

Methods of Assessing Slope Deformation in Surface Mines and Defining Threshold Limits-a Review

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Abstract

The increasing depth of surface mines and rising mineral demand have resulted in the generation of large volumes of waste material, leading to the construction of increasingly large waste dumps and associated slope stability challenges. Waste dump slopes, composed of loose and unconsolidated materials with low shear strength, are particularly vulnerable to deformation and failure under the influence of rainfall infiltration, pore water pressure development, and improper slope design. Several slope failure incidents in Indian surface mines have highlighted the necessity of effective monitoring and early warning systems for ensuring operational safety and mitigating geotechnical risks. This paper reviews the various slope deformation monitoring techniques employed in surface mining operations, including conventional methods such as total station-prism monitoring, extensometers, GPS/GNSS, and modern technologies such as 3D laser scanning (LiDAR), satellite InSAR, and slope stability radar (SSR). A comparative assessment of these techniques is presented with respect to coverage, accuracy, monitoring capability, and suitability for mining applications. The study further examines approaches used for forecasting slope failures, including displacement-time and velocity-time based analyses, inverse velocity methods, acceleration-time ratio criteria, creep deformation theory, and integrated monitoring frameworks. Findings from previous studies indicate that slope acceleration and tertiary creep behaviour are among the most reliable precursors of impending failure, while SSR has emerged as the preferred technology for real-time monitoring and threshold-based warning systems in open-pit mines. The review highlights the advantages of integrating multiple monitoring technologies to improve the detection of zones of instability and enhance forecasting reliability. It is concluded that effective slope risk management requires a combination of continuous monitoring, predictive analytics, geotechnical characterization, and robust early warning frameworks to improve the safety and sustainability of modern surface mining operations.

1. INTRODUCTION

Due to increase in demand of various minerals, there is significant increase in the number of surface mines being operational in India (Malik and Koner 2024). Open-pit mining accounts for more than 90% of the total available mines in India for various minerals. The depth of the open-pit mine in India ranges from few metres for stone mines to as deep as 400 m for hard rock mines. With increasing depth of the surface mines and ever-growing demand for various minerals, huge amount of waste material is generated for optimum recovery of the mineral (Read and Stacey 2010). Surface mines which are already operational are also going deeper for maximum recovery of the minerals thereby introducing dangers of waste dump slope failure due to excessive heightening (Oggeri et al. 2019). To recover the orebody or minerals at deeper depths, massive volume of waste material is generated leading to additional land required for accommodating waste material. With large scale excavation, the waste dumps are also becoming large in size and simultaneously height of the waste dumps are also increasing. The increase in height of waste dumps to accommodate large volume of waste material in both internal and external dumps in a smaller area leads to slope instability issues which is becoming more critical in recent years (Malik and Koner 2024).

The waste dump slope is made of loose and unconsolidated rock mass with minimal shear strength and to ensure long term stability of the waste dump slopes, the overall slope angle is generally kept gentle (Read and Stacey 2010; Kliche 1999). Slopes that are not properly designed are more susceptible to failures which are sometimes attributed by wrong assessment of the slope designs & its governing factors. The factors which normally affect the stability of slopes are geological structures, water pressure, overall angle of the slope, weight acting on the slope and tension crack (Hoek and Bray 1981; Wyllie and Mah 2004; Duncan and Wright 2005). It is accepted that slope movement will occur with incidence of partial slope failures during the life of the mine (Wyllie and Mah 2004). The slopes usually do not collapse or fail instantaneously and the slope failure takes place only after accumulation of enough displacements that has been observed periodically over a long time for a moving slope (Hoek and Bray 1981). In waste dumps, the rate of slope movement is faster compared to pit slopes due to involvement of multiple factors such as non-availability of inherent cohesion, poor consolidation & compaction and rapid flow of water during rainy season causing saturation throughout the dump mass leading to generation of pore water pressures (Read and Stacey 2010). With varying degree of slope movement, many open-pit mines continue to operate safely for years with moving slopes that are carefully monitored to give warning of deteriorating stability conditions of the slope (Armstrong et al. 2020). However, in some cases, initial slope movement may be a precursor for accelerated movement followed by collapse of the slope (Wyllie and Mah, 2004). Accelerating slope displacements are taken as a warning of imminent failure (Federico et al. 2012).

The surface mining operation in India has witnessed around 23 slope failure incidents due to side falls or landslides leading to 143 fatalities between 1901 to 2016 (Dash, 2019). The stability and monitoring of waste dump slopes is now recognized to be an important aspect of designing large surface mines (Read and Stacey 2010). In dump materials, failure is likely to form as a shallow, large radius surface extending from a tension crack close behind the crest to the toe of the slope (Kliche 1999). The slopes with loose, weak and soft rock masses can basically have three different failure geometries viz. slope or face failure, toe failure and base failure. The slope geometry and the geo-mechanical strength of the dump material always control the stability of the dump (Khaintola et al. 2011). In waste dump slope failure, instability due to loss of shear strength is a major influencing element. This is characterized by the rapid onset of significant plastic deformations under the weight acting on the dump, resulting in slope failures (Duncan and Wright 2005). The primary factor that has a significant effect on the stability of waste dump slopes is moisture content which alters the shear strength within the waste dump material. Rainfall and groundwater levels have a considerable impact on shear strength of the dump mass because it alters the moisture content (Nayak et al. 2025). Although more than moisture content, the pore water pressure has a major role to play in the instability of waste dump slope when the dump mass is saturated or water flows within the waste dump. Excessive rainfall infiltration can increase the pore water pressure within the dump mass (Nayak et al. 2021). Such waste dump slope failures occur due to rainfall infiltration, change in groundwater levels or phreatic lines, affecting the volume of water within the waste dump.

