IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Slope Stability Analysis With Batter Angle Variation

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Abstract: A system was developed to identify the optimal highwall batter angle in an open pit mine. The initial design specified a batter angle of 70°, with the option to modify it in response to changing wall conditions as mining progresses from the northern to the southern sections. The mine has faced various challenges concerning slope stability, especially in regions with significant jointing and faulting, leading to wedge and planar failures. To mitigate these problems, the high wall is being methodically surveyed as it is exposed. By leveraging the newly gathered data, slope stability is reassessed in light of mining experiences, with the goal of determining if the benefits of lowering the batter angle justify the additional costs incurred from mining extra overburden.

Index Terms:slope, highwall, Stereographic

I. Introduction

The mine represents an extension of the earlier excavation site, leading to the formation of a larger pit. The final high wall spans approximately 4 kilometers in length and reaches a peak height of 240 meters, composed of premium-quality material. The coal seam within the mine has a thickness of 11 meters and is overlain by layers of lithic sandstone, siltstone, sandstone-siltstone laminates, silty mudstone, and carbonaceous mudstone. These geological layers are from the Late Permian and Early Triassic eras. Situated about 1 kilometer east of a regional thrust, the mine's geological formations exhibit characteristics of faulting and folding, with the strata inclined towards the east-northeast at an average angle ranging from 15° to 35°. In some locations, especially near significant structures, the dip angle can exceed 35°. The main structural orientations are outlined in Table 1, and three sets of joints are commonly found throughout the mine.

Table 1 Base report joint sets

Defect Set	Defect Type	Dip (°)	Dip Direction (GN
JA1	Joint	74	256
JA2	Joint	71	216
JA3	Joint	81	171
B	Bedding	23	54
SH	Shear	57	241
FA1	Fault	64	11
FA2	Fault	45	62
FA3	Fault	50	182

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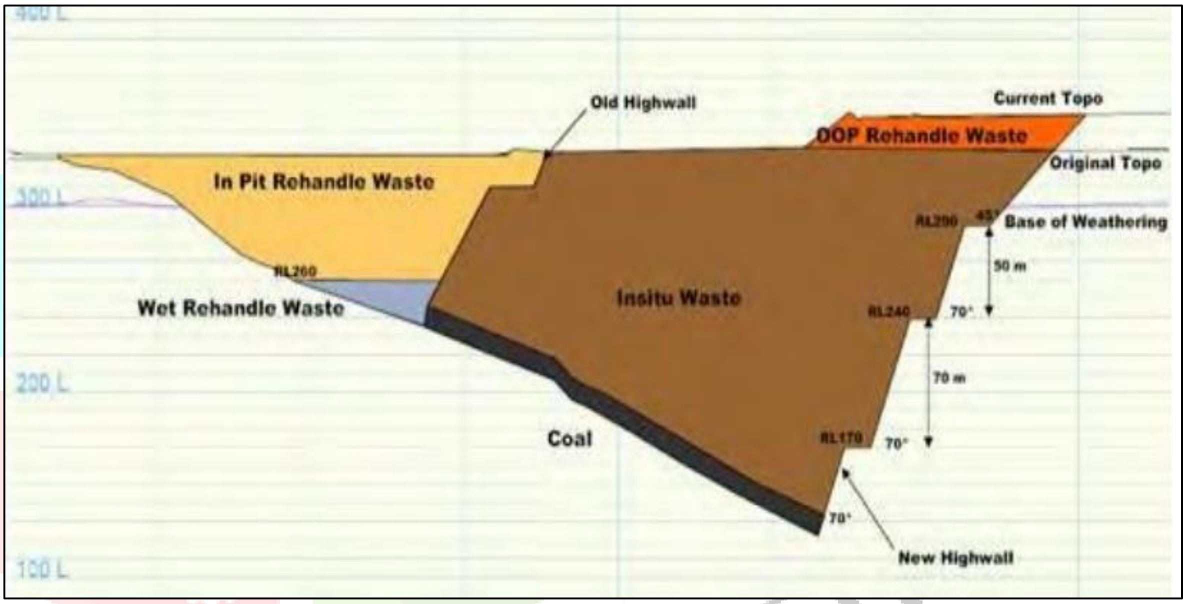
Groundwater is visible behind the high wall as it seeps through. The pit floor is made up of soft mudstone with numerous bedding plane shear planes present.

Various monitoring and instrumentation systems are utilized, such as vibrating wire piezometers, inclinometers, and time domain reflectometry systems in boreholes, survey prisms along the high wall, and slope stability radar systems in specific areas. Additional investigations and modelling are carried out as needed.

Shear test block used for the study.

