Int. J. of GEOMATE, Feb., 2016, Vol. 10, No. 1 (Sl. No. 19), pp. 1575-1583
Geotech., Const. Mat. and Env., ISSN: 2186-2982(P), 2186-2990(O), Japan

KINEMATIC ASSESSMENT OF SLOPES AT HANDLEBAR HILL OPEN CUT MINE, MT. ISA, QUEENSLAND, AUSTRALIA

Maged Al Mandalawi, Greg You, Kim Dowling and Peter Dahlhaus

Faculty of Science and Technology, Federation University Australia, Australia

ABSTRACT: A complete kinematic analysis was conducted for the west slope at the Handlebar Hill mine using the Rocscience/Dips 6.0 software. The west slope was divided into three zones: W1 (south-west), W2 (mid-west) and W3 (north-west), which were then subdivided into nine small elements to increase the certainty of parameters. This enabled the analysis to define the potential kinematics of motions of critical structures. Small scale joints, bedding, faults, shears along the discontinuities were plotted and the data were analysed systematically. The results indicated that the potential toppling mode created by discontinuities can lead to direct/flexural toppling failure. The kinematic feasibility also revealed that the intersections of the discontinuities within the critical zone can structurally control the wedge planar failure modes. The results will assist the mine geotechnical engineers to understand the potential slope failure mechanisms and their locations.

Keywords: Slope Stability, Kinematic Analysis, Critical Zone, Failure Mode

1. INTRODUCTION

The zinc ore body of the Handlebar Hill Open Cut mine (HHOC) lies one kilometre south of George Fisher silver ore deposit, near Mt. Isa, Queensland, Australia (Fig. 1). The open pit mine commenced operations in 2007 and had two stages of excavation. The slope geometry was designed based on the stability assessment of the slope, presented by Kevin Rosengren & Associates (Xstrata Technical report of Handlebar Hill Study, 2011). The stability of the overall and inter-ramp angles of the slope was viewed in terms of both the mining safety and economic conditions. In open pit mines, slope instability can be expected because of careless or poorly designed blasting (Sjoberg, 1999). In some circumstances a relatively high probability of rock failure may be acceptable while in others, such as benches adjacent to haul roads, even localised bench scale failures may resulting in costly delay and disruption in production (Hoek, 2009). Therefore, the instability of slope benches in an open pit mine is a primary safety topic, and there is typically a rock movement prior a failure event occurs (Harries, 2008).

Rock slope failures are frequently controlled by a complex combination of discontinuities that facilitate kinematic release, and these discontinuities are often associated with discrete folds, faults, and shear zones, and/or related tectonic damage (Brideau, 2009). Rock slope failures are stereotypically characterised as follows: (1) Overall slope in which the entire slope might collapse, (2) Inter-ramp slope in which a part of the slope may fall and significantly affect the mining operations, (3) Localised bench slope in which the failure affects the local operation in the zone of the failed bench (Steffen et al., 2008).

Most of bench failures at the HHOC west slope are controlled by geological structures. The mechanical nature of the geological structures is a critical factor that can dramatically affect the mechanism of failure. Evaluation of the stability of geological structures is usually done through using stereographic projection, in which the discrete structures with similar orientation will be grouped together in joint sets using various statically techniques (Sjoberg, 1999).

2. STABILITY OF THE WEST SLOPE

The stability of slopes posed a problem at the HHOC mine due to localised bench failures that occurred on the western side of the pit with consequent safety issues and actual loss of production. The west slope covers an area of 950m x 220m including three hundred and sixty dip and dip direction values that were simulated using stereographic projection in this study. The structures of the rock mass forming the west slope of the pit have complex geological conditions including the following:

1. Five different geological units including Urquhart Shale, Spears Siltstone, Magazine Shale,

weathered and Fresh Eastern Creek Volcanic.
2. The rock mass is moderately jointed and includes other discontinuities.
3. The major structural features include faults (dips at 60^{o} – 70^{o} to the west), shears and faults, which intersect the west walls from the north to the bottom of the pit. Therefore, very weak and highly fractured rock is present in the west slope.
4. Natural hills are adjacent to the west of the pit, increasing infiltration of rainfall into the west slopes, and the water infiltration will increase pore pressure, softens rock and may cause erosion of rock slopes.

