2. LITERATURE REVIEW

A literature review implies examining and evaluating the reported contributions in the area of interest. After exploring the available material, we learned about the existing knowledge, limitations, challenges, benefits, which helped in developing a deep knowledge of the subject of the research work (Bairagi & Munot, 2019). The chapter has been divided into three sections. The first section gives an overview of rock slope deformations. The second section is a review of slope monitoring techniques and the third sections details the slope failure prediction methods.

2.1 Rock Slopes

Natural deformation within the rock mass is confined by the surrounding rock elements prior to mining. The confinement is removed during the excavation process, which exposes the natural geological instabilities that are present in the rock mass. Openings in the earth are inevitable when mining operations, whether underground or on the surface, are initiated to mine minerals. In these excavations with free surfaces, the deformed rock is free to be deformed. Excavation mining causes additional deformation of the rockmass by disturbing and redistributing the in-situ stress field. Using seismic monitoring, (Xu et al., 2012) discovered a relationship between excavation and the development of micro-cracks in deep rock mass. Additionally, Stacey validated the presence of excavation-induced cracks in a shallow, high-quality granite rock (Stacey, 2007). The process of excavating ore bodies, which are close to the surface, results in the creation of pit with sequence of benches referred to as high-walls. The expense of removing the debris would be too high if the benches were designed with a shallower slope angle. Thus, mining firms face the conundrum of constructing a slope that strikes a balance between economic efficiency and worker safety.

Competent rocks typically have a steeper pit slope than weak rocks, and the pit slope may vary in steepness even within a single mine. The geomechanical features of the slopes and operational parameters determine the maximum inter-ramp angle, which in turn is a function of the bench face angle, the bench height, and the bench width. Slope, as a result, is determined by a combination of factors, including the dimensions of the benches, the distance between ramps, and the number of access roads used for hauling (Sjöberg, 1996).

Figure 2. 1 : Slope geometry in an open pit (Williams, et al. 2009).

In India, surface mines are mostly open-cast. An open-cast coal mine's bench arrangement, is quite different from that of an open-pit mine. A dragline is stationed on the high wall of an open-cast mine to remove overburden, and the mining is done in strips. A low-wall, also known as spoil, is a stack of waste material formed when the overburden around an ore deposit is removed and dumped in the mined-out region. Both operating characteristics and safety concerns play a role in determining the strip shape, with the high-wall and low-wall receiving careful attention throughout the design process. Several cases of dump or low-wall collapse in open-cast mines have been recorded by (Kasmer & Ulusay, 2006; Okagbue, 1987; Ulusay et al., 2001). The effects of these massive dump failures on production and safety have shifted the focus to the stability of dump slopes in addition to high-wall stability (Kasmer & Ulusay, 2006; Okagbue, 1987) found that in some mines, dump instability—specifically, when the dump consists mostly of loose sand with inadequate waste rock to support the low strength soil—is the primary cause of slope instability.

Table 2. 1 : Some terminologies used in this chapter of the thesis

Term	**Definition**
Deformation	Structural modification or displacement formation as a result of external stresses. Failure on a slope always occurs after a period of deformation.
Fracture	Breaking rock bonds creates planes of separation. Rock failure may not follow fracture.
Peak Strength	Maximum stress averaged over a plane, which the rock can sustain under a specified set of conditions (Brady & Brown, 2006).
Brittle Deformation	Occurs when the stress exceeds the rock strength and there is an abrupt loss of strength with fracture on a rock plane without significant preceding plastic deformation (Brady & Brown, 2006).
Ductile Deformation	Stress exceeds the rock strength but it can accommodate further permanent deformation without breaking.
Yield	The stress at the end of elastic behaviour. The yield point is the start of progressive displacement behaviour in slope monitoring and typically the onset failure point.
Failure	The rockmass fails when the load or pressures acting on it exceeds the strength. When the strength is at its highest, failure is imminent or begins. In open-cast mining, the terms failure and collapse are used interchangeably to describe the state of the slopes (Read & Stacey, 2009a).
Functional Failure	If a slope cannot serve its intended purpose. This means that although localised parts of the slope may have failed, it does not always imply total collapse (Frizzell et al., 2020).
Operational Slope Failure	Rate of displacement greater than the rate at which the slide material may be safely mined (Broadbent & Zavodni, 1982)
Slope Collapse or Slope Failure	The point at which the developing failure's effects make mining the slope unfeasible. When a slope fails on a local scale, just a few benches may be affected, but when it fails on a global scale, the whole slope may be affected (Sjöberg, 1996).

When compared to open-pit mines, open-cast coal mines do not have nearly as intricate highwalls. Because comparable rock types tend to be found in different mines, the geology is simple, and the rock mass strength is rather consistent. When compared to the high-wall of most open-pit mines, the high-wall of open cast coal mines is intentionally built to be rather steep. This is due to the fact that unlike in an open-pit mine, where the high-wall is anticipated to remain stable throughout the life of the mine, high-walls in open-cast coal mines have a very limited lifetime.

2.1.1 Slope Stability

Mining and civil engineers, engineering geologists, and environmental engineers, scientists, and managers are all interested in and concerned with the stability of slopes in soils and rocks, whether they are natural or man-made. It is possible to categorise natural slopes into two main categories, active slopes and passive slopes, based on the degree to which they have been shaped by natural causes. Active slopes are ones that are either now moving or have moved during the past seasonal cycle but are still moving at the present time. Slopes are considered inactive if they have not shown any signs of movement throughout the past seasonal cycle. Either the reasons liable to produce a failure have been eliminated, either naturally or by human effort, or the slopes are in a dormant condition, meaning that the failure causes are still there and a movement may take place again. Artificial slopes are those that have been created by human intervention. One alternative name for them is "man-made slopes." Excavation or cut slopes, embankments including earthen dams, and spoil or waste dumps are the three primary types. Slope angle, material qualities, geological features, and hydrogeological factors all have a role in the stability of designed slopes.

2.1.2 Factors Affecting Slope Stability

Slope geometry: Slope stability in open-pit mining and quarrying is strongly impacted by the shape of the slope. Slope geometry is defined as the height, overall slope angle, and area of the failure surface used in slope design. Bench height and area restrictions are also a part of the fundamental geometric slope design. Maximum slope angle has a major bearing on slope stability. There may be a correlation between the steepness of the slope and the eventual collapse of the rock face. When the whole rock slope is 45 degrees, open-pit mines are considered safe and stable.

The wall's stability is also affected by how the slope is curved. Stability of a slope is compromised by convex pit wall structures; hence they should be avoided. The likelihood of failure and the consequences of failure are affected by the slope's planned geometry. Whenever the geometry of the slope is convex, the probability of a failure increases. The stability of concave slopes is superior than that of straight ones. Convex slopes are less stable than straight ones because they lack containment and experience the effects of side resistance, both of which make it more difficult for prospective failures to spread. Slopes with concave geometries are used most commonly in open-pit mines, long, narrow pits, circular pits, and pit walls.

Geological structure: Geological features such as faults, joints, the presence of bedding planes, and intra-formational shear zones all contribute to the stability of a rock slope. Sometimes called discontinuities, geological features frequently govern the kind of collapse that happens in rock slopes. The stability of a rock slope depends on a number of factors, including the roughness, direction, and persistence of the discontinuities, and the presence of mineral infillings like clay material between the rocks. The instability and inadvertent failing are caused by the junction of discontinuities such as joints and fractures in rocks, where the true strength of the in-situ rock mass is lower than the strength of the complete rock. These breaks, which may occur singly or in multiples and in a wide range of directions, cause the rock to fracture into individual, nested pieces. As the rock slides along the structural plane, its shear and tensile strength is diminished as it crosses discontinuities.

Ground water: When groundwater activates wedges and blocks, it causes tiny fissures in the rockmass to expand, making the slopes unstable. Water pressure on likely failure planes reduces frictional strength and, by extension, normal stresses across planes. This impacts the slope's stability by increasing the driving and pushing forces. When water is present below the surface, it modifies the rock's structure and weakens its normal effective stress, as well as other rock strength factors like cohesion and friction. Consequences of groundwater pressure and transient water movement inside the rock and soil have an influence on pore pressure conditions, strength, and deformation behaviour. Interfaces along discontinuities become very weak due to presence of water.

Blasting: When mining operations utilise ineffective blasting techniques, the rock behind the slope face may be loosened and vibrated, reducing the stability of the slope. If the blasting isn't done properly, the ground will shake, which will shift the tensions in the rock face. This results in dynamic acceleration of the materials, which generates slope-plane instability. Poor blasting techniques result in the formation of rock slope discontinuities such as cracked zones, faults, joints, and fissures. The cohesiveness of the rock mass is reduced by ineffective blasting, and the likelihood of water penetration is increased, leading to additional loosening. When bench-face angle is lowered due to poor blasting, the rockmass might potentially collapse. Blasting decreases the shear strength of a rock mass, which allows existing cracks to spread and make rockmass unstable.

Mining method and equipment usage: The rockmass around the excavation undergoes deformation as a result of changes in the in-situ stress field conditions caused by mining activities. Excavation may cause natural slopes to bend owing to a loss of shear strength, which can ultimately lead to slope collapse. Slope stability as a whole must be taken into consideration while deciding on mining methods and equipment. As the mining process progresses, the surcharge rises and the forces that cause the slope to descend as a result of the movement of heavy gear used for mine haulage and other tools like rigs.

2.1.3 Slope Failure Mechanisms

The failure mechanisms in slopes may be influenced by a number of variables. Particularly where the shear stress exceeds the strength of the rock mass, the redistribution of excessive shear stress loading causes sections of rock slopes to move downward. Slope failures in rock mass are primarily categorized into four modes: plane failure; rotational/circular failure; wedge failure; and toppling failure. (Wyllie & Mah, 2004). These modes are further explained.

Plane failure: A plane failure occurs when a discontinuity sinking at a lower angle and impacting nearly parallel to the slope face causes the slope to slip. The occurrence of plane failure, as seen in figure 2.2, entails the downward and outward displacement of the rock block along a gently undulating surface. The rock slips or slopes outward and downward over an irregular surface as a result of this failure. The bedding plane will break out of the slope and strike parallel to the slope when failure is possible. Planer failure on a slope is inevitable under such conditions because of the loss of control.

A plane failure occurs when a discontinuity sinking at a lower angle and impacting nearly parallel to the slope face causes the slope to slip. The rock slips or slopes outward and downward over an irregular surface, resulting from this kind of failure. The bedding plane will break out of the slope and strike parallel to the slope when failure is possible. Planer failure on a slope might come from a loss of control under these conditions. The presence of ground water, which worsens the slope's stability at periods of transitory ground water pressure like rainfall, is a major contributor to planar collapse.

A rock block experiences plane failure as it slides downhill and outward over a slightly undulating release surface (Hoek & Bray, 1981). Structural surface weaknesses including joints, faults, and bedding planes are often responsible for regulating the movement (Krause et al., 1999). Plane failure occurs when the plane of weakness has a strike that is within +200 of the strike of the slope's crest (Hoek & Bray, 1981). There must be enough room for the failure plane to daylight between the foot of the slope and its peak. They added that the failure plane's dip must be less than the slope face's dip and larger than the failure plane's angle of internal friction.

(a) (b)

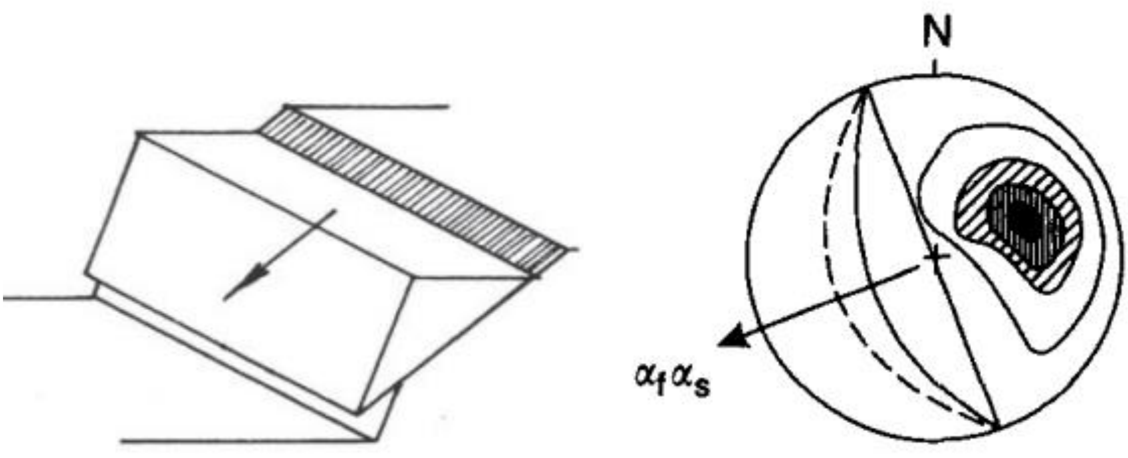

Figure 2. 2 : (a) Plane failure mode in slopes (b) Kinematic analysis of plane failures (Hoek & Bray, 1981)

Wedge failure: When a rock slope collapses and two sets of discontinuity planes connect at an angle, this is known as a wedge failure. For this kind of failure to occur, at least one of the joint intersections must have a friction angle greater than the dip angle. Favourable circumstances for this failure include the presence of sloped bedding, foliation, and well-defined cleavages. When two sets of planes of discontinuities connect at an angle, a wedge failure has occurred on the rock slope. Commonly, the wedges have a tetrahedral shape, meaning that the slope and top face function as the third and fourth sides of the tetrahedron, while the joint planes function as the second and third. When the stress crack is considered, the tetrahedron is truncated into a five-sided block along the plane of the tension fracture.

As shown in figure 2.3, if two discontinuities (plane A and B) intersect the slope face at an oblique angle with a visible intersection line, the rock wedge above these discontinuities will slide along this intersection line.

