A Review On Slope Monitoring And Application Methods In Open Pit Mining Activities

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Abstract: A failure at mining sites is a basic cause of death, serious injuries, economic and production losses. As open pit mines get larger and deeper with its related high risk of failure and consequences, slope monitoring methods become more important. Sub-surface methods and surface methods are common methods that have been applied to monitor stability of slope. Survey monitoring is technique of surface methods which include total station; global positioning system (GPS) and slope stability radar (SSR) are pointed as the most recent monitoring instruments in mining fields. Early detection of failure in mine slope can help implement appropriate monitoring technique and minimise failure effects. Slope monitoring in mining environment basically eliminates the residual risk associated with uncertainty in design and can play leading part of the final design implementation. Accurate monitoring program is a detailed plan of reporting procedures with a list of data collection by Geological engineer at early time, then processing and summarising the data to present it in simple format that is easy to read and identify problem area quickly.

Keywords: open pit mine; slope failure; slope monitoring; slope stability radar.

1 Introduction

As open pit mine gets larger and deeper, slope design is becoming more aggressive with concomitant high risk in size of failures and consequences. Because of the occurrence of unknown geological structures, weather change or seismic shockwave, slopes with traditional design may experience unexpected collapse. Even a small rock fall threatens the safety of personnel, plant and equipment, productivity and potentially overall mine viability [1, 2]. Consequences Geological structures (e.g. major fault zones) often play a most powerful role in controlling the kinematics and stability of large pit slopes, largely ignored by empirical slope stability procedures used to evaluate potential failure Fukuzono [3]. The unexpected failure of rock walls at mining sites is a major cause of death, serious injuries, economic and production losses and can bury critical equipment. Slope failure disrupts the mine plan and can disturb mining for several days or weeks following a wall collapse due to uncertainty over stability. Direct economic losses in remediation alone can easily exceed $1,000,000 per incident while economic costs of injuries or fatality are much higher including closure of mines during the incident investigation process [4]. Early detection of ground movement lets mine operators to plan and carry out appropriate actions (evacuation plans) with sufficient notice to minimise the effect of the failure on people's safety and mining activities. The strength of a monitoring program depends on the capabilities of the equipment and techniques, and on the people driving the program. The success of the monitoring also depends on support from higher levels of mine management. Controlling the possible ground movements hazardous or instability in an open pit mine to within acceptable limits is essential to eliminate or minimise safety risks. A comprehensive slope monitoring program aimed at managing potential large scale instabilities and able to detect local scale movements should be part of every ground performance monitoring system [5].

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The paper illustrates the main role of slope monitoring and describes the applications of monitoring equipments for open pit slope especially recent technology like slope stability Radar (SSR). It also presents a brief outline of some common methods used in slope monitoring technique and compares the effectiveness of each monitoring system by using data obtained from different monitoring tools.

2 Open pit slope monitoring methods

2.1 Current common slope monitoring methods

Various methods have been applied in recent times for open pit slope monitoring. They are classified into two main types which are: sub-surface methods [i.e. Inclinometers, Shear strips and Time Domain Reflectometry (TDRs), In-place inclinometers and Portable inclinometer probes] and surface methods [i.e. Visual inspection, Cross-crack measurements, Crack measuring pins and Survey monitoring]. The survey methods [i.e. total station, Global positioning systems (GPS), geographic information system (GIS) and slope stability radar (SSR) are the most recent monitoring methods in mining fields. [6] provided useful reference for the methods and monitoring requirements for open pit applications in relation to the type and scale of the mine slopes being considered.

