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What can we learn from long-term creep trends in open pit slopes?

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Abstract

Slope creep is the time-dependent movement of a slope under gravity loading. In hard rock mines, slope creep is generally characterised as being a short-term episode that precedes slope failure with limited deformation. Long-term slope creep poses a special challenge in assessing open pit slope stability, as the creep rates and magnitudes can make it difficult to interpret and predict slope failure. In addition, the transition from creep to 'instability' is unique for each set of circumstances, and this can complicate the application of displacement-based response plans (e.g. suspension of mining, pit evacuation, etc.). Well-established factors that affect slope stability also influence creep, but the behaviour of creeping slopes is not well understood as it falls out of the range of traditional pit slope analyses.

This paper presents the results of analyses conducted on long-term slope creep records, ranging from one to several years. The results presented indicate that signatures of potential slope failure may be present well before the slope failure occurs. Correlations between creep rate and total displacement (three-dimensional) appear to provide reasonable guidance to predicting future slope failure, which can then be used to inform mine design (e.g. haul ramp placement, etc.).

Keywords: *slope creep, slope failure, long-term*

1 Introduction

In surface mining operations, open pit slopes are intended to be stable over the life-of-mine (LOM). Pit slope designs require knowledge on the rock mass characteristics, structural features, and surface and groundwater conditions, as well as mining equipment selection and orebody geometry.

Once a slope is developed, mining operations monitor performance using a number of tools, including prism surveying, radars, laser scanning, extensometers, photogrammetry, and drone- and satellite-based inspections. For the most part, much of the slope monitoring activities are focused on short-term (hours-to-weeks) slope performance as a means to maintain safe working conditions within the pit. Analytical tools like inverse-velocity, prism vector plots, and movement heat-maps are geared well for this purpose.

While the focus on short-term slope performance is appropriate and required to support day-to-day operations, long-term (months-to-years) time-dependent slope movements (creep) are often not considered as important in overall slope performance. The reason for this is that creep movement rates are often very low (less than a 1 mm/day) and well below the threshold and resolution levels typically used for short-term slope monitoring. Only when these movements are evaluated over longer periods are potentially useful trends are observed.

An evaluation of long-term prism records from both stable and unstable (failed) hard rock pit slopes suggests that important insights in slope performance can be made that can be useful in predicting future large-scale slope instabilities. These insights include: (a) slope creep trends that precede the onset of failure by several months; and (b) the ability to identify structures within the pit wall that dominate wall response.

Given these insights, there is a potential for long-term displacement trends to provide useful information that can be used as a screening-level tool to identify future slope failure (within timeframe of the LOM).

These trends can be used as follows:

- Guide short-term monitoring programs (radars, scanners, etc.) in critical areas, well before the slope movements exceed threshold levels.
- Identify areas in the pit that may develop slope instabilities in the future, thereby allowing mine operators, planners, and geotechnical staff to develop mitigation plans (e.g. changes in pit geometry, buttressing, mechanical support, etc.) ahead of the failure rather than being 'surprised'.
- Provide a tool to communicate potential future risks within the pit and to the business plan.

2 Continuum of rock slope movement

Rock slopes are constantly in motion, whether it is a cut pit slope or a mountain rock slope millions of years old. Time-dependent rock slope movement (creep) occurs as a result of the formation and propagation of fractures from stress release (e.g. blasting and excavation), weathering (chemical, mechanical, thermal), seismic activity, and glacial activity. From a macroscopic viewpoint, creep behaviour implies a reduction in the rock mass properties (Goodman 1993) leading to ultimate failure.

Studies of long-term creep from natural rock slopes show that slope movement can occur over the course of many years. For example, Brückl & Parotidis (2004) presented a study of deep-seated creep failure of natural slopes (rock and soil) in Austria. These natural slopes were oversteepened by glacial erosion some 15,000 years ago and have deformed 100–200 m (averaging from 0.16–0.01 mm/day) since glacial retreat. Bedoui et al. (2009) studied the La Clapière slope, located in the French Alps. Their study focused on the movement of a large (60×10^6 m^3) slope that has been progressively failing over the last 10,000 years, culminating in a rock slide in 1960, with a peak velocity of 2.7 mm/day (see Figure 1).

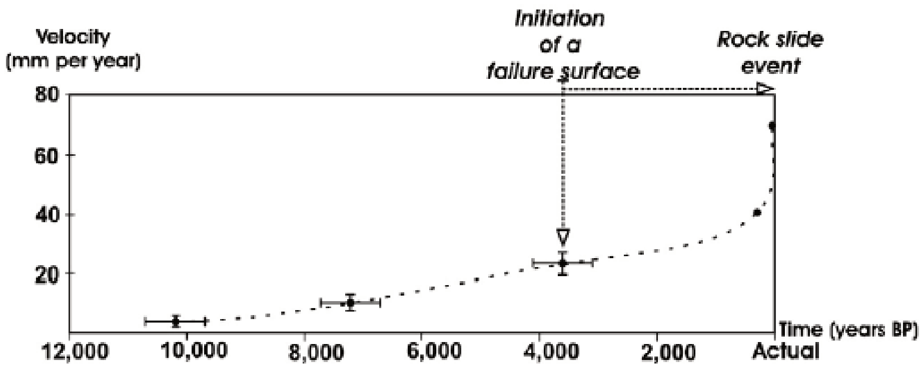

Figure 1 La Clapière slope creep record (Bedoui et al. 2009)

With respect to the mining environment, several important papers have been written to describe the continuum of rock slope movement. Broadbent & Zavodni (1982) and Zavodni (2001) proposed three stages of movement within rock slopes (Figure 2):

- Phase 1 – Initial response.
- Phase 2 – Regressive failure stage (short-term decelerating displacement).
- Phase 3 – Progressive failure stage (strain softening and large-scale deformation leading to collapse).