Fig.1 HHOC pit and view looking north, this study focuses on the western wall, located to the left of the image.

3. AIM AND PLAN OF STUDY

Several geological structures and fractures were identified at the west slope by previous investigations undertaken. It is necessary to know the realistic potential of rock movement, and unstable zones controlled by discontinuities of the rock slopes. Because of this fact, the analyses presented involve the in-situ geological condition of the west slope. The current research includes the following:

1. Subdivide the west slope into elements to increase the certainty of parameters.
2. Use kinematic analysis to describe the motions of critical structures included in the west slope.
3. Demonstrate a qualitative modeling of small scale structures in the slope.
4. Investigate the type of failure mechanisms related to the structures parameters.

In large scale open cut mines, failures often occur on critical pre-existing discontinuities which are daylighting at the toe of the slope (Gray, 1988), and as a result, the parameters of the discontinuities are of primary importance for slope stability. The strength and orientation of different scales of geological structures in excavated slopes could fully or partly control the slip surfaces.

In the Handlebar Hill open cut pit, the scale of past failures did not exceed a local bench. At maximum, in a rare event two benches were involved in the rock slope failure. These local failures of the west slopes did not cause major interruption to the mining, but one such case adjacent to the haul road led to the clean-up and repair of the bench. This type of failure is commonly seen in slopes of up to 30m high in hard jointed rock masses (Hoek et al., 2000). The probability of multiple bench failures will be considered, since they potentially could result in more serious disruption of operation and loss of ore.

Examples from Australian open cut pits of rock failure events in which the structures were involved in the mechanisms of failure are listed in Table 1.

Table 1 Examples of slope failures in open cut mines in Australia initiated by geological structures.

Mine	Type of failure	Location	Geological structure daylighting at slope toe
Cleo open pit gold WA	Leached weak bed rock mass	South-west wall	Circular-translational failure surface
Riverside Pit Coal QLD	Sliding on dipping contact	Highwall	Shear Plane in weak clay shear
Yallourn Pit Coal, VIC	Complex sliding + rotational	North-East wall	Large scale joint set/ sheared zone approximately parallel to slope face angle
Handlebar Hill Pit QLD	Wedge failure	Contact between domains	Two geological structures
Cadia Hill Pit NSW	Large scale wedge + planar	North wall	Most failures were restricted to planes within multi benches

Newman Iron Pit WA	Complex bedding + sliding	South slope	Bedding
Koolan Island Iron Pit WA	Wedge failure	Hanging-wall	Two joint sets
Ora-Banda Gold Pit WA	Unclear wedge	South slope	Joint dip steeply sub-parallel to the slope face in sheared zone

4. KINEMATIC ANALYSIS

The kinematical admissible displacement of rock slope stability will be assessed, where mechanisms of rock failures are controlled by discontinuities and this is regularly tested for translational planar failure. The potential plane of failure must dip at the inclination angle higher than its internal friction angle and lower than the slope face angle. It is a way that potentially unstable blocks in rock slopes could be quickly recognised. Priest (1985) has used kinematic analysis to model the stability of wedges, rock blocks and any possible rock displacements at the slope surface. This could be achieved by plotting the dips and orientations of geological structures such as joints, and the slope dip angle, orientation and friction angle together into stereonet and stereographic projection.

The kinematic stability analysis can be performed using the stereographic projection technique, which is a robust tool for discontinuity data collection and presentation. Data requested to perform this method are dip and dip direction of all discontinuity. Whereas, a study by Oztekinm et al., (2006) confirmed that joints constitute the main discontinuity type at the excavated slopes, and these geological structures have to be typically defined.

