

Analysis of failures in open pit mines and consideration of the uncertainty when predicting collapses

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Abstract

The Inverse Velocity (IV) Method, by Fukuzono (1985), has been used in the mining industry along with slope monitoring radars for almost a decade to predict collapses, with significant successes but also with certain limitations due to the uncertainty associated with the method and the characteristics of the different mechanisms of failure in rock masses.

This paper summarises the results of research undertaken on 74 pit wall failures, on high and low walls, in different type of mines all over the world, since 2004. Only the characteristics of the failures associated with the application of Fukuzono's method are discussed.

The results are presented statistically, aiming to illustrate the different values of inverse velocity at collapse that could be achieved and the possible errors when forecasting the time of collapse. Keeping in mind the variability of results are essential to a successful risk management at any open pit mine.

Some discussions on the type of inverse velocity plots and its possible association to different failure mechanism are also presented for geotechnical practitioners to be aware of when forecasting collapses.

1 Introduction

The behaviour of collapsing rock masses in open pit mines is a topic that has not been sufficiently studied due to several difficulties, such as: the vastness of the rock mass involved, the limited resources for monitoring activities, the cost of the technology to perform real time monitoring, the lack of consistent safety culture and the uncertainty about the time and location of the next wall collapse.

With the introduction of the Slope Stability Radar (SSR) by GroundProbe in 2001 (and later by other companies), the mining industry acquired the ability to gather monitoring data in real time. Since then, data has been collected from a significant number of pit wall failures in different geotechnical environments. Today there are over 200 radar units deployed around the world, some of which have been gathering data since the very beginning. This provides an enormous amount of geotechnical data that is available and waiting to be analysed by the geotechnical community. Research on this data will improve the understanding of the deformational behaviour of the rock mass in open pits and allow better strategies to be defined to mitigate the risks associated with carrying out mining operation under unstable wall faces.

In this paper several wall failures have been analysed and the main deformational characteristics of the collapsing process was extracted. This will be useful for the geotechnical community when defining alarms and predicting collapses. Information such as deformation versus time, velocity versus time using different time windows, early detection versus updated forecasting during critical monitoring of impending failures, scan angle corrections, rate of change and spatial variability of the deformation must be taken into consideration when defining a slope monitoring strategy.

As a result of the analysis undertaken, the reader will have a better understanding of the behaviour of the rock walls in different environments; in particular the degree of uncertainty that a geotechnical engineer might encounter when trying to define alarms or forecasting a collapse. Awareness of the importance of having trained personnel in charge of the monitoring activities is crucial when defining geotechnical teams and for the creation of Targeted Action Response Plan (TARP) procedures.

This paper neither intends to define specific guidelines for alarm procedures, nor to provide rules of thumb valid for every situation. The paper aims to provide a better understanding of the multiple variables that should be considered when monitoring walls in open pits. Every mine manager, geotechnical manager, operations manager and the monitoring teams in charge of the slope monitoring tools need to understand the limitations and the correct application of each technology.

2 Predicting the failure time of a slope using Fukuzono’s method

In 1985, Professor Fukuzono, published the paper ‘A new method for predicting the failure time of a slope’ at the 4th International Conference and Field Workshop on Landslides, Tokyo. In this paper the author presented a mathematical expression to estimate the time to collapse of a soil mass under laboratory controlled conditions simulating a rain fall. For further details on the application of the method please refer to Rose and Hungr (2007). Equation (1) is the expression developed by Fukuzono (1985) based on his laboratory methods, which indicates that as the collapse is approaching the value of the inverse velocity approaches the horizontal axis. A and α are constants and t_f is the time to failure. Fukuzono showed that different values define different shapes of the inverse velocity versus time, in particular convex, linear and concave plots, as shown in Figure 1.

$$\frac{1}{v} = [A(\alpha - 1)]^{\frac{1}{\alpha-1}} (t_f - t)^{\frac{1}{\alpha-1}} \tag{1}$$

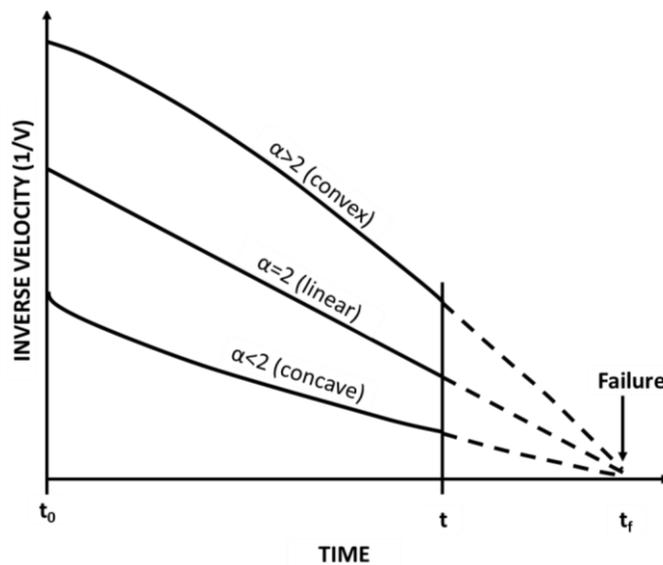


Figure 1 Theoretical inverse velocity versus time plot (Fukuzono, 1985)

The simplistic application of the method (applied on most of the mine sites) consists on a linear extrapolation of the current data trend until the projection intersects the time horizontal axis. The intersection defines the predicted collapse time of the wall and all operations and evacuation activities are defined based on that date and time.

3 Considerations for velocity calculation

3.1 Secant velocity definition

A simple definition of velocity is shown in Equation (2). This expression defines the secant velocity based on the accumulated deformations at two different times. The instant velocity is the differential form of this expression and is not covered in this paper.

$$V = \frac{\Delta Deformation}{\Delta Time} = \frac{\Delta Deformation}{Time Window} = \frac{Deformation_n - Deformation_m}{Time_n - Time_m} \tag{2}$$

The application of this formula in monitoring instruments is simple, but could lead to different velocity results for the same data sample at the same time depending on the width of the time window used. Figure 2 shows an example where the measurement of the secant velocity at t_n leads to different results of velocity (inclination of the secant line).