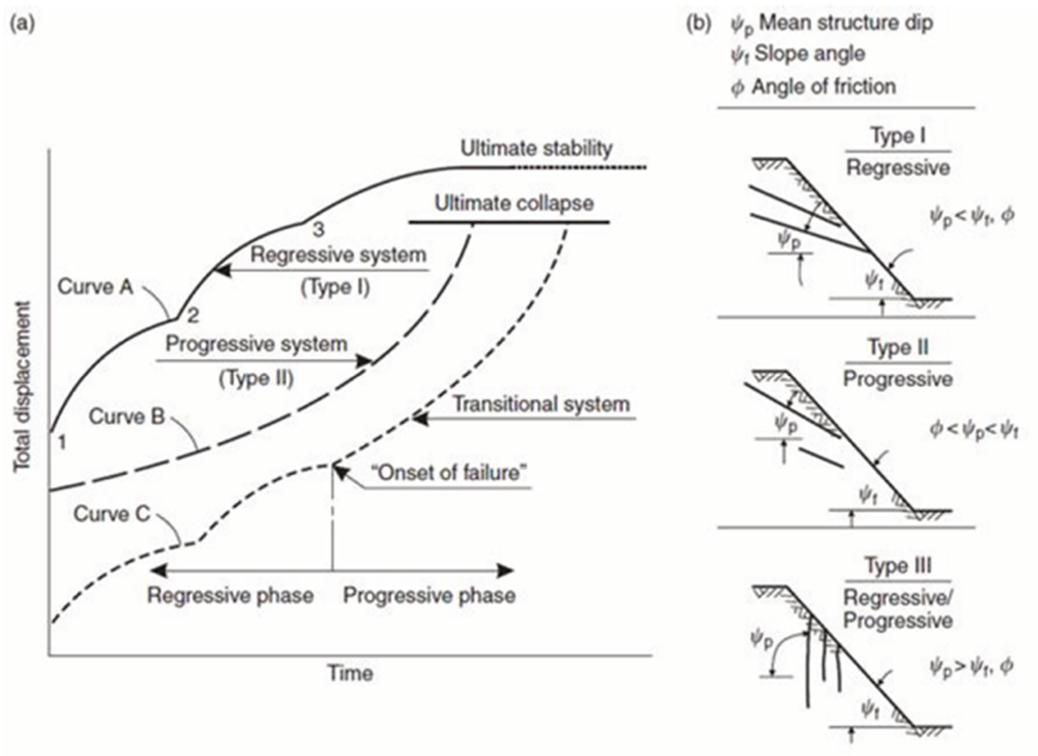

Figure 2 Regressive/progressive slope movement (Broadbent & Zavodni 1982)

Sullivan (2007) proposed five stages of slope movement, as illustrated in Figure 3, to match observed behaviour during pit slope failure:

- Elastic.
- Creep.
- Cracking and dislocation.
- Collapse (failure).
- Post-failure deformation.

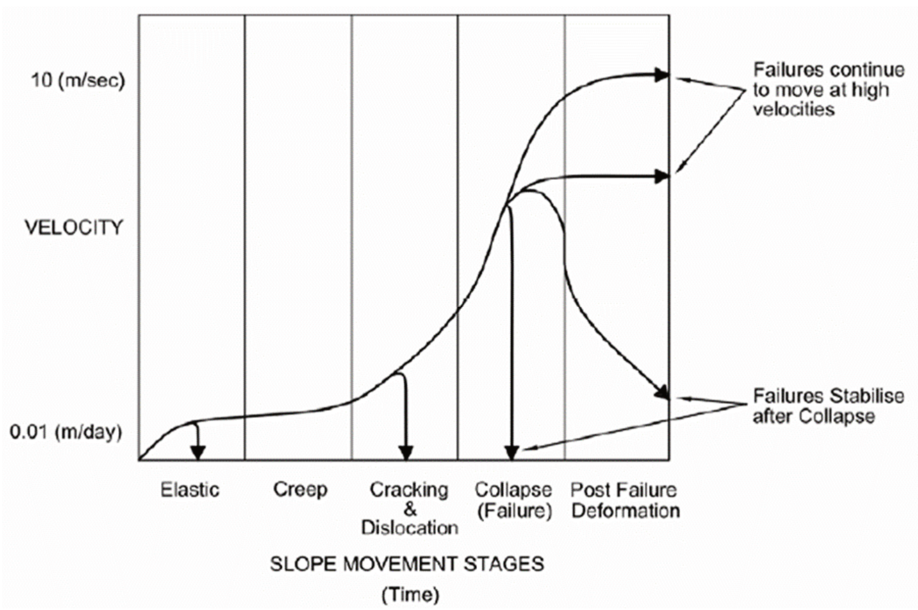

Figure 3 Slope movement stages (Sullivan 2007)

Sullivan (2007) further defines eight additional pre-failure movement rate patterns:

- Linear.
- Bi-linear.
- Stick-slip.
- Regressive.
- Transitional.
- Slow accelerating.
- Linear accelerating.
- Accelerating.

Noting that slopes can express some or all of these patterns, making interpretations and failure predictions are fairly difficult.

3 Short-term versus long-term displacement trends

With the advent of robotic total stations and radars, operations are capable of gathering large amounts of information on slope movements, with scanning or survey cycles in minutes. The result is a very high-resolution record of movement that can show the effects of blasting, rainfall, and excavation on the slope. A typical prism record (covering about three months) showing the influence of blasting on slope movement is presented in Figure 4.

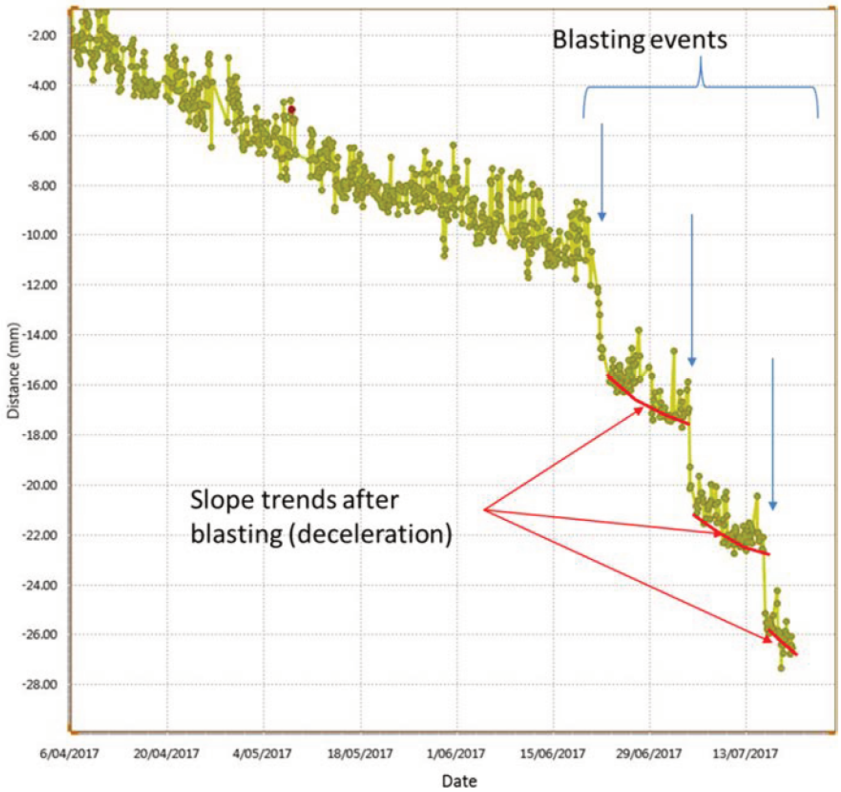

Figure 4 Typical prism record showing blasting effects

Blasting, rainfall, and excavation are short-term stresses that influence slope movement. The recorded 'jump' and subsequent recovery (deceleration) shown in Figure 4 suggest progressive degradation in the rock mass, but the rock is still resilient enough to maintain a stable slope. The response shown in Figure 4 fits well within the categories described by Broadbent & Zavodni (1982), Zavodni (2001), and Sullivan (2007).