5. DIVISION OF THE WEST SLOPE

Joint is a very common type of the natural geological structure in the rock masses. This term is used in rock mechanics for a mechanical discontinuity as a fracture in a rock mass has low or no tensile strength. Practically, joint is a plane discontinuity that may develop some fracture and displacement by the presence of material fillings into the space between adjacent joint surfaces. In length, they may range from tens of centimetres to hundreds of metres. Joints are the most common rock discontinuity encountered in the west slope of HHOC mine.

On one hand, some joints at the west slope of the HHOC pit have long traces, form nearly parallel sets and are almost equally spaced. On the other hand, many joint sets are curved, typically short and irregularly spaced. Mapping of geological structures indicated that the majority of the pre-existing joints in the rock mass were of limited length ranging between six and ten metres.

The west slope of the pit is considered as moderately jointed according to the rock structure rating (RSR) described in three tables by Wickham et al., (1972), which was used to evaluate the rating of the west slope joint pattern and average joint spacing. The joint mapping and core logging results tabulated in this study provided inputs for the statistical stability code Dips 6.0 (Rocscience, 2014). The variation of the joint sets orientations and properties with other structures has been calculated and is presented in this study.

Based on the west slope geometry and geological units, the slope was divided into three main elements and as follows:

- W1 element presents the south-west wall of the west slope and this slope will be divided into three different sub-elements
- W2 element presents the mid-west wall of the west slope.
- W3 element presents the north-west wall of the west slope.

AutoCAD software was used to divide the west slope of the pit in order to study each element (wall) with its own discontinuities derived from on-site outcrop mapping and as shown in Fig. 2.

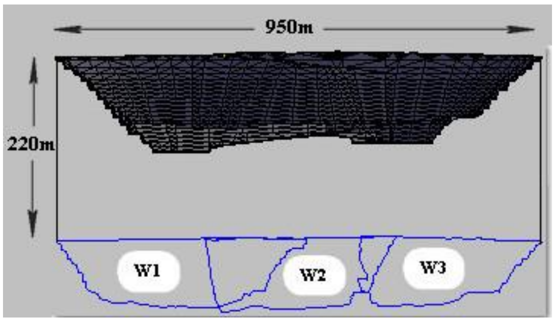

Fig.2 Outline of west wall (front view) shows total divisions applied to the west slope of the pit using AutoCAD. The slope is divided into three main elements to include the discontinuities of each element separately.

5.1 Division of W1 Slope

Searching for a more accurate representation of the slope discontinuity data, AutoCAD software was used to divide the three slope elements of the pit into three vertical subdivided slices in order to study each slice (wall) with its own discontinuities and as shown in Figs. 3, 7 and 11.

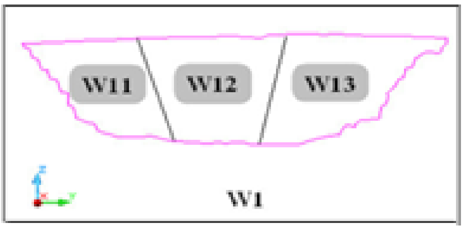

Fig.3 Subdivision outline of W1 slope of the pit into three vertical slices to study each slice (wall) with its own discontinuities.

5.1.1 Kinematic analysis for W11 slope

The W11 wall is located at the south-west corner of the west slope of the pit. Work on this element of the west slope resulted in 62 joints and three faults being defined based on geological structural surface mapping and core logging measurements during fieldwork. Although the joints could be clustered into five different joint sets, these joints have been used in the stereographic analysis.

Kinematic analysis was used to investigate different rock slope failure modes on stereonet pole plotting easily. Transitional failure including planar sliding, wedge sliding, flexural toppling and direct toppling, can be shown quickly by adding such inputs as the slope friction angle, orientation, slope direction and lateral limits.

Stereographic projection represents 3-D orientation data to be analysed in 2-D. This projection consists of a sphere, in which its equatorial plane is horizontal, and its orientation fixed to north direction, and the equatorial projection is preferred for plotting and analysing data of geological structures (Hoek & Bray, 1981).

The discontinuities global orientation format used for proceeding input data of W11 is Dip/Direction in the project setting option in Dips 6.0. The data of geological structures was transferred into new Dips 6.0 file to create stereographic projection mapping as defined in Fig. 4.

