The Fahrböschung angle, defined from the crest of the back-scarp to the toe of the landslide deposit (failure debris) was 22.5°. The failure occurred on an ultimate pit wall approximately eight months after completion of mining and had no adverse impacts on the open pit mining operation.

4.2 Case Example 2

Case Example 2 involves a slope failure that encompassed a 365m slope height, within 210m of consolidated Tertiary alluvial sediments overlying intrusive bedrock. High groundwater conditions, a highly fractured rock mass and the occurrence of steeply in-slope dipping faults, resulted in deep-seated toppling deformations that propagated into the overlying sediments, resulting in tensile failure of the upper slope. Slope deformations had occurred in a regressive fashion in response to mining over a one year period before signs of progressive failure were recognized.

Figure 4 is a plot of data for five survey prisms and one wireline extensometer, showing the linear best-fit trends projecting to a failure time that was forecasted from one to two weeks prior to failure. Velocities for five prisms were calculated based on incremental total vector survey readings. The wireline extensometer was measured at 15-minute intervals via radio telemetry, but velocities were calculated on a 24-hour basis to reduce the effect of error and instrument resets. The wireline extensometer data provided the most accurate prediction of slope failure time, which was forecasted to within three hours of the actual failure. The R^2 linear regression coefficient for the wireline extensometer data was 99%, as compared to 83 to 99% for the five survey prisms.

Mining activities were successfully stopped in advance of failure and no adverse impacts were experienced by the mining operation. The failure occurred on an interim slope and contingency planning provided alternate mining faces.

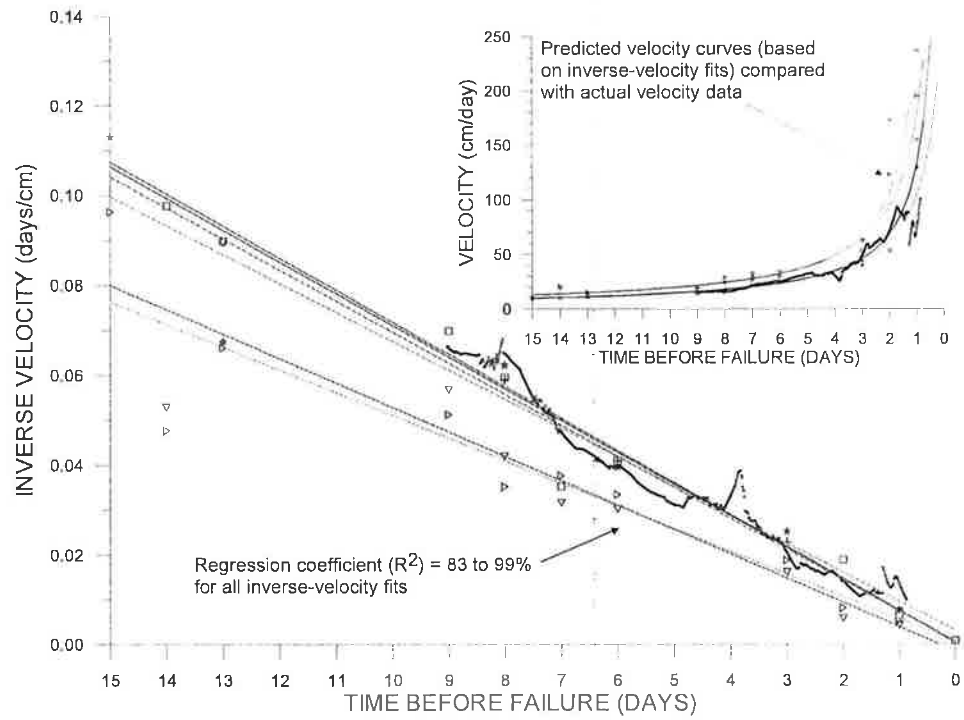

Figure 4: Case Example 2 – Plot of inverse-velocity and velocity (predicted curves versus actual values on inset graph) versus time for five prisms and one wireline extensometer (time 0 was observed time of failure).

Approximately 1 million m^3 (2 million tonnes) of material from the upper slope was deposited on the working level, defining a debris lobe that extended approximately 100m from the toe of the slope. Prior to failure, the slope was mined at an interramp slope angle (IRA) of 44°. The head scarp of the failure extended approximately 50 to 75m behind the pit crest, defining a Fahrböschung angle of 35°. Boulders of up to 3m in diameter rolled to a maximum distance of 130m from the original toe of the slope, but were arrested by a safety impact berm.