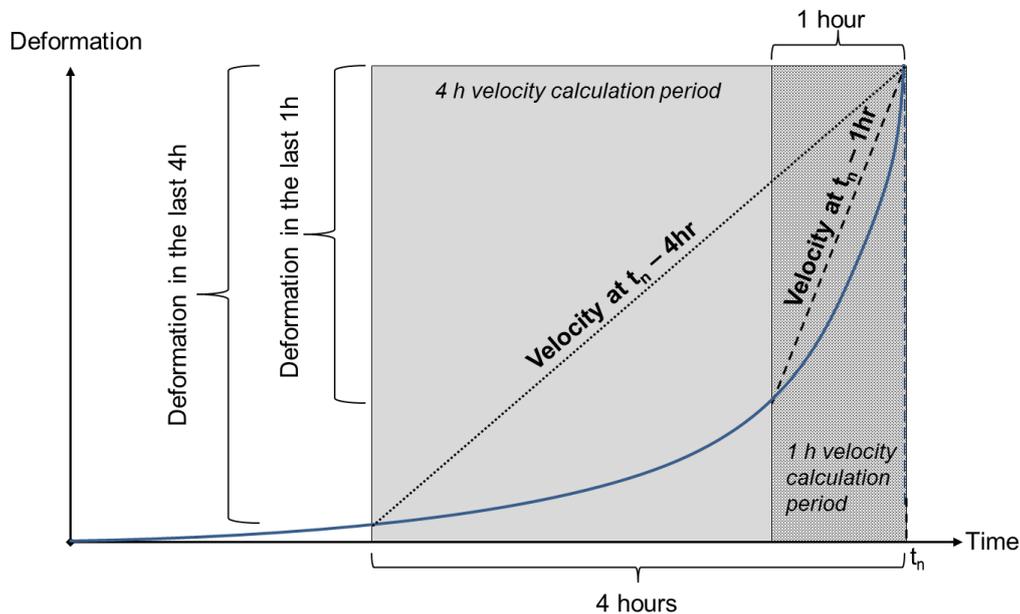


Figure 2 Influence of the time window in the calculated velocity

3.2 Effect of the time window on the velocity calculation

Applying the formula to real monitoring data delivers results as shown in Figure 3, where each deformation data point has two different results of velocity, one for a time window of 60 minutes and another for 300 minutes. In this particular example the results are clean from noise and there is no significant benefit in using two different data sets.

Figure 4 shows a typical collapse where the calculation of velocities using 1 hr as a time window leads to significant amount noise that makes it difficult for the reader to define any obvious trend (illustrated by the scattered dots). In contrast, the velocity plot calculated using a time window of 1,440 minutes (triangles) is a smoother plot that clearly indicates the accelerating nature of the deformation. As the deformation progresses towards failure, both plots show an upward trend; note that at the time of collapse the Velocity 60' calculation shows a clear acceleration trend but was omitted in Figure 4 in order to show the prevalence of noise at early stages of the failure.

In the same way the velocity calculation is affected by noise, the inverse velocity is also affected. The occurrence of noise limits the ability of detecting a trend that could be extrapolated in order to estimate the time to collapse. Figure 5 shows the inverse velocity for the data shown in Figures 3 and 6 shows the inverse velocity of the data shown in Figure 4. Note that in Figure 6 the 1,440 minutes plot clearly define a collapse trend much earlier than the 60 minutes data set; a geotechnical practitioner could detect the likelihood of collapse based on the 24 hours analysis and start planning for the event.

The following can be concluded from examining Figures 2 to 6:

- In a regressive deformation movement (decelerating) the longer the time window the higher the velocity of deformation; the shorter the time window the lower the velocity of deformation.
- In a linear deformation movement (constant) the length of the time window doesn't introduce any change to the final result.

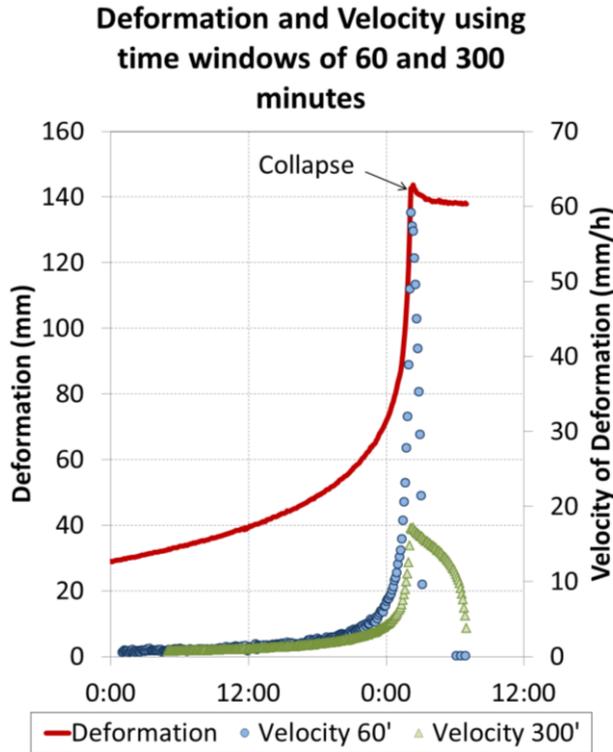


Figure 3 Example of a 'noise-free' deformation plot and two velocity calculations

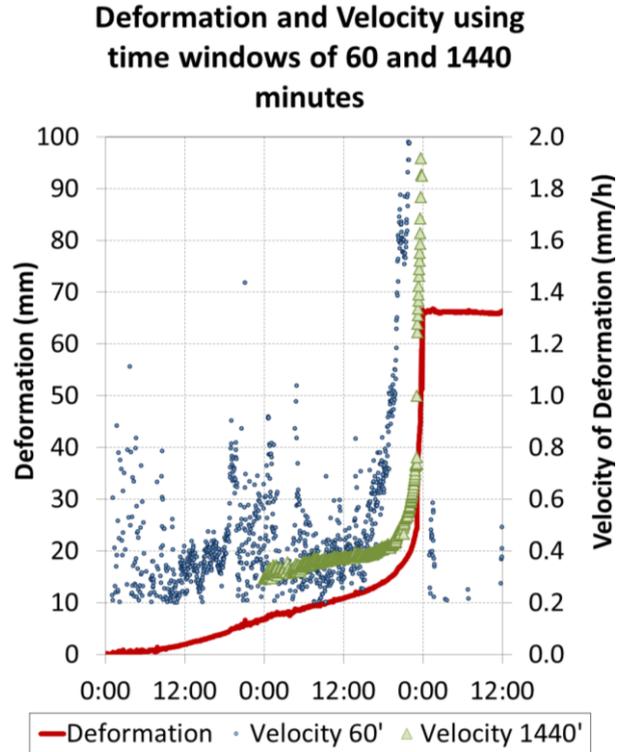


Figure 4 Effect of noise in the calculation of velocity and its correlation to the time window