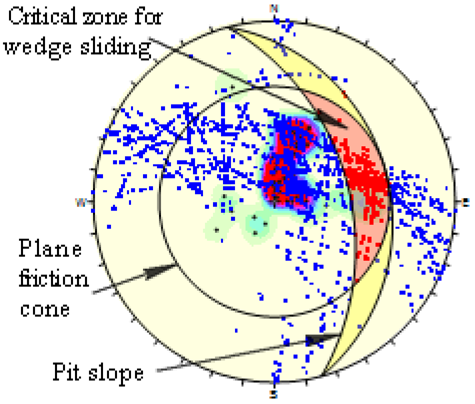

Fig.4 Wedge kinematic slope stability analysis for W11 slope using stereographic constructions.

From the kinematic analysis of W11, a potential wedge sliding failure mode was defined through the intersection of two rock planes and the plane friction cone. The slope angle was 45^{o}, which presents the steep portion of the west slope. The internal friction angle for discontinuities was assumed to be close to the residual value of the heterogeneous rock mass, and was estimated to be 25^{o}. Rocscience (2014) described the key elements of the wedge kinematic analysis modeling as slope plane, intersection plotting and plane friction cone, and the friction angle is measured from the perimeter of stereonet.

For the potential wedge failure, 65 pole vectors intersect within the friction circle (friction angle < slope dip angle < intersection dip angle) and will daylight from the slope face, resulting in a high probability of wedge failure. The primary critical pole vector zone for wedge sliding is the red crescent area located inside the plane friction circle and outside the slope face. A wedge may slide along the line of intersection of two planes or on one of the two planes when one plane has orientation for sliding more suitable than the line of intersection. So, the mode of wedge sliding is built on the study of intersections of rock planes on the slope. The dip angles of the two planes were considered to check if wedges will slide on a singular plane or two planes. Typical wedge failure along discontinuities intersection lines are illustrated and a number of intersections within the critical zone are counted. Wedge failure is kinematically feasible when the discontinuity plane or the intersecting line of two discontinuities dips lower than the slope face at W11, but steeper than the internal friction angle of the discontinuities. The peak orientation of the dominant intersection on W11 slope is 25° (dip angle) and 75° (dip direction). However, the result of kinematic analysis indicated a probable flexural toppling mode of rock failure at the top of W11.

5.1.2 Kinematic analysis for W12 slope

Kinematic analysis result of a stereographic for W12 is presented in Fig. 5.

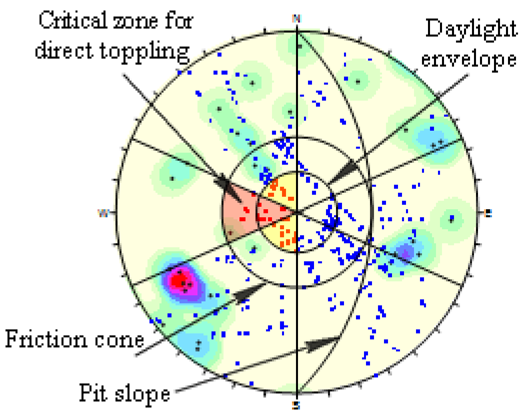

Fig.5 Toppling kinematic slope stability analysis for W12 using stereographic constructions.

In Fig. 5, it can be seen the highlighted red region in W12 slope contains the primary critical zone for direct toppling. Intersections which fall in the critical region represent the risk of developing toppling blocks. These intersections are dipping into the slope and within the lateral limits of toppling mode of rock failure. Moreover, several joint sets intersect in this slope and can form a wedge which probably slides out of the slope to the south-east of the pit, which depends on kinematic and frictional reflections. The peak orientation of the dominant intersection on W12 slope is 46° (dip angle) and 90° (dip direction).

5.1.3 Kinematic analysis for W13 slope

The illustration of the stereographic shown in Fig. 6 presents the result of the analysis of W13 section to address the potential directional movements of planes of weakness in the slope.