During the designing process of slopes, the geotechnical and geological data are difficult to fully account for. Therefore, a need arises for having an effective slope monitoring system to manage the geotechnical

risks (Hoek 2007; Read and Stacey 2010). The slope monitoring systems, if implemented effectively produce critical information and facilitates in understanding the slope behaviour with time (Armstrong et al., 2020). In such a case, diligently monitoring such slopes for early warning signs will prove to be imperative in protecting the men & machineries involved in the mines (Osasan and Afeni, 2010). Regular monitoring of appropriately placed targets and careful examination of the displacement vectors often provide a valuable insight into the mechanism of failure (Hoek and Bray 1977). There is considerable evidence to indicate that slopes do give ample warning, which means that it is well worth the effort to spend time on investigating and implementing appropriate monitoring systems (Ding et al., 2000). Selection of proper and site-specific slope monitoring method is dependent on several parameters such as coverage of the area, operation mode, capital cost, accuracy to be achieved, weather conditions, and installation & maintenance concerns (Masood et al. 2022). For any slope monitoring system to be effective, achieving desired accuracy is important and it should be in the range of millimetres (Kumar and Rathee 2017). The essential steps in the design of an effective slope monitoring scheme are selecting appropriate monitoring methods, monitoring physical quantities specific to slope types, and strategically arranging monitoring points (Malik and Koner 2024).

The main purpose of any monitoring system is to predict time to slope failure (Fukuzono 1985; Carla et al. 2017; Niekrasz 2018). The data collected from a slope monitoring program can be represented on a graph as displacement versus time or velocity versus time curves which can help in analysing the trend or change in trend leading to slope failure. Also, the frequency of monitoring observations should be decided based on the movements observed per day on an average (Read and Stacey 2010; Niekrasz 2018). Once the slope monitoring observations are available, it becomes necessary to determine the onset of acceleration (OOA) using different types of plots such as Cumulative deformation versus time, Deformation over a given time period versus time, Deformation rate (velocity) versus time and Inverse velocity versus time (Niekrasz 2018). An effective early warning system (EWS) functions both as a monitoring and disaster mitigation system by integrating key components namely risk detection, emergency planning, social awareness and response actions (Malik and Koner 2024).

2. SLOPE DEFORMATION MONITORING TECHNIQUES AND METHODS

To detect slope movements, surface monitoring methods are prominently used which are applicable only in scenarios where the surface movement reliably reflects the total movement of the slope (Dunnicliff 1993; Read and Stacey 2010; Armstrong et al. 2020). Additional considerations for choosing a monitoring system encompass the time required for instrument setup, the speed of movement, and the safety of access to the site. During the design of the monitoring system, thorough consideration is given to issues to be dealt are measuring techniques & frequencies, accuracy, precision and personnel responsibilities (Dunnicliff 1993; Read and Stacey 2010). Key features of a well-designed slope monitoring system include; early detection of potential impending failure; notification of alarm exceedance; analytical capabilities in analysing present circumstances and estimating future

projections; and, confirming physical parameters are within acceptable tolerance range (deformation, pore pressures, etc.) (Barla et al. 2006). The slope monitoring techniques are basically divided into conventional and modern-day types which is shown in Fig. 1.

Today there are multiple surface monitoring techniques used to monitor slopes and slope stability radar (SSR) technology is the one of the key effective methods amongst all (Niekrasz 2018). Slope stability radar, a modern-day advanced geotechnical slope monitoring technique and surveying system is now widely used in surface or opencast mines for slope monitoring purpose due to its advantages such as wide coverage of the area, twenty-four functioning without reflectors and providing data in real-time by sending early warning signals with submillimetre precision (Read and Stacey 2010; Carla et al. 2017). With the use of SSR, thresholds can be set for different trigger actions when the ground movement rate exceeds a pre-set value (Masood et al. 2023; Kumar and Rathee 2017). The threshold values depend on various factors such as slope geometry and rock mass properties which are site-specific (Read and Stacey 2010; Carla et al. 2017). The SSR covers a large expanse of the wall slope and can detect deformations within the slopes well before slope failure occurs. This makes the SSR an effective tool for early warning signal for an impending slope failure. The major requirement of the SSR technique is the availability of the line of sight between the SSR and the monitored wall (Niekrasz 2018). Figure 2 shows the SSR deployed at an open-pit mine face to detect slope movement. Though SSR is the most advanced and efficient monitoring technique among all, but the other slope monitoring techniques such as total station-prism monitoring, laser imaging, GNNS, etc. have equal importance (Read and Stacey 2010; Armstrong et al. 2020; Masood et al. 2022).

2.1 TOTAL STATION-PRISM MONITORING

In situations involving extensive slopes where accessing the area poses risks, and where there is a requirement for frequent, accurate measurements and swift analysis of results, utilizing total station equipment for surveying is the most appropriate monitoring technique (Dunnicliff 1993; Read and Stacey 2010; Armstrong et al. 2020). It is one of the widely used and efficient method. The survey network consists of specified prisms located in areas prone to instability, complemented by one or more stationary control points for the survey stations. The base or control stations are positioned on completely stable ground to ensure that all prisms are visible from them (Dunnicliff 1993). A schematic view of the total station-prism based monitoring is shown in Fig. 2. The frequency of monitoring is determined by the characteristics of the rock type, the activities occurring near the slope, and the goals of the established monitoring program (Read and Stacey 2010).

2.2 TERRESTRIAL 3D LASER SCANNER (LiDAR)

An improvement in the observation of individual stations on a potential sliding surface is achieved through laser imaging based on LiDAR technology that involves making a precise three-dimensional map of the entire face (Jaboyedoff et al. 2012). Laser scanning is a technology that measures distances to surfaces by sending out laser pulses and calculating the time it takes for the reflected signal to return,

known as time of flight. The system uses a laser to target a specific slope area, adjusting the scan density before rapidly conducting multiple closely spaced scans to cover the chosen region. This process creates a precise three-dimensional point cloud suitable for generating a contour map (Lichti et al. 2005). By generating a sequence of these maps over time from a consistent reference point, it becomes possible to compare the position of the face across each scan, allowing for the measurement of both the location and extent of any movement (Jaboyedoff et al. 2012). A TLS deployed at a mine is shown in Fig. 4 along with 3D point cloud of a mine.

2.3 GNSS MONITORING

The Global Positioning System (GPS) or Global Navigation Satellite System (GNSS) can serve as an effective means of tracking slope movement in situations where the affected area is extensive and high precision is not essential (Gili et al. 2000; Read and Stacey 2010). Monitoring stations can be established on the slope, with their coordinates recorded at any chosen interval using the GPS/GNSS device. Enhanced accuracy is attainable by positioning a base station on stable terrain outside the sliding zone and precisely establishing its location (Leick et al. 2015). Subsequently, the GPS/GNSS data collected on the slope is correlated with the coordinates of the base station through differential GPS techniques.

