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Applications of rock mass monitoring for stability assessment of pit slope failure

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ABSTRACT: The displacement records of fourteen slope failures in open pit mines have been examined. Case histories of progressive displacement for three of the slope failures are presented in this paper. These case histories were examined to determine the reliability of current empirical displacement models. It was found that for all of the slope failures studied, both rigorous engineering stability analysis of the failure mode and extensive surveying are the key to predicting slope displacement. The slope failures studied had a wide range of displacement magnitude, duration, and velocity; however, in all cases at least 48 hours separated the time at which a velocity of 5 cm/day was reached and the time of collapse. Additionally, acceleration appears to be a more definitive indicator in the final 48 hours than actual velocity magnitude, as the ratio of measured velocity 24 hours prior to collapse to measured velocity 48 hours prior to collapse was consistently 1.7 to 2.3.

1 INTRODUCTION

The effort to predict large scale displacements in open pit mine slopes is well documented. The need for predicting movements of large scale slope failures is great considering the economic consequences and operational hazards related to displacement. The problem is essentially threefold: first, to be capable of monitoring displacements in real time; second, to analyze and assimilate the data within a reasonable period, and third, to be able to predict future displacement with a minimum level of accuracy. All three components of open pit slope monitoring have inherent problems, the first being a matter of precision and cost, the second being related to the time available for practical implementation, and the third being a matter of theoretical development. While the development of displacement models has tended to lag behind hardware advancements, the technology for monitoring displacement continues to improve both in precision and cost effectiveness. This acceleration in capability has led to data being generated at increasingly faster rates, taxing the proficiency of many design engineers to assimilate the data into a meaningful interpretation. The operational procedures, available hardware, and appropriate levels of monitoring effort are discussed in detail elsewhere (Brown [1981], Call and Savely [1991], CANMET [1976]). It is the purpose of this paper to focus on the final and most important aspect of a slope monitoring program, that of predicting future displacement. Fourteen slope failures that have progressed to partial or total collapse have been reviewed as part of the preparation of this paper. First the general approach to displacement modeling is described, a review of currently accepted modeling strategies is discussed, and three key questions in displacement prediction are posed. Following the discussion of the displacement models, data from three case histories are presented in detail. These case histories are then examined within the context of the overall review to determine the reliability of current modeling strategies.

2 GENERAL DISCUSSION

The authors' experience with slope failures and the economics of slope failure in open pit mining consistently indicates that in most cases the economic optimum slope design has a significant probability of failure. Accepting that some slope instability can occur in an optimized mine design inevitably leads to a commitment to a monitoring program to ensure safe operational conditions. After some consideration and practical experience, it is evident that the definition of slope "failure" is not as simple as it would first appear, nor can it be defined only by a simple mechanistic law. Because of the considerable procedural flexibility that most open pit mine operations possess, large displacements within active slopes do not necessarily constitute "failure" from a mine management standpoint. This relationship between theoretical and operational slope failure has been explored by others (Munn [1985], Call [1982]), and it is generally useful to distinguish between the two in mine engineering practice. Quite often the real hazard to operations is not from steady state or regressive creep of the rock mass, but rather the potential for greatly accelerated movements occurring near to equipment and personnel. Because large slope displacements are preceded by small, but measurable phenomena (displacement, tension cracks, acoustic emissions, changes in ground water levels, raveling), a comprehensive monitoring program is essential for sound mine operation.

Although most techniques used to model slope stability are based on static, rigid block, limiting force analyses, these models cannot be used to predict post-failure deformation because of the dynamic energy relationships between the moving blocks. It is for this reason that most post-failure models are based primarily on empirical relationships derived from slope monitoring data (Cruden and Mazoumzadeh [1987], Zavodni and Broadbent [1980]). In the past, examination of displacement data has led to the development of two general displacement models: a progressive failure model where slope displacement will continue to accelerate to a point of collapse (or greatly accelerated movement), and a regressive failure model where the slope will re-stabilize (or decelerate to a creep state). Experience in many active slope failures in complex geologic environments also indicates that a third, steady state condition can also occur at displacement rates far above those generally associated with creep. In general, past research indicates that an exponential function appears to be most representative of displacement with time for both regressive and progressive failure models. Both Cruden and Mazoumzadeh [1987] and Voight, Orkan, and Young [1989] present an excellent overview of exponential and power relationships between displacement and time. In general, slope monitoring data is presented in terms of cumulative resultant displacement, and resultant velocity. Resultant velocity can be calculated in several ways, however, for the purposes of this paper velocity will refer to the first derivative of the total cumulative displacement curve. Appendix A presents some useful relationships and conversions for commonly accepted units of measurement.