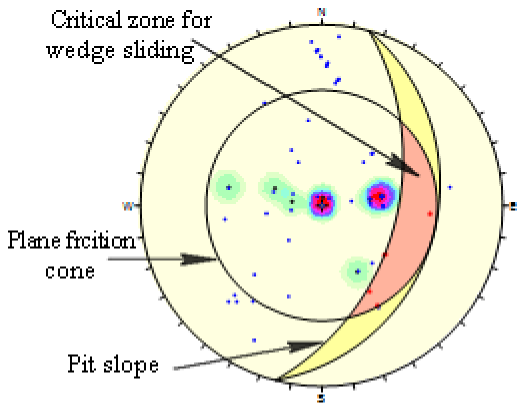

Fig.6 Kinematic analysis for W13 results in low probability of wedge and less of flexural toppling feasibility.

Kinematic analysis for W13 shows that the potentially unstable block at this wall element is in a limit condition. There is 9% probability of a wedge mode of all critical surfaces and dip vectors that plot in this region and this represent a risk of potential wedge failure. Although a critical toppling region for dip vectors appears to be the least probable mode failure, however, a sliding wedge mode region was more possible to be performed. The peak orientation of the dominant intersection on W13 slope is 24° (dip angle) and 105° (dip direction).

5.2 Division of W2.

As illustrated in Fig. 7, the slope element W2 was subdivided into three parts (W21, W22 and W23).

Fig.7 Subdivision outline to W2 slope element of the pit into three vertical slices to study each slice within the slope with its own discontinuities.

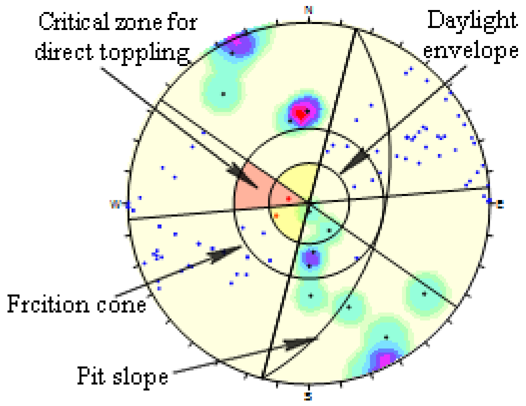

Fig.8 Dip vector plot within W21 region represents toppling risk.

5.2.1 Kinematic analysis for W21 slope

Fig. 8 shows a discontinuity is plotted in the critical zone of toppling. The wedge failure analysis was carried out for the slope indicates a less probability of potential wedge mode at W21 slope. The peak orientation of the dominant intersection on W21 slope is 45^{o} (dip angle) and 110^{o} (dip direction).

5.2.2 Kinematic analysis for W22 slope

W22 is located in the mid-west slope of HHOC pit, and a kinematic feasibility and stability analysis using stereographic constructions is shown in Fig. 9.

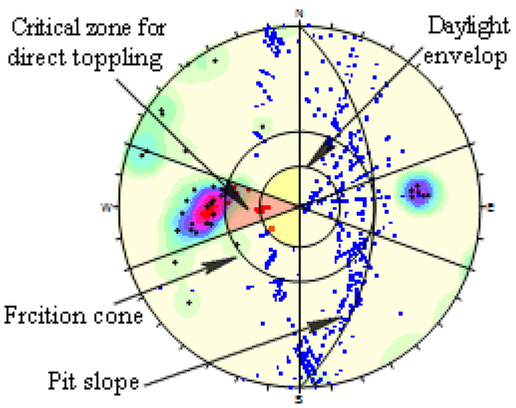

Fig.9 Kinematic feasibility and stability analysis for W22 results in toppling mode of slope failure.

From the kinematic analysis a daylight envelope of toppling mode was illustrated. The kinematic slope stability has tested the probability whether a planar or wedge failure planes may structurally control the failure mode of many joints that intersect through this slope. Considering the orientation of all geological structures, the analysis has suggested that these two modes of failure are feasible. The peak orientation of the dominant intersection on W22 slope is 44^{o} (dip angle) and 90^{o} (dip direction).