2.4 SATELLITE InSAR

A method for accurately tracking movement across extensive regions involves the application of radar satellite remote sensing techniques. This method, referred to as Interferometric Synthetic Aperture Radar (InSAR), entails acquiring radar images of the Earth's surface at different times and analysing the phase differences between them to determine relative ground displacement (Massonnet and Feigl 1998; Hanssen 2001). Depending on the satellite platform, InSAR can monitor very large areas in a single acquisition with millimetre to centimetre level deformation accuracy and can provide measurements independent of weather conditions, cloud cover and daylight (Hanssen 2001; Ferretti et al. 2007). However, its application may be constrained by revisit intervals, temporal and geometric decorrelation, and, in some cases, the cost associated with acquiring high-resolution commercial satellite imagery and specialised data processing (Ferretti et al. 2007).

A comparison of various slope monitoring systems based on coverage type and best utilised role in open-pit mining operation is shown in Table 1.

Table 1
Comparison of Various Slope Monitoring Systems (Little 2006)

Instrument	Wall Coverage Type		Best-Suited Monitoring Role	
	Point	Area	Background	Active
Total Station (Laser & Prism)	✓		✓	
Satellite InSAR		✓	✓	
Ground-based Laser Scanning (3D TLS)		✓		✓
Extensometer	✓			✓
GPS/GNSS	✓		✓	
Ground-based Radar (SSR)		✓		✓
Photogrammetry		✓	✓	

It is proposed that instead of relying on a single slope monitoring method, each monitoring technique shall be complemented with at least one other monitoring technique(s) and geotechnical instrumentations. This will improve spatial coverage, temporal resolution, redundancy and interpretation of the deformation mechanism. The appropriate combination should be determined according to site-specific conditions and risk-management requirements.

3. FORECASTING SLOPE FAILURE AND DEFINING THRESHOLD LIMITS

The monitoring system is used to acquire slope monitoring data which can be used to assess slope deformation behaviour and, under appropriate conditions, predict time to a failure. Interpretation of the slope movement data is an essential part of monitoring operation in order to identify acceleration or deceleration of the slope that indicates deteriorating or improving stability conditions, respectively. This will allow appropriate action to be taken with respect to the safety and economics of the operation (Wyllie and Mah 2004). The monitoring program, carried out by any technique or method will provide readings of movement against time. Plotting the rate of movement is the key parameter variable to track. Plots of this data are fundamental to understanding the mechanism of the slope movement, and possibly predicting the time of failure (Zavodni and Broadbent 1980). If the rate of movement decreases, the slope movement indicates regressive behavior. If the rate of movement increases, slope failure may be pending and more frequent readings of the site should be taken (Girard 2002; Rose & Hungr (2007). The type of monitoring data should be thoroughly analysed to help predict the time of failure once the progressive stage of slope movement has developed (Zavodni and Broadbent, 1980; Fukuzono 1985; Rose & Hungr (2007). For progressive movements, the simplest method is to extrapolate the time-displacement curve as shown in Fig. 7 for the point(s) which is moving fastest to the point where the curve will be vertical or almost vertical (Kliche 2011). Zavodni and Broadbent (1980) established a

similar method to estimate the number of days prior to a failure using the predicted velocity at the point of a collapse which is shown in Fig. 8.

Forecasting the time of slope failure remains a major challenge in slope deformation monitoring because no single forecasting approach is universally applicable to all slope-failure mechanisms and deformation behaviours (Intrieri et al. 2019). Existing approaches can broadly be classified into threshold-based early-warning methods and failure-time forecasting methods. Threshold-based approaches employ predefined levels of displacement, velocity, acceleration, or other monitoring parameters to identify changes in slope behaviour and trigger corresponding warning or response actions. Such approaches are commonly incorporated into slope early-warning systems; however, they generally provide warning levels rather than a direct estimate of the time of failure (Carla et al. 2017; Intrieri et al., 2019).

Many slope-failure forecasting approaches are based on the evolution of creep deformation preceding failure. Creep behaviour is conventionally divided into primary, secondary, and tertiary stages, with tertiary creep characterized by accelerating deformation and commonly associated with progressive failure development (Intrieri et al. 2019). Conventional monitoring systems rely primarily on displacement measurements from which velocity and acceleration can be derived to characterize the temporal evolution of slope deformation. However, failure prediction in high-quality hard-rock masses can be particularly challenging because brittle failures may develop following very short acceleration phases and negligible precursor deformation. Moreover, substantial acceleration does not necessarily culminate in complete slope failure, making it difficult to distinguish failure-related deformation from non-failure instabilities (Carla et al. 2017).

Advances in ground-based slope stability radar, satellite-based InSAR, GNSS, robotic total stations, and other near-real-time monitoring technologies have substantially improved the spatial and temporal resolution of slope deformation measurements, thereby enhancing the detection of accelerating deformation and supporting early-warning decisions (Rose and Hungr 2007; Intrieri et al. 2019). Among the available failure-time forecasting techniques, the inverse-velocity method proposed by Fukuzono (1985) remains one of the most widely used approaches because of its conceptual simplicity and ease of graphical interpretation. The method is based on the relationship between displacement velocity and time during accelerating deformation. As the displacement velocity increases, its reciprocal, termed inverse velocity, decreases towards zero. When the inverse-velocity data exhibit an approximately linear trend, extrapolation of the fitted trend towards zero inverse velocity provides an estimate of the potential failure time (Fukuzono 1985; Rose and Hungr 2007).

Despite its simplicity, inverse-velocity forecasting is subject to uncertainties associated with measurement noise, data smoothing, sampling frequency, selection of the analysis interval, and changes in the deformation regime. Consequently, the predicted failure time should generally be interpreted as an estimate of the potential failure period rather than as an exact prediction of collapse (Carla et al., 2017; Intrieri et al., 2019). Carla et al. (2017) further proposed procedures for defining alarm thresholds and

improving the operational use of inverse-velocity analysis in early-warning systems. Their work highlights the importance of appropriate data filtering and the establishment of alarm levels to support timely decision-making during accelerating slope deformation.