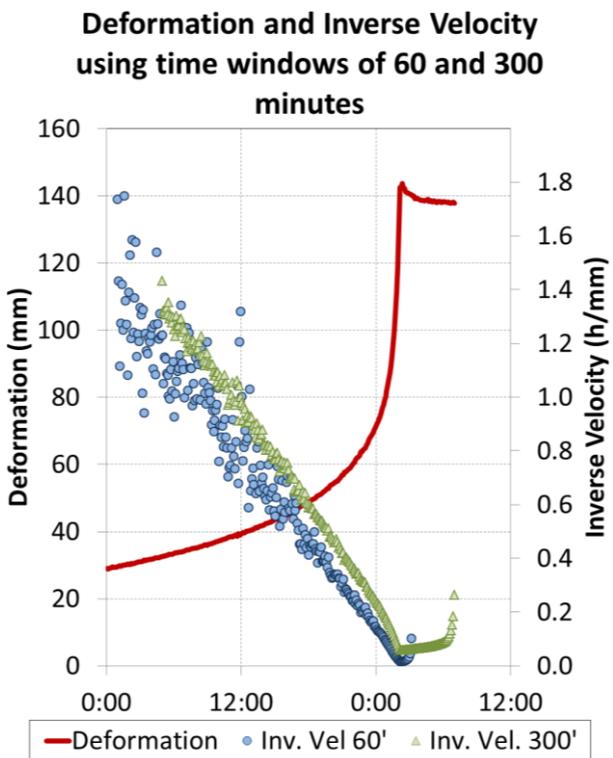


Figure 5 'Noise-free' inverse velocity plots (see Figure 3)

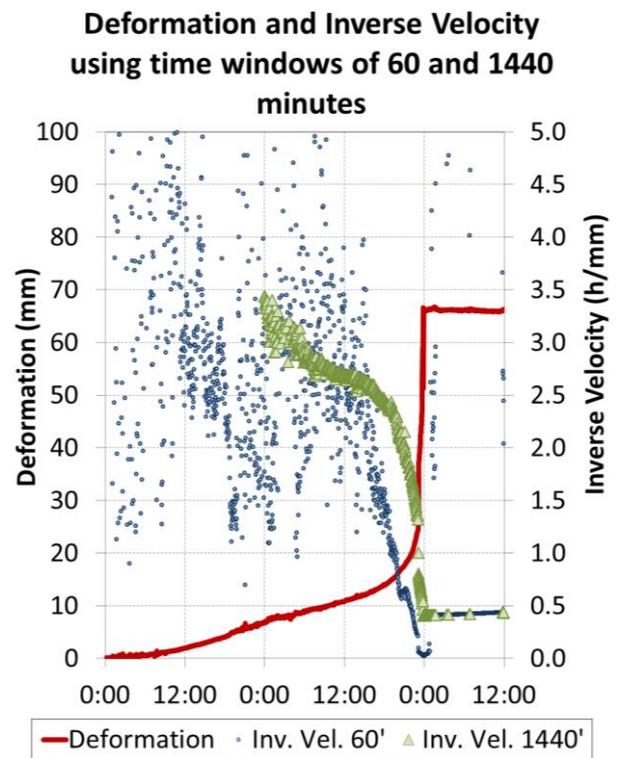


Figure 6 Effect of noise on the inverse velocity plots (see Figure 4)

- In a progressive deformation movement (accelerating) the longer the time window the lower the velocity of deformation; the shorter the time window the higher the velocity of deformation.
- For any shape of the deformation plot: the longer the time window the smoother the data trend, the shorter the time window the noisier the data trend.

These conclusions are very important in order to determine the correct time window for the calculation of velocity. Some deformation processes occur at a very slow pace so that the instrumental or environmental noise tends to be of a similar magnitude to the real deformation on the wall. To more effectively detect early deformation rates, a longer time window should be used for velocity analysis. However, the shorter the time window the more accurate the collapse forecast; the longer the time window the less accurate the collapse forecast (see Figure 5).

In general, but not always, the longer time windows for velocity analysis allow the early detection of an ongoing deformation process, while the shorter time windows are more accurate at the time of estimating the time of failure since they are affected by the most recent deformation state of the rock mass.

It is recommended to have flexibility with the calculation of velocities of deformation in order to have the opportunity of changing the calculation parameters and obtain different results, cleaner (or noisier) data and more usable collapse trends.

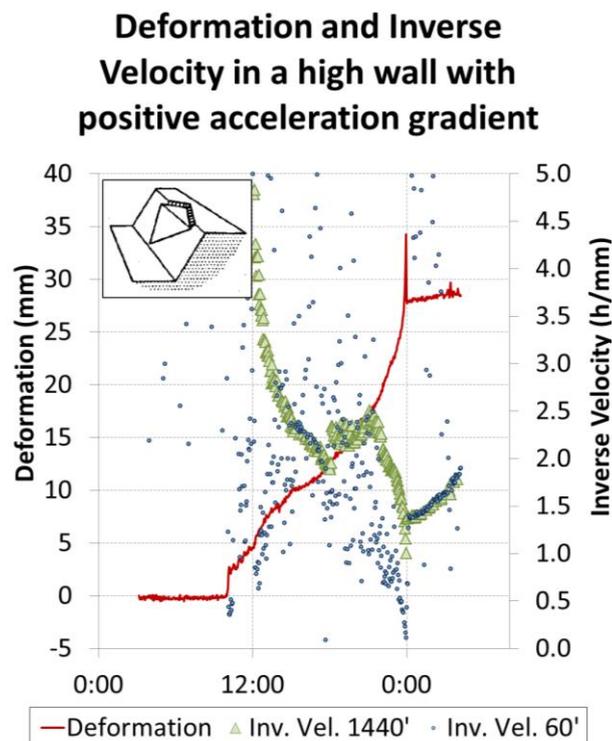


Figure 7 Bend-down effect (concave) on the inverse velocity plots using different time windows on a hanging wedge failure

Within the Figure 7 a descriptive image of a potential scenario for this type of failure is presented, taken from Hoek (2000). After a blast an instable wedge could experience some initial regressive deformation, but after certain level of strain the wedge collapses without any restriction in front of it.

These types of failures tend to describe almost linear trends in the inverse velocity using 1 hr as time window. The inverse velocity analysis using longer time windows such as 24 hrs tend to provide bend-down shaped or concave inverse velocity plots where the collapse will occur earlier than any linear extrapolation of the current trend. This 'bend-down' effect is not too significant when the time window used is short (i.e. 1 hr). In this case the material experiences acceleration, and this acceleration is increasing over the time.

An analogy to describe this behaviour is like when a car driver pushes the gas pedal progressively, starting the movement of the car very slowly (which is appreciated by the passengers) and slowly pushing the gas pedal more and more, so that the car keeps accelerating faster than the instant before. This failure was the size of a bench and occurred on a hanging block left on the wall after a previous collapse of the materials underneath. The hanging wedge slowly accelerated towards collapse and suddenly disappeared from the scanned pixel, which means that after the collapse the stable readings correspond to the new materials left at the back of the failure.

When the rock mass deforms and slides down at the same time its geometry changes in such a way that the toe works as a growing buttress for the rest of material above, the inverse velocity plots are similar to the ones shown in Figure 8. The materials accelerate towards the failure, but the acceleration is reducing over the time. In the car analogy for this scenario might be when the car driver is less experienced and starts the car roughly by pushing too hard on the gas pedal at the beginning; after he realises that this might be dangerous, the driver smoothly releases the gas pedal while the car is still gaining speed. This is positive acceleration but with a decreasing gradient, which is exactly what the collapsed buttress does to the rest of materials above. This failure was measured on a wall where the rock surface was totally fragmented during the failure and started to behave like loose materials rather than a rock wedge or plane. The descriptive image inside the figure, also taken from Hoek (2000), pictures a highly fractured highwall (HW) or a dump at a low angle, which during the failure process reaccommodates its shape, building up a buttress in front of itself, hence reducing the acceleration as it fails.