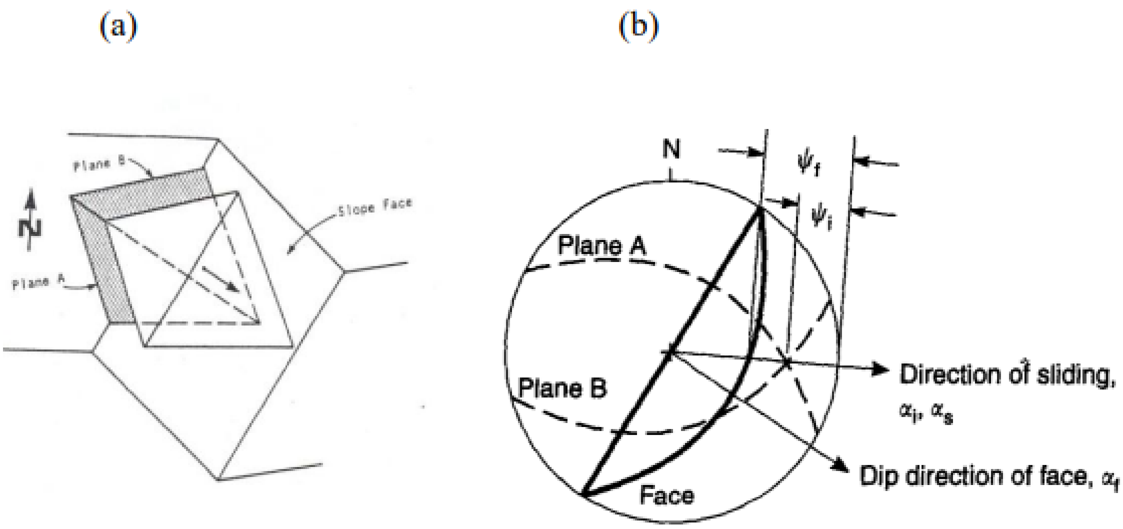

Figure 2. 3 : (a) Wedge failure mode (Piteau & Martin, 1982) (b) Kinematic analysis of wedge failure.

This sliding occurs when the inclination of the line is significantly greater than the internal friction angle along the discontinuities. Additionally, for wedge failure to transpire, the plunge angle of the intersection line (ψi) formed by plane A and B must be less than the dip angle of the slope face (ψf) measured in the direction of sliding, i.e., ψi < ψf (Hoek & Bray, 1981).

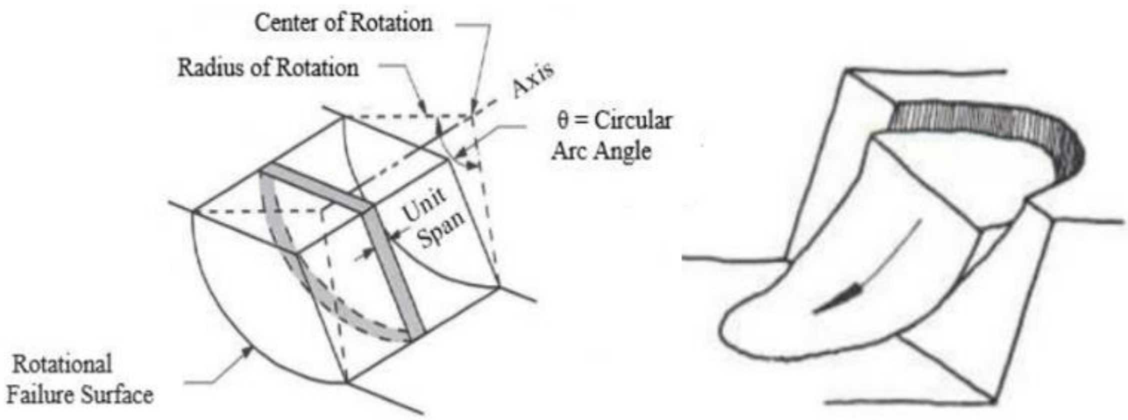

Figure 2. 4 : Rotational and circular failure modes (Hoek and Bray, 1981)

Circular failure: Soil and heavily worn or cracked rock are the most common environments for such collapses to occur in a circular fashion. Continuum slopes with a weak or extensively jointed rock mass are prone to circular collapse. Circular failure may also occur in hard rock.

Figure 2.4 illustrates the first phase, characterised by elastic displacement resulting from the extraction of rock material during mining operations. Removal of rock material during mining causes (a)elastic displacement; (b)yielding, which begins at the toe and spreads upward as more material is removed or as a result of mining to a new and critical slope height; (c)accumulation of shear strain, which begins at the toe and moves upward; (d)when failure surface is developed, the slope will start showing some displacements, which can be tracked if a good monitoring system is in place;

Toppling failure: Failure to topple occurs on slopes with joint sets that are vertical or nearly vertical. Failure of this kind occurs when the mass of the earth shifts and the base of a rock block that is resting on an incline is shifted away from the block's centre of gravity. As represented in figure 2.5, the occurrence of toppling failure is observed when the weight vector of a block of rock, which is situated on an inclined plane, extends beyond the base of the block. When joint sets are broken, the slope will fall from a small to a large size. The failure of a slope is due to the downslope overturning brought on by the rotation and flexure of blocks with abrupt discontinuities. In addition, pebbles falling from the upper bench face might bounce off the benches and over them, posing a threat to those below. The bench's width has to be enough to stop boulders from being bounced over the crest in the zone where this is suspected to happen.

Observable phenomena, such as the steady formation of stress fractures adjacent to the slope's crest, may serve as early warning signs for major toppling instability and provide enough time for rescue workers to arrive. Nonetheless, before breakdowns occur, there will be time to implement stabilising measures or evacuate the area. Small toppling failure from bench faces is a possible hazard during mining activities such as drilling, charging, and mucking. The following are necessary for a collapse; (1) The joint sets need to slant down the slope and slide easily with respect to one another; (2) The rock mass must be deformable for toppling to occur; (3) The rock mass' tensile strength must be low to allow for a tensile bending failure at the base of the falling columns.

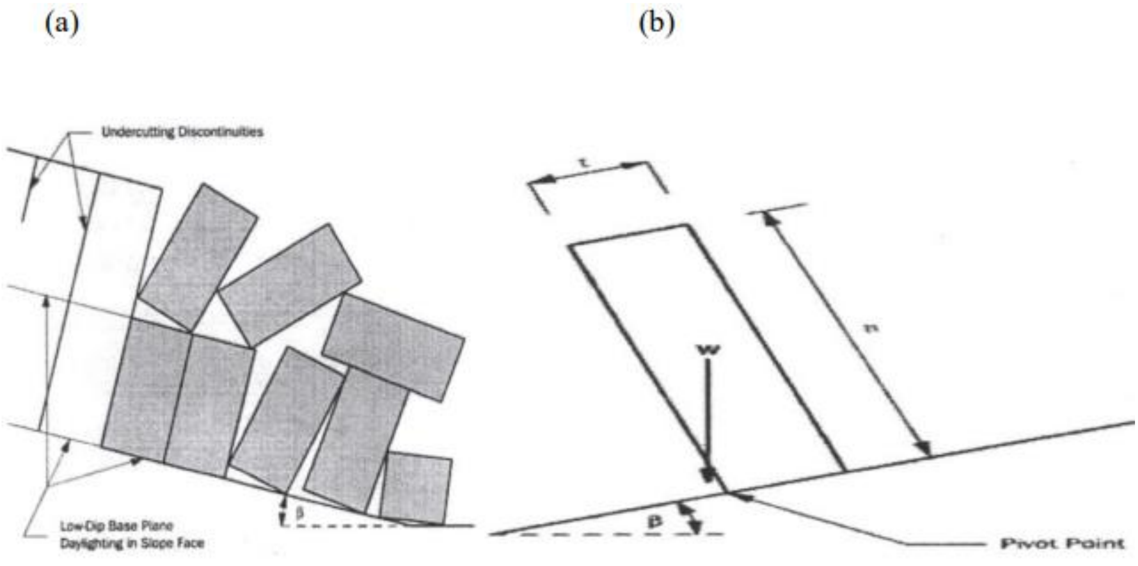

Figure 2. 5: (a) Toppling failure mode. (b) When W is outside the pivot point, toppling may occur (Kliche, 1999)

Rock falls, spread, flow, and buckling of sinking thin beds are further secondary failure types. Slope failure with many failure modes is a complex failure mechanism. (Sjöberg & Norstrom, 2000; Stacey, 2007) argued that mine slope failure modes may differ from the accepted processes, especially in high stress and hard rock situations. Stacey (2006) raised several concerns about the lack of knowledge and research around these systems.; Does failure really occur on the failure surface that was chosen? Does failure just occur on the particular failure surface that was chosen, or does it occur on several failure surfaces? What number of breakdown surfaces and locations inside the slope are involved in the eventual collapse? Do the strength parameters derived from a back-analysis of this failure surface adequately describe the rock slope's "strength"? How does the geometry of the failure unfold in three dimensions?

A complex failure mechanism involves two or more of the four major failure mechanisms, or additional secondary failure mechanisms. There are a wide variety of failure modes that may occur in weathered rock materials due to their low shear strength, which allows collapse through the rock itself rather than just at discontinuities (Vaziri et al., 2010). Multiple step-wise failure and intact rock fracture through strength deterioration along non-persistent sliding surfaces characterise failure. (Kemeny, 2003; Mencl, 1966) established the idea of damage zones inside the active part of the 1963 Vaiont slide to explain the complex failure along sliding surfaces. Martin and Kaiser (1984) expanded on this idea, showing how deformation of a rock mass causes it to expand internally, allowing the bulk to slide along the sliding surfaces. At the foot of a failure zone, Vaziri (Vaziri et al., 2010) observed toppling failure, whereas sliding failure occurred in the higher half of the failure zone. Martin refers to one such complicated failure process as "ratchet mechanisms" in a back-analysis of a slope collapse more than 17.8 million tonnes at the Cassiar Mine in British Columbia, Canada.

Using geological mapping and prism monitoring, researchers examined how the failures occurred and found that groundwater recharging of many steeply descending fissures led to a ratchet mechanism of displacement rates. An open pit mine, a complicated toppling-circular failure mode due to the weight of toppling limestone slabs on a weaker sedimentary sequence at the slope's base was experienced (Alejano et al., 2010). The combined stresses of the limestone slab and the water surcharge cause a circular collapse in the sedimentary portions of the slope. Simmons and Simpson also detailed complex failure mechanisms (Simmons, 2006). Based on their research, they determined that complex failure mechanisms are notoriously tough to foresee, may happen quickly, and often do so without any prior notice. In addition to active-passive sliding blocks and laccolith slides, slide toppling mechanisms and wedge toppling are all examples of complicated failure mechanisms (Calder & Blackwell, 1980; Wang, 1981; Way et al., 2003). Failure processes on steep, hard rock slopes are more nuanced than the standard planar, wedge, circular, and toppling (Stacey, 2007).

2.1.4 Slope Deformation Behaviour

Long-term stability and deformation of rock slopes may be understood and predicted with knowledge of the time dependent behaviour of rock mass (Lajtai & Bielus, 1986; Lajtai & Schmidtke, 1986). Mechanical qualities of the rock mass, structural geology, slope geometry, excavation rate, failure mechanism, influence of external factors including groundwater pressures, seismic activity, and in-situ stresses, and excavation rate all play a role in the time-dependent reaction to excavation (Zavodni, 2000).

In their model of the Rand Rockslide, (Eberhardt et al., 2004) proposed that brittle strength deterioration and gradual collapse arising from time-dependent processes were the primary contributing factors in the absence of any triggering event. Substantial weakening of the granite mass over time triggered the Pandemonium stream rockslide in western Canada (Eberhardt et al., 2004). According to (Zavodni, 2000), there are three distinct periods of time-dependent deformation behaviour on rock slopes. Phase I is the onset of the effect; Phase II is the decelerating displacement over a relatively short period of time; and Phase III is the strain-softening and ultimately failure-causing large-scale deformation.

The elastic rebound, relaxation, and dilatation of the rock mass owing to changes in stresses generated by excavation is the first reaction stage of all slopes. The first reaction of the slope to the excavation is seldom represented in monitoring data since monitoring often begins after the first excavation has already taken place (Zavodni, 2000). Initial deformation occurs at a rate of 0.1 mm/day to 4 mm/day without the establishment of a clearly defined failure surface or failure mechanism (Zavodni, 2000)

If the slope's environment is no longer perturbed by events occurring outside the rock, a regressive failure will occur in the form of short-term decelerating displacement cycles.

Instead, a progressive failure happens when the slope displacement accelerates towards the point of failure, and this acceleration is typically algebraically predicted in the absence of adequate control mechanisms (Zavodni, 2000).

As soon as a failing condition is recognised, it is crucial to ascertain whether or not a slope is regressive or progressive to allow effective rectification attempts. Dewatering, control blasting, and buttressing are all examples of control methods that may be used to eliminate the external source of regressive displacement. The opposite is true for a gradual failing, which necessitates rapid preparation for the possibility of collapse (Zavodni, 2000). Stages of regressive and progressive displacement are shown in the figure 2.6. As each cycle between the external stimuli slows down at points 1, 2, and 3, we classify Curve A as a regressive curve.

The progressive stage is shown by curve B, which indicates a quickening pace. The progression from the regressive to the progressive phase is shown by curve C. (Zavodni, 2000). Discontinuities that drop off of the face at an angle greater than the friction angle are one kind of geological feature that may cause progressive failure (Type II). When the shear strength of a slide surface decreases monotonically with motion, progressive failure may also occur. The progressive stage of failure lasts anywhere from four days to forty-five days, as described by (Zavodni & Broadbent, 1978).