The inverse-velocity approach has the advantages of conceptual simplicity and relatively low computational requirements, and it can provide useful failure-time estimates when a clear accelerating deformation trend is established (Fukuzono 1985; Intrieri et al. 2019). Ground-based radar interferometry has been increasingly applied for continuous monitoring of unstable open-pit mine slopes because it can provide spatially distributed displacement measurements at high temporal resolution (Carlà et al. 2017; Intrieri et al. 2019). The evolution of slope deformation is strongly influenced by geological structure, rock-mass characteristics, failure mechanism and external conditions, resulting in substantial variability and uncertainty in the observed deformation trends (Read and Stacey 2010; Intrieri et al. 2019). In hard-rock open-pit slopes, the final acceleration phase preceding failure may be extremely short, requiring high-frequency or continuous monitoring to capture the transition into tertiary creep. Peak velocity and peak acceleration can provide complementary kinematic indicators for distinguishing failure-related acceleration from non-failure instabilities (Carla et al. 2017).

Carla et al. (2017) proposed a combined peak-velocity and peak-acceleration criterion to complement velocity-only thresholds. Their analysis of nine hard-rock open-pit slope instabilities indicated that failures were generally associated with higher peak velocities and accelerations than non-failure instabilities. The acceleration ratio was assumed to be independent of failure size, rock type and slope configuration. The studied mines appeared to have different geo-mining conditions, therefore, the geological details and failure mechanisms in many cases remain unavailable.

Santos et al. (2019) developed the first quantitative hazard classification framework (HAS-Q) integrating multiple geotechnical variables. The study primarily focused on hazard classification rather than real-time failure prediction and achieved an error rate of only 11.36% in classifying slope stability conditions. The methodology applied includes principal component analysis (PCA), discriminant analysis and confidence ellipse techniques. However, the HAS-Q framework primarily incorporates static and quasi-static geotechnical, geometrical and operational variables and does not explicitly incorporate dynamic deformation-monitoring parameters such as displacement velocity and acceleration. Consequently, it provides a complementary hazard-classification framework rather than a real-time failure-forecasting tool.

Carla et al. (2018) integrated ground-based radar (GBR) + Sentinel-1 InSAR to monitor an opencast copper mine. The failure detection method applied was accelerating creep analysis and deformation mapping with prediction of accelerating creep and inverse velocity trends. The study demonstrated benefits of combining GBR and satellite InSAR for identifying unstable areas outside the effective monitoring coverage of the ground-based radar where failure source area extended beyond radar visibility; satellite data captured larger instability zone. Ground-based radar and satellite InSAR provide complementary spatial and temporal characteristics: ground-based radar offers high-frequency near-

real-time monitoring over its field of view, whereas satellite InSAR provides broader spatial coverage and retrospective/long-term deformation information. Their integration can therefore reduce uncertainties associated with radar field-of-view limitations and improve the characterization of spatially extensive slope instabilities (Carla et al. 2018; Carla et al. 2019).

Sattele et al. (2016) investigated the reliability and effectiveness of rock-slope warning systems using a combination of extensometers, total stations and warning-system sensors. Their framework incorporated inverse-velocity forecasting and probabilistic reliability analysis to assess warning-system performance. The study highlighted the trade-off between detection reliability, warning time and false-alarm rates: increasing sensor redundancy and lowering detection thresholds can improve the probability of detecting hazardous deformation but may also increase false alarms and associated operational costs. Although the study focused on natural rock slopes rather than open-pit mine slopes, its findings provide useful principles for designing reliable monitoring and early-warning systems in mining environments (Sattele et al., 2016).

Collectively, these studies indicate that slope-failure assessment can be considered at three complementary levels: geotechnical hazard classification based on static and geological factors, kinematic early warning based on deformation velocity and acceleration, and failure-time forecasting based on the temporal evolution of accelerating deformation. Integrating these complementary information sources may provide a more robust basis for slope-risk assessment than reliance on any single monitoring parameter or forecasting method.

A model trigger action response plan (TARP) presented in Table 2 was developed by P G Carvill (Head, Geotechnical and Rock Engineering, AngloGold Ashanti) based on some threshold values observed for both soft and brittle type of rock mass. The TARP also incorporated the depth of working and monitoring criteria chosen for a particular type of rock and also proposed the various actions to be taken.

Table 2
Model Trigger Action Response Plan (Carvill 2010)

Rock Mass	“Soft “			“Brittle”		
Depth	< 50 m	50 to 300 m	> 300m	< 50 m	50 to 300 m	> 300m
Increase Monitoring Frequency	> 5 mm/ day	5 to 10 mm/ day	5 to 10 mm/ day	> 3 mm/ day	> 3 mm/ day	> 3 mm/ day
TARP 1						
Continuous Monitoring	> 10 mm/ day	10 to 50 mm/ day	10 to 50 mm/ day	> 8 mm/ day	> 8 mm/ day	> 8 mm/ day
TARP 2						
Evacuate	> 30 mm/ day	> 50 mm/ day	> 50 mm/ day	> 20 mm/ day	> 20 mm/ day	> 20 mm/ day
TARP 3						

The reliability of slope-failure forecasting depends on several factors, including geological and geotechnical conditions, failure mechanism, deformation behaviour, quality and continuity of monitoring data, environmental influences, and the availability of sufficiently long and representative time-series observations. Reliable forecasting of impending slope failure requires appropriate monitoring strategies that provide adequate spatial and temporal resolution, high-frequency or continuous measurements where rapid deformation is anticipated, timely transmission of monitoring data, and appropriate noise reduction and data-filtering procedures. Because the applicability and reliability of individual forecasting methods vary with the deformation regime and failure mechanism, the use of complementary forecasting approaches can provide a more robust assessment of slope behaviour than reliance on a single method (Intrieri et al. 2019).

Retrospective analysis of monitoring data from slopes that have experienced failure can provide valuable information regarding the evolution of precursory deformation, the transition from stable or quasi-stable deformation to accelerating movement, and the characteristics of the final failure stage. Such analyses can contribute to understanding failure mechanisms and to establishing site-specific early-warning criteria. In hard-rock open-pit slopes, Carla et al. (2017) demonstrated that some failures were preceded by a short-lived phase of rapid acceleration and tertiary creep, followed by a rapid increase in displacement rate immediately before collapse. However, the authors also observed that substantial acceleration did not necessarily result in complete slope failure. Therefore, acceleration, velocity, and displacement trends should be interpreted together with the geological setting, failure mechanism, and other monitoring information rather than being treated as independent or universal indicators of impending failure (Carla et al. 2017; Intrieri et al. 2019).