The cumulative impact of these short-term stresses, combined with stress-relief cracking, will undoubtedly have an effect on the long-term performance of the slope. To examine these effects, long-term prism records were gathered from numerous pit slopes, some that have been stable for several years and others that have failed (inter-ramp or global failure). Approximately 50 prism records were synthesised into this current study. The records included various rock types, rock quality, and groundwater conditions. A plot of total displacement (three-dimensional) versus time of a select set of prism records is presented in Figure 5, with notations regarding whether the slope failed and the average deformation rate (a linear fit to the total dataset, not peak velocity). A select dataset is presented in Figure 5, for sake of clarity.

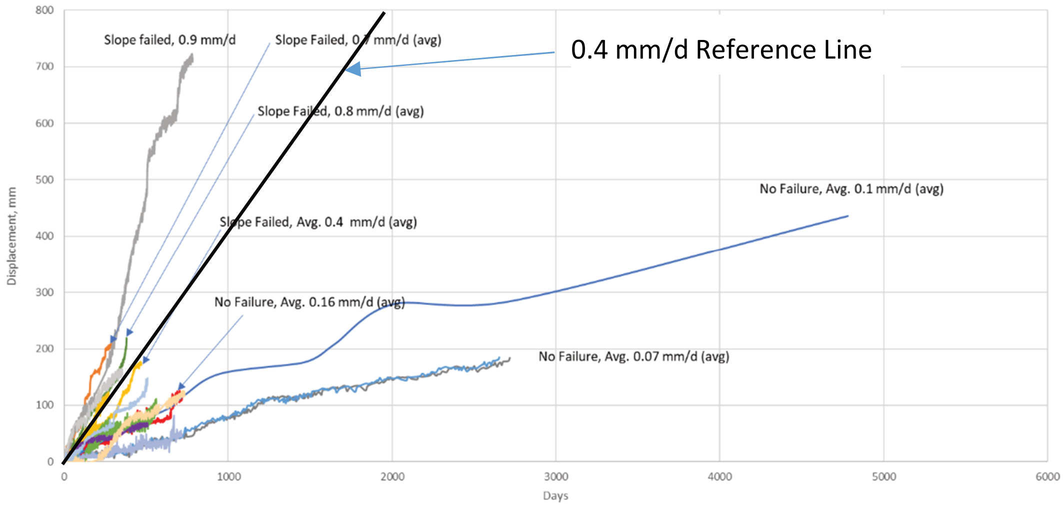

Figure 5 Select slope prism deformation records

While the prism records have non-linear features (e.g. jumps, deceleration, acceleration, etc.), it was clear from this set of data that slopes deforming at an average rate of 0.4 mm/d or greater always failed within a 1.5–2 year timeframe. The average rate is determined by a simple linear fit to the total dataset, not peak velocity. The unstable slopes also tended to accumulate more than 200 mm of displacement before failing.

Slopes deforming at low rates (less than 0.2 mm/d) generally creep for a number of years, while still remaining stable even with accumulated displacements in excess of 400 mm. The performance of these slopes is similar to those of the natural slopes studied by Brückl & Parotidis (2004) and Bedoui et al. (2009).

A summary plot of total displacement versus average velocity for stable and unstable slopes of pit slopes considered in this study is presented in Figure 6. This plot suggests that over the long term, there appears to be a correlation between the average velocity and total displacement measured between stable and unstable slopes. Intuitively, it makes sense that slopes with higher average velocities would accumulate more displacement and eventually become unstable. The correlation presented in Figure 6 therefore provides a glimpse of what may be used as a simple way to assess the stability of slopes based on their long-term prism records. However, there are other elements of movement that should also be considered.

4 Long-term prism vector trends

The discussion up to now has been focused on total displacement from prisms. Long-term trends of prism vectors (displacement in three dimensions) can also shed light on slope performance.

Prism vectors (e.g. displacement in the x, y, and z directions) are often used to interpret slope movements in the short-term (days to weeks). The same process, however, can be used to gain insight on how a slope behaves over the long term, yielding some important trends that can be used, in conjunction with Figure 6, to assess stability of a slope.

Figure 7 presents a total displacement versus time record from a stable slope covering about 450 days. Note the average velocity is 0.11 mm/day with a total displacement of 60 mm, which plots on the 'stable' side of the curve in Figure 6. As shown in Figure 7, the displacement curve exhibits 'step-changes' in velocity over time due to blasting and rainfall events.