2.1.1 Sub-Surface Monitoring Methods

Sub-surface measurements which include Inclinometers, Shear strips and Time Domain Reflectometry (TDRs), In-place inclinometers and Portable inclinometer probes are useful component of a monitoring program to obtain a more complete picture of the slope behavior. Inclinometers and Time Domain Reflectometry (TDR) cables give very valuable and precise information on the locations of deep-seated slide surfaces, but it is more expensive than surface monitoring due to the requirement for drilling. The main purpose of these measurements is to locate the slide surface or sub-surfaces, and monitor the rate of movement. For slopes in soil and overburden, inclinometers are the instruments of choice for sub-surface measurements, although shear plane indicators can be used for crude measurements.
The most common type of inclinometer used in open pit slope monitoring is the probe inclinometer in which the probe travels along guide grooves in an aluminium or plastic tube grouted

into a drill hole. It generally operates in holes inclined up to 30° to the vertical. It can detect differential movements of 0.5–1.0 mm per 10 m length of hole. Inclinometers are used to detect lateral displacements and shear planes in excavations and slopes. A sacrificial casing with orthogonal grooves is installed in a grouted borehole with one set of grooves aligned in the direction of principal displacement (Figure1). A wheeled probe with orthogonal tilt sensors is placed inside the casing with the wheels in the groove. The tilt sensors record the angle of inclination at 0.5 m intervals and the results are summed from the bottom to calculate the profile of the casing. Subsequent readings of the casing are compared with the initial profile to calculate the relative displacement.

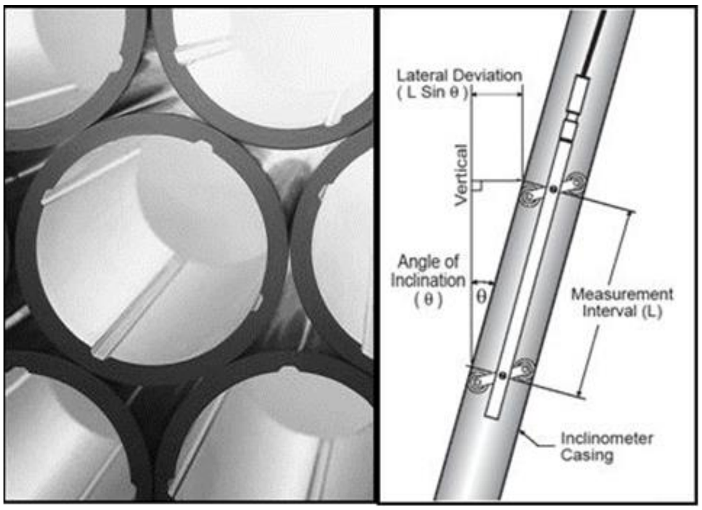

***Fig.1**. Groove inclinometer casing on the left and Inclinometer probe on the rite*

Time Domain Reflectometry (TDR), shown in Figure 2, is a technique in which electronic pulses are sent down a length of a coaxial cable. When deformation or a break in the cable is encountered, a signal is reflected giving information on the sub-surface rock mass deformation. These devices detect the location, but not the magnitude, of deformation in a drill hole. While inclinometers are more common for monitoring sub-surface displacements, TDR cables are gaining popularity and have several advantages over traditional inclinometers [7]. These advantages include less installation cost, deeper hole depths, rapidly and remote monitoring, immediate deformation and complex installations possible.