4. CONCLUSION

This review demonstrates that reliable assessment of slope deformation and early warning of slope failure in surface mines require an integrated approach combining continuous or appropriately frequent deformation monitoring, suitable forecasting methods, and site-specific geotechnical assessment. Although acceleration, velocity evolution and tertiary-creep behaviour can provide important indications of deteriorating slope stability, no single deformation parameter can be considered a universally reliable precursor of failure. Deformation indicators should be interpreted together with geological and geomechanical conditions, failure mechanism, and external influences such as rainfall and groundwater conditions. Among the monitoring technologies reviewed, ground-based slope stability radar (SSR) provides important advantages for open-pit mine applications because of its high temporal resolution, spatially distributed measurements, continuous operation and ability to support near-real-time warning. However, SSR should not be considered a standalone solution. Satellite InSAR, GNSS, total station–prism systems, terrestrial 3D laser scanning and other geotechnical instruments provide complementary spatial, temporal and physical information. In particular, the integration of ground-based radar with satellite InSAR can improve the characterization of instability extending beyond the radar field of view by combining high-frequency monitoring with broad-area and long-term deformation information.

The review further indicates that inverse-velocity analysis remains a useful approach for estimating the potential time of failure when a well-defined accelerating deformation trend is established. Nevertheless, its results are sensitive to data quality, filtering, sampling frequency, selection of the analysis interval and changes in deformation regime. Predicted failure time should therefore be interpreted as an estimate of the potential failure period rather than an exact prediction of collapse. Similarly, velocity and acceleration thresholds should be developed through site-specific analysis and, where possible, retrospective back-analysis, and should be incorporated into trigger action response plans (TARP) that link measured deformation behaviour with clearly defined operational responses. An important research gap identified in the reviewed literature is the limited integration of deformation-monitoring data with geological, geomechanical, hydrogeological and operational parameters. Further, none of the studies have been performed for waste dump slopes where the stability is often critical. Many available forecasting approaches are based primarily on retrospective analysis of deformation records, while the relationship between site-specific geotechnical conditions and observed kinematic behaviour remains insufficiently quantified. Future research should therefore focus on integrated, site-specific forecasting frameworks that combine multi-sensor monitoring, geotechnical characterization, environmental observations, statistical or probabilistic analysis, and predictive analytics.

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P. K. D. conceptualized the idea, guided on the article and reviewed the final manuscript. K. V. worked on literature review, analysing past research outcomes, comparison of different slope monitoring technique,

identifying key deformation characteristics and identifying research gaps. V. B. prepared the outline of the article, identified key areas to be addressed and reviewed the draft manuscript.

REFERENCES

1. Armstrong J, Sharon R, Williams C, Ross B. Risk-based Slope Monitoring Framework', Slope Stability 2020. Perth: ACG; 2020. pp. 101–16.
2. Barla G, Chiappone A, Vai L. Instability of Slopes - Interactions with man-made structures, inhabited areas and the environment. Bologna, Italy: Patron Editore; 2006.
3. Carla Tommaso T, Veronica L, Luca R, Federico B, Silvia B, Davide T, Patrick. and Casagli Nicola 2019, 'Combination of GNSS, satellite InSAR, and GBInSAR remote sensing monitoring to improve the understanding of a large landslide in high alpine environment', *Geomorphology*, 35, pp. 62–75.
4. Carla T, Intrieri E, Traglia FD, Nolesini T, Gigli G, Casagli N. Guidelines on the use of inverse velocity method as a tool for setting alarm thresholds and forecasting landslides and structure collapses. *Landslides: J Int Consortium Landslides*. 2017;14:517–34. 10.1007/s10346-016-0731-5.
5. Carla T, Farina P, Intrieri E, Botsialas K, Casagli N. On the monitoring and early-warning of brittle slope failures in hard rock masses: Examples from an open-pit mine. *Eng Geol*. 2017;228:71–81.
6. Carla T, Farina P, Intrieri E, Ketizmen H, Casagli N. Integration of ground-based radar and satellite InSAR data for the analysis of an unexpected slope failure in an open-pit mine. *Eng Geol*. 2018;235:39–52.
7. Carla T, Intrieri E, Raspini F, Bardi F, Farina P, Ferretti A, Colombo D, Novali F, Casagli N. Perspectives on the prediction of catastrophic slope failures from satellite InSAR. *Sci Rep*. 2019;9:14137.
8. Dash AK. Analysis of accidents due to slope failure in Indian opencast coal mines. *Curr Sci*. 2019;117(2):304–8. <https://doi.org/10.18520/cs/v117/i2/304-308>.
9. Ding X, Ren D, Montgomery B, Swindells C. Automatic Monitoring of Slope Deformations using Geotechnical Instruments. *J Surv Eng*. 2000;126(2):57–68.
10. Duncan JM, Wright SG. Soil Strength and Slope Stability. John Wiley & Sons Inc; 2005.
11. Dunnicliff J. Geotechnical Instrumentation for Monitoring Field Performance. USA: Wiley; 1993.
12. Federico A, Popescu M, Elia G, Fidelibus C, Interno G, Murianni A. Prediction of Time to Slope Failure: A General Framework. *Environ Earth Sci*. 2012;66:245–56.
13. Ferretti A, Monti-Guarnieri A, Prati C, Rocca F, Massonnet D. 2007, 'InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation', European Space Agency.
14. Fukuzono T. A method to predict the time of slope failure caused by rainfall using the inverse number of velocity of surface displacement. *J Japan Landslide Soc*. 1985;22(2):8–13.
15. Fukuzono T. 1985, 'A New Method for Predicting the Failure Time of a Slope', In *Proceedings of the Fourth International Conference and Field Workshop on Landslides*, Tokyo, pp. 145–150.
16. Gili JA, Corominas J, Rius J. 2000, 'Using Global Positioning System Techniques in Landslide Monitoring', *Engineering Geology*, Vol. 55, pp. 167–192.