4.3 Case Example 3

Case Example 3 involves a 2 million m^3 (5 million tonne) failure that occurred over a 120m slope height on the southwest wall of the Betze-Post pit on May 22, 2005. The failure occurred approximately two weeks after a low shear strength lithologic contact was daylighted with an average dip of about 17° towards the open pit. The failure was progressive in nature and followed 115 mm of rain in eleven days, and a peak rainfall event of 53 mm in 24 hours, six days prior to failure. The failure occurred as a result of the adverse orientation of low shear strength materials at the lithologic contact and pore pressures associated with infiltration of up to 4000 litres per minute of surface water in tension cracks at the pit crest.

As shown on Fig. 5, inverse-velocity trends were defined four to five days before failure, prior to which slope movements had behaved in a regressive fashion. Figure 6 is a photo approximately two months after the failure. The failure occurred on an interim wall and had no adverse impacts on mining activities. Remediation included diversion of surface water near the pit crest and a stepout at the failure toe. Preceding failure, the slope was mined at an IRA of 38°. The Fahrböschung angle was 27°, and the maximum runout distance from the original mined toe was about 90m.

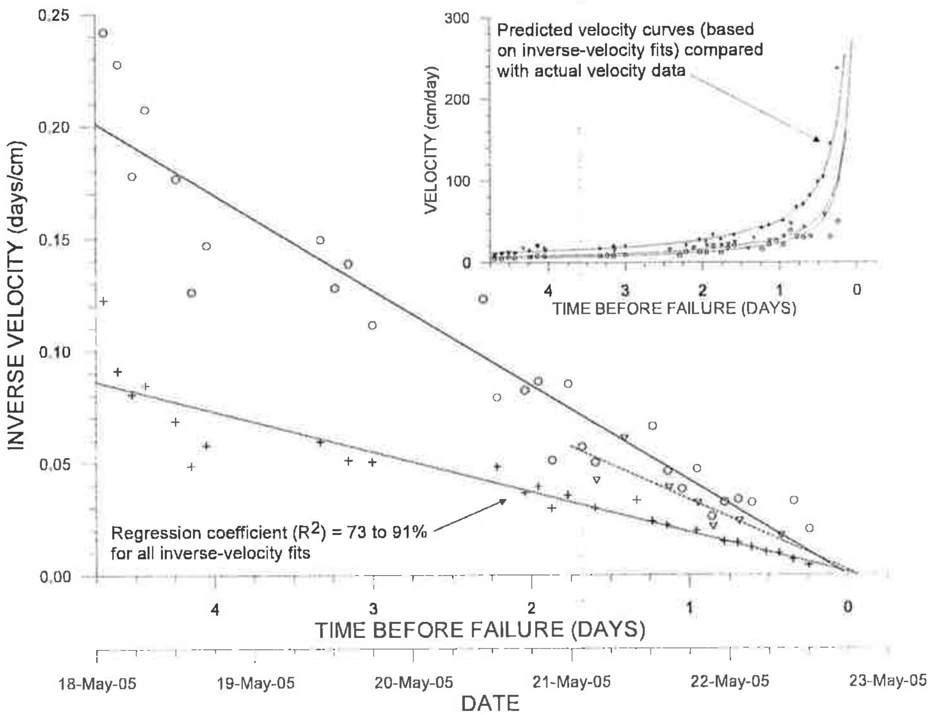

Figure 5: Case Example 3 - Plot of inverse-velocity and velocity (predicted curves versus actual values on inset graph) versus time for three prisms (time 0 was the observed time of failure).