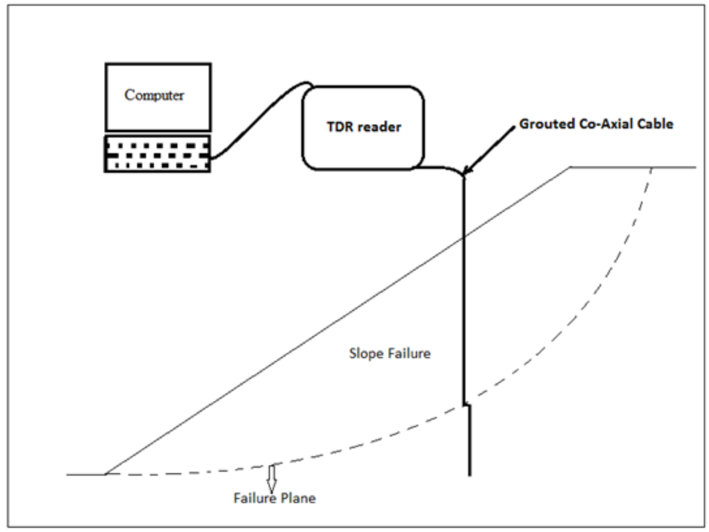

***Fig.**2.Working mechanism of TDR system*

2.1.2 Surface Monitoring Methods

The surface monitoring methods include visual inspection, geodetic and terrestrial surveying, imaging techniques such as photogrammetry, and the use of satellite-based positioning techniques such as GPS. These techniques are less costly to set up and maintain than sub-surface measurements that require drilling holes to install the instruments. Other techniques include ground-based slope stability radar interferometry, satellite-based radar interferometry, microseismic emissions and laser scanning. The visual inspection method consist of walking along the perimeter of the pit, inspecting all access methods, high walls and crests close to possibly risky working areas with the emphasis on identifying any new, visible movement or cracks that may have occurred [7]. An essential part of any slope monitoring system is visual observation, which is qualitative but has the advantage of involving the experience of people working in a particular environment. A basic element of a slope monitoring program should be visual inspection by the mine geotechnical engineer and members of the engineering staff, combined with observations by all personnel working in the mine. A record of the pattern of cracking in rock around the crest of an open pit mine gives very useful information on the mechanisms and directions of movements. Cracks should be marked with spray paint so that at each subsequent date of observation, it will be possible to recognise new cracks and measure the elongation of old ones. Crack patterns and the history of cracking should be recorded on plans and cross-sections just as carefully as more complex types of measurement. In difficult mining situations, such as mining below unstable ground, it is often prudent to employ one or more spotters in radio contact with the operators working below the slope. The role of the spotter is to warn of the onset of any rock fall or apparent changes in the condition of the slope, and thereby allow personnel to be evacuated from the area. Any visual monitoring program must be supported by instrumentation to provide a quantitative basis for defining any movement. Another surface method is Cross-crack measurements in which a tension cracks at the crest of the slope (Figure 3) may be the first sign of instability. When cracks appear at the crest of the slope or elsewhere, their lengths, widths and vertical offsets should be monitored. Crack measurements give clues of the behavior of the entire slope and the direction of movement may often be inferred from the pattern of cracking, particularly by matching the irregular edges of the cracks. Since it is much easier to observe crack movements on a shotcreted surface than on the rock, a thin coating of shotcrete, concrete or plaster can be applied to aid monitoring of ground movements. Measurements between deeply embedded anchor targets are better in soils and weathered or weak rocks where the surface is friable [6].

***Fig.3**. Device used as cress crack measurement after [7]*

Crack measuring pins is another surface method in which steel pin or timber peg is fixed firmly on each side of a tension crack at selected locations and the distance between the two pins/pegs is measured periodically using a measuring tape, a vernier caliper or a micrometer to determine the progress of the crack. This method involves a vibrating-wire extensometer designed to measure displacement across joints and cracks in concrete, rock, soil and structural members. The switch end and the shaft are attached firmly to steel or timber pegs on each side of the crack. Movement of the shaft changes the tension in an internal wire, causing a corresponding change in its frequency of vibration. The instrument has high accuracy and resolution, and displacement beyond a preset threshold can trigger a visual or audio warning alarm activated through an alarm controller.

2.1.3. Survey monitoring

There are various ways to conduct survey monitoring methods which are related to the amount of expected movement and possible impact of failure [7]. Geodetic survey remains the standard method for monitoring large open pit slopes. The techniques used are traditional methods of general survey measurement and positioning. Mine surveyors are therefore usually more familiar with these techniques than are other professionals such as engineers and geologists. Depending on the methods and procedures, geodetic techniques can be used to determine the absolute position and the positional variations of selected points on the surface of a pit slope in one to three dimensions.