17. Hanssen RF. Radar Interferometry: Data Interpretation and Error Analysis. Dordrecht, Boston: Kluwer Academic; 2001.
18. Hoek E. Practical Rock Engineering. Evert Hoek Consulting Engineer, Inc; 2007.
19. Hoek E, Bray J. Rock Slope Engineering. London: The Institution of Mining and Metallurgy; 1981.
20. Jaboyedoff M, Oppikofer, Thierry, Abellan, Antonio, Derron, Marc-Henri, Loye, Alex, Metzger, Richard and Pedrazzini, Andrea 2012, 'Use of LIDAR in Landslide Investigations: A Review', Natural Hazards, Vol. 61(1), pp. 5–28.
21. John Read and Peter Stacey. Guidelines for Open Pit Slope Design. Australia: CSIRO Publishing; 2010.
22. Khaintola A, Verma, Dhananjai, Gupte SS, Singh TN. 2011, 'A Coal Mine Dump Stability Analysis', Geomaterials, vol. 1, pp. 1–13.
23. Kliche CA. Rock Slope Stability', Society for Mining, Metallurgy, and Exploration. Littleton: Inc.; 1999.
24. Kliche CA. Rock Slope Monitoring: Detection, Analysis and Warning of Rock Slope Failures in Open Pit Mines. SME Mining Engineering Handbook; 2011.
25. Kumar A, Rathee R. Monitoring and Evaluating of Slope Stability for Setting out of Critical Limit at Slope Stability Radar. Int J Geo-Engineering. 2017;8–18. 10.1186/s40703-017-0054-y.
26. Leick A, Rapoport L, Tatarnikov D. GPS Satellite Surveying. 4th ed. USA: Wiley; 2015.
27. Lichti DD, Gordon, Stuart J, Tipdecho T. 2005, 'Error Models and Propagation in Directly Georeferenced Terrestrial Laser Scanner Networks'. J Surv Eng, 131(4).
28. Little MJ. 2006, 'Slope Monitoring Strategy at PP Rust Open Pit Operation', in Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering, pp. 211–230.
29. Malik BA, Koner R. 2024, 'Comprehensive review of the monitoring and sensing system in slopes with a special focus on the mining sector', Environmental Science and Pollution Research, 31, pp. 66588–614.
30. Masood M, Verma T, Murmu S. 2023, 'The Use of Radar in the Assessment of the Stability of Mine Slopes in Open Cast Mines', in Proceedings of the Second International Conference on Emerging Trends in Engineering (ICETE 2023), pp. 1234–1246.
31. Masood M, Maneed, Raju G, Yuga, Verma T. Slope Monitoring and Failure Prediction Techniques in Mines: A Review. J Mines Metals Fuels. 2022;70(8):171–81.
32. Massonnet D, Feigl KL. Radar Interferometry and its Application to Changes in the Earth's Surface. Rev Geophys. 1998;36(4):441–500.
33. Nayak PK, Dewangan PK, Dash AK. Investigation on Effects of Rainfall Infiltration and Groundwater Levels on Stability of Coal Mine Waste Dump-A Case Study. J Mines Metals Fuels. 2021;69(7):233–40.
34. Nayak P, Kumar, Ravikant, Dewangan P, Dash AK. To Investigate the Effects of Changes in Moisture Content on Shear Strength Parameters of Coal Mine Waste Dump Material. J Mines Metals Fuels.

35. Niekrasz J. 2018, 'Review of radar system performance and estimation of slope deformation threshold values for the Leveäniemi open pit', Master's Thesis, School of Engineering, Aalto University.

36. Osasan SK, Afeni TB. Review of Slope Monitoring Techniques. J Min Sci. 2010;46(2):177–86.

37. Rose ND, Hungr O. Forecasting potential rock slope failure in open pit mines using the inverse velocity method. Int J Rock Mech Min Sci. 2007;44:308–20.

38. Santos TB, Lana MS, Pereira TM, Canbulat I. Quantitative hazard assessment system (HAS-Q) for open pit mine slopes. Int J Min Sci Technol. 2019;29(3):419–27.

39. Sattelle M, Krautblatter M, Brundl M, Straub D. 2016, 'Forecasting rock slope failure: How reliable and effective are warning systems', Landslides, 13(4), pp. 737–50.

40. Zavodni ZM, Broadbent CD. 1980, 'Slope Failure Kinematics', Bulletin of the Canadian Institute of Mining, vol. 73, no. 816, pp. 69–74.