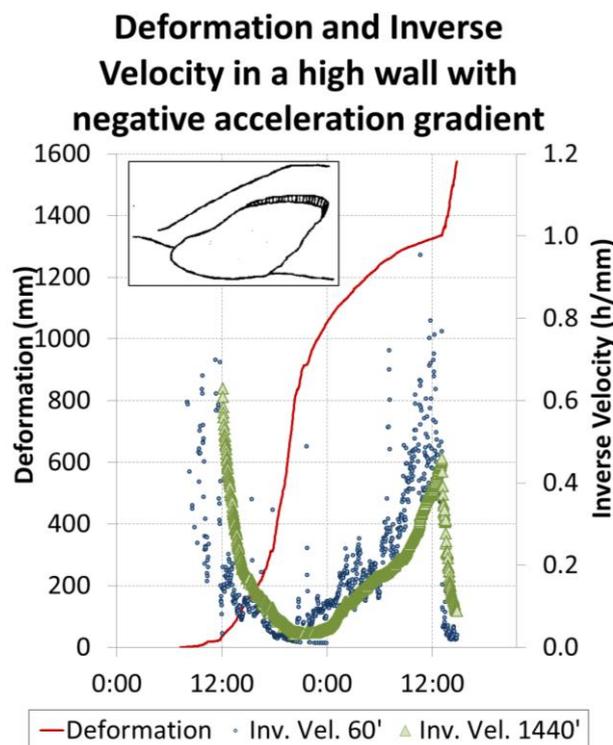


Figure 8 Bend-up effect (convex) on the inverse velocity plots on buttress build-up

Another type of behaviour is presented in Figure 9 (and Figure 5), where the acceleration doesn't seem to change and the different inverse velocity analysis calculated with different time windows tend to be linear for a significant period before the failure. The linear extrapolation of the trends seem to be applicable both inverse velocity plots and the forecast tend to be very similar. In this case the driver pushed the gas pedal and left it still during the whole acceleration period. This was an inter-ramp failure involving three and a half benches, over a structure that seems to be a plane. No support from a buttressing toe was observed and the material did not collapse, just slipped.

Regarding low walls (LW) and waste dumps, the failures on these materials are typical of loose materials where large rearranging movement of the soil particles takes place. Normally, the failures in low walls do not develop steep deformation plots at the collapse time (as opposed to Figure 10), instead, they develop a smooth 'S' shape on the change between progressive to regressive without steep patterns. The common characteristic of the failures measured in loose materials is that most of the failed mass experience large regressive plots corresponding to the settlement (and perhaps consolidation) of the materials towards the final new geometry. Figure 10 is an atypical collapse plot in a low wall, where a peak velocity was achieved in the hinge point between the accelerated and the decelerated phases. The failure mechanism shown in the embedded image, taken from Hoek (2000) describes another possible scenario, where some materials of relatively low shear strength collapse, but the materials at the back of the slip continue experiencing some small deformation. Since the materials are heavily fractured before the failure, there is no significant further damage to the shear strength of the rock mass, hence the acceleration is not significant during the failure process. Since the slip is at a high position on the wall, there is no possibility of building a buttress as the collapse occurs.

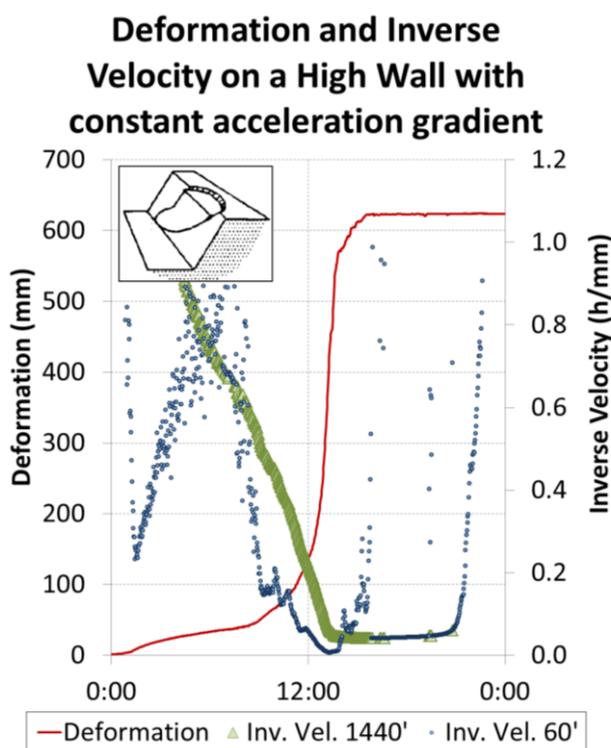


Figure 9 Near-linear inverse velocity plots on a planar failure that slipped but kept its structure

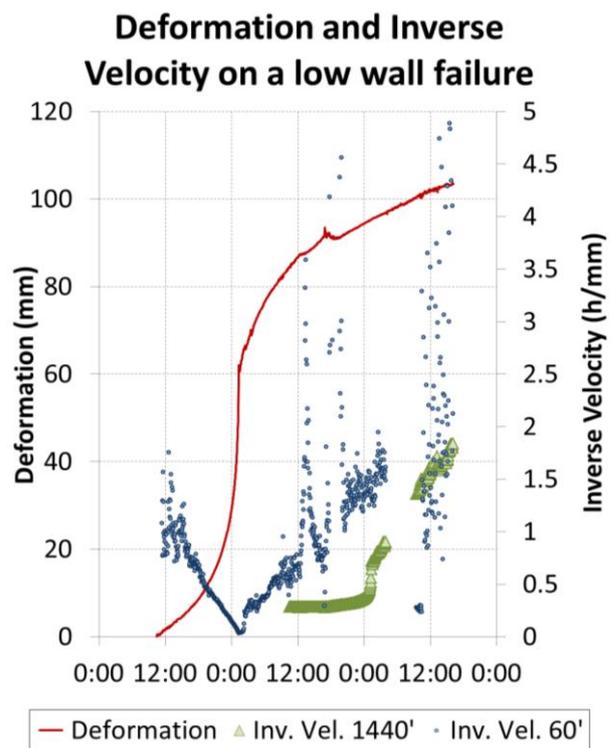


Figure 10 Deformation plot in a low wall failure where a clear peak velocity was achieved before the regressive phase

4 The challenge of forecasting a collapse – discussion on Fukuzono’s method

Forecasting a collapse is one of the tasks that geotechnical practitioners must undertake in a mining environment. By predicting when a collapse is about to happen they can provide recommendations for safety of employees, equipment and for operations.