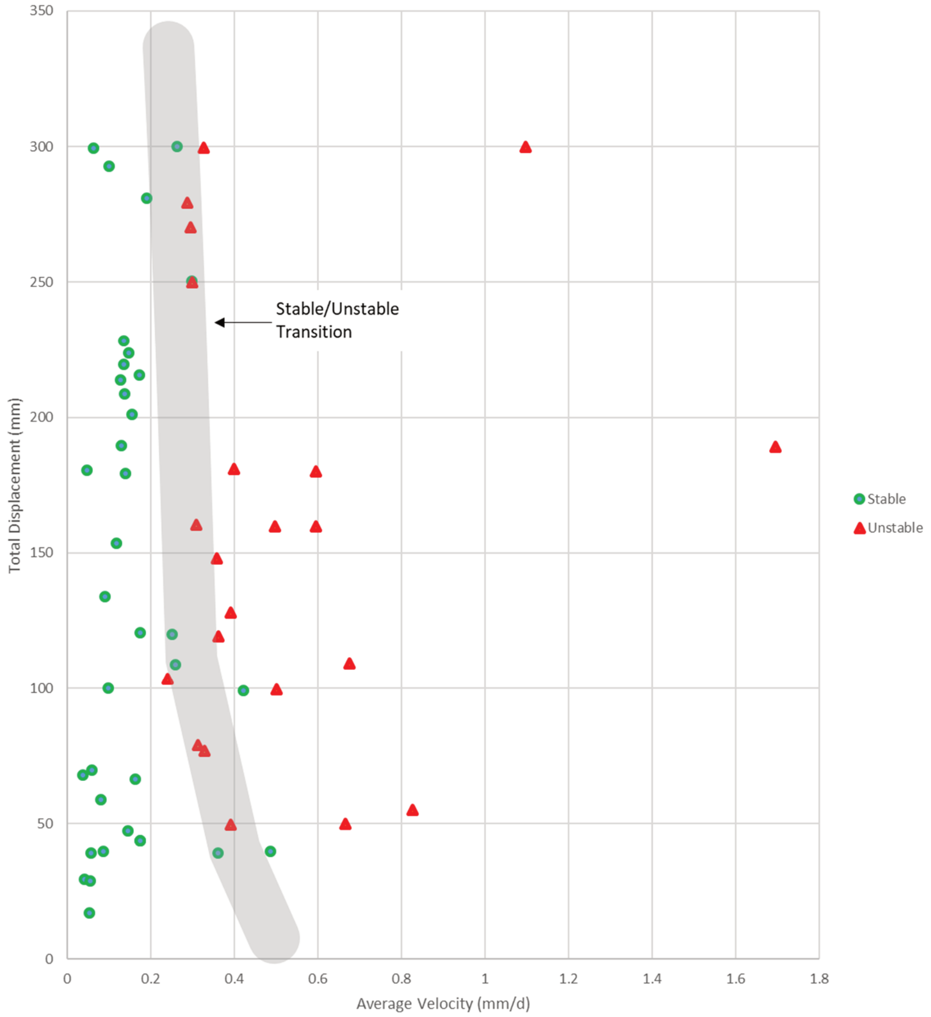

Figure 6 Summary plot of stable and unstable slopes

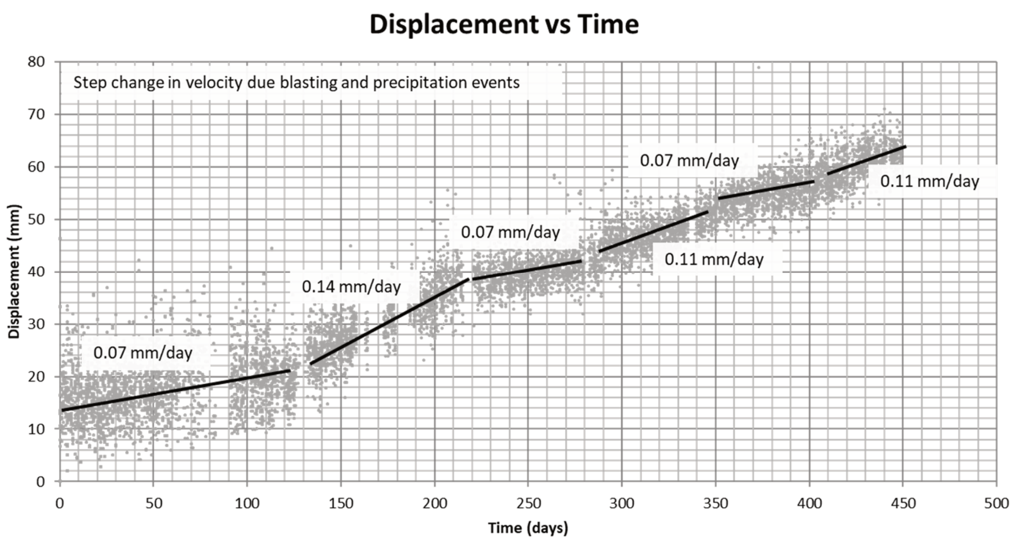

Figure 7 Total displacement versus time: stable slope

The prism data from Figure 7 was broken into its three individual components: elevation, northing, and easting. The time series plots for each of these components are presented in Figures 8, 9, and 10.