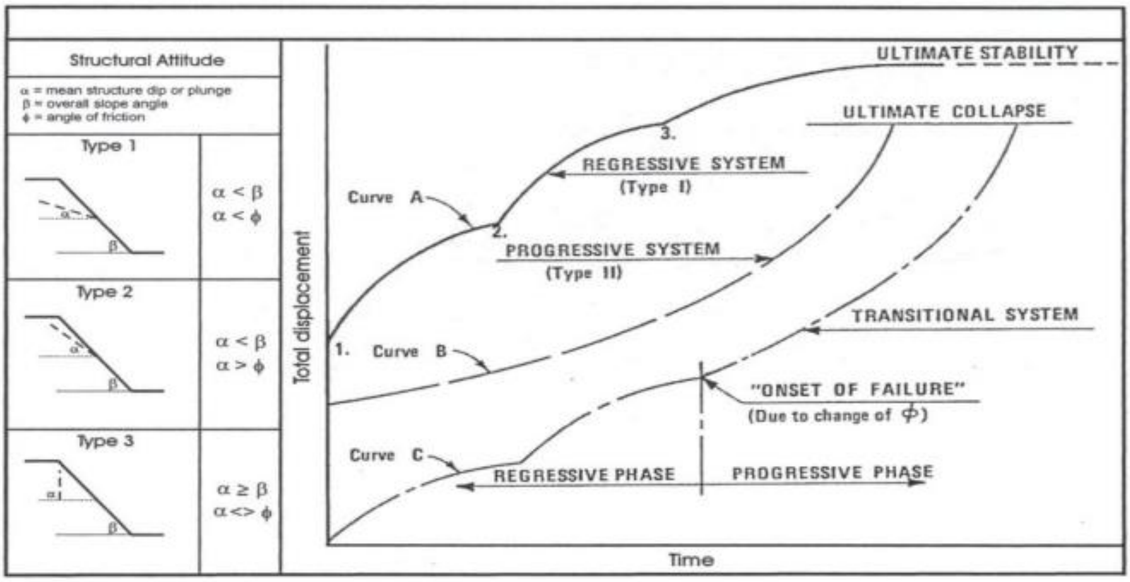

Figure 2. 6 : Stages of regressive and progressive displacement (Broadbent and Zavodni, 1982).

Slope collapses in mines throughout the globe were studied in detail. Broadbent and Zavodni model illustrate additional categorization of the pre-failure state of events into categories 1 and 2 (Cahill M, 2006). He claims that category 1, pre-failure deformation behaviour is event driven since it is influenced by a continuous duration of a particular, macro event like mining. Deformation patterns can be attributed to micro events, such as crack propagation within the rock and category 2 pre-onset-of-failure deformation does not involve a continuous period of a specific macro event, such as mining, and that the onset of-failure can occur with little or no prior warning (Cahill M, 2006).

(Cahill M, 2006) categorised the stages in the deformation of a mine slope as follows: Stage 1: Pre-collapse, primary rock mass creep modes; Stage 2: Pre-collapse, secondary rock mass creep modes; Stage 3: Onset of failure to collapse behaviour modes; Stage 4: Post-collapse behaviour modes; Stage 5: Post-collapse, post-mining/recovery behaviour modes.

Zavodni's regressive stage (type I, figure 2.6) corresponds to the pre-collapse main rock mass creep mode, or stage 1 of Mercer's model. Phase 2 of the secondary rock mass creep mode before a collapse is analogous to the progressive system (type II, figure 2.6). In both the transitional system and the failure-to-collapse behaviour pattern, stage 3, the slope goes from experiencing gradual displacement to failing. The most noticeable difference between the two models concerns the post-collapse behaviour of mine slopes categorised as stages 4 and 5.

The slope's behaviour immediately after a failure (stage 4) is increasing displacement, while the slope's behaviour after mining (stage 5) is the opposite. (Cahill M, 2006) identified six principal post-collapse deformation modes, which are named as follows: S4-type 1: Disintegration; S4-type 2: Partial recovery and gradual deceleration to creeping; S4-type 3: Full recovery, velocity almost completely stops; S4-type 4: Partial recovery followed by another final collapse; S4-type 5: Ratchet mechanism; and S4-type 6: High creeping rate and probably accelerating. If the failing slope rapidly changes between types 2 and 6, as (Cahill M, 2006) suggests it may, a complicated deformation pattern would emerge between minutes to years. Transient causes, such as a shifting phreatic surface, seismic activity, or a shift in geometry, may potentially cause a reversal in the deformation mode (Cahill M, 2006). Long-term stabilisation of the rock mass occurs in the post-mining condition, however reversal from stage 5 to stages 3 and 4 is possible according to long-term creep theory. The fifth stage of slope rehabilitation is characterised by a regressive condition (Cahill M, 2006). The deformation can simply be explained as initiation typically occurs at a local level that grows progressively to larger areas.

This section of the literature review explains that rocks deform in a number of different ways, and they can move about at different speeds and in different ways, depending on the conditions. When occurring on pre-existing structural discontinuities or through intact rock mass, deformation is simple and easy; when involving a mix of failure mechanisms, it is more complicated. Slope failure in mines is often caused by rock deformation, although the causes of this failure vary from mine to mine and even from slope to slope within the same mine. In various environments, the same rock mass might have distinct responses.

2.2 Slope Monitoring Systems

The primary goals of a slope monitoring programme are safety of humans and production operations, offer prior notification of instability, slope behaviour related to geotechnical details and evaluate a slope remediation design (Sjöberg, 1996). These objectives can be achieved by verifying mine design, providing technical confirmation of stability for production and management personnel, serving as a warning system for unstable areas, monitoring and measuring unstable zone movements, and providing a crucial technique for minimising the danger of slope instability (Kayesa, 2006b).

To monitor slopes and dumps in opencast mines in real-time and to send out early warning signals, many mines currently use radar for slope stability monitoring. In India, opencast mines make up about 4 out of 5 mines. Therefore, slope monitoring is essential to the design of any surface mine, particularly as the mine grows deeper and steeper as a result of production demands and technological advancements. Slope monitoring systems have developed over time, and when choosing a system, factors including coverage, mode of operation, cost, installation, and maintenance are crucial. The monitoring system installed is at the mine operator's discretion and will vary according to the mine's nature and size.

A more in-depth analysis of the goals and preparations for monitoring programmes may be found in the works of Barla, Chiappone and Vai (N. Harries & Holmstrom, 2007). Key features of a well-designed monitoring system include; Early detection of potential impending failure; Notification of alarm exceedance; Analytical capabilities in analysing present circumstances and estimating future projections; Confirming physical parameters are within acceptable tolerance range (deformation, pore pressures, etc.).

Table 2. 2: a risk-based, hierarchical strategy for slope monitoring, Rio Tinto Iron Ore (de Graaf, P.J.H., & Wessels, S.D.N. 2013).

<table>
<tr><th>Risk of Failure of Slope</th><th>Method of Monitoring</th><th>Frequency of Monitoring</th></tr>
<tr><td rowspan="2">Low</td><td>Visual inspections</td><td rowspan="4">The monitoring frequency increases top to bottom (Visual inspection to Automated extensometers)</td></tr>
<tr><td>Manual extensometer</td></tr>
<tr><td rowspan="2">Moderate</td><td>Laser scanners</td></tr>
<tr><td>Automated extensometers</td></tr>
<tr><td>High</td><td>Automated total station</td><td rowspan="2">Near-real-time monitoring and urgent alarms</td></tr>
<tr><td>Critical</td><td>Ground-based radar</td></tr>
</table>

Maintaining a safe working environment and maximising ore recovery requires quick monitoring data analysis, and reaction. Rio Tinto made GRAHAMS, or Geotechnical Risk and Hazard Assessment Management System, to analyse and record the concerns of economics and safety of the slopes. Each risk evaluation addressed instability mechanisms, slope geometry, design recommendations, and personnel and equipment exposures. Visual inspections are used to monitor lower-risk slopes. As the risk rises, the intensity and frequency of monitoring increase to provide accurate data and real-time monitoring. Table 2.2 summarises Rio Tinto Iron Ore risk-based monitoring. The monitoring system is part of the geotechnical of their Trigger Action Response Plan (TARP).

Slope failure is not natural and does not occur on its own. Each failure has a scientific basis, and if the failed area is monitored correctly, the failure will not occur without notice. Predicting the exact point of failure is difficult because the eventual collapse depends on various elements, including the kind of rock, the height of the slope, the presence of water, and the manner of failure itself. Using displacement monitoring results, the best-proven sign of approaching failure is an increase in any slope's movement rate.

Slope monitoring has traditionally relied on wireline extensometers, inclinometers, borehole extensometers, and other similar instruments. These methods are limited to working in the daylight; they cannot identify the failure processes involved. To prevent failures, remedial actions, and solutions to instability, slope monitoring programmes should be in place. Continuous detection and monitoring of deformations are required to take appropriate preventive measures. Modern-day methods allow for continuous monitoring. Robotic total stations, LIDAR (Light Detection and Ranging) scanning, Global Positioning System (GPS), Time Domain Reflectometry (TDR), digital photogrammetry, high resolution micro-seismic, and Slope Stability Radar (SSR) are some of the more current and upcoming technologies used to monitor slopes.

(Read & Stacey, 2009a) state that the major goals of a slope monitoring programme are to maintain safe operating conditions, warn of potentially unstable terrain, offer information for slope analysis, and evaluate an implemented slope repair scheme. (Sjöberg, 1996) lists three slope monitoring programme aims as to keep activities safe, allow personnel time to respond, and provide geotechnical information about slopes. (Kayesa, 2006b) stated that slope stability monitoring's main goals are I to ensure a mine's design, (ii) to maintain, steepen, or reduce slope angles for economic and safety reasons,

(iii) to give mine workers confidence in the open-pit mine's stability, (iv) to warn of unstable pit portions, (v) to provide information on how fast unstable zones are moving, and (vi) as a critical risk factor. A surface mine monitoring system usually includes a surveillance system that monitors slope performance and movement (Wyllie & Mah, 2004). Background monitoring evaluates slope stability throughout the mine to determine long-term slope movement patterns. An active monitoring system with near-real-time data, analysis, and slope instability warnings must be installed in problem locations identified by the background monitoring system. Active monitoring requires better precision and faster measurement updates than background monitoring.

Some of the basic terminologies that will be used in this section of the literature review and further in the thesis has been defined in table 2.3;

Table 2. 3 : Basic slope failure terminologies

Instability	Deformation behaviour not involving collapse or failure (Amitrano & Helmstetter, 2006)
Progressive deformation stage	Acceleration stage of the slope leading to failure 12(Zavodni & Broadbent, 1978)
Regressive deformation stage	Deceleration stage leading to a stability (Zavodni & Broadbent, 1978)
OOA or Onset-of Acceleration	Transition point from a deceleration to an acceleration stage of a slope.
TU or Trend Update point	Indicating a transformation in an accelerated deformation trend and/or a substantial decrease in noise (Dick et al., 2015a)
Slope failure	Irreversible deformation of a slope, and the slope does not meet its function.
Predicted life expectancy	The difference between slope failure and the time predicted (Mufundirwa et al., 2010a)
Inverse Velocity Trend Line	Straight line showing the best fit of the Inverse Velocity data.
Onset of Failure	This is the point that describes the transition from regressive deformation to progressive deformation (Broadbent & Zavodni, 1982)

All the above terminology is illustrated in figure 2.7 for better understanding;

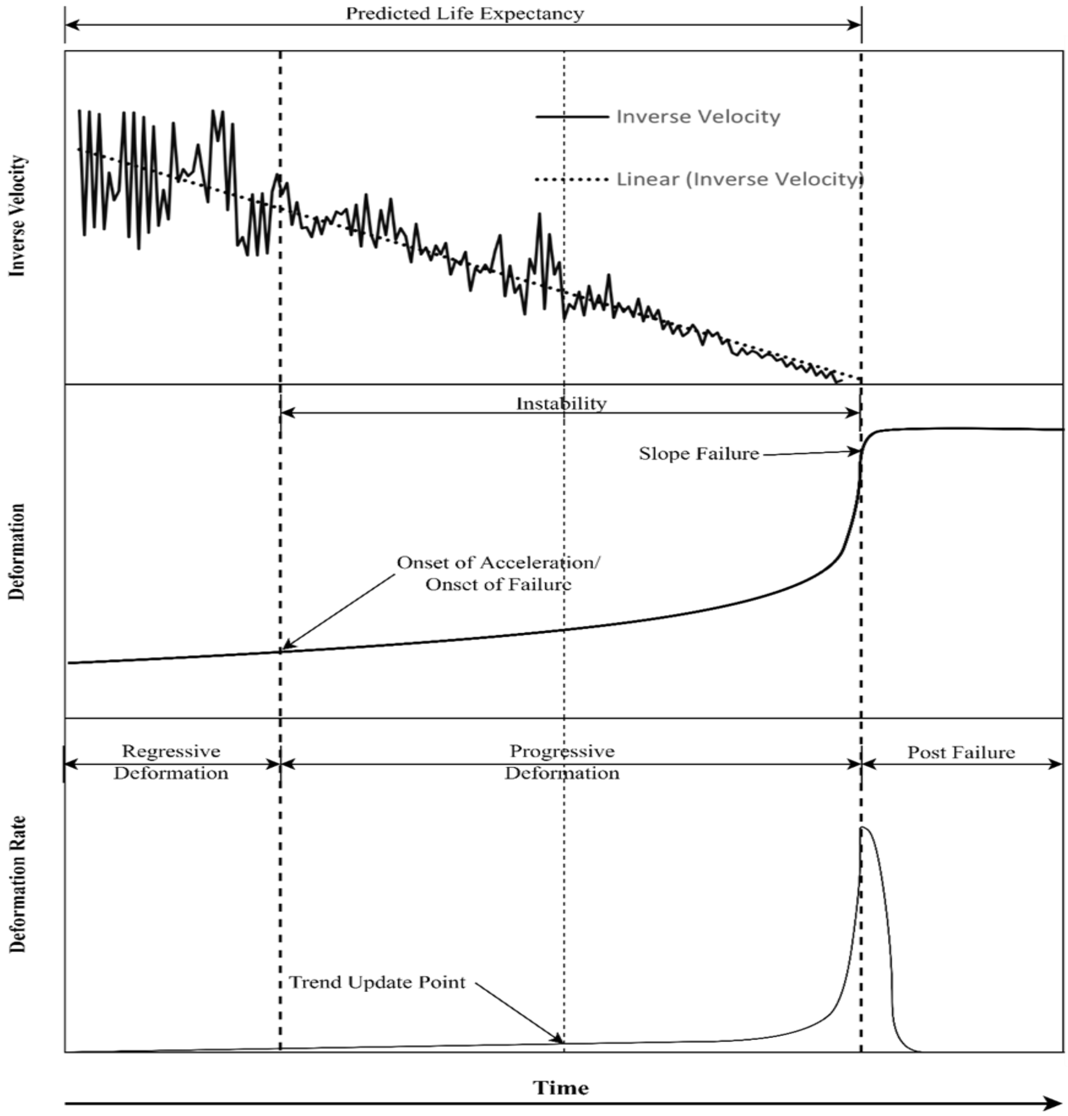

Figure 2. 7 : Basic Terminologies related to Slope Failure are represented with graphs of Inverse Velocity, Deformation and Deformation Rate versus time

For monitoring mine slopes there are various monitoring techniques from simple visual inspection to complex GPS and radar scanning. All these techniques can be classified into conventional and modern-day techniques, as presented in figure 2.8.