However, Section 3 has shown some of the different types of deformation and inverse velocity plots that a wall could experience. Forecasting a failure requires some geotechnical sense (not common sense), knowledge of the type of material, wall geometry, environmental conditions, and likelihood for strain

hardening or strain softening behaviour, failure mechanism among others. For the purpose of this research, only the deformation and inverse velocity trends were analysed.

It has been seen that the different type of inverse velocity plots proposed by Fukuzono (Figure 1) are not always applicable, which is perhaps a consequence of the modelling process and its applicability to the mining industry environment. One example where the inverse velocity method is not applicable (at least with the current technology) is on brittle failures. Future technologies might allow better track of rapid brittle failures, but this does not necessarily means that there will be enough time to react.

A modelled landslide induced by rain in loose materials is not very likely to change the shear strength properties of each soil particle. Instead, it will reduce the effective stress in the soil mass due to the presence of water until the point where the acting forces exceed the opposing ones and the collapse occurs, but, this author believes that the mechanical properties of each individual particle remains almost unmodified.

In the mining environment, the stresses could be extremely high and the failures are not only controlled by water pressure but also by geology and structures. Some of the failures imply breaking of rock bridges, which is an intrinsic change in the mechanical properties of each particle of the rock mass. Many collapses in rock walls have shown a dramatic change in the condition of the materials from a solid rock mass before the failure to a totally dislocated and disaggregated loose material, almost a gravel soil. These processes have a high correlation with strain hardening and strain softening processes.

In rock masses the reduction of shear strength at a particle level cannot be easily recovered after the materials dry out. The recovery of the cohesion and the friction in a dislocated rock mass is a process that might require the generation of new chemical bonds, ageing processes, and high pressures and temperatures, being all of them events not very likely to occur in a mining environment where the pit bottom is always deepening and the walls shaken by blasts that break any new bonding process due to ageing or mineralisation within the joints.

It is perhaps due to the previous reasons that the plots obtained by Fukuzono could be significantly different in the mining environment or applicable to a limited set of failures where the acceleration tends to be constant, probably due to the absence of strain softening processes.

Another limitation of the inverse velocity method is that collapses never occur when the inverse velocity crosses the time axis (inverse velocity, $IV = 0$). For this to happen the velocity needs to be infinite and this would require an infinite amount of energy not available in the nature, not even for the electromagnetic waves which also have a maximum speed that can't be surpassed. In other words, the collapses always occur before the inverse velocity reaches zero. The question is how much time before or at which values of inverse velocity?

It is a very unsafe practice to extrapolate the inverse velocity plots and trust that the collapse will take place near that time. The next section will present some statistical results that might provide some understanding of the behaviour of the inverse velocity in collapses on highwalls and low walls. It will also show some of the possible forecasting errors associated to the use of different time windows and the intrinsic geotechnical practitioner's error (this author's error).

5 Collapse statistics

5.1 Data sample

A total of 74 collapses were analysed, 59 in highwalls and 15 in low walls. These collapses include, e.g. arctic to tropical environments; from sea level to 4,000 m.a.s.l.; from hard rock to coal mines; triggered by blasts, rain or induced by mining operations at the toe, and bench scale to inter-ramp scale, all these are in addition to the diversity of topographical, geological and geotechnical conditions. The complexity of each environment and the lack of information made it impossible to include all the variables into the statistical analysis. However, based on the author's experience, most of the times it is not mandatory to know all the

variables to accurately forecast a collapse, or at least forecast it on the safe side so that evacuations are completed before the materials collapse. Working remotely and without the knowledge the geotechnical engineers have on site, the author has been able to assist remote teams in analysing the deformation data and forecasting collapses; sometimes even before the site was aware of the situation. This does not mean that the geotechnical parameters along with the others mentioned above do not play an important role, but perhaps it means that all of the above parameters end up expressing their interactions (and degradation) in one single consequence: deformation and its differential expressions with respect to time (velocity, inverse velocity and acceleration).

5.2 Statistical exercise

Two variables were the main focus of this investigation: minimum inverse velocity values and collapse forecast error. These values were measured using different velocity calculation periods (time windows): 1 hr and 24 hrs. The objective was to understand what might be the magnitude of the errors that an experienced geotechnical engineer might incur in when trying to predict when a collapse is about to happen.

The Error (E) is used in this paper was the difference between the actual collapse time (as measured by the SSR) and the forecast collapse time determined by extrapolating the inverse velocity until it intersects the time axis. The difference in time is the error, which could be on the safe side (forecast before the collapse) or on the unsafe side (forecast after the collapse).

The collapse was defined at the point where any progressive plot changed its accelerated behaviour to either static or decelerated (Figure 3). The deformation measurements during a collapse are challenging as the rate of displacement usually exceeds the system ability to measure them (up to 7.85 mm/scan). This means that the radar could stop tracking the deformations slightly before the actual collapse on the wall face, leading the data interpreter to believe that the collapse occurred slightly earlier. New radar techniques as the measurement of coherence allows the data interpreter to have a better understanding of when the collapse actually happened, regardless of the proper measurement of the deformations associated. Coherence however was not available in all of the 74 collapses of the database because this measurement was introduced in 2007. Since the real application of the inverse velocity method is supposed to take place before the collapse, then the wall has a low chance of de-correlate (low coherence means high variability of the surface the radar is looking at) by the time the forecasts are made. This measurement limitation should not be a problem in critical monitoring where everyone should have evacuated the area long before the radar loses track of the rapid deformations.

5.3 Minimum inverse velocity at collapse, 1 hr and 24 hrs

Figures 11 to 14 show histograms of minimum inverse velocity at collapse for time windows of 1 hr and 24 hrs, for highwalls and low walls. Important to note is that for high and lowwalls the minimum inverse velocity at collapse lies below 1.0, mainly below 0.06 for the 1 hr time window. However, the cases above $IV = 0.06$ are as equally as important and cannot be disregarded.