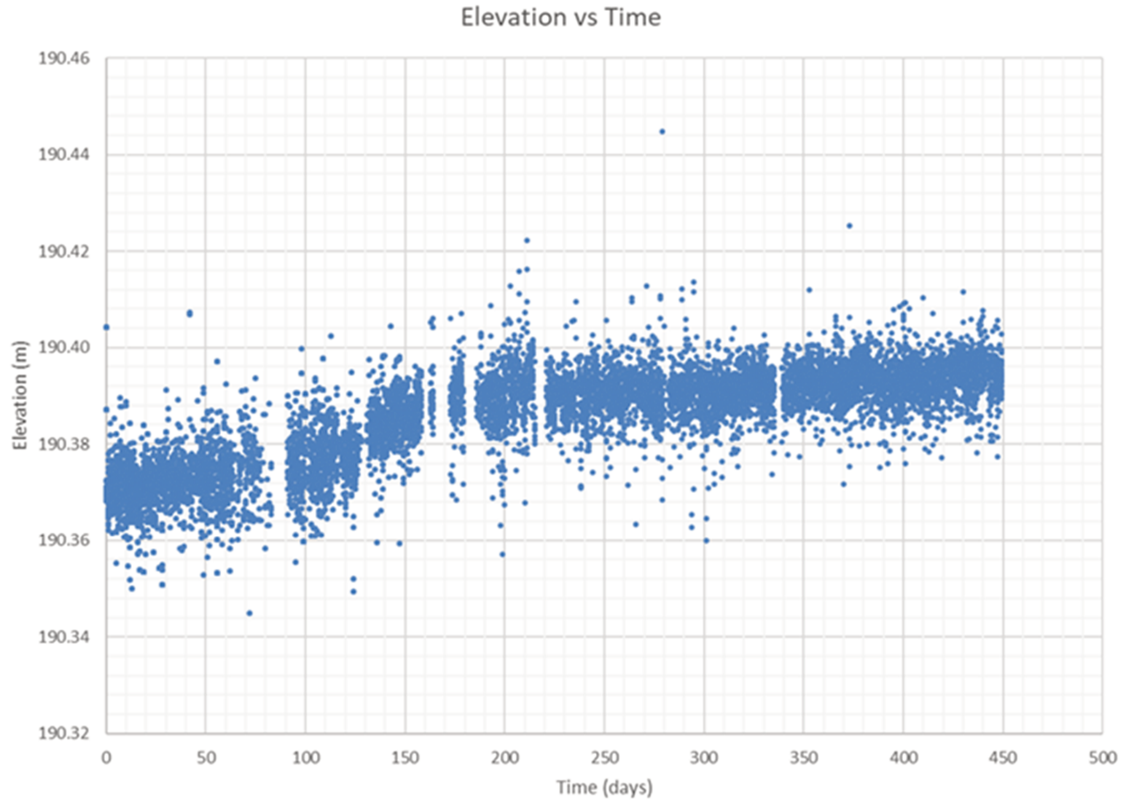

Figure 8 Elevation versus time: stable slope

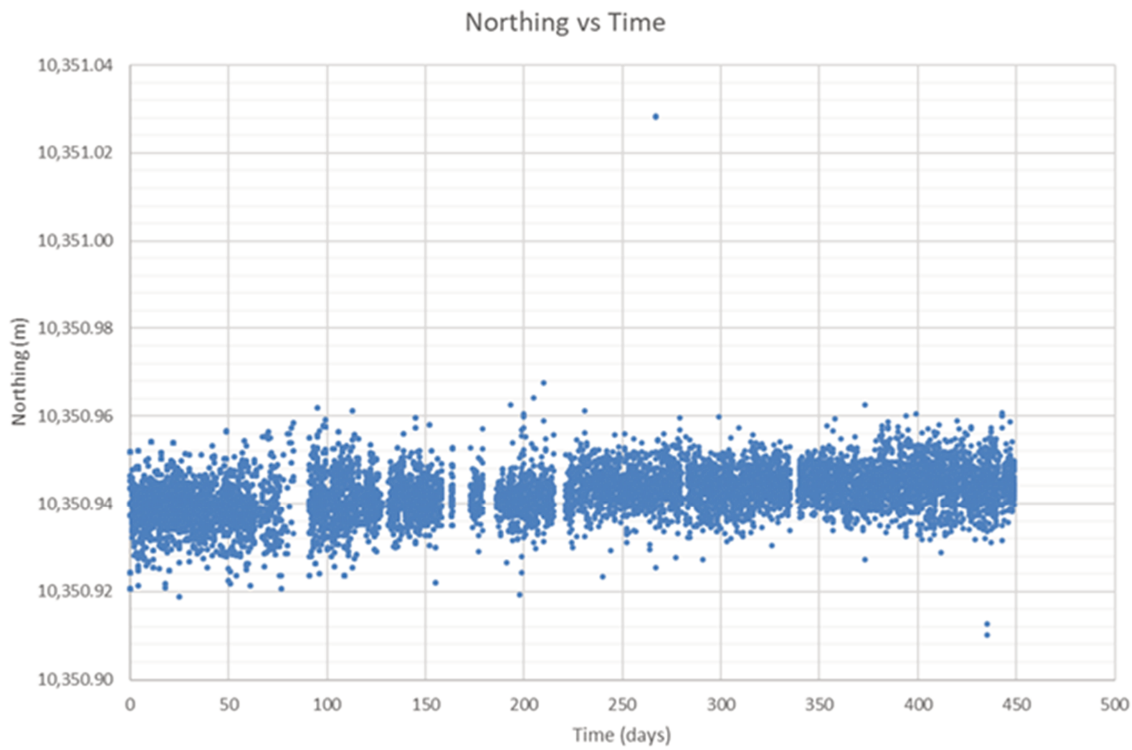

Figure 9 Northing versus time: stable slope

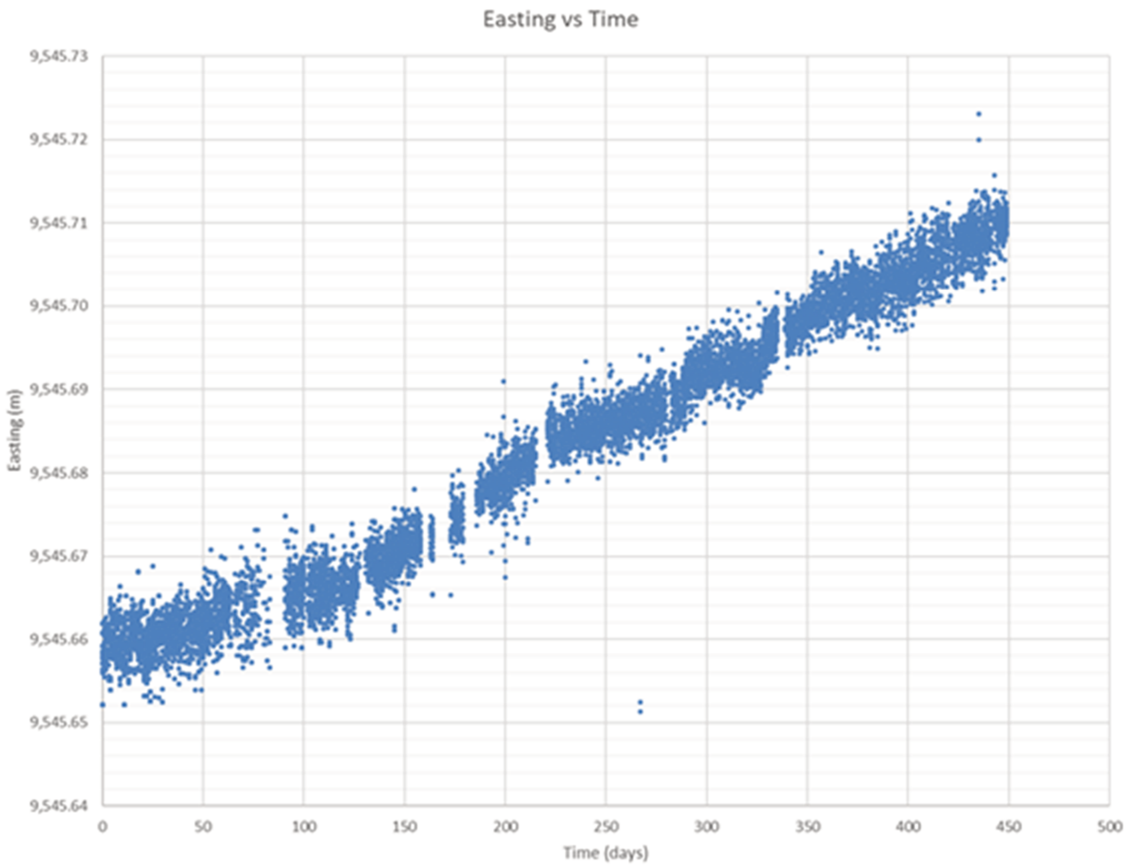

Figure 10 Easting versus time: stable slope

Upon inspection of Figures 8 to 10, there are several trends that can be observed:

- For the first few hundred days of the record, the prism location moves upward (about 20 mm) and has remained at a constant elevation thereafter.
- The prism location has drifted slightly to the north by a few millimetres.
- The prism location has a strong trend of moving eastward through the period of record (about 50 mm).

While these observations are interesting, without the context of the prism location in the pit, they are not very useful.

Figure 11 presents an orthogonal view of the prism velocity vectors, represented as arrows, on the pit wall. The vector colours represent different periods of time, but only two are labelled for this discussion: 50 days and 450 days. In this format, it is easy to see the change in the slope movement as a function of time. The initial slope response is upward and into the pit, reflecting relaxation of the rock mass. However, over time, the slope movement becomes nearly horizontal and moving strongly to the east, into the pit. Note that the vector of movement is not perpendicular to the pit wall orientation but is oblique to the wall, which is atypical. Most often, pit wall movements are nearly normal to the wall orientation.

Why does this prism location have such a strong easterly influence? The answer is shown in Figure 12, which shows the same prism vector set but a view above the prism location. Figure 12 also shows the trace of a northwest striking, east-dipping fault within the pit wall, approximately 50 m from the prism location. The fault is undoubtedly influencing the wall movement, as the prism vectors are nearly perpendicular to the fault plane. While the current prism location is stable, continued monitoring of the prism vector is warranted to assess any change in behaviour that may lead to instability related to the fault.