Figures

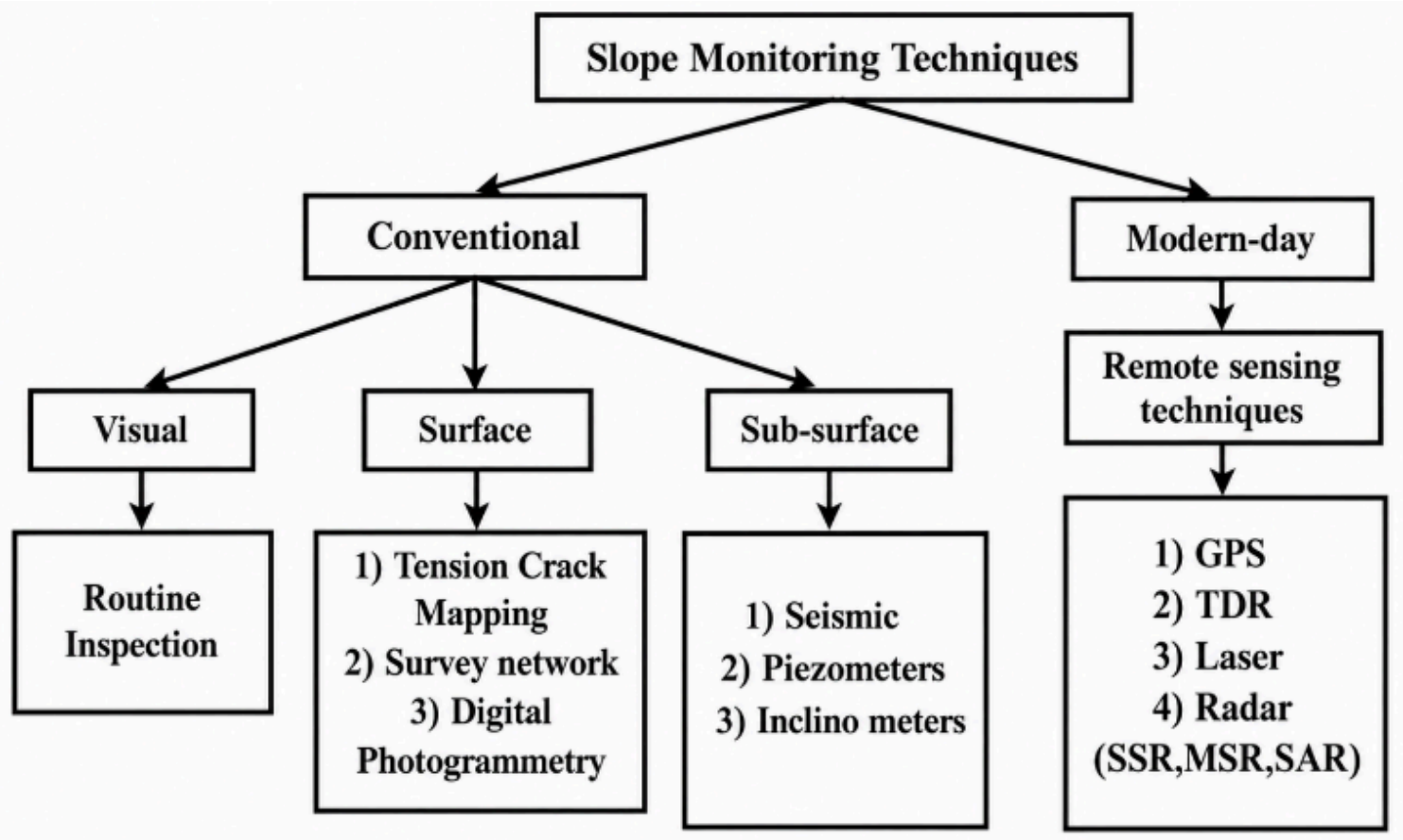


Figure 1

Slope Monitoring Techniques (Masood et al., 2022)



Figure 2

Slope stability radar for continuous monitoring of slope

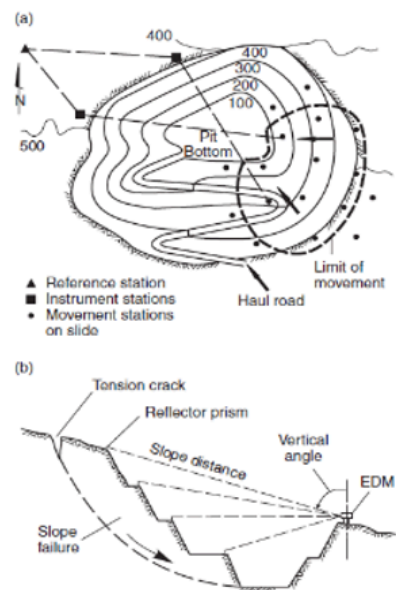


Figure 3

Total station-based surveying method of monitoring to measure slope movement (Wyllie and Mah 2004)