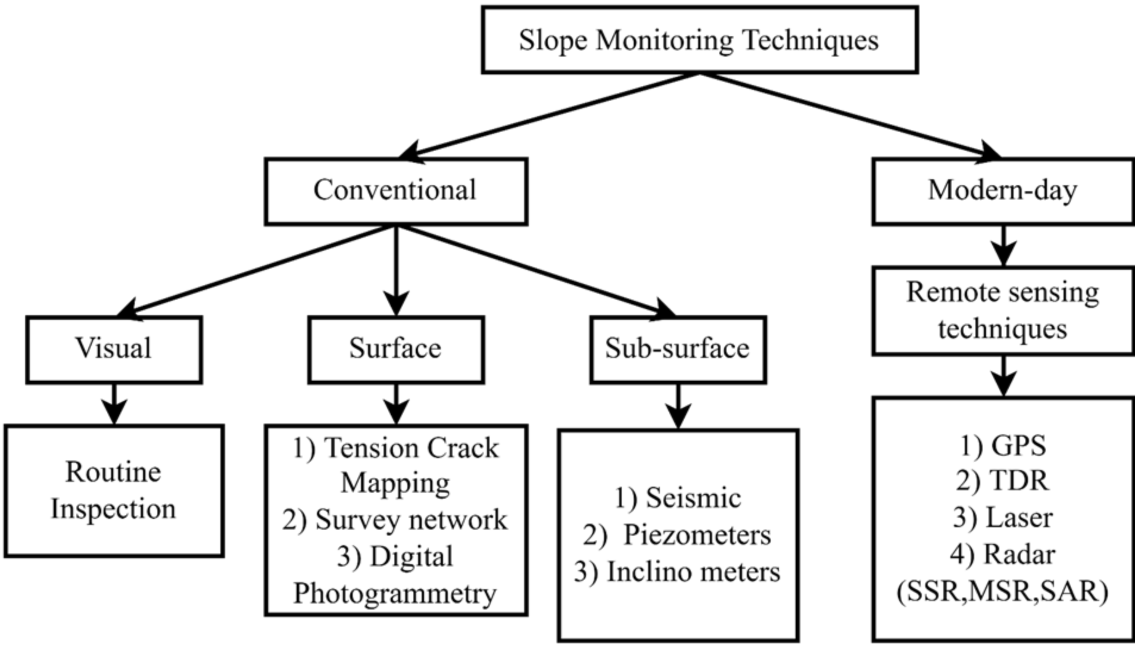

Figure 2. 8 : Slope monitoring techniques

2.2.1 Conventional Techniques

Conventional or traditional monitoring techniques for slope monitoring encompass a spectrum of approaches vital in geotechnical and mining engineering. Physical examination involves scrutinizing tension cracks on the slope face and analysing surface features and topography to identify signs of potential instability. Surface surveys employ inclinometers and tape extensometers to measure slope angle changes and surface displacement, crucial for detecting deformations. Subsurface techniques using instruments like piezometers, inclinometers, and tiltmeters provide critical data on pore water pressure, slope deformation, and weather-induced risks. Historical data examination further enhance understanding of potential failure behaviours.

Visual Inspection

Slope monitoring within mining operations encompasses the active involvement of all personnel engaged in mining activities. The initiation of any slope monitoring program commences with a fundamental yet pivotal step, namely visual inspection. In this stage, mine workers diligently scrutinize the slope to detect and report any indications of deformation, which warrant closer inspection and ongoing monitoring. In practice, the monitoring process extends to managerial levels, where regular and comprehensive inspections of both active mine slopes and dump slopes are conducted. These inspections are not arbitrary but are guided by a systematic approach. The data obtained during these inspections is meticulously compared with observations from previous visits. This comparative analysis provides essential insights into the evolving state of the slope.

Slope monitoring used to rely on visual observations and basic instruments. Visual observations were crucial for identifying slope instability. Tension cracks, irregular water flow patterns, bulges or creeping movements, and changes in the arrangement, position, or distribution of loose rocks, debris, or fragments commonly found at the top of a slope were among these cues (Girard, 2001b).

Surface Monitoring

Surface cracks indicate instability. Existing cracks are highlighted to distinguish them from new ones. A survey tape, rod, or extensometer can measure crack separations to calculate surface point movement. Figure 2.9 shows crack metre types.

Figure 2. 9 : a) Optical, b) Mechanical and c) Electrical Crack Meter (source: Dusense LLC, RST Ltd., Earth System S.r.l.)

Total stations need a survey network of prisms or monitoring stations spaced regularly on the slope. The target prism's relative motions at monitoring locations help identify deformation and key failure zones. Surveying robots or robotic total stations are increasingly used in monitoring to save time. With long-range, high-accuracy total stations, prism slope monitoring is nearly real-time. A built-in photogrammetric camera and GNSS receivers enable automated, accurate, efficient, and cost-effective survey solutions with robotic total station networks. Figure 2.10 shows slope survey station identification.

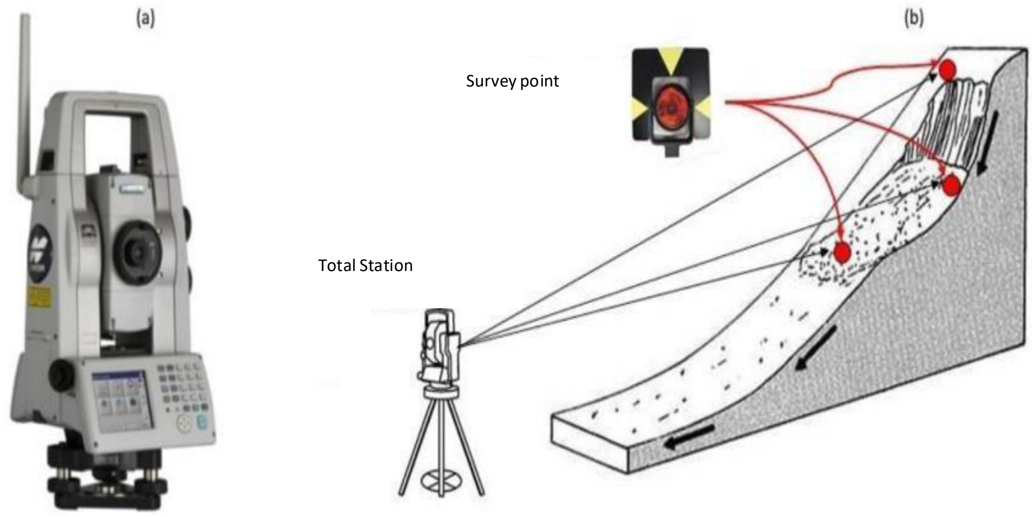

Figure 2. 10 : (a) Total Station and (b) recognition of survey points along the slope (Source: ELEDIA Research Center)

For decades, digital photogrammetry has compared images to study slopes. Recently, it has added 3D models from terrestrial images. The latest digital image processing tools can automatically collect discontinuities and related data, eliminating human bias and allowing the survey of inaccessible areas and steep rock faces. Digital photogrammetry compares slope photos and 3D models from land photographs. Photographing a subject from different angles and using each location's lines of sight creates a 3D image. These photos create 3D faces. A 3D graphic shows faults, dykes, joints, and failure planes. Repeating the method may reveal more failure planes and zones (Little, 2006a). Digital photogrammetry reduces human error and labour expenses and permits scanning steep rock faces. This saves money and enables real-time measurements (Girard, 2001b). Slope monitoring is now more accurate as a result of robotic total stations and remote sensing.

Subsurface Monitoring

Subsurface methods include installing equipment in long boreholes or sending signals into rock. Sensors detect slope deformation and stress accumulation along weaker planes. Extensometers map crack movement to distinguish unstable from stable rock mass. As earth accelerates along fractures, the wire weight moves, and the monitoring device with digital outputs records displacement measurements. Inclinometers detect steady or accelerating subsurface motions to limit deformations. Slope inclinometers measure slope amount, depth, direction, velocity, and type. Inclinometer sensors measure acceleration with servo-accelerometers. An extensometer and inclinometer measure slope relative movement. Groundwater-related slope instabilities are monitored with piezometers.

2.2.2 Modern-Day Techniques

Remote sensing systems like Ground-based radars and Global Positioning System (GPS) are increasingly integrated into many slope monitoring and management programmes. GPS is a navigation and positioning system that follows satellites' electromagnetic signals. It continuously monitors slopes, landslides, and subsidence. Deformation and slope movements are calculated by comparing GPS station start and end positions. Location precision in each system's range of operations is improved by Differential GPS (DGPS) from 15 m to 1–3 cm. DGPS provides real-time slope stability and deformation rates. GPS, photogrammetry, total station networks, and remote sensing images are used to monitor mine slope stability. However, vegetation and mountains limit GPS's suitability for fast deformation scenarios. Other systems like laser scanners, LiDAR (Light Detection and Ranging), Time Domain Reflectometry (TDR) are also being used in mines.

Monitoring system selection depends on area coverage, mode of operation, cost, installation, and maintenance. Inclinometers, TDRs, extensometers, and LiDARs are too slow and inaccurate for real-time information and early failure prediction. The slope monitoring radar transformed surface mine geotechnical risk assessment. Last decade, radar became a cutting-edge technology for real-time slope monitoring of pit wall movements in surface mining. Vertical and horizontal slope faces are scanned by the antenna's radar beam and a rapid, wide-area slope tracking is done in all weather. New Slope Stability Radar (SSR) features include broad area coverage, remote operation from farther away, and better spatial resolution. SAR/InSAR and MSR can detect large rapid slope failures and small slope deformation movements over time in open-cast mines (Osasan, 2012). Radar systems provide sub-millimetre accuracy for long-range monitoring, broad aerial coverage, and customised aerial coverage.

Laser Scanner

Survey networks are too risky and impractical to monitor every mine slope failure block, but new scanning laser rangefinders can detect movement over large areas. Laser scanners model mine slopes without reflector prisms (McHugh et al., 1900). Laser scanner point cloud data is automatically analysed by systems like Site-Monitor. A detailed, accurate, and uninterrupted slope profile can be created with up to 8,000 measurements per second. For automated and manual long-range surface profiling up to 2,500 metres with 50 mm accuracy, and can capture 10mm slope movements at 1000m

(Little, 2006c). Laser scanners are portable like radar systems, but compared to radar, they are less accurate for slope monitoring.

Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) uses an electrical pulse delivered through a conductor to check for material discontinuities. A reflected pulse's polarisation, amplitude, and frequency can indicate material failure. The most typical use of TDR in slope stability is measuring rock mass deformation (Chung & Lin, 2011). A coaxial cable is grouted into a drill hole, and TDR transmits an electrical pulse down this cable. The coaxial cable has crimps at regular intervals to reflect signals. Examining the reflected signals determines rock mass deformation. The cable signature "spikes" when an electrical pulse contacts a break or distortion. The size of spike rise determines movement magnitude through a computer attached to the tester (Dowding et al., 1989). As coaxial cables are better than inclinometers for sensing rock mass displacements, they provide lower installation costs, higher hole depths, real-time remote monitoring, and fast deformation detection. TDRs are cheaper than probe inclinometers and data recording software. TDR's benefits over regular inclinometers like cable costs roughly 20% less than inclinometer casing; possible deeper operation (Kane & Beck, 2000). All TDR equipment is surface-based, and the remote monitoring is quick and the data is received over telecommunications with remote scanning and recording intervals to analyse zones of interest (Chung & Lin, 2011).

Light Detection and Ranging (LiDAR)

Laser imaging devices or three-dimensional scanners can detect slope stability, deformation, and other geotechnical data with simple, quick, and accurate 3-D scanners by directing a laser beam at the monitoring area to graphically/digitally depict slope and relative motions based on reflected radiation journey time. Virtual slope replicas are created in minutes, like photos of key areas. Static and mobile surveying platforms can instantly generate digital elevation models with modern LiDAR scanners. A simpler scanner setup increases productivity and these units are speedier and more contemporary than conventional total stations. Sensors gather data from a vast area concurrently by rotating mirrors and prisms broadcast and receive several beams of data acquiring 6,000 to 10,000 data points every second. Survey office computers utilise Ethernet to receive scanned data quickly. Depending on the target's reflection coefficient, they can scan up to 2500 metres with 1/25-mm precision. Customised software lets users choose data gathering places and frequency. Laser monitoring, like prism monitoring, may not always detect slope failures in their early stages (Little, 2006a). While these technologies are valuable for monitoring and measuring various aspects of slope stability, they have limitations when it comes to early detection of potential failures. LiDAR is suitable for large-scale topographic mapping from the air, providing a broad overview of a slope's surface. Laser scanners, being ground-based, provide highly detailed, localized 3D models of specific areas, making them well-suited for accurate and detailed monitoring of slope stability and structural features.

Global Positioning System (GPS)

Surface mines can track slope movement with GPS. This method is more accurate and cheaper than inclinometers and extensometers. Monitoring area has GPS antennas. GPS satellite data locates these antennas, and computers collect these location data and analyse slope displacement to predict failures. Table 2.4 summarises the most common surface mine deformation monitoring instruments. The table shows each instrument's coverage and monitoring roles, highlighting its best uses.