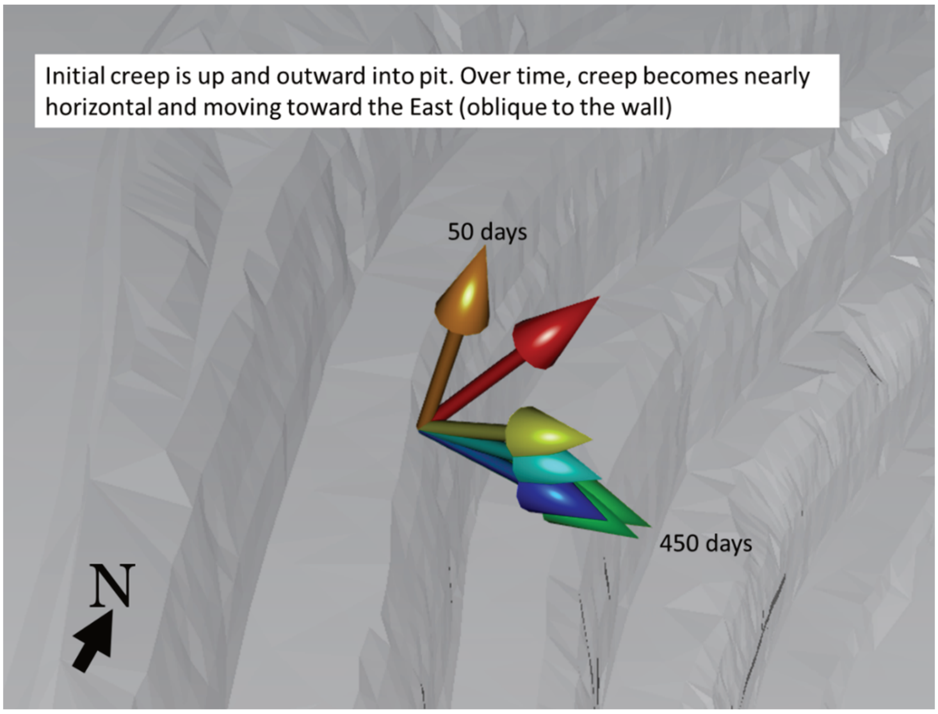

Figure 11 Prism velocity vectors (arrows) orthogonal view: stable slope

Figure 12 Fault location and orientation with respect to prism location

While the previous discussion was focused on a stable wall, the next discussion will be focused on an unstable wall to illustrate differences in behaviour. Figure 13 presents a total displacement versus time record for a prism from an unstable wall covering a period of just over 500 days. The velocities are much higher than that in Figure 7, as well as the accumulated displacement. This prism plots within the stable/unstable transition are shown in Figure 6.

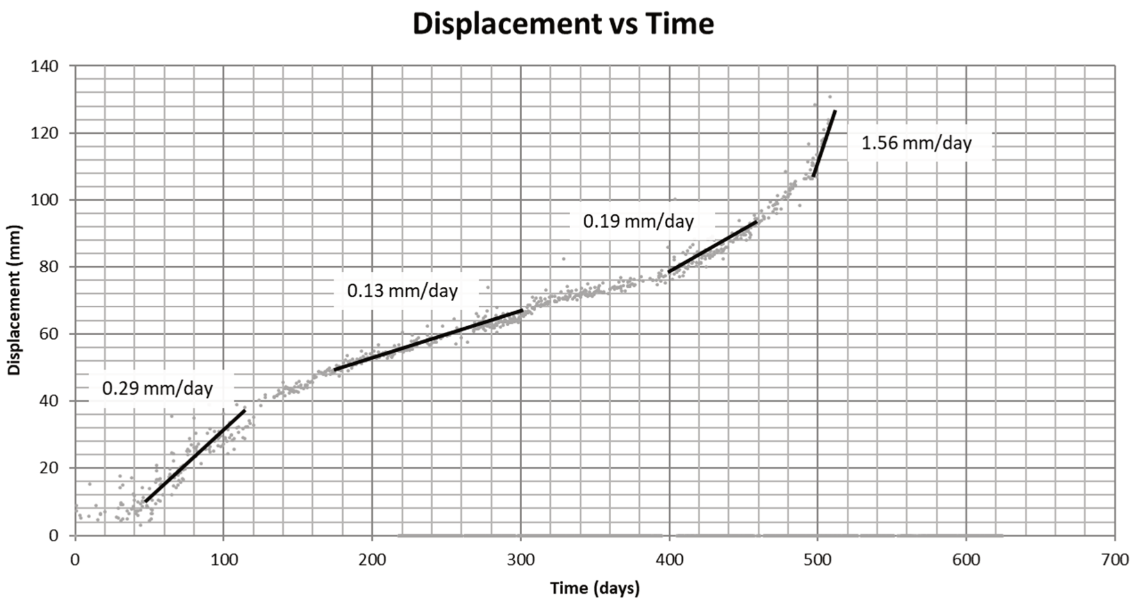

Figure 13 Total displacement versus time: unstable slope

Breaking the total displacement into its individual components, the time series plots for elevation, northing and easting are shown in Figures 14, 15, and 16.

As before, several trends can be observed upon inspection of these figures:

- For the first one hundred days of the record, the prism location moves upward (about 25 mm), but then begins a slow and steady drop in elevation. Dropping over 40 mm in the remaining 400 days before failing.
- The prism location has drifted to the south approximately 25 mm.
- The prism location has a strong trend of moving eastward through the period of record (about 140 mm).