5.2.3 Kinematic analysis for W23 slope

The details of W23 discontinuities were verified, a kinematic feasibility and stability analysis using stereographic constructions is presented in Fig. 10.

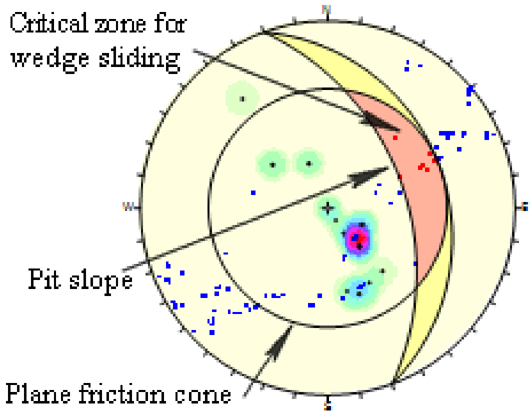

Fig.10 Wedge kinematic feasibility and stability analysis for W23.

From the kinematic analysis of W23, a wedge sliding mode of slope failure was possible. The peak orientation of the dominant intersection on W23 slope is 23^{o} (dip angle) and 72^{o} (dip direction).

5.3 Division of W31 Slope.

As illustrated in Fig. 11 the slope W3 was subdivided into three parts (W31, W32 and W33), where the data of discontinuities of each was verified. W3 west slope element is located at the north-west of the pit and kinematic stability analyses using stereographic constructions in which the relative directions of plane of weakness in the rock mass and the slope face are to define the rock failure mode.

Fig.11 Subdivision outline to W3 slope element of the pit into three vertical slices to study each slice with its own discontinuities.

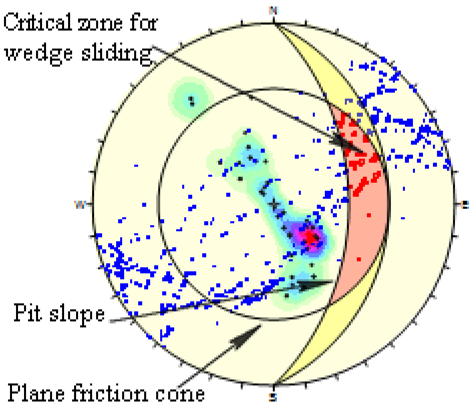

Fig.12 Wedge kinematic feasibility and stability analysis for W31.

5.3.1 Kinematic analysis for W31 slope

From the kinematic analysis was conducted for W31 as shown in Fig. 12, a wedge sliding mode of failure was predicted. Also, a critical planar region for dip vectors may poorly appear within the slope indicating a probable mode of rock failure occurs near the slope crests. The peak orientation of the dominant intersection on W31 slope is 26^{o} (dip angle) and 92^{o} (dip direction).

5.3.2 Kinematic analysis for W32 slope

A kinematic stability analysis of W32 slope using stereographic constructions is shown in Fig. 13. In Fig.13 the highlighted red region presents area of the primary critical joint sets for wedge sliding mode. The highlighted yellow region is the secondary critical area where weak planar failure possibly occurs (intersections and base plane poles).

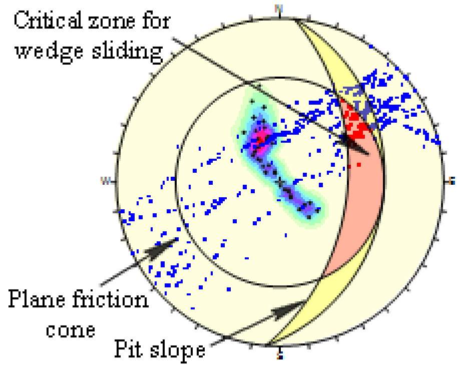

Fig.13 Primary and secondary critical areas of wedge mode failure in W32 slope.

Direct block toppling could initiate as some joint sets intersect and the intersection line dipping into the slope and slides. This allows the block to topple directly. The peak orientation of the dominant intersection on W32 slope is 25^{o} (dip angle) and 96^{o} (dip direction).