3 ACCELERATING DISPLACEMENT MODELS

Time-displacement relations for accelerating displacement (progressive failure) have consistently received the most attention by engineers in the recent past. The most generally accepted equations for the power and exponential progressive failure models are presented in Table 1. The time-velocity relationship is usually constructed on a log scale which allows a transformation of both the exponential and power functions into linear relations. By linearizing the data, readily available regression analyses can be applied to the data in order to determine both mean trends and confidence limits to the data set.

However, previous work and back analysis of slope failures indicates that single mathematical functions are generally incapable of predicting the overall displacement record. Instead, past experience indicates that multiple stages are usually evident in the time-displacement relation and that mathematical modeling must take these cycles into account. Additionally, in most cases there appears to be a critical slide velocity that once reached, indicates that progressive deformation to the point of collapse is irreversible. One of the first papers to substantively identify stages of deformation in terms of velocity was that of Wyllie and Munn [1979], in which they proposed that the critical, pre-collapse slide velocity was 72 cm/day. Following a review of 13 slope failures in open pit porphyry mines, Zavodni and Broadbent [1980] concluded that progressive failure displacements could be modeled using two stages: a stage 1 regressive, and a stage 2 progressive. They proposed that a displacement velocity above 5 cm/day indicated that a slope failure was in the second progressive stage of failure, and that collapse of the slope would occur within 48 days. They also proposed a mathematical relationship between the slope velocity at the onset of progressive failure

Table 1. Commonly Used Empirical Displacement Functions

$u = A*(e^{Bt} - 1)$	$V = V_0*e^{St}$	[exponential]
$u = (V_i*t^{C+1})/(C+1)$	$V = V_i*t^D$	[power]
$V_{collapse} = K^2*V_0$	$K = 4.6 - 10.4$	[Zavodni & Broadbent]

u = displacement; v = velocity; t = time
Vi = velocity at onset of progressive failure
A, B, C, D, S are empirical constants

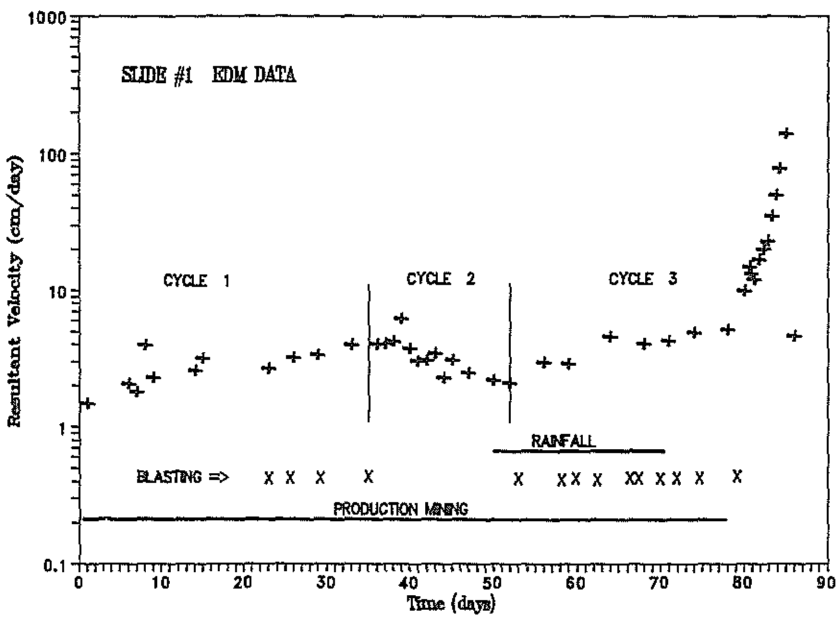

Figure 1. Velocity record for station #45. Note relationship between both blasting and rainfall on movement. Although inconclusive, displacement cycles appear to be closely related to production blasting in the slide vicinity.

(stage 2), and the final, pre-collapse, critical slide velocity. Cruden and Mazoumzadeh [1987], using a similar approach for a coal mine slope failure (Luscar), identified three stages in displacement. They reported that the critical slide velocity of 72 cm/day proposed by Munn was in fact achieved in the final 24 hours prior to collapse at Luscar, and that a third accelerating stage was required for accurate prediction of slope velocity at times close to failure. They identified threshold slide velocities of 3 and 15 cm/day for the transition between stages 1-2 and 2-3 respectively.