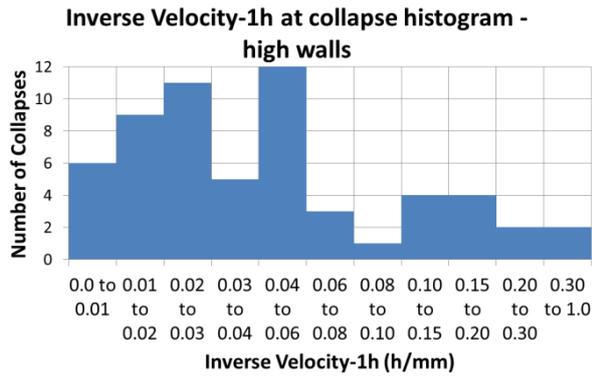


Figure 11 Histogram of IV – 1 hr at collapse – HW

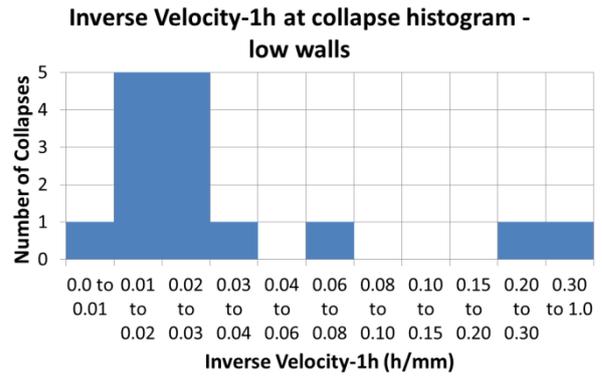


Figure 12 Histogram of IV – 1 hr at collapse – LW

Figure 13 and 14 show the frequency analysis using a time window of 24 hrs to calculate the inverse velocity. Notice that in highwalls and low walls the inverse velocity at collapse can be as high as 4.0. It is clear (and expected) the displacement to the right hand of the histograms in comparison with the 1 hr velocity analysis. It shows the importance of using different inverse velocity thresholds to assess the likelihood of collapse based on the time window. For example, this difference is highlighted for a value of IV between 0.3 and 1.0 for both the 1 hr velocity analysis and the 24 hr velocity analysis; the former has 2 collapses while the later has 12 collapses in the histograms for highwalls.

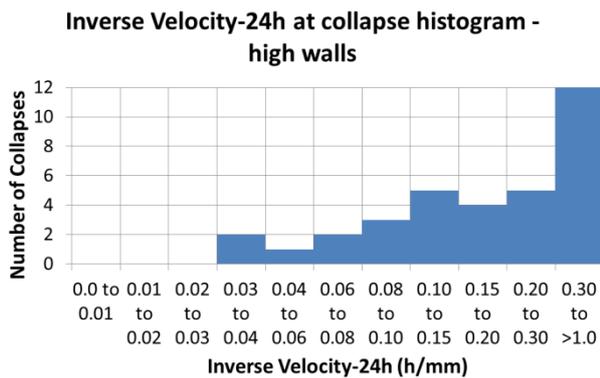


Figure 13 Histogram of inverse velocity-24 hrs at collapse – HW

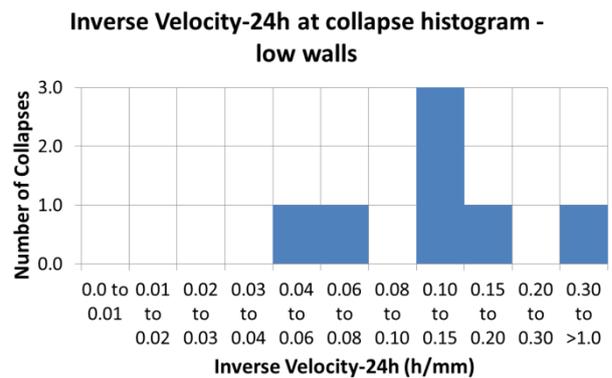


Figure 14 Histogram of inverse velocity-24 hrs at collapse – LW

Figures 15 to 17 show accumulated probability curves of inverse velocity for high and lowwalls using time windows of 1 hr and 24 hrs. The plots must be read entering from the horizontal axis, choosing an inverse velocity value and based on the graph reading the corresponding actual frequency (probability). For instance, in Figure 15 an IV = 0.8 leads to a probability of near 100%, which means that all the collapses recorded inverse velocities below 0.8. Likewise, an inverse velocity of 0.2 leads to a probability of failure of about 94%. The 50% probability of failure was achieved in Figure 15 at about IV = 0.02, meaning that 50% of the collapses recorded IV smaller than 0.02 h/mm. For low walls, this 50% threshold is achieved at around IV = 0.02 h/mm (Figure 16).

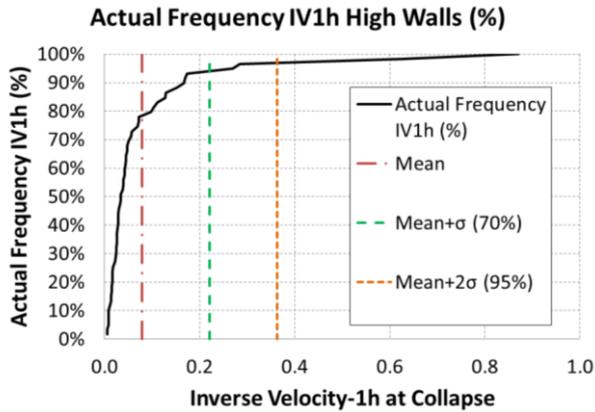


Figure 15 Accumulated probability of the IV – 1 hr in HW

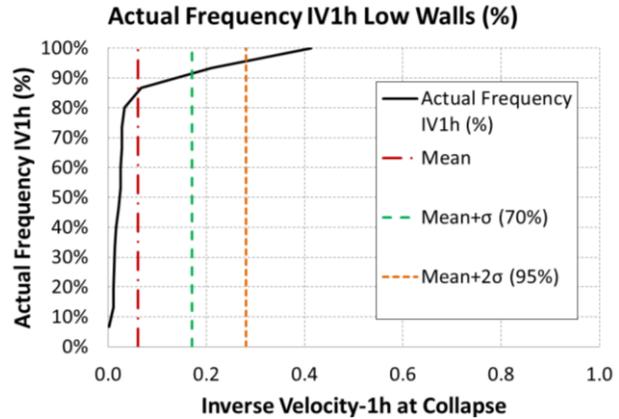


Figure 16 Accumulated probability of the IV – 1 hr in LW

For a time window of 24 hrs the 50% threshold is achieved in highwalls with IV = 0.18 h/mm and in low walls with IV = 0.11 h/mm (Figures 17 and 18).

The Mean+σ and Mean+2σ represent the percentiles 75 and 95 for each case. The values of inverse velocity under the percentile 95 could be used to increase the likelihood of undertaking an opportune action in 95% of the collapse situations (but not guaranteed!).

Table 1 summarises the values of inverse velocity that correspond to the percentiles 70 and 95. This could be considered as an initial parameter for the definition of alarms based on velocity.

It is important to keep in mind that not all the low values of inverse velocity are hazardous. Some materials could be moving in a linear or regressive fashion, at high speeds but slowing down or without a collapse trend (accelerated). All the cases represented in this paper correspond to materials that once were relatively stable and at a given point during the SSR deployment started to move. The most important factor of the inverse velocity method is the trend, not the net value.