5.3.3 Kinematic analysis for W33 slope

The data of discontinuities of W33 was verified, a kinematic stability analysis using stereographic constructions is shown in Fig. 14.

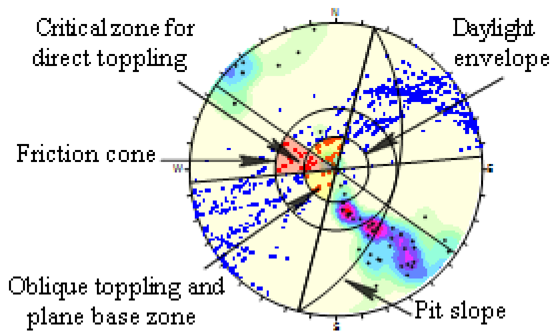

Fig.14 Primary and secondary critical areas of direct toppling failure mode in W33 slope.

The highlighted red region in the stereographic illustration indicates the area of the primary critical joint sets that initiate direct toppling mode. The highlighted yellow region within the friction cone is the secondary critical area where oblique toppling mode of failure exists. The peak orientation of the dominant intersection on W33 slope is 46^{o} (dip angle) and 110^{o} (dip direction).

6. DISCUSION OF RESULTS

This study was motivated by observations and measurements for the natural geological structures at the mine. A detailed description of the potential instabilities, including geological setting and mode failure kinematics was presented for nine elements through W11 to W33 of the west pit slope. The stereographic analyses were performed and the modes of potential kinematic failure are summarised.

Within the Handlebar Hill west slope, the study revealed that the potential wedge failure of local benches was the most likely expected slope instability. Typically, controlling structures, wedge sliding and toppling failure modes are the mechanisms of mobilised blocks. Wedge and toppling are common rock failures in open cut mines; they are more existent in slopes and are mainly controlled by the orientations and the spacing of structural planes with slope surface. The configuration of the critical structures may include a single discontinuity, two intersected discontinuities, or a combination of several discontinuities that are interconnected with each other to form a translational failure mode. This was suggested by Hatzor and Goodman (1992) in their investigation to rock failures in a pilot tunnel, in which they indicated that 33 out of 35 failures were bounded by a maximum three joint sets. Wyllie & Mah (2004) outlined the condition that has to be fulfilled to initiate these plane shear failure, as the sliding plane must strike parallel or nearly parallel within (+/-20°) to the slope surface and with a dip angle higher than its internal friction angle.

The potentially unstable blocks resultant from the kinematic analyses of the west slope are developed by average values of structural orientations and their intersection lines that control the sliding direction of unstable blocks. Comparing field photos shown in Figs. 15 to 17, assisted through the kinematic models to align with the post localised bench failure events occurred in the slope. Furthermore, the in-situ condition observed in the mine confirmed the failure mechanisms revealed in the kinematic analysis.

Despite that the stereographic projection is considered as a normal procedure to identify the combinations of structures that could cause kinematical admissible slipping volumes (Hoek and Bray, 1981), the shear strength failure on the slipping planes is ignored. Moreover, different joint sets or structures could have different internal friction angles, while in the stereographic define material procedure, only one value has to be identified that represents all joints parameter. Based on the site observation and available data, it is often that wedge and toppling modes are predicted, but will not take place due to non-persistence of the controlling discontinuities. Therefore, kinematic analysis should be accompanied with additional analysis tools to give more total evaluation of the stability of the pit slope.

Fig. 15 Toppling failure mechanism at W22 wall of the west slope within the Magazine Shale domain at ramp level 3400, looking south of the pit.

Fig. 16 Wedge failure at W13 wall at ramp level 3352, looking west.

Fig. 17 Wedge failure at W21 wall at ramp level 3376, looking west.

7. CONCLUSION

Several local bench instability problems in the form of small-sized wedge, toppling and rockfall occurred along the west slope of the excavated pit of Handlebar Hill open cut mine. This research selected the west slope to conduct complete kinematic analyses based on the stereographic projection method utilising Dips 6.0. For more certainty in evaluating the stability, the west slope was sub-divided into nine vertical zones using AutoCAD.