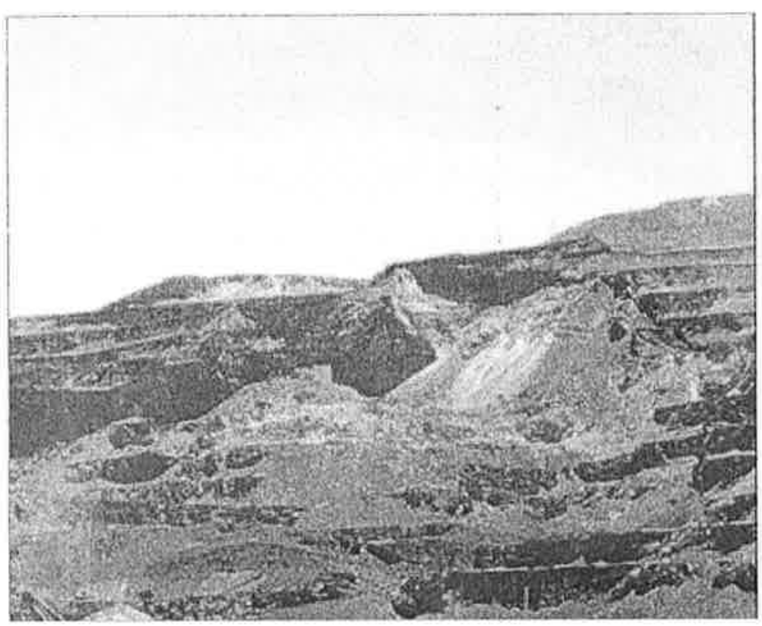

Figure 6: Photo of 2 million m^3 Southwest Wall Failure at the Betze-Post Open Pit that occurred May 22, 2005.

5. Example of Inverse-Velocity Used to Implement Remedial Measures and Mitigate Slope Failure

A fourth case example is presented that illustrates the use of inverse-velocity to plan and implement remedial measures to mitigate possible slope failure, using selected threshold movement rates based on forecasted failure times. This example involves a 3 to 10 million m^3 (5 to 18 million tonne) instability on the northeast wall of the Betze-Post open pit that developed in late 2000 and continued to deform at controlled rates, through to completion of mining in January 2003. During mining, slope deformations were managed by implementing well placed offloading cuts, step-outs, mid-slope waste rock buttresses and temporarily splitting layback development. A detailed account of the engineering geology, hydrogeology, design and development of the Northeast Layback is included in Sharon, Rose and Rantapaa [12].

From early May to the end of June 2002, slope movements within the Midnight/Pats complex wedge exhibited slope accelerations with an indicated potential failure time of early to mid August 2002. Slope movements were related to low angle shearing along the low shear strength (i.e., ϕ=9°, c=35 kPa) Carlin waxy silt unit. Figure 7 is a graph of inverse-velocity versus time for six prisms located on the upper slope. Stability analyses carried out using CLARA-W (Fig. 8) were used to determine the volume of material that could be required to stabilize the wedge. It was estimated that up to 360,000 tonnes of material would have to be excavated at the pit crest, and approximately 90,000 tonnes placed at the daylight level of the Carlin waxy silt unit to stabilize the slope. It was estimated that up to one month could be required to implement the remedial measures, without causing significant disruption to the mine plan. Threshold movement rates were selected for remediation activities such that construction and operation would be completed with a two-week buffer period prior to failure, if it were to occur.

Approximately three days after construction started, decelerations were noticed in the slope monitoring data. A threshold movement rate of about 2.5 cm/day, or an inverse-velocity of about 0.4 days/cm, was used to schedule construction and excavation. As seen on Fig. 7, remediation continued over a period of about three weeks until slope displacements stabilized to acceptable levels.

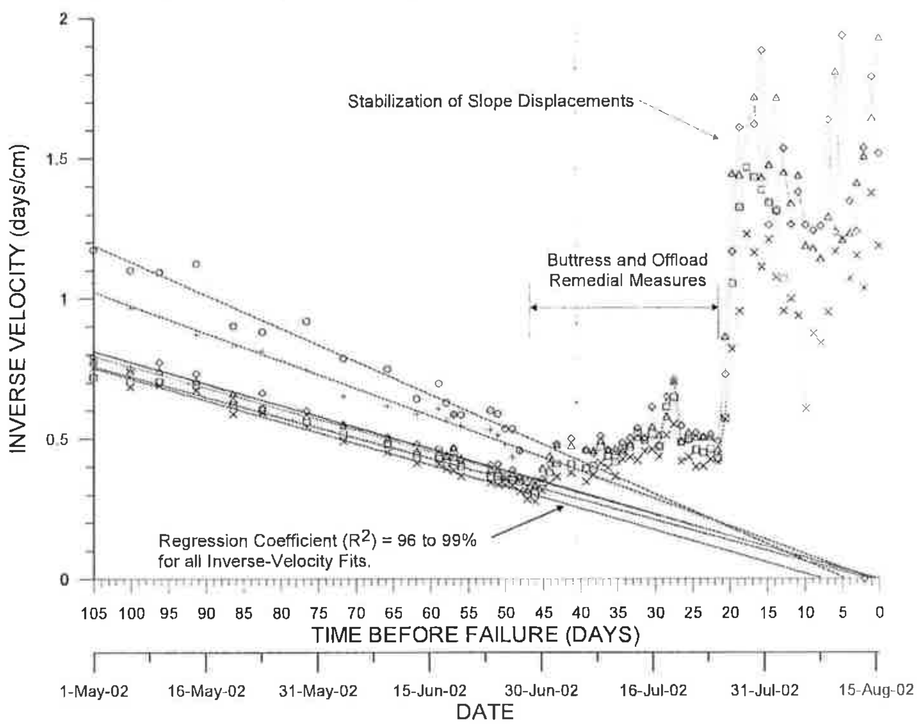

Figure 7: Case Example 4 - plot of inverse-velocity versus time for six prisms on the upper northeast wall.