Table 2. 4 : Comparison of various slope monitoring systems (Little, 2006)

Instrument	Wall Coverage Type		Best-Suited Monitoring Role	
	Point	Area	Background	Active
Laser & Prism	✓		✓	
Satellite InSAR		✓	✓	
Ground-based laser scanning		✓		✓
Extensometer	✓			✓
GPS	✓		✓	
Ground-based radar		✓		✓
Photogrammetry		✓	✓	

Radar Systems

Radio Detection and Ranging (RADAR) detects and locates moving and stationary targets' range, height, direction, and speed. Radar emits electromagnetic radiation and detects echoes from targets, and echo signals offer target information (Merrill & SKOLNIK, 1990). The time it takes radiated energy to travel to and from the target determines the range. A directional antenna measures the echo signal's arrival angle to determine the target's angle. The scanning pattern of a radar system is demonstrated in the figure 2.11.

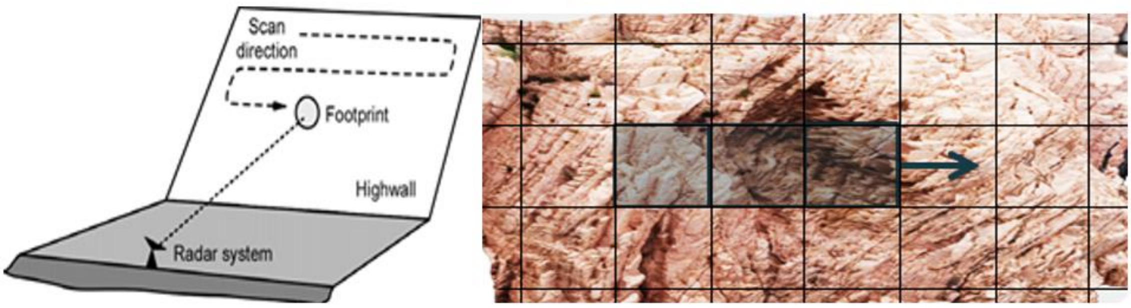

Figure 2. 11 : Slope Stability Radar scanning pattern (McHugh et al., 1900)

RADAR Types

Radar may be categorised depending on its main properties: Meteorological observation radar, Surveillance Radar, High-resolution radar, Pulse compression radar, Pulse radar, FM-CW radar, Moving Target Indication (MTI), Pulse Doppler radar, Continuous wave radar, Imaging radar, Side looking Airborne Radar (SLAR), Synthetic Aperture Radar (SAR), Inverse Synthetic Aperture Radar (ISAR), Weapon control radar, Guidance radar, Tracking radar (Merrill & SKOLNIK, 1990).

South Africa's Reutech Radar Mining developed the Movement and Surveying Radar (MSR-200) in January 2006. It offers geo-referenced surveying information, enabling inaccessible surveying places (Kothari & Momayez, 2018). Mining Slope Radar (MSR) surveys offer crucial 3-D slope data with submillimeter precision, operating seamlessly in all weather conditions day and night. Widely used in mining regions globally, including Africa, South America, the U.S., Europe, Indonesia, Papua New Guinea, and Australia, MSR, particularly the IBIS-M radar, boasts exceptional spatial resolution (1km at 0.5m x 4.4m) and a remarkable working range of 4,000m. It's power-efficient, running on solar panels, batteries, or a backup diesel generator, and offers remote control capabilities via radio with automated atmospheric adjustments, ensuring uninterrupted monitoring (Baranwal et al., n.d.-b).

Synthetic Aperture Radar (SAR) is a critical ground-mapping tool used in satellites and aircraft, providing high-quality Digital Elevation Models (DEMs) and pinpointing surface changes or moisture variations with high-resolution images, regardless of day or night. Elevating the capabilities, Interferometric SAR (IFSAR or INSAR) merges multiple SAR images for elevation and surface change maps, offering comprehensive insights into terrain dynamics and alterations (Peltzer et al., 1997). Radar has been used since 2002 at Leinster nickel mine, Australia, to monitor walls with poor trust in prisms and eye examination to study movements preceding slope collapse (Cahill M, 2006).

In 2002, Australian researchers from the University of Queensland developed SSR, a radar system for monitoring mine slopes using differential interferometry. SSR-XT, a type of SSR by GroundProbe shown in figure 2.12, is tailored for targeted safety-critical monitoring, while SSR-FX quickly detects hazards in broad areas, and SSR-SARx is ideal for long-range and long-term monitoring. These radar systems utilize wireless Personal Alerts (PALS) for timely warnings via text, audio, vibration, sirens, and lights. They can be conveniently mounted on vehicles for site flexibility, ensuring accurate monitoring with a signal-to-noise ratio (SNR) of 1.0 or above, critical for achieving a 0.1 mm system accuracy (N. Harries & Holmstrom, 2007).

Figure 2.13 is an image of SSR from a field visit conducted during this research work. During field visits in this research, SSR technology's prowess was evident. SSR scans slopes both horizontally and vertically at a rate of 10° per second, covering 60° vertically and 340° horizontally. Equipped with a 0.92m scanning parabolic dish antenna, computer, remote power supply, warning systems, CCD camera, and communication setup, SSR ensures thorough monitoring (McHugh et al., 1900).

Figure 2. 12 : SSR-XT (Source: GroundProbe SSR).

Operating at a remarkable distance of 2800m from the target slope without reflectors, SSR achieves a line-of-sight displacement of just 0.1 mm. It effectively geo-references deformations and overlays them with mine coordinates, aiding mine planning and design. The system compares phase measurements across scans to estimate slope movement, creating images displaying deformation relative to a reference image. These visuals, like rainbow plots, provide a comprehensive view of displacement, facilitating quick evaluation of failure extent and high-movement zones. Time/displacement graphs are available for precise rate analysis, and dedicated software enables remote data examination and analysis, empowering informed decision-making.

Figure 2. 13 : SSR installed in Kusmunda Mines, SECL, India

Unlike conventional monitoring systems, the SSR does not need reflectors or other equipment on a wall, as radar waves penetrate rain, dust, and smoke to give 24/7 readings. Signal processing may reduce atmospheric and false signals. An umbilical connection links the scanning antenna and radar electronics box. An umbilical connection refers to a physical link or cable that connects the scanning antenna to the radar electronics box. In the context of radar systems, particularly ground-based radar systems like the Slope Stability Radar (SSR), this connection is vital for transmitting data and signals between the scanning antenna and the radar electronics box. A computer in the radar electronics box can adjust the parabolic dish's elevation from –15° to 165° and azimuth from –170° to 170°. The scan takes 15 minutes for a 4000-pixel wall. A 100-meter-away rock slope has 2m x 2m pixels. The radar electronics box's intermediate frequency signal is up-converted to X-band (9.4-9.5 GHz) at the scanning antenna's feed. Radar data automatically compensates for variations in temperature, pressure, and humidity.

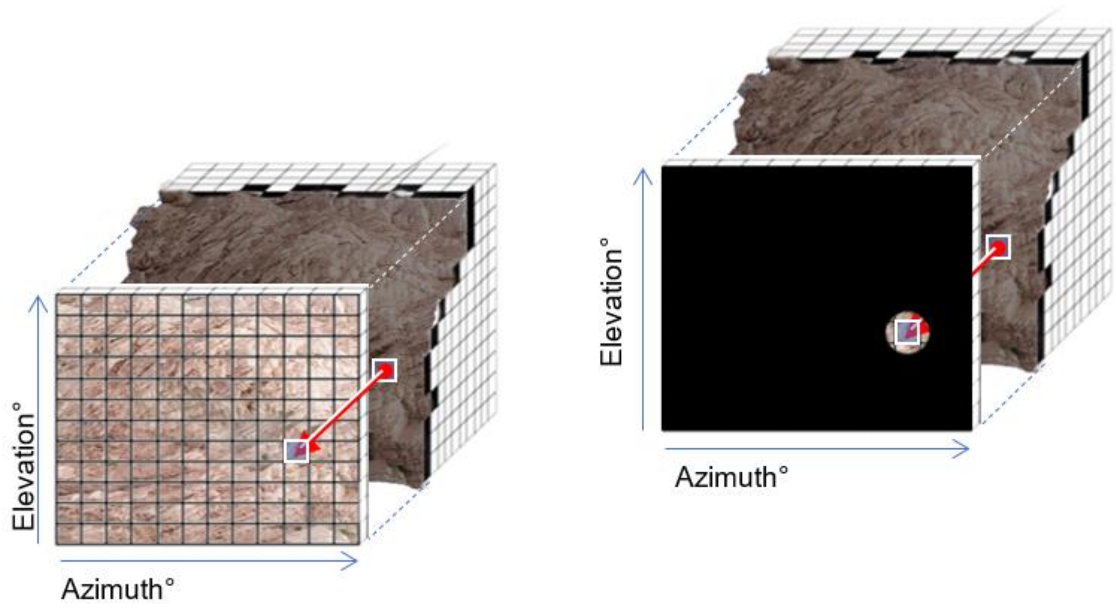

Figure 2. 14 : A 3-D wall surface to a 2-D pixel image (Source: GroundProbe SSR)

Slope Stability Radar (SSR) captures slope wall data in units called voxels, which are essentially three-dimensional pixels. These voxels represent small volumes of the slope, accounting for its length, width, and height. They play a crucial role in SSR data analysis, offering insights into the slope's deformation over time. SSR divides the monitored slope into a 3D grid, with each grid element or voxel storing deformation information like displacement and velocity. By studying these voxel-based changes over time, we can assess slope stability, identify potential concerns, and predict failures. Voxels are fundamental in understanding and ensuring safety and stability in mining operations, forming a detailed picture of the slope's behaviour for effective analysis.

A wall/slope which is scanned is converted into a 2D image as shown in figure 2.14. The conversion from a 3D voxel representing a portion of a slope to a 2D pixel displaying deformation on a pixel-by-pixel basis involves a process known as projection. In this case, it's specifically a 3D to 2D projection, where the information within the 3D voxel is transformed and represented in a 2D image or display. Initially, data is collected from the SSR system in three dimensions (3D). This data includes information about deformation, such as displacement, velocity, or other parameters, for each voxel within the monitored portion of the slope. The deformation information from each voxel is projected onto the chosen 2D plane, resulting in a 2D representation of the deformation data. The deformation information obtained from the 3D projection is mapped to corresponding 2D pixels. Each pixel in the resulting 2D image represents area on the projection plane. The 2D pixel-based representation allows for easy visualization and analysis of deformation on a pixel-by-pixel basis. Each pixel's intensity or colour can represent the magnitude of deformation, allowing for a clear visual understanding of deformation patterns. This helps to interpret the 2D representation to gather insights into the deformation patterns and behaviour of the slope.

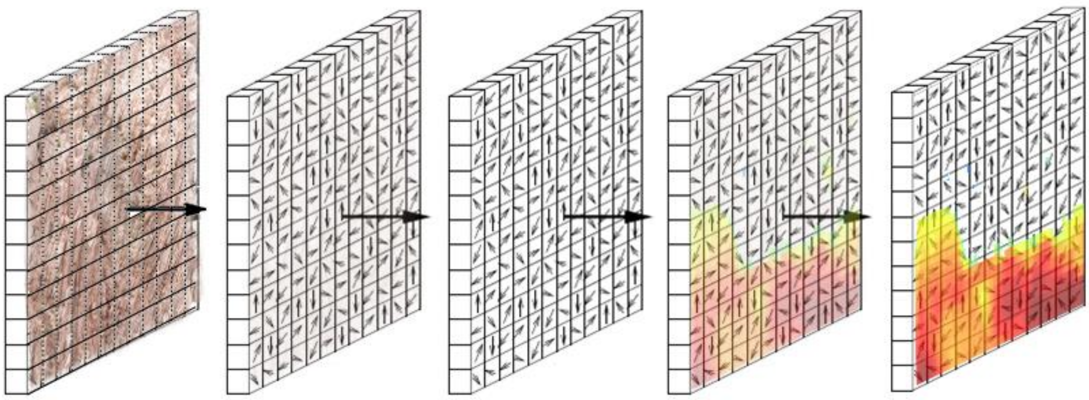

Figure 2. 15 : 2D deformation images of the wall generating deformation heatmaps (Source: GroundProbe SSR)

A spatial filter helps fix signal problems caused by weak signals in radar images. When moving vehicles block a small part of radar pixels, this can be corrected in subsequent scans. To study how walls move or change over time, interferograms are used. These are created by merging radar images of the same area taken at different times. By comparing these images, changes in pixels can be seen by colour variations. Heat maps of deformation are generated by SSR after the evaluation of the deformation pixel-by-pixel as shown in the figure 2.15.

According to Bye research (Table 2.5), slope stability radar has a 93% success rate in identifying slope failures, whereas other technologies have a rate below 90%. Combining radar with other approaches yields almost 100% effectiveness (Bye, 2009).

Table 2. 5 : Success rate of various slope monitoring techniques (Bye,2009)

Monitoring Type	**Success Rate**
Only Visual Monitoring	32%
Only Prism/Crack Meters	45%
Visual + Prism/Crack monitors	63%
Visual + Prism/Crack + Laser	86%
Radar Only	93%
Visual + Prism/Crack + Radar	97.5%
Visual + prism/crack + laser + radar	99%

Slope stability radar can act as a warning system. In general, an early warning system has a few main goals, such as monitoring, which consists of data collection, transmission, and equipment maintenance; prediction and analysis, which thresholds can do, engineer's expertise, and prediction methods. As technology has advanced, it has become common practise to use both conventional and cutting-edge methods for monitoring slopes. Conventional monitoring is used to complement modern techniques for improving active monitoring of slopes at a number of mines, including the Leinster Nickel Mine, Potgietersrust Platinum Mine, Tom Price Mine, Barrick Goldstrike Mine, Bingham Canyon Mine, Kemess South Mine, Grasberg Open Pit, Wallaby Mine, and Savage River Mine. Progress in slope monitoring has been spearheaded by ground-based radar, which conducts periodic scans of monitoring stations to search for accelerations and extrapolate them to anticipate impending collapse. Monitoring slope movement is the best way to identify and can help greatly to anticipate slope instability.