Figure 4

Terrestrial 3D laser scanner for slope monitoring in mines



Figure 5

GNSS method of slope monitoring

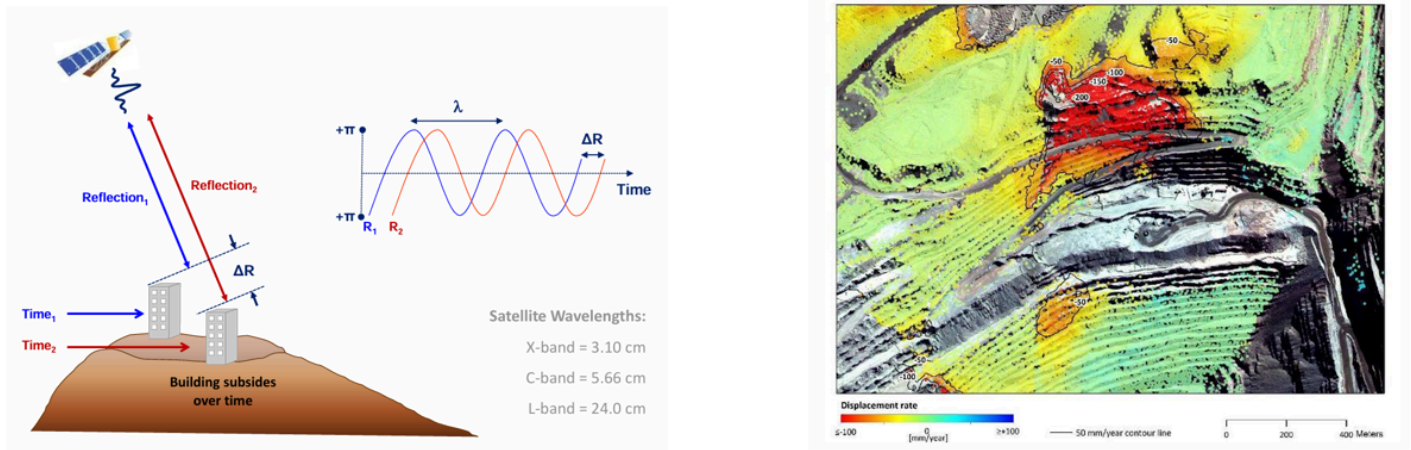


Figure 6

InSAR method of slope monitoring

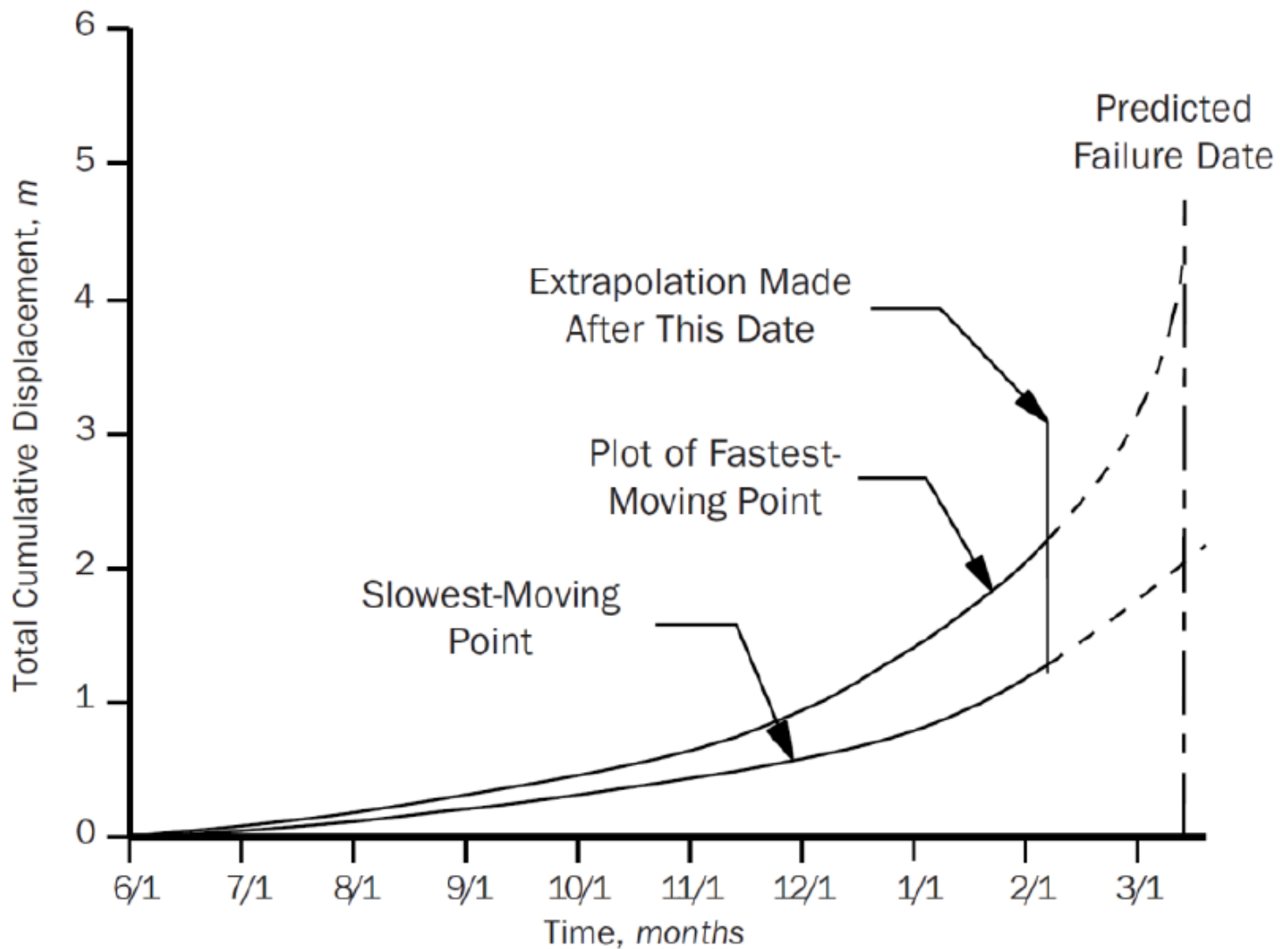


Figure 7

Plot of cumulative displacement against time for the fastest and slowest moving points

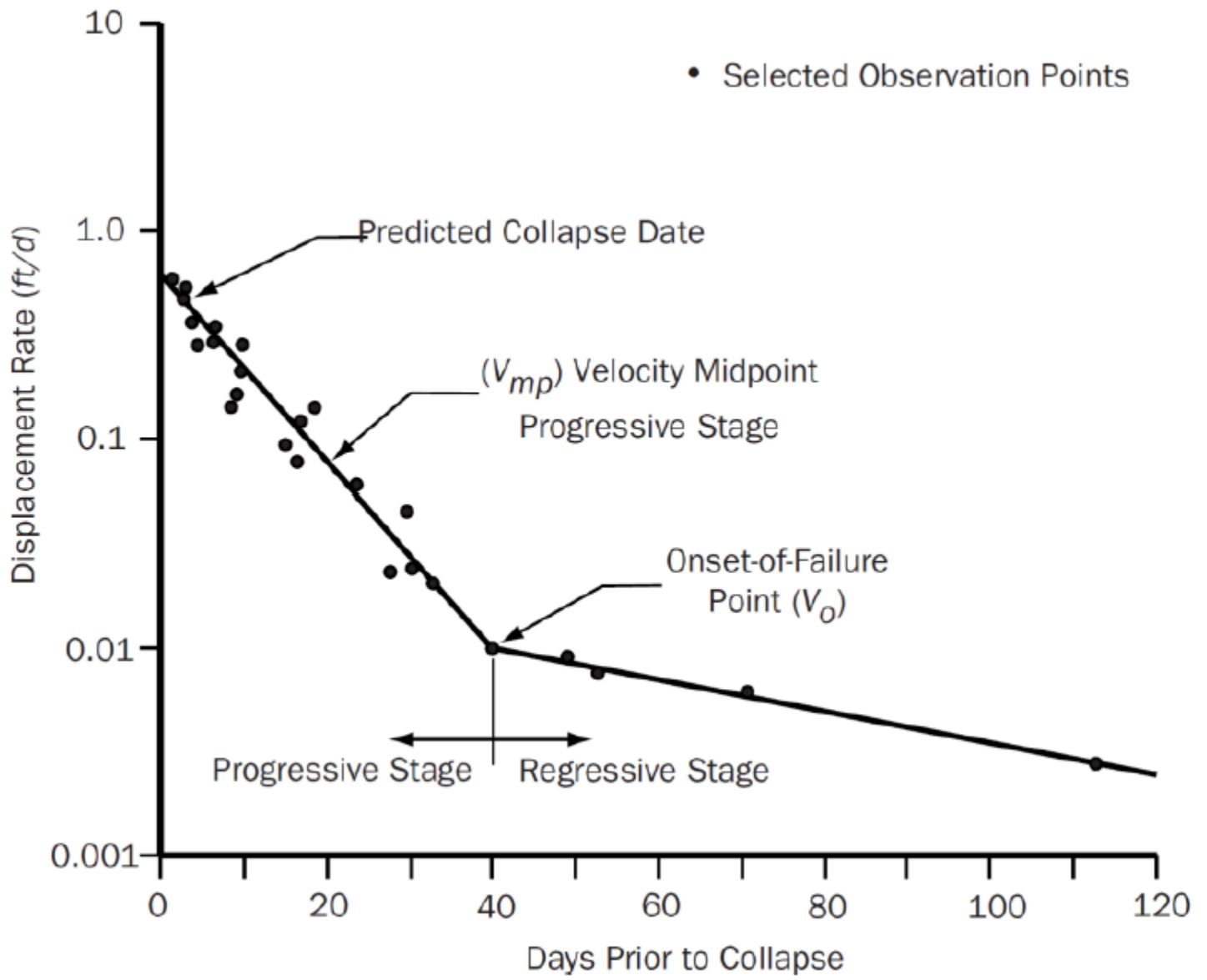


Figure 8

Broadbent and Zavodni failure prediction method