3. SURVEY MONITORING TECHNIQUES

When using survey techniques, survey instruments such as levels, Theodolites, total stations, GPS receivers, photogrammetric cameras, slope stability radar or a combination of these instruments are used to collect field data. These data are processed to determine the positions of the surveyed points in a given reference frame such as the reduced level coordinate system. Displacement of surveyed points can be determined by comparing the coordinates from two or more survey periods. The following are some of the common survey monitoring instruments:

3.1. Total Station

Employment of total station surveying instruments for monitoring structures movement with good results were reported by many authors [8-12]. Electronic total stations are the most commonly used survey instruments for pit slope monitoring. The instrument is designed to survey the 3D coordinates of reflective prisms located around the slope being monitored. Readings (distances and/or angles) are usually taken from a fixed instrument station on the crest of a pit to all prisms in view. The prism locations and movements are then computed from the readings [6]. Depending upon the environment, it is usual for the total station unit to be housed in a protective building immediately behind a pit crest (Figure 4)

***Fig.4**. Total Station Monitoring Instrument*

3.2 Global Position System (GPS)

Global positioning systems (GPS) based on satellites orbiting the earth can be used for real-time positioning at any location 24 hours a day in any weather. It is a potential tool used to measure ground displacements over an extensive area in various engineering projects involving high cut slopes, large open pit mines, subsidence and landslide. Several researchers have already studied the applications of GPS in ground displacements [13-16]. Scientists from different fields developed GPS and reported that the system could measure displacements almost as accurately as total station surveying. With two or more receivers working simultaneously in a so-called differential mode, relative positions (3D coordinate differences) between the receivers can be measured with an accuracy of a few millimetres to about 20 mm over distances up to several kilometres, and about 1 ppm (parts per million) over distances up to several hundred kilometers [6]. A GPS receiver requires an unobstructed view of at least four satellites. It requires three satellites to determine its horizontal

(2D) position, and a fourth satellite to determine its altitude (3D). GPS is not affected by local atmospheric conditions when the GPS baseline length is within 1 km, thus it is usually more efficient and accurate, and requires less labour than conventional survey techniques. This advantage also makes it an ideal tool for setting up control surveys for slope monitoring.

3.3 Slope Monitoring Radar

Slope monitoring radar (Synthetic Aperture Radar, Slope Stability Radar) based on real aperture radar technology (Figure 5) (typically large dish antennas used to scan the observed scenario) were originally introduced into the surface mining industry for near real-time monitoring of specific “critical” areas of the pit, providing alarms in case of fast movements [17]. It is a type of ground radar can used to create terrain maps, to yield high class digital elevation models (DEM) and to discover surface disturbances, [18]. The idea is based on the significant success achieved by differential interferometry obtained with synthetic aperture radar (SAR), which can measure small movements of land masses from satellites [i.e. along-fault slippage associated with earthquakes, ground subsidence associated with underground mining and velocity of slowly moving ice masses [19]. Slope monitoring radar has risen in the last decade as a leading-edge device for safety-critical monitoring in mining. Due to its capability to rapidly checking up displacement with high accuracy (sub-millimetric) over wide areas in any weather conditions, obviating the need to install artificial reflectors [5]. Radar units are used effectively for safety critical slope monitoring with the aim of providing alerts in the event of progressive movements which could potentially lead to slope failure, and therefore with the aim of assessing worker safety and increasing mine productivity [20].

Fig.6. *A deformation plot and graph showing slope instability using SSR*

The first type of slope monitoring radar introduced into the mining market was based on a parabolic dish-antenna radar (Real Aperture Radar – RAR) using a fine radar beam to illuminate the target over a series of small footprint areas. SAR is an active device depend instrument able of recording the electromagnetic repeat from the ground surface. Anew version of SAR system can be used for short and long term slope monitoring.[21]. Various generations of Real Aperture ground-based radars (RAR) have been developed in the last few years for monitoring slope movements [22, 23]. Records from the SSR is generally offered in two formats. A colour ‘rainbow’ plot of the slope figure.7, and, time/displacement graphs can be selected at any positions to assess movement rates lower part of figure. 6. Extra software can also be installed to allow the data to be viewed at locations remote to the SSR site. The SSR system can also provide data to aid in the analysis of risks related to slope instability. It provides data useful both for assessing the likelihood and for estimating the consequences of slope failure. In both cases, geotechnical input is required and without skilled staff reviewing the data, the value of the SSR for analyzing risks is compromised [24].