Given the wide range of reported slope failure behavior, the question then arises: are there enough similarities exhibited by various slope failures that will enable us to form general stability criteria? If so, how can the back analysis of previous failures be applied to help predict development of other slope failures? After a review of slope failures in the past several years, it is apparent that the following three key questions must continue to be addressed.

1. How can the difference between regressive and progressive failure displacement be distinguished?

2. Is there enough similarity in the kinematic stability of rock slope failures

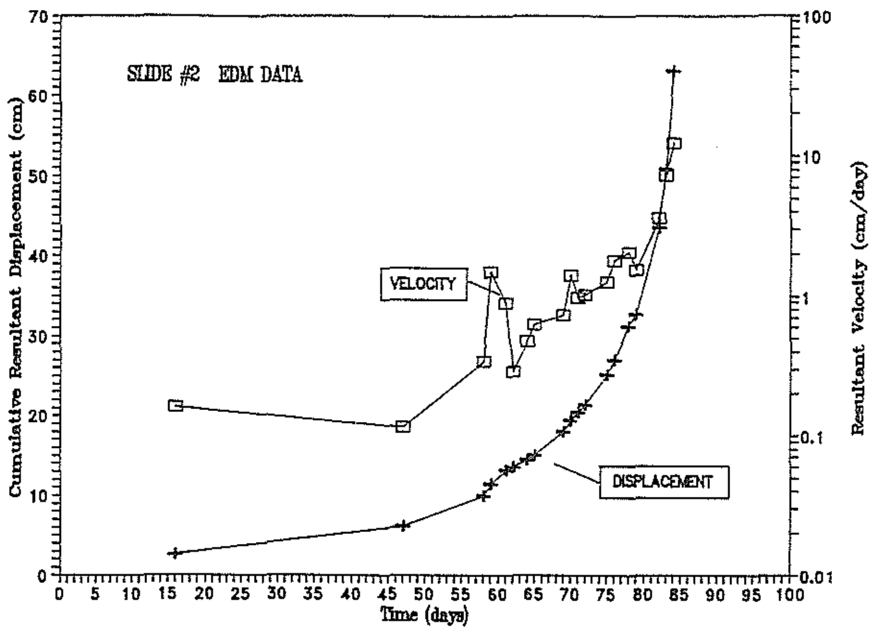

Figure 2. Velocity and displacement records for Slide #2.

to enable the use of general velocity criteria in modeling individual failure stages?

3. How precisely can the time at which collapse will occur be predicted?

4 THREE CASE HISTORIES OF PROGRESSIVE SLOPE FAILURE

The role of the observational method in rock mechanics is well established. In order to answer any of the key questions posed in this paper, an ongoing program of review and back analysis is required.

4.1 *Slide #1, A Copper Mine in Peru*

Monitoring of instability was accomplished through the use of both wire extensometers and EDM prism surveying at the surface. Surface monitoring of the failure began during mid-October of 1988. Final collapse of the slide occurred on March 6, 1989 at 11 PM. Slope height at the time of failure was 210 meters, at an overall slope angle of 40 degrees. The failure was the result of a combination of non-daylighted plane shear structure and a weak, altered rock mass in the toe of the slope. Data from five surface monitoring stations were examined. Station #45 was typical of the time-displacement relation for the slide (figure 1). Three cycles of displacement were evident in the data; an initial cycle (72 days) of gradually accelerating movement with velocity between 1 to 6 cm/day, a second decelerating cycle (10 days) where velocity receded to between 1 to 2 cm/day, and a third accelerating cycle (35 days) which led to collapse. Mining was continuous within and below the slide up to six days prior to collapse of the slide.

Although the reason for deceleration in the second cycle is unclear, the second cycle of movement does correspond to a period when no production blasting was attempted. Precipitation during the initial 21 days of the third cycle is thought to have contributed to the acceleration of the slide prior to collapse. Further examination of the velocity records for the third cycle indicates that three linearized stages can be delineated in the time-velocity relation. The threshold velocities for the stage 1-2 transition vary from 3.02 to 5.56 cm/day, with a mean transition velocity of 4.16 cm/day occurring 6.5 days prior to collapse. The threshold velocities for the stage 2 to 3 transition vary from 18.25 to 27.04 cm/day, with a mean transition velocity of 22.60 cm/day occurring 36 hours prior to collapse. Final measured velocities prior to failure varied from 61.20 to 90.22 cm/day, with a mean final velocity of 74.19 cm/day measured 8 hours prior to collapse.