Radar monitoring has revolutionized failure prediction and provided insights into previously unobservable processes. The effectiveness of real-time identification and failure prediction hinges on both monitoring equipment and human comprehension. Traditional equipment such as theodolites, total stations, extensometers, inclinometers, and piezometers offer limited data, covering only specific sites, potentially overlooking failure occurrences between these sites, especially when they are widely spaced. Installation of conventional monitoring techniques poses challenges, particularly in surface mines with steep high-walls and restricted access to unstable regions due to lack of benches. Moving traditional monitoring equipment is not only costly and time-consuming but also perilous on unstable slopes. Accuracy of measurements is affected by vegetation on the face, and erroneous signals can be generated by vehicles. Radar monitoring systems integrate crucial modules like atmospheric correction and disturbance detection to enhance accuracy by correcting slope displacement readings for atmospheric anomalies and identifying disturbances such as vehicle movements that might cause errors. Prominent radar systems like Slope Stability Radar (SSR), Measurement and Surveying Radar (MSR), and IBIS-M stand out in monitoring vast slope regions day and night, regardless of weather conditions or environmental hindrances like dust or haze.

This section highlights various slope monitoring methodologies, with a special spotlight on the mining sector's groundbreaking utilization of RADAR, paving the way for real-time data on wall movements even amidst challenging environmental factors and ensuring continuous improved safety against slope movement related hazards.

2.3 Slope Failure Prediction Techniques

Techniques and recommendations for predicting the moment of failure or outlining the conditions of a predicted slope collapse abound in scientific literature. Most forecasts of failure time are based on the idea that displacements on slopes preceding failure may be characterised by a creep curve (Bennett, 1982). Figure 2. 16 shows creep curve. Creep is time-dependent deformation that takes place under steady, mostly plastic stress (i.e., most of the deformation is not recoverable after an initial elastic, recoverable strain). Some researchers have described the second stage for brittle materials as a linear superimposition of the first and third phases or a transition between the two, despite the fact that the standard model only accounts for three stages (Amitrano & Helmstetter, 2006; Main, 2000).

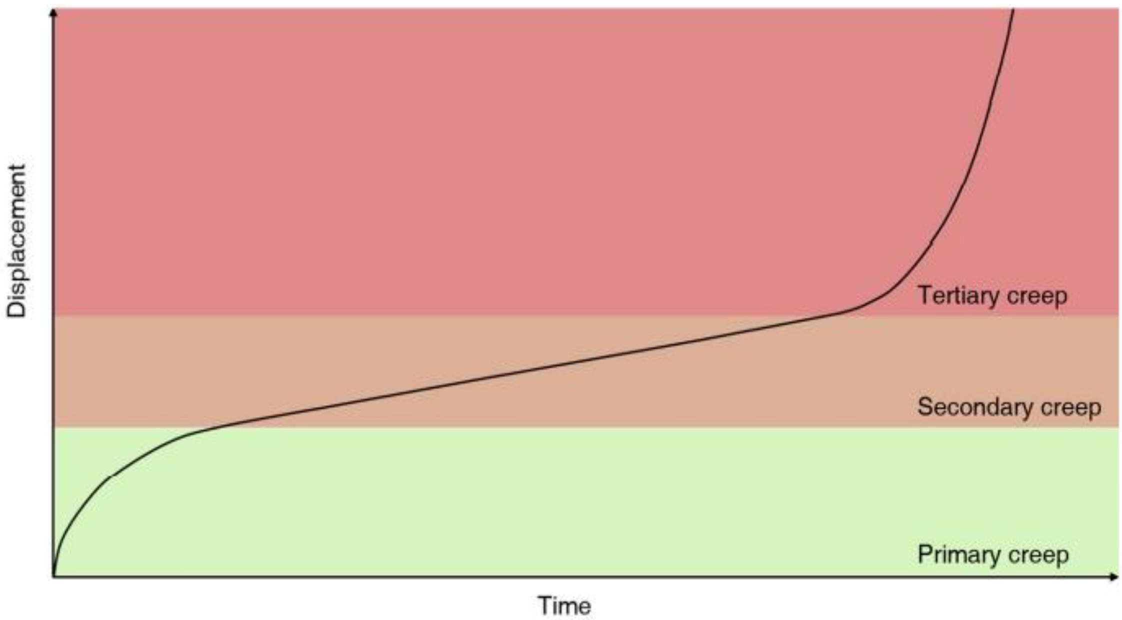

Figure 2. 16 : Conventional three-state interpretation of creep behaviour

However, the traditional view holds that there are three stages of creep: primary (or decelerating or transient) creep, where the strain rate decreases logarithmically; secondary (or steady-state) creep, where the strain rate remains constant; and tertiary (or accelerating) creep, where the strain rate rises steadily until failing or rupturing occurs or in simple terms; creep behaviours include decreasing of deformation with time (Primary), constant displacement rate (Secondary) or increasing of deformation with time (Tertiary). (Cruden & Masoumzadeh, 1987; Dok et al., n.d.; Liang et al., 2008; Varnes, 1983) all provide extensive research papers on the topic of creep.

Time-of-failure prediction techniques based on kinematic characteristics may be broken down into a various category. There are empirical approaches which encompass methods often extrapolate the time of failure by geometrical reasons, and they are based on the fact that the displacement velocity critically rises before failure. In certain circumstances, equations defined using semi-empirical techniques are derived and explained as special cases of the defining equations. Moreover, semi-empirical techniques which base their calculations on a general equation that connects the displacement rate to the acceleration, but they also make use of certain empirical constants. The aforementioned techniques may be used on slopes of any scale, regardless of their current activity level or the composition of the material they are made of (Intrieri & Gigli, 2016)

The first noteworthy approach to failure forecasting was developed by (Saito, 1965), who introduced a method to forecast the remaining time to slope failure from the secondary creep curve (Saito, 1965; Saito & Uezawa, 1961) or, more successfully, from the tertiary creep curve (Saito, 1965) not considering the earliest attempts at time-of-failure prediction in the literature (Heim, 1932; Jäggli, 1928; Sharon & Eberhardt, 2020).

While investigating the problem of predicting slope stability in open-pit mines, (Brox & Newcomen, 2003) referred to many different types of failure mechanisms, including planar, wedge, toppling, rotational/rock mass, complex, and some combination of these mechanisms. Instead of explaining how thresholds should be established, these authors offered concrete values for them, drawing in part on Zavodni's earlier recommendations relying on the deformation, where is the ratio of the highest deformation of the highwall to the overall height of the highwall, which is a more normalised quantity than the displacement and suggests more applicability outside of the lab. These authors identified 3 thresholds corresponding to ε, with values of 0.1% (indicating the emergence of tension cracks), 0.6% (indicating an acceleration of movement), and 1% (indicating impending collapse), which are then stated as a function of the rock-mass quality (described by the RMR, (Bieniawski, 1979). The region specified by and the RMR is partitioned into a stable region, an unstable region, and a transition zone. The authors acknowledged that the suggested technique does not take into account the kind of failure, and that the dependency on rock-mass quality and the tolerance to strain vary depending on the failure mechanism. As a result of the realisation that the displacement-time curve becomes almost vertical in the terminal stage of tertiary creep, (Xu et al., 2012) devised a method to account for this phenomenon. The displacement is normalised by dividing it by the mean velocity of the secondary creep in order to provide a universal and quantitative standard. The two-dimensional graphic generated by this technique is time-based. (Xu et al., 2012) proposed thresholds based on the values assumed by the tangential angle of the curve of this plot: when the angle is > 45°, the slope enters the tertiary stage; a value of 80° corresponds to a second threshold; eventually, if the tangential angle is > 85°, the slope deformation enters a highly accelerated state that is typical of pre-failure conditions.

Despite their inability to offer a time estimate for collapse, other approaches are often used in conjunction with slope failure prediction are numerical methods that include a broad variety of techniques for predicting future displacement values from historical measurements, such as analysing and modelling a time series (by, for instance, dividing it into numerous components, typically using machine learning). Furthermore, methods for defining thresholds are also used and they come in a variety of forms, and they all use different quantitative signals to hint at the possibility of a failure but cannot pinpoint exactly when it will happen.

Classifications within each category are not strict and might be argued over, but the approaches will be explained in a general historical sequence and grouped together based on resemblance. Therefore, getting an overview of these methods has become complex. To simplify, we have classified the available works on slope monitoring techniques based on the input and output data, as represented in figure 2.17. Some of these techniques have been used only in landslides, but we have included them because they show great potential in mine slope failure prediction.

Excluding the early attempts in literature (Heim, 1932; Jäggli, 1928; Eberhardt et al., 2008; Bonnard, 2006; Federico et al., 2015), the pioneering effort in failure prediction was by Saito and Uezawa (1961). They introduced a method to predict the time remaining before slope failure using either the secondary or more effectively, the tertiary creep curve (Saito, 1965; Saito & Uezawa, 1961). In their approach, they derived an empirical formula relating the constant strain rate ($\dot{\varepsilon}$) to the time left for failure or life expectancy (t_L) as mentioned in the table 2.6 equations.

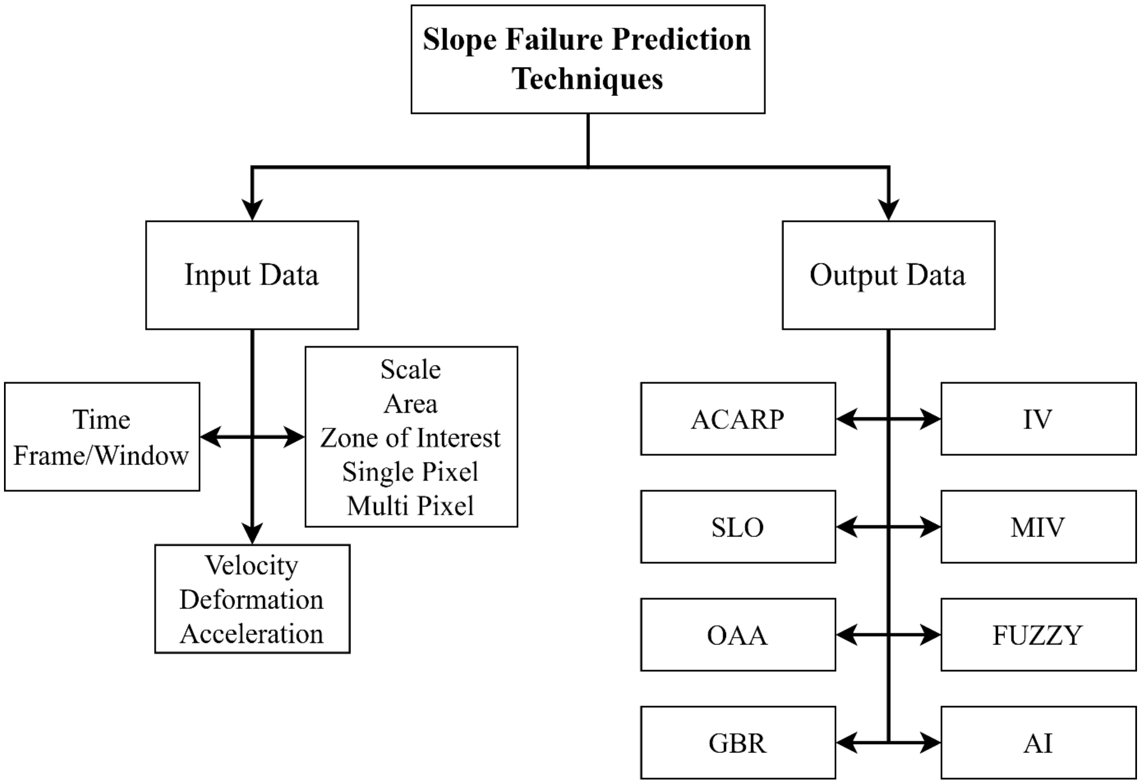

Figure 2. 17: Slope Failure Prediction Techniques

2.3.1 Input data for prediction of slope failure

Most researchers have taken deformation/displacement data or some derivative of deformation/displacement data as the input. The input in some cases started varying with the advent of better technologies such as remote sensing techniques as per the operator's requirements in accordance to the area, pixel size, zone of interest for analysis, time frame, deformation rate, and acceleration. Moreover, the operator can also decide the size of the pixel depending on the needed clarity. It can also be decided whether to use multi-pixel selections or single-pixel selections to calculate deformation or displacement, which leads to velocity and acceleration. Despite its limitations and assumptions, multi-pixel selection gives better slope failure prediction than single-pixel selection analysis. The deformation or displacement values in slope monitoring systems using Radar are taken from the pixels updated every few minutes (~15 minutes in the case of SSR), leading to velocity and acceleration data. These inputs can be further divided into various time frames, for example, velocity of 60 minutes, over 480 minutes, over 1440 minutes. Similarly, acceleration or inverse velocity data can be collected as input over various time frames.

2.3.2 Output

Once reliable monitoring data is collected, the most challenging task for the mine personnel in charge of safety is to put up appropriate alerts that indicate when a slope collapse is imminent. Most of the majority of work in slope failure prediction uses graphs to find the time of failure of a slope and can also be integrated to achieve better results.

Saito devised a graphical technique grounded in the tertiary creep curve (Saito, 1969) as shown in figure 2.18. This method involves selecting three points, A1(ΔD1, t1), A2(ΔD2, t2), and A3(ΔD3, t3), evenly spaced in terms of displacement ΔD. A1′ and A3′ are the projections of A1 and A3 on a line passing through A2, parallel to the time axis. M and N are the midpoints of A1′A2 and A1′A3′, respectively. The time of failure (t_f) can then be determined as the x-coordinate of the intersection of a line passing through A1′ and N′ with a line passing through M' and parallel to the time axis. Although initially recommended as a graphical approach, advancements such as calculation sheets and algorithms have made numerical solutions more practical since then (Saito, 1969).