The result obtained from kinematic analysis of more than three hundreds dips and dip directions from the west pit indicates the presence of conditions that could lead to wedge failure on the benches of W11 at the southern-west of the pit and benches of W23 and W31. The critical structures on the western pit that form the wedge mode of failure have tended to be local and small limiting failure to a single bench. However, at the north-west benches of W33, it indicates that the discontinuities are widely oriented and intersected consistent with a toppling mode. The kinematical behavior of W12 and W21 suggest failure by direct and oblique toppling.

8. ACKNOWLEDGEMENTS

The authors sincerely extend their appreciation to Glencore Zinc Asset Australia for their support of this research project, and in particular, Dr Ahmed Soliman, Principal Geotechnical Advisor.

9. REFERENCES

[1] X-strata, 2011, Handlebar Hill consultant report, Technical Report in 2007, Mt. Isa, Queensland, Australia.

[2] Sjoberg, J., 1996, "Large Scale Slope Stability in Open Pit Mining: A Review," Lulea University of Technology, Lulea, Sweden.

[3] Hoek, E., 2009, "Fundamentals of slope design", Keynote address at Slope Stability, 9 - 11 November 2009, Santiago, Chile, from: www.slopestability.cl.

[4] Harries, N., Noon, D., and Rowley, K., 2008 ,"Case studies of slope stability analysis radar used in open cut mines", The South African Institute of Mining and Metallurgy, International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering, pp. 335-342.

[5] Brideau, A. M., Yan, M., and Stead, D., 2009, "The role of tectonic damage and brittle rock fracture in the development of large rock slope failures", Geomorphology, V. 103, Issue 1, 1 January 2009, pp: 30–49.

[6] Steffen, O., Contreras, F. L., Tebrugge, J. P., and Venter, J., 2008, "A Risk Evaluation Approach for Pit Slope Design," 42 US Rock Mechanics Symposium, ARMA 08-231, 29 June - 2 July 2008, San Francisco, USA.

[7] Gray, A. P., 1988, "The problem of estimating the shear strength of unstable rock slopes", The fifth ANZ Geomechanics, Sydney, Australia.

[8] Hoek, E., Read, J., Karzulovic, A., and Chen, Z., 2000, "Rock Slopes in Civil and Mining Engineering", International Conference on Geotechnical and geological Engineering, GeoEng2000, 19-24 November, Melbourne.

[9] Priest, S. D., 1985, "The statical analysis of rigid block stability in jointed rock masses", Technical Report to Koolan Island at WA, Imperial College, London.

[10] Oztekin, B., Topal, T., and Kolta, C., 2006, "Assessment of degradation and stability of a cut slope in limestone, Ankara-Turkey", Engineering Geology, 84(1-2), pp. 12-30, Turkey.

[11] Wickham, G. E., Tiedemann, H. R., and Skinner, E. H., 1972, "Support determination based on geologic predictions", In Proceeding, North American rapid excavation, Tunneling Conference, AIME, PP. 43-69, New York.

[12] Roccsience, 2014, Dips 6.0, Toronto, Canada.

[13] Hatzor, Y., and Goodman, R. E., 1992, "Application of block theory and the critical key block concept to tunneling: two case histories', Proceeding Conference on Fractured and Jointed Rock Masses, pp. 663-670. Rotterdam: Balkema, Britain.

[14] Wyllie, D.C. and Mah, C., 2004, "Rock slope engineering: civil and mining", 4TH edition, Spon Press, New York, USA.

[15] Hoek, E., and Bray, J. W., 1981, "Rock Slope Engineering," In- stitution of Mining and Metallurgy, London.

Int. J. of GEOMATE, Feb., 2016, Vol. 10, No. 1 (Sl. No. 19), pp. 1575-1583.
MS No. 09596 received on March 18, 2015 and reviewed under GEOMATE publication policies.

Corresponding Author: Maged Al Mandalawi