4.2 *Slide #2, Iron Mine in Mexico*

EDM surveying of prism stations was used to monitor slope instability in Pit #1 at an iron ore mine in 1990. Surface monitoring of the failure was accomplished over an 85 day period, at which time final collapse of the slide occurred. Slope height at the time of failure was 80 meters, at an overall slope angle of 75 degrees. The failure was the result of a daylighted tetrahedral wedge bounded on two sides by fault planes. A combination of both short mechanical anchor bolts (split-sets) and longer, fully grouted cable bolts were routinely being employed to control bench scale backbreak and interramp slope stability within the slope sector at the time of failure.

Data from twelve surface monitoring stations were available for analysis. The velocity record from station #65 was typical for the slide (figure 2). Tension crack development over a 50 meter section of the pit slope was first noticed in May of 1990, and four prisms were deployed on the slope to monitor movement while mining continued below the slide. Eight additional prisms were added as movement of the slide developed during the period of June and July of 1990. Final collapse of the slide occurred on July 26, 1990. The cumulative displacement records for the slide show no obvious stages in displacement, but rather a continuous, persistent acceleration. A total cumulative resultant displacement of 65 to 80 centimeters was measured on the prisms 24 hours prior to collapse. The last measured velocities prior to collapse varied between 12.2 and 18.5 cm/day, with a mean velocity of 14.1 cm/day measured 24 hours prior to collapse.

4.3 *Slide #3, Coal Mine in Colombia*

EDM surveying of prism stations was also used to monitor slope instability at a coal mine in 1989.

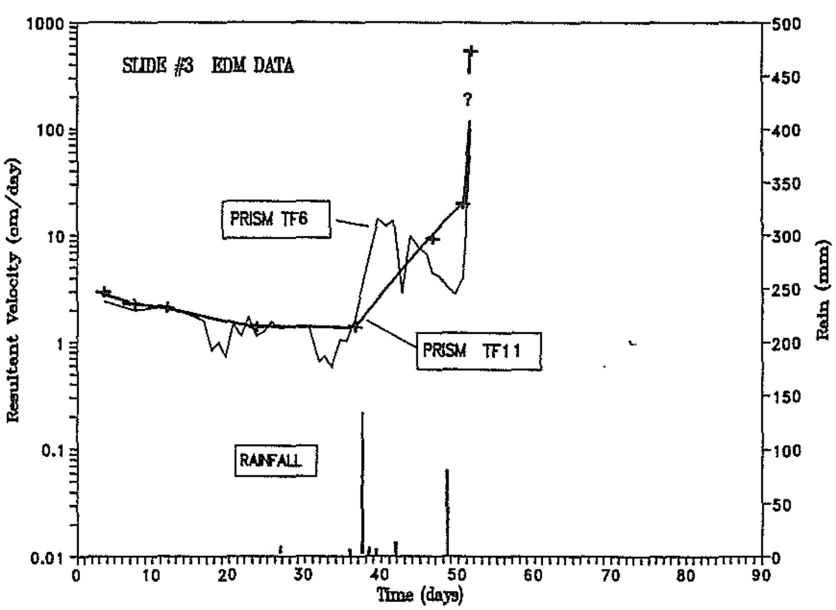

Figure 3. Velocity records for Slide #3. Note apparent discrepancy between prisms in the week prior to failure. Prism TF6 showed an apparent regressive displacement behavior up to 24 hours prior to collapse, while other prisms indicated that progressive collapse began 2 weeks prior to collapse.

Data records from 30 stations over a 110 day period were available for back analysis. Although total collapse of the slope did not develop, a greatly accelerated movement of 20 meters did occur over a four hour period on August 4, 1989. The slope failure involved sliding along non-daylighted, clay-shale bedding surfaces to a depth of 10 meters. Bedding and slope angle varied from 18 to 22 degrees in the 120 meter high footwall slope.

Because of the complex geologic structure at the toe of the slope, displacement was not uniform throughout the slope failure. Prisms at a point near the center of the slope failure showed a consistent acceleration, however, prisms elsewhere in the slide showed a remarkably different development (figure 3). Slope displacement was affected greatly by precipitation, and 3 cycles of displacement are readily apparent in the monitoring data. There was an initial decelerating cycle (36 days) during which slope velocity gradually decreased from an initial 3 cm/day to 1 cm/day. A second accelerating cycle (15 days) is then apparent during which velocity accelerated from 1 cm/day to 20 cm/day, followed by a third accelerating cycle in the final 36 hours prior to collapse.