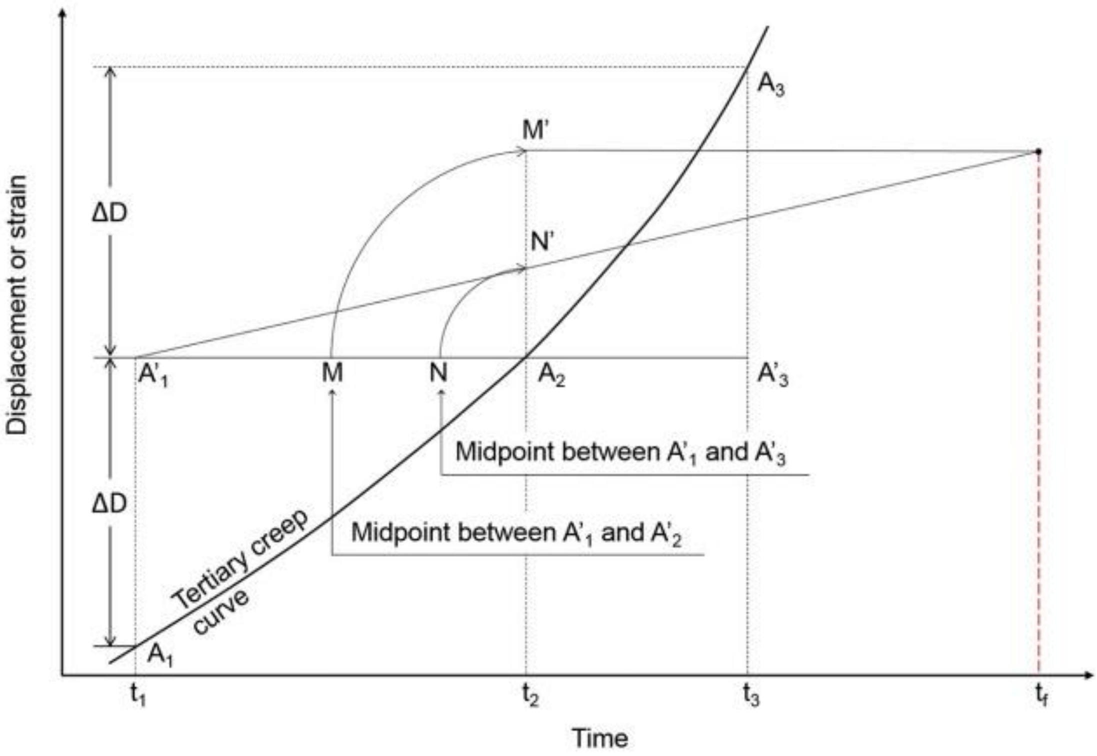

Figure 2. 18: Graphical approach for determining the time of failure in the tertiary creep range (Saito, 1969).

Hayashi et al. (1988) formulated an equation to forecast failure during the early phase of tertiary creep. Unlike many methods that are more effective in the later stages of tertiary creep, Hayashi et al.'s approach focuses on early prediction. They observed a correlation between higher initial velocity at the start of tertiary creep and the proximity to failure, leading to this predictive equation shown in the table 2.6. This approach hasn't gained widespread popularity, and the extent of variation in the values for c and m remains uncertain without broader application across different case studies. Its primary strength lies in early predictions, but this also means that adjustments for changing trends aren't possible, and the monitoring data must cover a sufficiently long period to detect the onset of tertiary creep. Fukuzono (1985a, 1985b, 1990) advanced Saito's concept by proposing a more straightforward graphical approach, widely adopted and considered the simplest method for determining a slope's time of failure. This method is applicable during tertiary creep, specifically when the slope experiences acceleration at time t_0 (onset of acceleration). At this juncture, two potential scenarios unfold: a) the velocity increases asymptotically until the collapse at time t_f, theoretically reaching v → ∞; b) following initial acceleration, the velocity declines, and the slope stabilizes without collapsing. Fukuzono (1985a) demonstrated that the inverse velocity (1/v or Λ) corresponds to the following in cases of gradual and continuous deformation under a constant load until failure.

Table 2. 6 : Slope Prediction Techniques with their basic formulae

Prediction Technique	Formulae
Saito &Uezawa (1961)	$log_{10}\, t_L = 2.33 - 0.916\, log_{10}\, \dot{\varepsilon} \pm 0.59; where$ $t_f = t_L + ti, where\ ti\ is\ time\ of\ prediction$ t_L *is time left to failure or life expectancy in minutes* t_f *is time of failure*
Empirical, graphical method (Saito, 1969)	$t_f = \dfrac{t_2^2 - t_1 t_3}{2t - (t_1 + t_3)}$
Hayashi et al. (1988)	$t_L = C(\Delta t)^m;$ *C & m constants (2.13 and 1.6, respectively* *Δt is the required time interval for a displacement of 10 cm starting from the beginning of the tertiary creep.*
IV	$\Lambda = \dfrac{1}{v} = A(\alpha - 1)^{1/(\alpha-1)}\left(t_f - t\right)^{1/(\alpha-1)}$ $where\ t_f\ is\ failure\ time, \Lambda\ is\ inverse\ velocity$ *A and α are constants and dimensionless,* *t is the current time, v is the velocity.* *Based on his laboratory results, α ranged between 1.5 and 2.2; α = 2 represents a linear inverse-velocity trend.* $\alpha = 2$ *gives linear IV curve (most cases)* $\alpha > 2$ *gives convex IV curve* $1 < \alpha < 2$ *gives concave IV curve*
SLO	$\varepsilon = -B\, log\left(t_f - t\right) + C;$ *ε is strain, B & C are constants* $\dfrac{dD}{dt} = \dfrac{B}{t_f - t}$ $t_v = t_f v - B$ $t_f = t + \dfrac{B}{v}$
OAA	$\dot{\Omega}^{-\alpha}\ddot{\Omega} - A = 0$; *Ω is displacement, dot refers to differentiation. A & α are dimensionless parameters*

	$\bar{v}_t = \frac{v_t + v_{t-1} + \cdots + v_{t(n-1)}}{n}$ *and*	*n=3 (SMA)* *n=7 (LMA)*
	$ESF = \bar{v}_t = \beta \cdot v_t + (1-\beta) \cdot \bar{v}_{t-1}; \beta = 0.5$ $v_i = \frac{d_i - d_{i-n}}{t_i - t_{i-n}}; T_{fw} = [T_{f(SMA)} - \frac{\Delta}{2};\ T_{f(LMA)} + \frac{\Delta}{2}]$	
ACARP	$R_a = a_{3/24} = 7$ $R_b = a_{3/48} = 13$ $R_c = a_{24/48} = 12$	

2.3.3 Inverse Velocity Method (IVM)

The IVM is the most frequent approach for predicting the failure of accelerating (progressively) slopes. It is developed from the accelerating creep theory. The time to accelerating creep failure is inversely related to the deformation rate (velocity) under gravity loading (FUKUZONO, 1985a). The time of failure (TOF) can be estimated by drawing the inverse velocity(Y-axis) versus the time(X-axis) curve and extending the inverse velocity trend to the y=0. Rose effectively predicted the slope collapse in three hard-rock open-pit mines (2001-2005) using the IVM with geodetic prism data (Rose & Hungr, 2007b).]. Based on his laboratory results, α ranged between 1.5 and 2.2; α = 2 represents a linear inverse-velocity trend and A is the slope of the inverse-velocity trend, which is specific to each data set. The variation in α changes the behaviour of deformation with respect to time as shown in figure 2.19.

If α ≠ 2, the inverse velocity curve is convex or concave (Fukuzono, 1984). Figure 2. 20 shows graphical method for determining the time of failure when α ≠ 2. In practise, however, this method is seldom used since rarely deviates by more than 2, making the simpler linear fit method the one of choice, with the caveat that it must be regularly updated to detect the emergence of trend shifts (Rose & Hungr, 2007a).

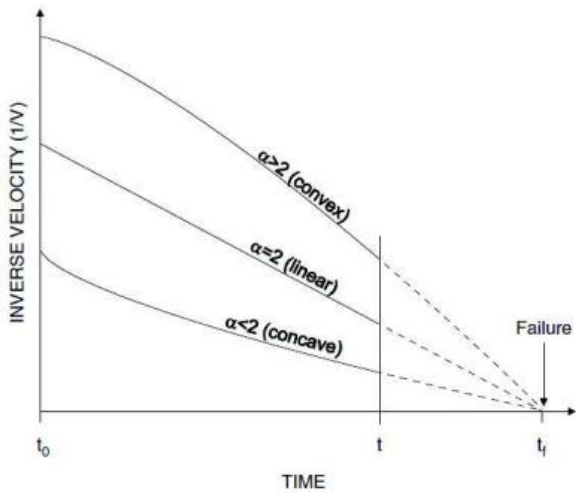

Figure 2. 19: Inverse velocity versus time relationship related to the variation of α

A tangent line is drawn to the curve at a chosen time t_1, in this case 1. At point t_{c1}, the tangent is perpendicular to the plane of the page. The segment t_{11} is therefore equal to the segment $t_1$tc1, and the point P_1 is shown vertically above 1. A second 2 point requires the same steps to be taken. The failure time is shown as the point on the t_f abscissa where a line from points P_1 and P_2 intersects the horizontal axis. The existence of a linear trend (α = 2) has been linked to brittle behaviour, namely crack development and first-time failures, as discussed by (Petley, 2004; Petley et al., 2002, 2005). However, (Intrieri & Gigli, 2016) showed cases where the inverse velocity charts have a concave shape, indicating first-time failures in brittle materials, while most landslides typically show linear trends. Majority landslides and slopes involve movement on a previously slid surface and that was considered as a reason for linear trends. When stress changes from increasing due to heavy rainfall, the inverse velocity curve isn't a straight line (De la Cruz-Reyna & Reyes-Davila, 2001). (FUKUZONO, 1985b) created artificial landslides and slopes using artificial rainfall technique on various slope inclinations and shapes. Interestingly, the failures induced by artificial rainfall still yielded accurate predictions.

The graphical technique assuming α = 2, offering rapid visual feedback, is often part of mining industry response plans (TARP; (Dick et al., 2015a; Read & Stacey, 2009b)).

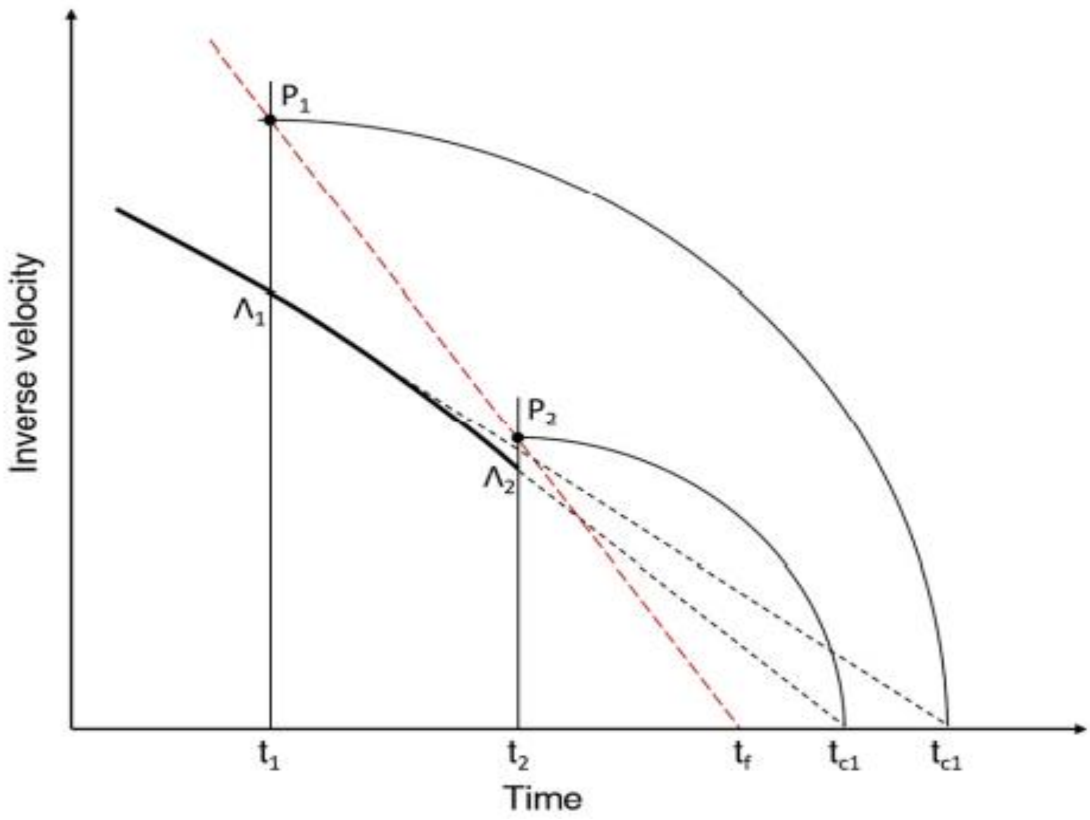

Figure 2. 20 : Graphical method for determining the time of failure when α ≠ 2 (Fukuzono, 1985a).

Minimum Inverse Velocity Method (MIV)

The Minimum Inverse Velocity (MIV) method operates on the fundamental premise that the inverse velocity of a slope cannot be zero, considering the physical constraints of movement. Thus, it calculates a minimum inverse velocity (≠ 0) and represents it on the Inverse Velocity (IV) vs Time graph. The intersection point of the IV curve and the MIV line on the graph yields a specific value on the Time axis, denoting the predicted time of failure. This method has demonstrated superior accuracy compared to the Inverse Velocity Method (IVM) in certain cases, emphasizing its potential for more precise failure predictions under specific conditions (Upasna & Moe, 2018).

SLO Technique

A technique was developed for calculating the time of geomechanical failure based on the slope of the t(du/dt)–du/dt plot, where 't' represents time and du/dt is the deformation rate. (Mufundirwa et al., 2010b), as shown in figure 2.20. Assuming strain divergence in the last stages of rock creep failure (Okubo et al., 1997), "life expectancy" charts were created. This SLO approach was later used at the Tom Price Mine to investigate open-pit slope failures. (Venter et al., 2013). Figure 2. 21 shows the application of the SLO technique application on Radar data.