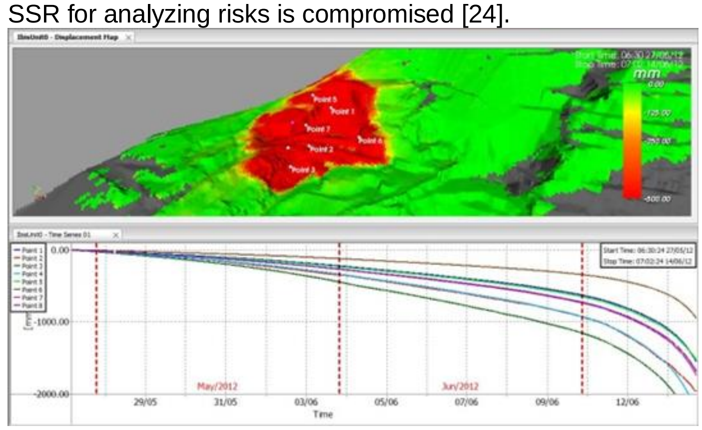

Fig.6. *A deformation plot and graph showing slope instability using SSR*

4. Slope Monitoring and data management

4.1. Risk managements

The main purpose of slope monitoring programme is to Maintain safe operational practices and provide advance notice of instability and additional geotechnical information regarding slope behavior [25]. Slope monitoring is routinely adopted in the mining environment to manage the residual risk associated with uncertainty in design. Even the most carefully designed slopes may experience failure from unknown structures, unexpected weather patterns or seismic shock, [26]. In most open pit mines, the physical environment in which slope designs must be developed and implemented is extremely complex. So the monitoring is paramount part of the final design implementation as shown in (Figure 7).

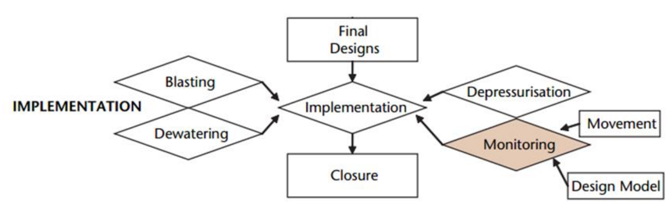

Fig.7. *Monitoring in slope design process*

Slope stability monitoring activities and slope movement analysis in open pit mine are important in evaluating the operation areas with varying levels of risk. This displacement monitoring system should start during early stages of mining, the aim of this displacement monitoring to detecting and recording any slope movement, investigating failures, confirming the design model and ensuring that the slope design criteria are being achieved. Deformations such as geological conditions, hydrology, geomechanics conditions and geometry of the slope and the knowledge of the kinematics analyses are crucial in managing and reducing possible risks [27].