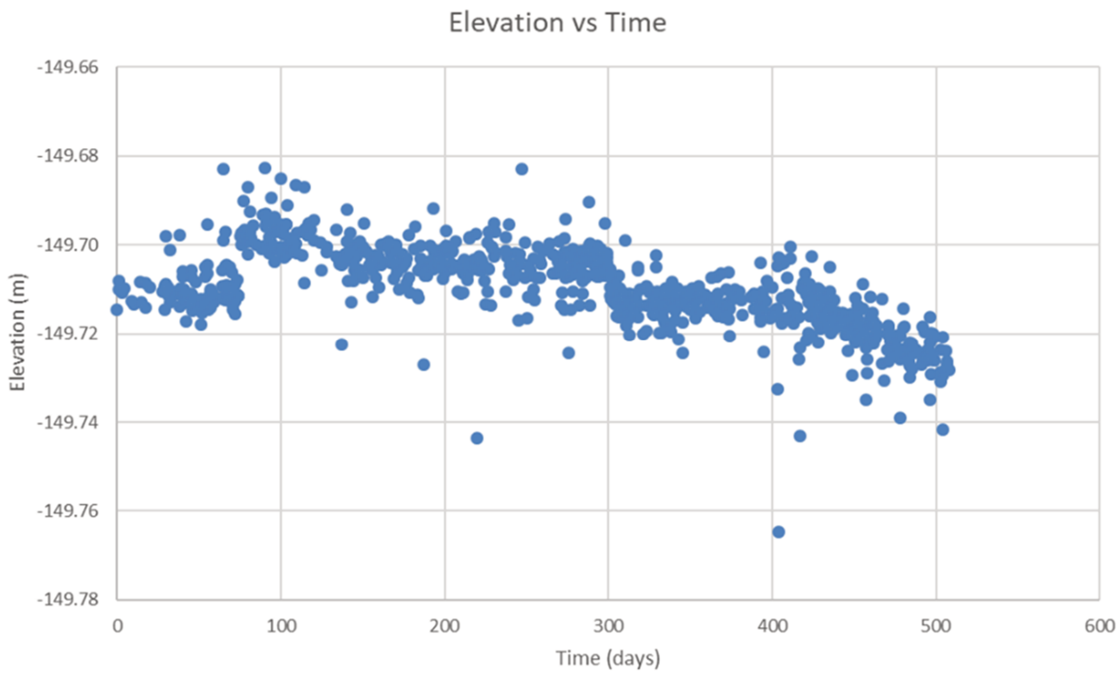

Figure 14 Elevation versus time: unstable slope

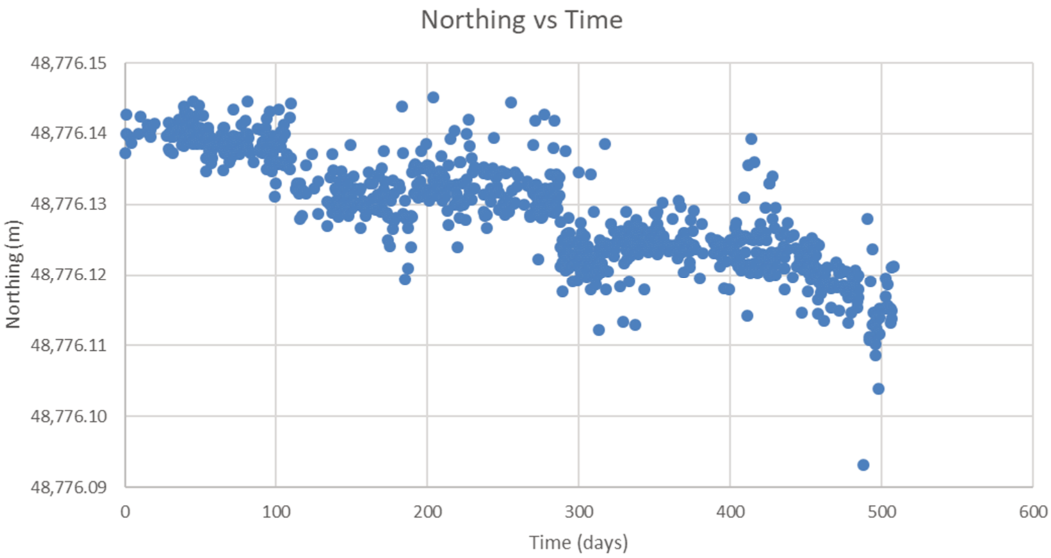

Figure 15 Northing versus time: unstable slope

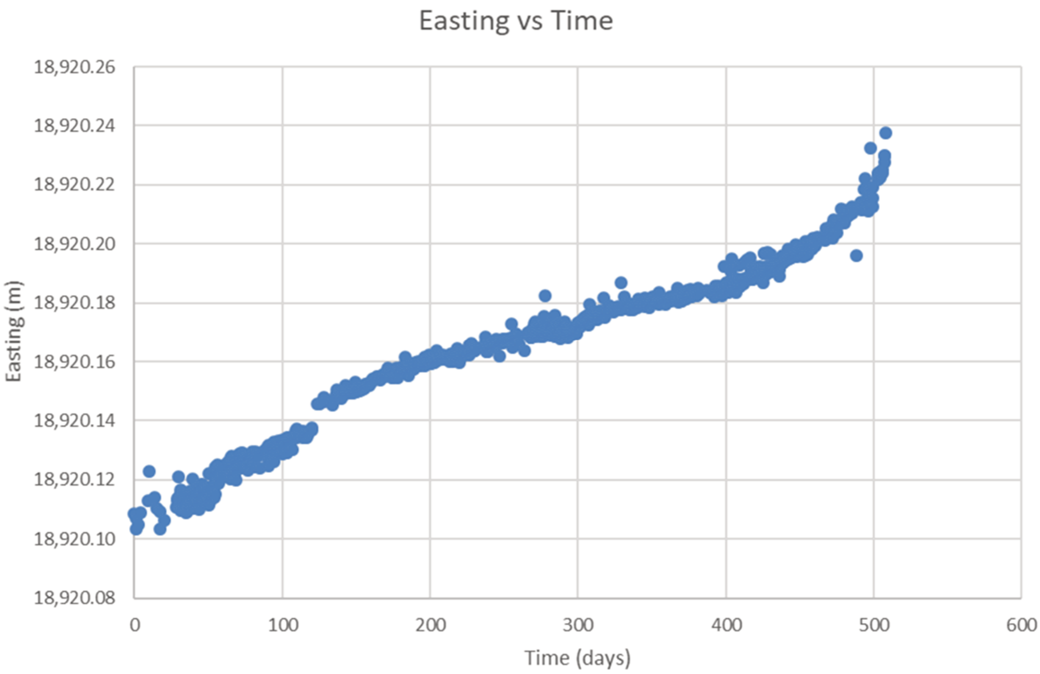

Figure 16 Easting versus time: unstable slope

Figure 17 presents a plan view (looking downward) of the prism vectors, again represented as arrows, on the pit wall. The red vector represents 50 days, while the blue vector represents 500 days. As shown, the vector moves south and east, into the pit. Figure 18 presents a side view (looking south along the pit wall) for the same vectors. As noted, the initial vector movement is upward (stress relaxation) followed by a progressive downward movement, until, at 500 days, the vector is nearly parallel to the bench face. This slope failed at day 508.

A comparison of the incremental vector trends and the total displacement versus average velocity graph (Figure 6) for both the stable and unstable slope examples suggests there are some changes in slope behaviour that may be used to predict long-term stability. In Figure 19, the displacement versus average velocity data from Figure 6 are reproduced, but with the addition of the time series 'path' of displacement versus average velocity for both the stable and unstable slope examples. In this figure, it is noted that the 'stable' slope time series path is nearly vertical along the 0.1 mm/d velocity, while the 'unstable' slope time series parallels the 'transition' line, then turns toward the 'unstable' end of the graph. This turn in the time series path coincides with the unstable slope vector change to a downward vector (Figure 18), occurring some 200 days before the slope failed. This suggests that by monitoring the prism vectors and plotting the total displacement versus average velocity, one could have predicted slope instability nearly a year before failure.