5 CONCLUSIONS

Although each slide will have its own character, and each situation will have unique criteria for safety, can generalizations be made as to the kinematic stability of displacing slopes? As further work is compiled by both the authors and other researchers in back analysis of past slope failures, the emerging answer appears to be yes, with some reservations.

5.1 *Key Question #1, Regressive vs. Progressive Displacement*

In agreement with Zavodni and Broadbent [1980], regressive slope failures which tend toward increasing stability with displacement have a very wide range of displacement velocity (figure 4). This can make failure prediction very problematic without a well developed monitoring program, and a well defined historical record of displacement for an area. The mode of failure appears to be one of the most important aspects for identifying the potential for progressive failure. It is clear that nearly all daylighted, structurally controlled slope failures (step-path, plane shear, wedge, and step-wedge) reviewed have become progressive in nature, although non-daylighted, complex rock

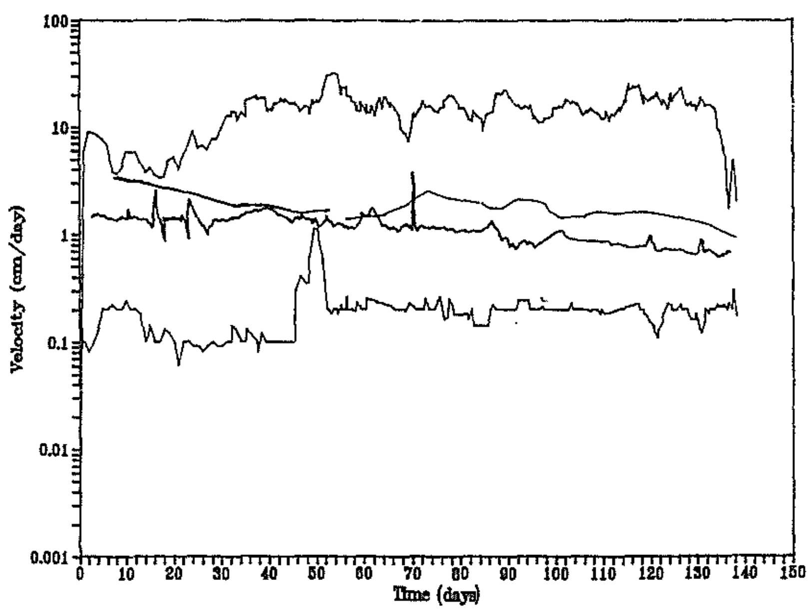

Figure 4. Velocity records for 4 regressive slides which have not progressed to collapse. Note the wide variance in velocity magnitudes between slides, and the magnitude of three of the slides relative to the initial progressive velocities outlined in Table 2.

mass failures can also become progressive. Therefore, a definition of the failure mode is one of the most critical items in failure displacement prediction.

5.2 *Key Question #2, Failure Stages*

It is not clear that a distinct point in the displacement record separates the progressive and regressive failure stages, and not all slope failures have readily identifiable stages in displacement. The Slide #2 failure, for example, shows a continuous, steady acceleration to collapse. For the eleven slides reviewed for this paper which did show a clear change in the velocity-time curve, the mean initial velocity (V_0) of the progressive stage was 1.2 cm/day. This marked change in the slope of the velocity-time curve occurred from six to sixty-three days prior to collapse. It is evident from the data presented in this paper alone, that the definition of failure stages from the velocity-time curve is largely empirical, and appears to be slide dependent. However, overall trends are apparent in the data. In general, it does appear that a minimum of 48 hours exists in all of the data between the time when a mean velocity of 5 cm/day was measured and the time of collapse. This correlates well with Zavodni and Broadbent's conclusions regarding the use of 5 cm/day as an indicator of progressive failure.