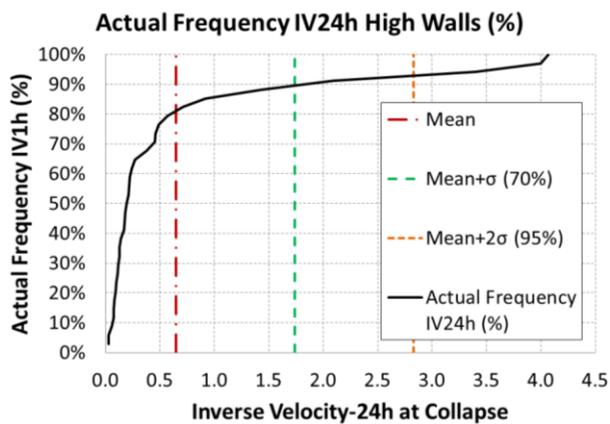


Figure 17 Accumulated probability of the IV – 24 hr in HW

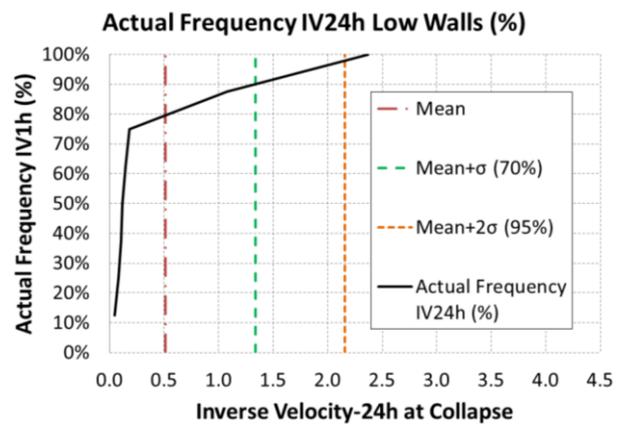


Figure 18 Accumulated probability of the IV – 24 hr in LW

Table 1 Percentiles of inverse velocity for HW and LW using time window of 1 hr and 24 hrs

Case	70th Percentile	95th Percentile
Highwall IV 1 hr	0.22 h/mm	0.35 h/mm
Lowwall IV 1 hr	0.17 h/mm	0.28 h/mm
Highwall IV 24 hrs	1.75 h/mm	2.8 h/mm
Lowwall IV 24 hrs	1.35 h/mm	2.2 h/mm

5.4 Collapse forecast error

For each collapse, a forecast of the impending failure was made based on the available data at some convenient point before the failure. The convenient point before the failure corresponds to a number of hours before the collapse was recorded that would have allowed enough time to evacuate. In other words, the last collapse forecast before having to call an emergency evacuation.

The error (E) was measured for each collapse (see Section 5.1) and statistics were constructed around the results; such results are summarised in the Figures 19 to 22.

The bars between -24 hrs to -1 hr error (E) in the histograms correspond to the cases where the collapse forecast fell within 24 and 1 hr before the actual collapse, on the safe side. This might have allowed for removal of most of the equipment and all the personnel.

The bars between -1 hr and 0 hrs correspond to the cases where the collapse prediction fell within 0 to 1 hr from the actual collapse, which might be just enough time to remove some machinery and personnel.

The bars between 0 hrs to 24 hrs correspond to the cases where the collapse prediction was after the actual collapse, which might have had consequences on equipment and personnel.

It is interesting to see how many unsuccessful forecasts are in those histogram bars, for all the scenarios. This is indicative of several possible errors in the process, such as:

- The late forecasted cases correspond to materials that experienced strain softening and did not build any buttress in front to help in mitigating the acceleration process due to a continuous loss of shear strength in the rock mass.
- The curves did not bend down (as in Figure 7), the linear extrapolation worked properly, but the assumption that the IV = 0 at the collapse time lead to a late collapse forecast.
- The data was too noisy, the correct configuration of the velocity calculation period (time window) was not used or the radar was deployed too late during the collapse process. It is important to note that this last possibility was observed in so many cases, which means that the radar was used more in a reactive way rather than as a preventive tool.
- The criteria of the geotechnical practitioner (the author in this case) were not sufficiently accurate and as a consequence the extrapolated inverse velocity trends were not accurate.

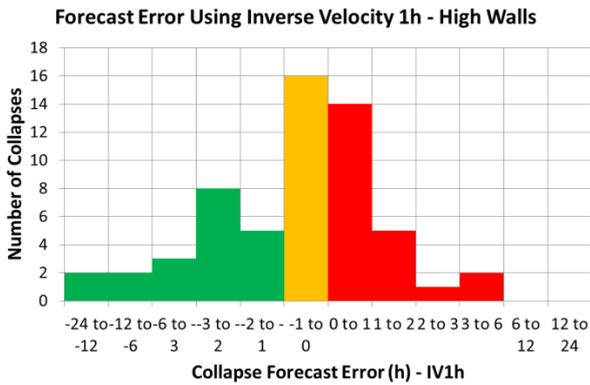


Figure 19 Forecast error using inverse velocity 1 hr – HW

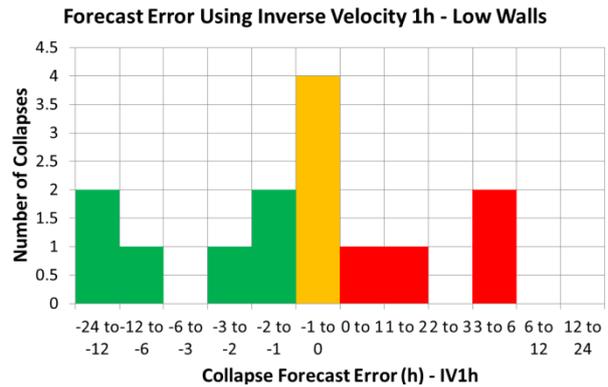


Figure 20 Forecast error using inverse velocity 1 hr – LW

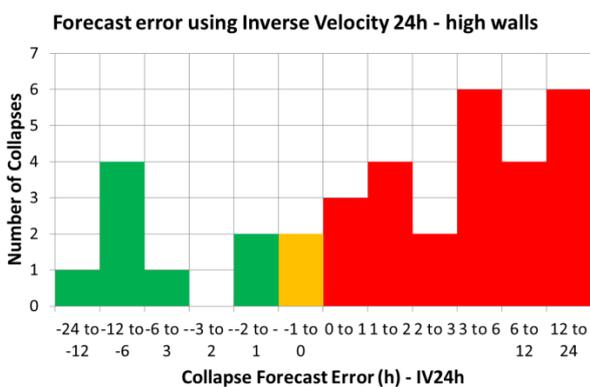


Figure 21 Forecast error using inverse velocity 24 hrs – HW

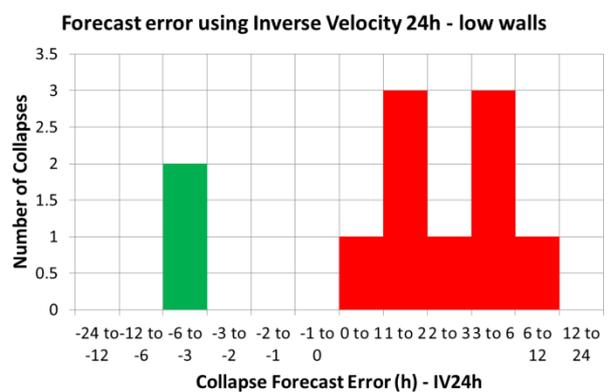


Figure 22 Forecast error using inverse velocity 24 hrs – LW

It is also important to note that most of the unsuccessful forecasts were made when using 24 hrs as velocity calculation period. This validates the hypothesis that the longer velocity calculation periods are useful for early detection of collapses but not very useful for an accurate prediction of the time of collapse.