4.2 Multiple monitoring tools managements

Bye [28], after performing a series of experiments by using data obtained from different monitoring tools, he compared the effectiveness of each monitoring system. He presented the data in fault tree as a monitoring type versus percentage of success rate results shown that visual monitoring only was 32%, Prism/ crack only was 45%, virtual plus prism/crack was 63%, virtual plus prism/crack plus laser was 86%, Radar only was 93%, virtual plus prism/crack plus Radar was 97%, lastly virtual plus prism/crack plus laser plus Radar was 99%.In the perfect analysis, a monitoring success is where a slope failure was identified with sufficient warning time to successfully collected and applying fault tree analysis, it was found that the highest success rate is obtained when a mine site uses multiple monitoring tools, evaluate the moving slopes. Slope stability monitoring by different methods also produce different degrees of success, in which more methods are combined for better data redundancy. With the use of robotic total station (RTS) and Slope Stability Radar (SSR) system in order to visually monitor the presence of the physical signs on the slopes such as cracks, water seepage and irregular geological structure which can cause slope instability. Diligent monitoring of structures and slopes for early warning signs are, thus, imperative for protecting life and equipment, [29]. New technologies are needed to facilitate synthesis of data from site investigation and characterisation for geotechnical hazard assessment in mining area. While there are many technologies in use today, GIS is increasingly viewed as a key tool for managing spatial and temporal data for natural hazards. Engineers responsible for hazard assessments could benefit through cross-fertilisation and mutual support of different technologies [30] and obtain more useful and robust solution by effectively using various types of data. There should be monitoring system of the open pit to evaluate slope performance and detected the onset of unexpected movement. And this system involves virtual observation and geodetic surveying of prisms around the pit and down the slopes. (Table 1) provide an example of the procedures typically associated with the monitoring of pit wall stability in an operation mine. The table gives summary of monitoring methods by potential failure and implication with detailed about block size, speed of failure, implications, monitoring for detection and typical remedial. For the accurate monitoring program a detailed plan of reporting procedures should be prepared before, in order to be familiar to responsible person. These procedures include: a list of data collection, equipment specification, processing, presentation procedure and interpretation procedures. Geotechnical engineer collecting data from early time, then processing and summarise the data to present in a format that is easy to read and indentify problem area quickly. Data processing and presentation depends on the specific monitoring system. Processing and presentation of instrumentation data is determined during the planning phase and should be under the direct control of the geotechnical engineer on site or, in special cases, consultants who have immediate 24-hour access to the data.

***Table 1:** Summary of monitoring methods by potential failure size and implication*

Block size (m3)	Speed of failure	Implications	Monitoring for detection	Typical remedial
10-Jan	Immediate	Rockfall – safety	**Visual**	**Catchment**
10 - 1000	Very rapid to rapid	Safety	**Visual**	**Catchment**
			Radar	
1000 - 100 000	Rapid to slow	Operational	Visual	Manage
			Surveying	Modify slope (step-out)
			Radar	
			Seismic (?)	
100 000 - 1000 000	Moderate to slow	Operational/financial	**Surveying**	**Manage**
			Radar	Modify slope (step-out)
			TDR/inclinometer	Recut (?)
			Seismic	
> 1 000 000	Slow to moderate	Force majeur	**Surveying**	**Modify slope (recut)**
			TDR/inclinometer	Mine closure (>10 Mm3)
			Seismic	Manage
			Radar	

This paper reviewed the main role of slope monitoring, presented a brief outline of the wide range of tools available to the engineer and geotechnique for slope monitoring and management and analysed effectiveness of different monitoring tools. Slope monitoring measurements are classified into two categories: sub-surface and surface methods. The main purpose of these measurements is to locate the slide surface or sub-surfaces, and monitor the rate of movement. Surface measurements are less costly to set up and maintain than sub-surface one that require drilling to install the instruments. Monitoring of slope becomes very important because as open pit mine gets larger and deeper, slope design becomes more complex with its related high risk of failures and consequences. Slope monitoring in mining environment is basically to eliminate the residual risk associated with uncertainty in design, so the monitoring is paramount part of the final design implementation. Accurate monitoring program is a detailed plan of reporting procedures which include equipment specification and data collection, processing, presentation and interpretation. Geotechnical engineer collects data from the beginning, then process and summarise it to present in a format that is easy to read and identify problem area quickly. Tools used in sub-surface measuring include Inclinometers, Shear strips and Time Domain Reflectometry (TDRs), In-place inclinometers and Portable inclinometer probes while in surface measuring, visual inspection, geodetic and terrestrial surveying, imaging techniques, and satellite-based positioning techniques are used. Survey monitoring methods which involve use of Total station, global positioning system (GPS) and SSR are pointed as the most recent monitoring methods in mining fields. The SSR is now used as the standard practice tool for the active monitoring of pit walls in mines as it can check up displacement with high accuracy (sub-millimetric) over wide areas in any weather conditions. Combination of more than one survey instruments are used to collect field data. The data is then processed to determine the positions of the surveyed points in a given reference frame such as the reduced level coordinate system. Through analysis of different monitoring methods, it was found that the highest success rate is obtained when a mine site uses multiple monitoring tools to evaluate the movements of slopes.

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