5.3 *Key Question #3, Predicting the Time of Collapse*

For the prediction of the time of collapse, it is apparent that the estimate of the critical slide velocity varies widely among previous reports of failures. Some of our data suggest (Slide #1) that the final pre-collapse slide velocity is close to that reported by Munn, although it is unclear as to whether Munn's critical slide velocity of 72 cm/day is reached hours, minutes, or seconds prior to collapse for most failures. At this point in time, a review of nine of the slides in this study revealed that the average velocity 48 hours prior to collapse varied from 5 to 21 cm/day, with a mean 48 hour velocity of 12 cm/day. Similarly, the average velocity 24 hours prior to failure varied from 12 to 38 cm/day, with a mean 24 hour velocity of 25 cm/day. Upon further review it also became apparent that the acceleration of the slope failures was even more consistent than the actual magnitude of velocity, with the 24 hour velocity typically being double that of the 48 hour velocity. The mean ratio of the 24 hour to 48 hour velocity was 2.01, with a standard deviation of 0.38. It is therefore likely that when slope velocity exceeds 5 cm/day, the acceleration of the slope may be a more important stability indicator than the actual magnitude of velocity.

5.4 *Pre-Collapse Slide Velocity*

Although measurements of many slope failures are not detailed enough within the final 24 hours to accurately estimate pre-collapse velocity, it does appear that final measured velocities are increasing in magnitude as the technology to monitor displacement becomes more sophisticated. The use of telemetered equipment, and automated EDM total station systems is increasingly providing more data regarding acceleration in the final 24 hours prior to collapse. In agreement with Cruden and Mazoumzadeh [1987], it is also becoming clear that predictions regarding velocity using regression techniques on data greater than 48 hours prior to collapse tends to underestimate the velocity of slides in the final hours prior to collapse. The Slide #1 data is a good example of the need for more than two stages in the analysis of velocity. It is important that a constant reassessment of velocity trends be initiated by the slope engineer as data is collected and analyzed. It is also likely that within the next five years, definitive data regarding the acceleration curve in the final stages of displacement will allow better definition of the pre-collapse velocity.

5.5 *External Factors and Other Concerns*

External conditions can have a great effect on slope failure development. In the open pit mine environment, the two major external factors which can lead to accelerated movement are rain-

Table 2. Velocity Summary for Nine Progressive Slope Failures

Slide #	V_0 progressive failure	Velocity $(t_f\text{-}t)$=48 hrs	Velocity $(t_f\text{-}t)$=24 hrs
	(*all velocities in cm/day*)		
1*	2.3	20.1	38.4
2*	1.6	6.2	17.9
3*	1.2	10.2	20.1
4	0.9	15.8	33.0
5	0.7	6.0	12.0
6	0.3	12.0	18.2
7	0.9	16.4	28.3
8	1.5	21.2	45.8
9#	1.4	14.0	26.0

* presented in this paper # presented in reference (5)

fall/ground water surcharges, and production blasting. The Slide #3 footwall slope failure is a good example of how quickly unstable slopes can accelerate due to rainfall precipitation. The correlation of progressive slope failure with rainfall or snowmelt is well documented in other slope failures as well. The implication for slope management is severe, as rainfall recharge is not readily controllable, and can cause rapid acceleration of an unstable slide, even when slope velocities appear to be in a regressive cycle. Additionally, the Slide #3 footwall slide shows the importance of adequate monitoring coverage in a complex slope failure. No one survey station or instrument tells the entire story, and there is clearly a need for constant visual observation (once per shift or more depending upon conditions) of any slide that is in a progressive displacement mode.

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APPENDIX A

Common units of measurement and conversions.

Velocity can be calculated in terms of the [1] Incremental Resultant Velocity (IRV), [2] Incremental Cumulative Velocity (ICV), and [3] Cumulative Resultant Velocity (CRV).

where

$$IRV = \left((x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2 \right)^{0.5} / (t_i - t_{i-1})$$
$$ICV = (CRD_i - CRD_{i-1}) / (t_i - t_{i-1})$$
$$CRV = (CRD_i - CRD_0) / (t_i - t_0)$$

The incremental resultant velocity is the total incremental distance traveled divided by the time interval between readings. It is always positive. The incremental cumulative velocity is the total change in the cumulative resultant distance traveled divided by the time interval. The ICV can be negative for the case where precision is lacking in the survey, or where slope movements are complex. The cumulative resultant velocity is the value of the total cumulative resultant distance traveled at any point in time, divided by the total time of travel.

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1 cm/day     =   0.42 mm/hour = 0.0069 mm/minute
1 mm/minute = 144.00 cm/day  = 4.72 ft/day
1 ft/day     =   0.50 in/hour = 0.0083 in/minute
1 ft/day     =  30.48 cm/day  = 0.21 mm/minute
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