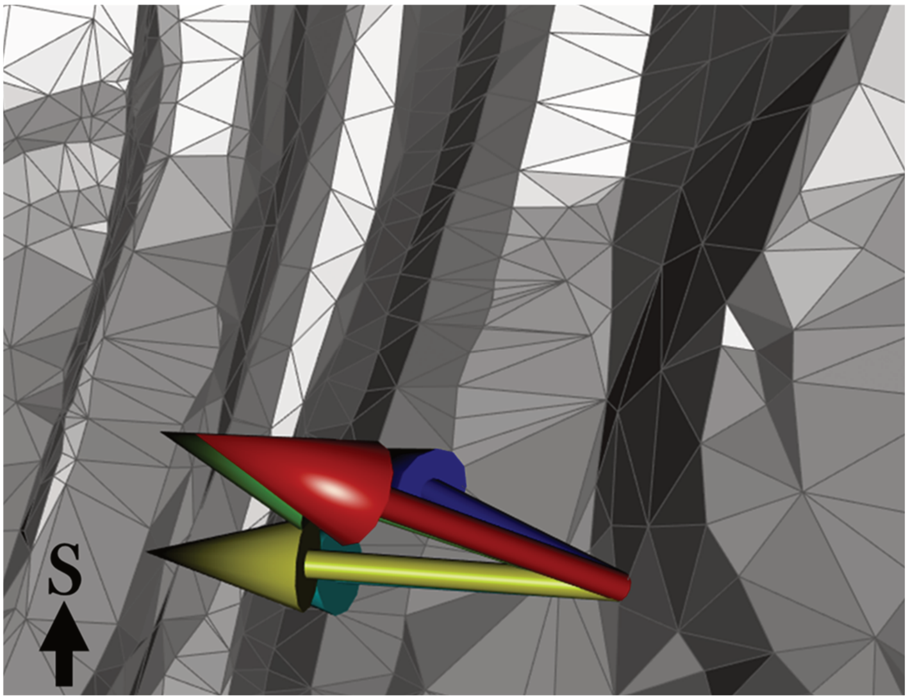

Figure 17 Prism vectors top view: unstable slope (red vector = 50 days, blue vector = 500 days)

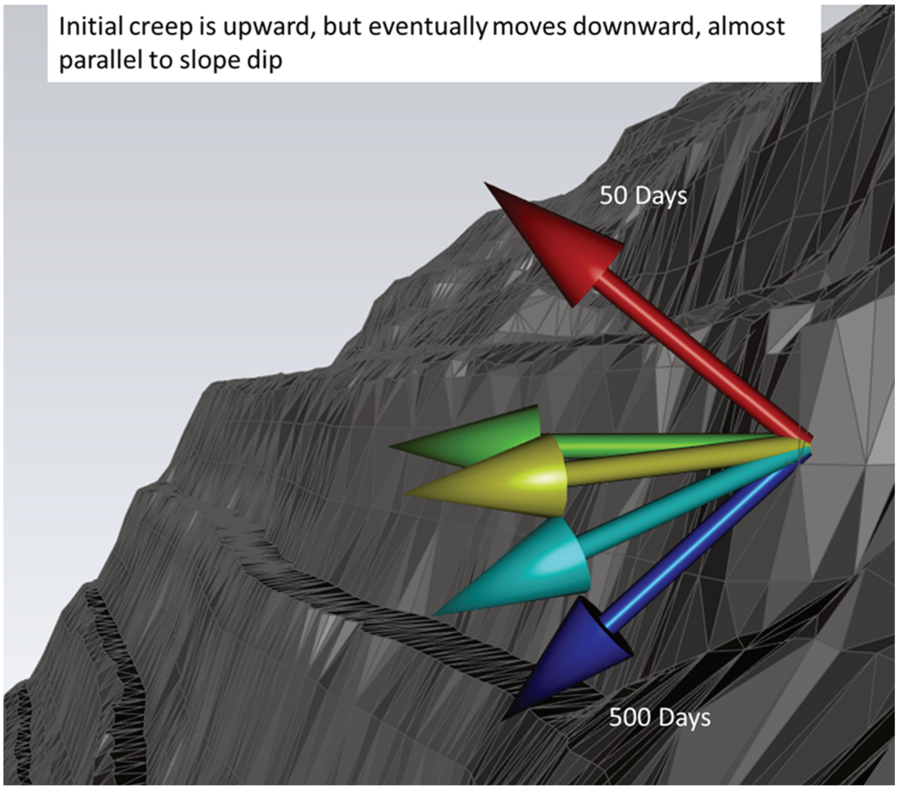

Figure 18 Prism vectors side view: unstable slope

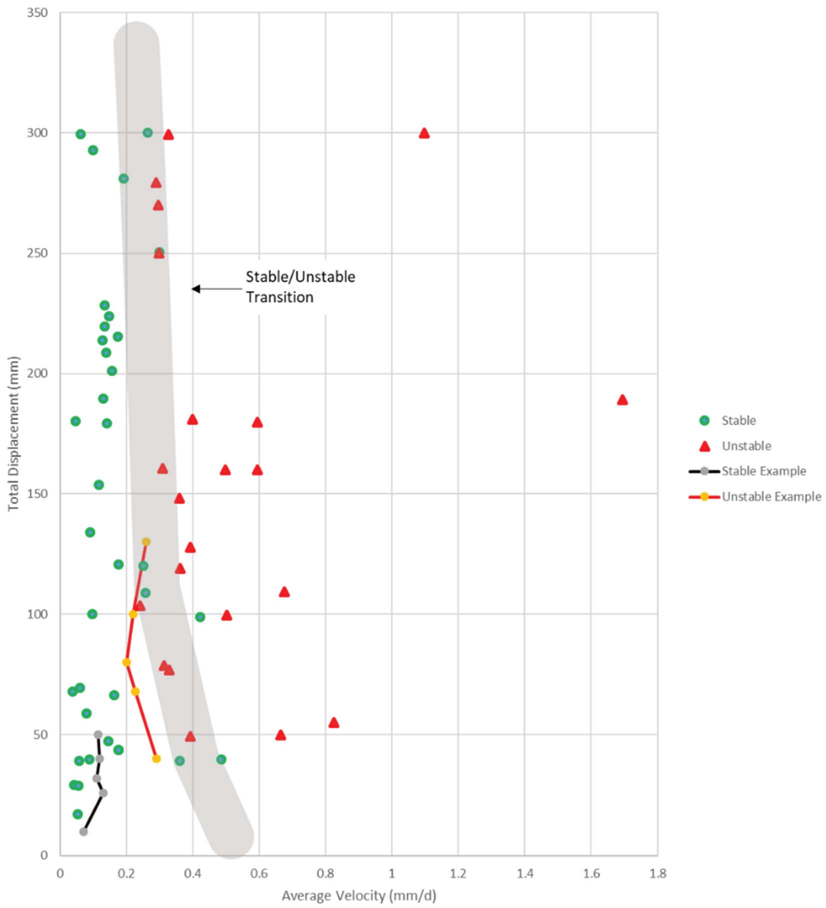

Figure 19 Displacement versus average velocity plot: time series paths

5 Conclusions

This paper presents an approach for assessing slope performance using data from long-term prism records. Data from stable and unstable pit slopes have been used to develop a graph that delineates stable versus unstable slope behaviour by considering total displacement and average velocity. Trends from three-dimensional prism vectors have been shown to be useful for identifying defects, such as faults in pit walls. Additionally, the prism vectors can be used to monitor the progressive failure of a slope.

By adding time series paths to the total displacement versus average velocity graph and the prism vector plots, it may be possible to assess and predict slope instability several months to a year prior to actual failure. This information can be used to inform mine planning (haulage ramps, infrastructure, etc.) as well as development of plans to minimise impact to the operation.

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