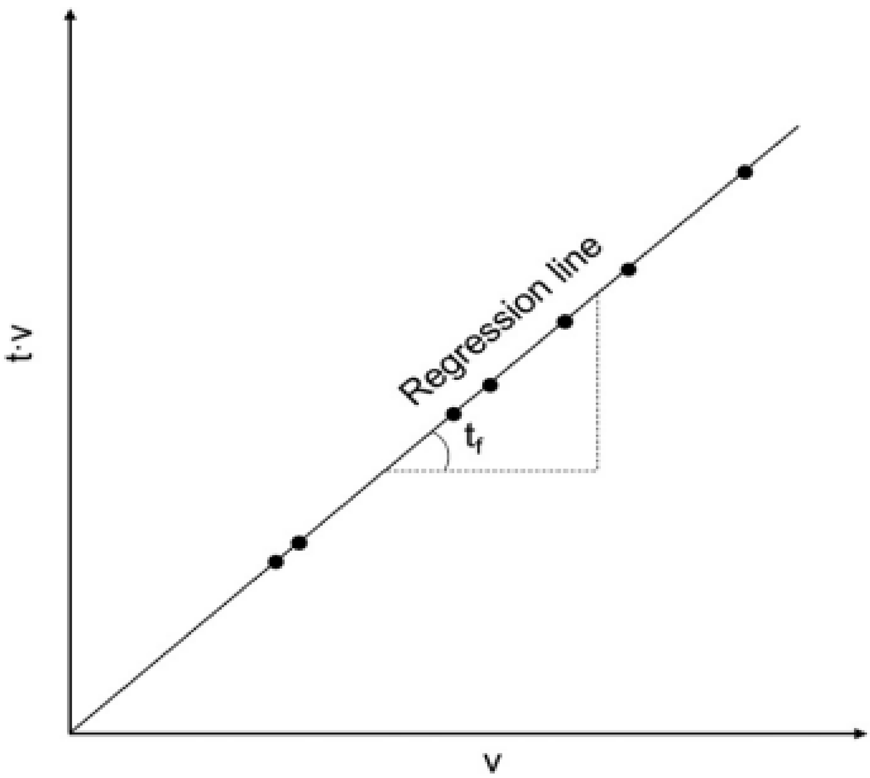

Figure 2. 21 : Plot for predicting failure with the SLO method (Mufundirwa et al., 2010).

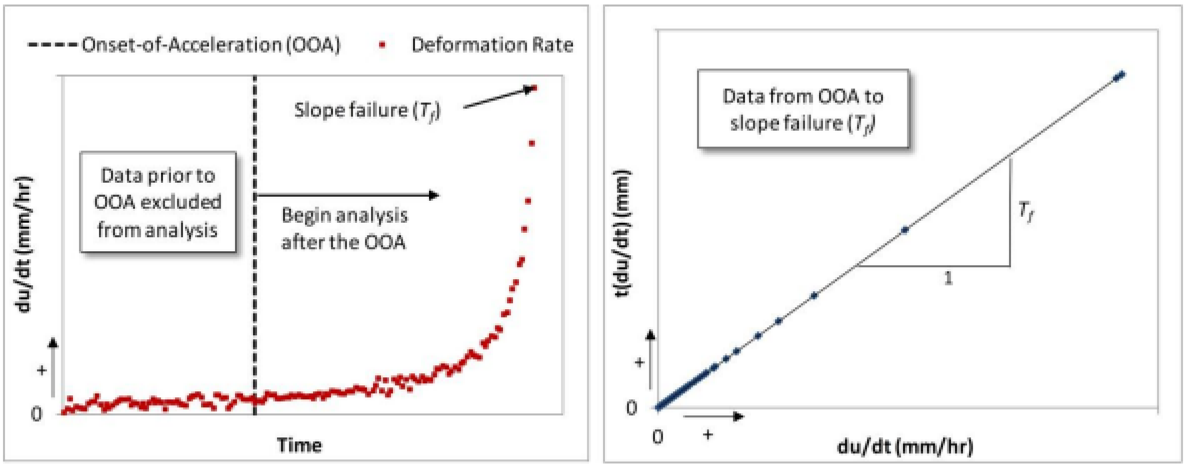

Figure 2. 22 : SLO technique application on Radar data (Dick et al., 2015a)

Australian Coal Association Research Program (ACARP) Method

In the context of 78 Australian case histories of slope failure in open cut mines, Australian Coal Association Research Program (ACARP) C17023 project, an extensive database of deformation/displacement data acquired by SSR. The authors investigated velocity and displacement data at various stages of the failure, but it did not lead to any realistic mathematical formulations capable of fully characterising the observed events. Cabrejo and Harries took the radar pixel with the greatest deformation (Cabrejo & Harries, 2012). They computed cumulative displacements and velocities at the failure moment, three hours before failure, twenty-four hours before failure, and forty-eight hours before failure. This technique emphasises the average acceleration experienced over numerous periods preceding the collapse. The ACARP database was examined, and linear correlations were found between many acceleration factors (0.99). It was discovered that the ratio of average acceleration in the final 3 hours to average acceleration in the final 24 hours was nearly constant, despite the vast range of fluctuation in slope velocity data (Carlà, Intrieri, Farina, et al., 2017b)

Using the Time and Event Dependent Deformation Model, Mercer created a technique for predicting deformation behaviour. In order to predict deformation behaviour, Mercer suggests employing non-linear curve fitting using standard non-linear regression statistics. Displacement data is fitted using n-order polynomials, iterated with fresh data, and differentiated to provide displacement rate and acceleration curves. Using a limiting deformation rate calculated in advance and the available data, a prediction of the time of slope collapse may be produced.

Ground-based radar is a type of remote sensing that uses phase-change interferometry to capture surface deformations and creates a cloud of deformation point (or pixel) data that is updated every few minutes (N. Harries et al., 2006c). When an accelerated slope deformation trend is observed, it is standard practise to examine a single or small cluster of pixels rather than the whole spatial range of the radar (Cahill M, 2006; Day & Seery, 2007; Little, 2006b; B. A. Reeves et al., 2000).

Ground-based slope stability radars use a fixed platform to remotely monitor the surface deformation without the need for reflectors or prisms (B. A. Reeves et al., 2000). Data is often accessible for interpretation within minutes (N. Harries et al., 2006c) without detrimental impacts from rain, fog, dust, or smoke (N. J. Harries & Cabrejo, 2010b). The use of MSR has specifically been extensive giving good prediction results (Osasan, 2012).

Based on the Onset of Acceleration (OAA)

Many researchers interchangeably adopt distinctive nomenclatures when talking about slope instabilities. For example, nearly every phase of slope instability development that led to a collapse in the literature was used to characterise the term "failure" (Mercer, 2006). Dick introduces two new definitions: (i) Instead of the onset-of-failure, the onset-of-acceleration (OOA) is employed (OOF) defined by (Zavodni & Broadbent, 1980) and (ii) a trend update (TU) point (Dick et al., 2015b). This method is based on first finding the OOA, then doing the TOF analysis based on the time window selected post OOA, as the Inverse Velocity data becomes more linear after the progressive deformation of the slope starts. This improves the predicted TOF significantly.

Artificial Intelligence

Using Machine Learning and Artificial Intelligence to predict slope failure has been done in the past decade. With the technological advancements in the field, it has become an important technique, most recently with ANN (Bui et al., 2020). Input, output, and a hidden layer make up the typical structure of a neural network. There are two main types of neural networks, supervised and unsupervised. In contrast to an unsupervised network, which is developed by allowing the network adapt to fresh input data, a supervised network is trained to generate the desired outputs from a fixed set of inputs. Using the above-described model, Juang et al. successfully applied a neural network to the problem of slope stability analysis (Juang et al., 1992). Before settling on the final network layout, they tried out a number of different combinations of the study's parameters.

Fuzzy Logic

The fuzzy set theory has recently gained popularity for slope stability research. Many effective forms of study for slope stability analysis have used the fuzzy neural network (Hwang et al., 2009; Lin et al., 2009; Sakellariou & Ferentinou, 2005). Several other research employ neural networks to measure slope instability. According to the research, this strategy aids in preparation for a probable slope failure, but it does not forecast the moment of slope failure.

Applications

Trigger Action Response Plans, often known as TARPs, are a component of ground control management at the majority of mines. These plans include pre-determined reactions to situations that are most likely to occur (Read & Stacey, 2009b). The use of triggers as a component of risk management enables objective recognition of a change in risk or hazard profile and subsequent appropriate action in mines, where geotechnical hazards may vary considerably over short distances (Hebblewhite et al., 2009). The specifics of a TARP may vary from mine to mine, but they always include color-coded warning levels (such as green, yellow, orange, and red) and predetermined actions for mine workers to take in reaction to changing pit slope conditions. Various slope conditions, such as the rate of slope movement, acceleration measurements, and visual inspections, all go into the determination of an appropriate degree of alert (Read & Stacey, 2009b). According to (Sharon & Eberhardt, 2020), TARPs need to make sure that: A specified trigger is set for each alert level Based on their roles, all staff members are familiar with the appropriate actions to take in the event of a predetermined trigger. By clearly outlining roles and duties, the strategy can be implemented quickly. If the evacuation level is activated, people leave the area in a safe and orderly manner. If collapse of a slope is imminent, mitigating its effects is usually the first priority. Eliminating the potential for injury or damage by removing all people and equipment from a slope's collapse zone is the most effective measure that can be taken to mitigate damage. Exiting a mine of medium to large scale may take anywhere from 15 to 60 minutes, however this time can be cut significantly with practised evacuation procedures (N. Harries & Holmstrom, 2007).

Slope failure prediction techniques might be used effectively following the creep theory. High sample rates and automated acquisition processes must monitor the assumption that the data should only have accelerating displacements to provide accurate forecasts, as it significantly impacts prediction results. As the sample rate is typically too low to adequately describe the acceleration phase, which may take several hours (Carlà, Farina, et al., 2017), when it comes to early warning purposes, a conventional monitoring strategy involving manual data collection is unsuitable. When done manually by an experienced operator, determining the acceleration phase might not be difficult, but the problem becomes more complex with near-real-time or real-time acceleration when the software has to automatically check the advancements of an accelerating phase and the onset-of-acceleration. The simultaneous monitoring of many slopes, becoming increasingly prevalent due to automated instrumentation, should also be addressed.

Many mines have applied modern-day slope monitoring and prediction techniques to measure slope movements and forecast slope failures empirically or semi-empirically. We have already discussed several of slope monitoring in mines. Fukuzono's method is the most widely adopted for slope failure prediction because of its simplicity and speed. Ground-Based InSAR (GBInSAR) is being used at the sandstone quarry in Firenzuola (Firenze, Italy) to monitor displacements and forecast failures. Firenzuola sandstone quarry uses Fukuzono's method for prediction(Carlà, Farina, et al., 2017). The personnel were warned of the risks days before a projected fall. The dangerous locations were blocked the afternoon before the occurrence. The cumulative displacement trend increased until 11 p.m. on November 5, 2012, when the observed velocity surpassed the radar ambiguity threshold (60 mm/h). The actual movement accelerated till failure around 3:00 a.m. on November 6. The fall did not harm machines or workers that were aware of it. This excellent case shows how GBInSAR technology may be used to control slope instability risks in open-pit mines by gathering long-range data and monitoring slope velocities and accelerations before a possible collapse event. Mitigating slope collapse danger, especially in open-pit mines excavated through hard rock masses with brittle behaviour, is still a serious problem. In an undisclosed mine, Carla et al. analysed nine instabilities observed by ground-based radar equipment at an unreported open-pit mine to assess typical slope deformation behaviour and establish a suitable alarm strategy. Five failed, while the other four revealed large volumes and rates of movement. Deformation in high-quality hard rock masses was researched in-depth, and "signature" failure features were established. Slope monitoring and early warning operating standards were also created using Fukuzono's IVM (Carlà, Farina, et al., 2017).

In an unidentified copper open-pit mine, a slope failure happened on November 17th, 2016. Analysis of slope monitoring data back to the time of the event necessitated an in-depth examination of its magnitude and development and the presence of any probable antecedents that may have predicted it. Observations from ground-based radar and satellite InSAR data from the last nine months leading up to the collapse were used to achieve this goal. Despite the ground-based radar detecting growing deformation in the pit's two topmost benches, the satellite InSAR data indicated that the great bulk of the instability occurred above the mine crest. The ground-based radar did not pick up on this particular area. For the first time, satellite InSAR measurements over an open-pit mine revealed apparent slope accelerating creep. Delimitation of the accelerating creep behaviour region matched the failure source area amazingly well after the incident, as plotted in the field after the event. As a result, conclusions were drawn about the size of the instability and the rate at which the failure process unfolded over time. Ground-based and satellite interferometry were used in conjunction to decrease the inherent uncertainties in the detection and characterisation of approaching catastrophic slope collapses (Carlà et al., 2018).

A rockmass failure occurred on a rock slope at a limestone mine in Japan in 2007. Fortunately, no injuries or damage to equipment were reported. Using the SLO created in this study, researchers could accurately anticipate outcomes in most instances. According to the findings, thermal fatigue was the most likely cause of persistent fracture deformations (Mufundirwa et al., 2010a) (Kothari & Momayez, 2018). Thermal fatigue is a form of fatigue that occurs in materials subjected to cyclic or fluctuating thermal stresses as a result of repeated temperature changes. When a material is subjected to alternating heating and cooling, it expands and contracts, leading to the accumulation of internal stresses. In situations where the stress exceeds the material's endurance limit, these cyclic stresses can cause material failure. A rockmass failure occurred on a rock slope at a limestone mine in Japan in 2007. Fortunately, no injuries or damage to equipment were reported. Using the SLO created in this study, researchers could accurately anticipate outcomes in most instances.

Recent research has enhanced the current IVM for predicting slope failure time. One of the latest IVM derived method is the minimum inverse velocity method. The radar's wavelength and scan rate affect the minimum inverse velocity (MIV). Using the MIV approach, this research found a 75% improvement in slope failure projections (Carlà, Farina, et al., 2017; Mufundirwa et al., 2010a). In India, there are several mines deploying the SSR for the monitoring of slopes and prediction of slope failures. These systems have greatly helped the mine management in monitoring, mitigation and prediction of slope movements.