The plots in Figures 23 to 26 show the probability of the forecast error in its actual distribution along with it the theoretical normal distribution for the Z factors associated with the data. The closeness between the actual frequency plots and the normal frequency indicates that the probabilistic distribution of the error follows a normal distribution. This makes sense because the forecast should tend to be around the actual time of collapse, the further to the earlier or later stages the less number of forecasted values should appear. This means that the use of percentiles is more valid here than where it was applied before.

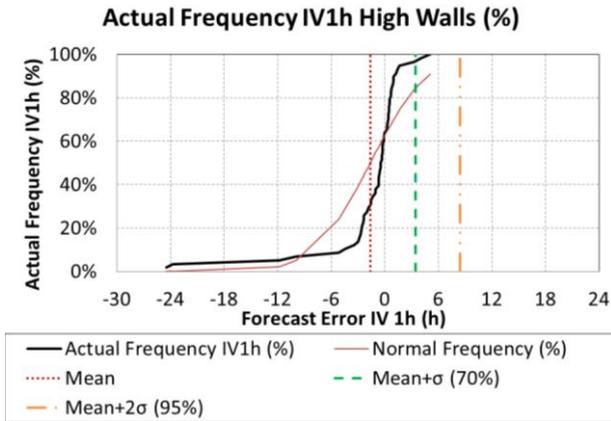


Figure 23 Accumulated error probability of the IV – 1 hr in HW

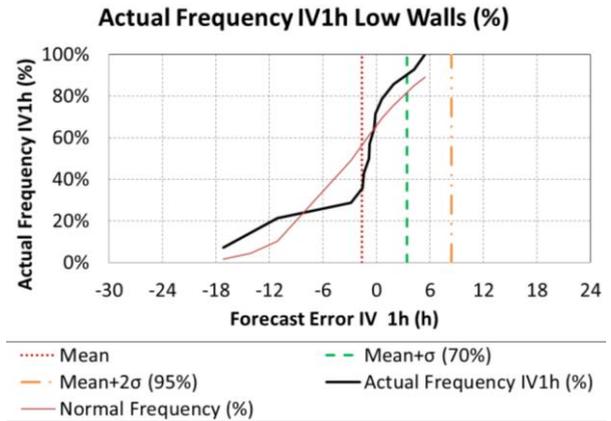


Figure 24 Accumulated error probability of the IV – 1 hr in LW

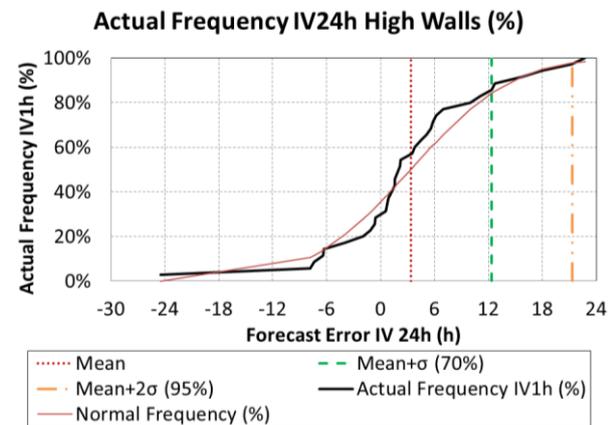


Figure 25 Accumulated error probability of the IV –24 hrs in HW

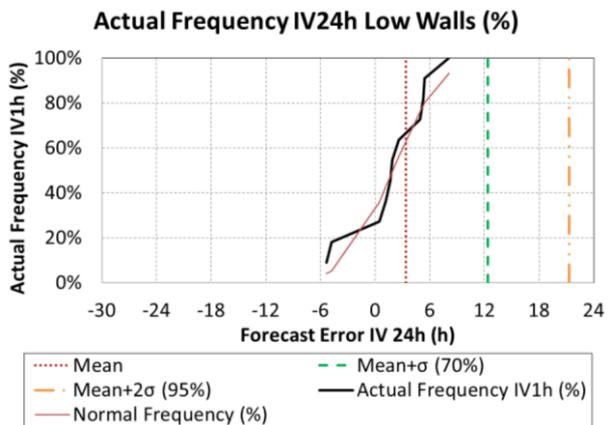


Figure 26 Accumulated error probability of the IV –24 hrs in LW

The results in Table 2 (this was constructed following the same description presented for Table 1) show the estimated errors that should be considered when forecasting a failure. For example, the 95th percentile for HW IV1h indicates that in 5% of the cases the collapse will occur 08:30 hours before the forecasted time to collapse. Likewise, the 70th percentile for LW IV24h indicates that in 30% of the cases the actual collapse will occur 06:00 hours before the forecasted time to collapse.

These statistical parameters should be considered when forecasting collapses and for alarm definition based on velocity of deformation.

Table 2 Percentiles of forecast error for HW and LW using time window of 1 hr and 24 hrs

Case	70th Percentile	95th Percentile
High wall IV1 hr	03:30 hrs	08:30 hrs
Low wall IV1 hr	04:00 hrs	10:30 hrs
High wall IV24 hrs	12:20 hrs	21:20 hrs
Low wall IV24 hrs	06:00 hrs	10:20 hrs

6 Conclusions

The inverse velocity method proposed by Fukuzono has proven to be very useful in many slope instability cases in open pit mines. However, its application requires rigour and complete understanding of the variables.

The velocity calculation period (VCP) plays an extremely important role in filtering out noise in the radar output data and in turn, improving the inverse velocity and collapse forecast. It has to be chosen wisely, or preferably a set of different VCP should be used in the radar monitoring software in order to detect different ongoing deformation processes that might not be clearly seen for certain VCP.

Evidence would suggest that collapses never reach Inverse velocity = 0, hence the failures always occur at a certain time before the intersection of any trend (curved or linear) with the time axis.

The magnitudes of the errors for the 74 cases reviewed are worryingly on the unsafe side. It seems more likely to forecast the failure after the collapse happens rather than before it. The longer the VCP, the more inaccurate the forecast. The shorter the VCP, the more accurate the forecast tends to be.

The radar software for the calculation of the velocity and inverse velocity needs flexibility in order to allow different configurations. The geotechnical practitioner must have full understanding of the behaviour of the variables and the consequences of choosing certain parameters. The safest recommendation is to choose a range of velocity and inverse velocity calculations using different VCP so that the chances for early detection and for accurate forecast are maximised.

When using IV with a 1 hr time window in highwalls, evacuations should be called about 08:30 hours before the time of collapse forecast (based on the source database for this study) and 10:30 hours for low walls. If the IV with a 24 hr time window is used, highwalls should be cleared 21:20 hours before the time of collapse forecast and low walls 10:20 hours before the forecast. This sort of approach tends to maximise the safety although the productivity might be reduced if the collapses occur at the lowest percentiles.

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