Periodically throughout the remainder of mining, additional crest offloading was required to maintain displacements below threshold values. Figure 9 is a photo showing the upper portion of the Midnight/Pats complex wedge (see Fig. 8) as crest offload mining was taking place.

The Northeast Layback was successfully completed in January 2003. Failure of the upper northeast wall was mitigated by implementing the remedial measures discussed above. Since that time in-pit backfilling has improved the stability of the ultimate slope.

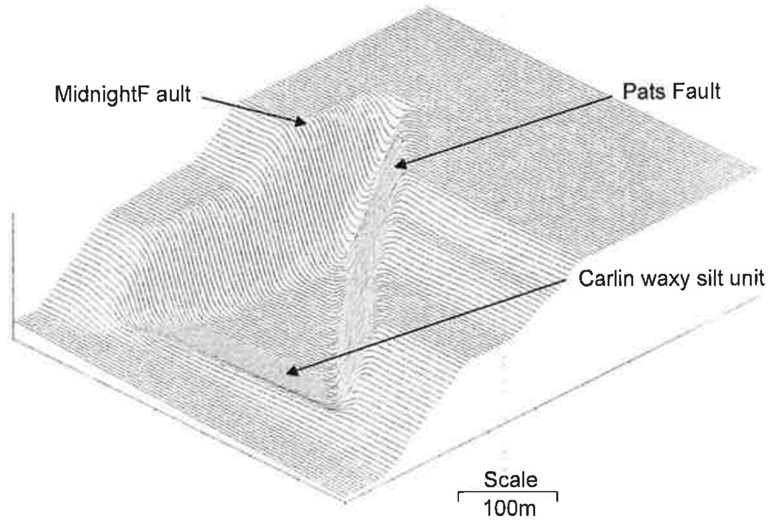

Figure 8: Complex wedge on the upper northeast wall of the Betze-Post open pit involving the Midnight/Pats faults and Carlin waxy silt (3 million m^3).

Figure 9: Photo of the upper northeast wall of the Betze-Post open pit showing the location of crest offloading in the Midnight/Pats complex wedge.

6. Conclusions and Discussion

Inverse-velocity has proven to be a useful tool for predicting the three large slope failures presented in this paper. Application of this method was also successful in mitigating a potential slope failure based on consideration of the time required to implement remedial measures and scheduling of remedial activities with appropriately selected threshold criteria. All of the case examples presented in this paper involved relatively large instabilities (i.e., =1 million m^3) that occurred in an extensional stress environment with a low insitu horizontal to vertical stress ratio. These conditions are consistent with gravity loading and accelerating creep-type conditions simulated in laboratory tests by Fukuzono [3]. Experience with this method has not been gained in a high insitu horizontal stress environment or in strong rock masses where increased potential for rapid brittle failure may exist. As such, caution should be used in applying this method in either of these environments.

At the time of writing, neither author was aware of other examples where inverse-velocity had been used to successfully predict large-scale slope failure time (though the method was shown to be successful in "predicting" certain past failures retroactively, e.g. Voight, [13,14]). A number of authors have proposed that inverse-velocity should be applicable for predicting large natural landslides, or sturzstroms, but their conclusions also appear to be based on back analysis of historical data, rather than actual predicted occurrences. Kilburn and Petley [15] present a back-analysis of the horizontal slope movements recorded before the catastrophic collapse of Mt. Toc into the Vajont reservoir in October 1963, claiming more than 2000 lives [16]. Linear regression of inverse-velocity data gives an R^2 correlation coefficient of 99% through data from 60 days prior to the event, adding a compelling case example where the use of inverse velocity may have been successful in averting possible disaster.

A failure forecasting methodology, similar the one in this paper, is presented by Crosta and Agliardi [17], but uses more complex inverse-velocity curves presented by Voight [13,14]. Their work utilized back analysis of historical natural slope and open pit mine failures to validate the use of inverse-velocity to develop threshold criteria for disaster management associated with large natural landslides. Data fitting using the non-linear inverse-velocity method may provide a more accurate assessment of long-term trends, but is more complex, which may limit practical use. Linear estimates of inverse-velocity should provide a reasonable estimate of failure time, if predictions are updated on an ongoing basis and an adequate level of filtering is used to reduce the effects of error. The primary advantage of the method is that inverse velocity-time plots, whether linear or not, are easier to extrapolate towards the failure limit than the usual hyperbolic curves recorded by accelerating deformations prior to failure. In principle, the same approach can be used for extrapolating any unstable phenomena, for example the frequency of micro-seismic events recorded at the onset of a rock slope failure.

7. Experience Database

In an ongoing effort to increase the database of experience with the inverse-velocity approach, the authors of this paper would like to extend an invitation for others to share their experience using this method. If necessary, confidentiality can be maintained by omitting reference to the location or source of the data. Correspondence to this effect can be made via electronic mail to Mr. Nick Rose at nrose@piteau.com or Dr. Oldrich Hungr at the University of British Columbia at ohungr@eos.ubc.ca.

8. Acknowledgements

The authors of this paper are grateful to the management of Barrick Goldstrike Mines Ltd., Barrick Gold Corp. and the anonymous mining company that provided permission to present the slope monitoring data and information included in this paper. Recognition is given to the staff at both mines that collected the slope monitoring data and contributed to the engineering judgement that was used in the successful application of this approach. Particular thanks are given to Bob Sharon, Mark Rantapaa, Tracey Miller, John Cash, Dave Pierce, Joe Gallegos and Jorge Armstrong. Editorial comments from Al Stewart, Ian Stilwell and Mike Scholz are also acknowledged with thanks.

9. References

[1] Martin, D.C., 1993. Time dependent defomation of rock slopes. Ph. D. Thesis, University of London, August.

[2] Zavodni, Z.M., 2000. Time-dependent movements of open-pit slopes. *Slope stability in surface mining.* (Eds. A. Hustrulid, M.J.Mc Carter, D.J.A. Van Zyl). Littleton: Soc. for Min., Metall. and Expl., 81-88.

[3] Fukuzono, T., 1985. A new method for predicting the failure time of a slope. *Procs. 4th Int. Conf. and Field Workshop on Landslides*, Tokyo, 145-150.

[4] Dunnicliff, C.J., 1988. *Geotechnical instrumentation for monitoring field performance*. John Wiley and Sons, Inc., New York.

[5] Turner, A.K. and Schuster, R.L., Eds., 1996. *Landslides, investigation and mitigation*. Transportation Research Board Special Report 247, Washington, D.C.

[6] Wyllie, D.C. and Mah, C.W., 2004. *Rock slope engineering. Fourth edition*, Spon Press, New York.

[7] Scheidegger, A.E., 1973. On the prediction of the reach and velocity of catastrophic landslides. *Rock Mechanics*, **5**, 231-236.

[8] Li, T., 1983. A mathematical model for predicting the extent of a major rockfall. *Zeitschrift fur Geomorphologie*, **24**, 473-482.

[9] Hungr, O., 1995. A model for the runout analysis of flow slides, debris flows, and avalanches. *Canadian Geotech. J.*, **32**, 610–623.

[10] Rose, N.D. and Sharon, R.P., 2000. Practical rock slope engineering designs at Barrick Goldstrike. In *Slope stability in surface mining.* (Eds. A. Hustrulid, M.J. McCarter, D.J.A. Van Zyl). Littleton: Soc. for Min., Metall. and Expl., 213-218.

[11] Hungr, O., 1994. CLARA-W – Slope stability analysis in two or three dimensions for IBM compatible microcomputers. *User's Manual*, O. Hungr Geotechnical Research Inc..

[12] Sharon, R., Rose, N. and Rantapaa, M., 2005. Design and development of the Northeast Layback of the Betze-Post Open Pit.*Pro cs. Soc. Min. Eng. Annual Meeting*, Salt Lake, **05-09**, 1-10.

[13] Voight, B. 1988. A method for prediction of volcanic eruption. *Nature*, London, **332**, 125-130.

[14] Voight, B. 1989. A relation to describe rate dependent material failure. *Science*, Washington, D.C., **243**, 200-203.

[15] Kilburn, C.R.J. and Petley, D.N., 2003. Forecasting giant, catastrophic slope collapse: lessons from Vajont, Northern Italy. *Geomorphology*, **54**, 21-32.

[16] Muller, L., 1964. The rock slide in the Vajont valley. *Felsmech. Ingeniergeol.*, **2**, 148-212.

[17] Crosta, G.B. and Agliardi, F., 2003. Failure forecast for large rock slides by surface displacement measurements. *Canadian Geotech. J.*, **40**, 176-191.