The terrace mining method is being used. This allows backfilling of the mining void soon after coal recovery has been completed which provides a buttress to the high wall. The reduced the span of the exposed highwall minimizes the risk of falls (Figure 1).



Typical Cross Section

The highwall design criteria include an overall slope angle of 55°-57°, a maximum height of 70m between benches, and berm widths of 16m. Highwall batter angles are set at 70° below the base of weathering and 45° in weathered rock, with benches located at 170RL, 240RL, and 290RL.

Controlled blasting practices such as pre-split and trim blast minimize wall damage, focusing on a single pass process for the 70m high batter. 4. Wall scaling during excavation ensures loose material is removed, leaving a clean batter to reduce potential rock fall and instability hazards

3.2 Stability Concerns

Low-strength layers within the overburden or the immediate coal floor, such as clay-rich tuff beds, carbonaceous mudstones, and claystone, contribute to localized instability. These strata typically possess low shear strength and are susceptible to moisture-related softening and slaking, which can create potential failure surfaces in the walls of excavated pits. Significant faults and persistent joint surfaces intersect the pit walls in ways that may lead to planar or wedge failures.

These geological features may be coated with clay, calcite, or crushed rock, which exhibit lower shear strength than the surrounding intact rock. The presence of larger structures can affect both bench stability and the overall slope stability. Closely spaced joint sets or faults that run sub-parallel to the pit walls can interact with the walls, resulting in geometries that may lead to planar, wedge, or toppling failure mechanisms. Such failures can manifest as bench-scale instability, influencing the design parameters for benches and berms.

Mapping these geological structures is a crucial aspect of the project's geotechnical hazard management plan, accomplished through the Siro vision photogrammetric mapping and analysis system.

Figure 2 Rock falls

The Problem Within the highwall there are at least two structural domains. The so called "Swarm Domain" in the south is an area of frequent faults and joints that are different to the frequent faults and joints in the Northern part of the pit.

The differences in the geotechnical domains mean that a suitable batter angle for north may not be applicable to south. The question to which an answer was sought is, how would a 65° batter design compare with a 70° batter in these two domains.

A push back from 70° to 65° would require moving a significant additional amount of waste, potentially costing approximately $12 - $15M. And the key issue is how would the probability of wall failures change if the batter angle was reduced to 65°? This is clearly a "Probability of Failure" question rather than a conventional "Factor of Safety" issue. If the likely volume of failed material could be estimated for both the 70° and 65° batter angles, then it would be possible to do a cost comparison.

3.3 The Process to Obtain a Solution Figure

Describes the process that was adopted to obtain a solution to the stated problem of comparing the predicted performance of a high wall with 65° batters with one containing 70° batters.

• A	Data Collection • Take Stereo photos • Create a georeferenced Siro vision model
• B	Data Analysis • "Define Orientation Sets" • Join models to a mosaic • Analyse models for joint sets/structural domains.
• C	Modelling work • Carry out kinematic analysis to test for planar, wedge, and toppling failures • Identify potential failures and & estimate volumes

3.4 Data Acquisition with software

The starting point was to acquire detailed, georeferenced, structural geological data. The tool used to generate these data was Siro Vision.
Siro vision is a mapping tool and analysis system that rapidly generates accurate, scaled, 3D images from stereo-pair photographs. It uses off-the-shelf DSLR cameras to generate the images and the software can process these images into a fully georeferenced 3D image on which the user can identify geological structures.

The Siro vision system offers various advantages compared to manual mapping. These include:

1) Safety. Most mine sites impose a mandatory exclusion zone that prevents personnel from approaching a high wall. Siro vision allows mapping to be undertaken from a safe distance.

2) Range. A whole face can be mapped by using photogrammetric images enabling the user to map structures that would not be physically accessible to a geologist on foot.

3) Speed. Siro vision enables very fast data collection and analysis. A face can be photographed and analysed within 1 or 2 hours.

3) Simplicity and low cost- Siro vision can be used by anyone following a short period of training. The use of off-the-shelf cameras helps to keep costs down. In this regard it should be noted that more camera pixels do not mean better results rather, they create very large files that computers struggle with, for no additional benefit.

4) Accuracy. The system uses 3D images as the basis for mapping. These can be created using various combinations of camera positioning and ground control points. The method that is used will influence accuracy which can range from very accurate to good enough for practical purposes.

5) One platform. Siro vision provides one single platform where data can be captured and analysed. The data can be exported to other software packages for example as meshes to **Pix pro software** or as orientation data to Dips.

6) Database. Siro vision comes with a database that permits the progressive accumulation of data over time.

In the field, the photographic data for the current problem was collected from a 700 m length of highwall. The camera used was Nikon D300S digital SLR equipped with an f=85 mm lens. Appropriate timing was selected to avoid sun flare and excessive shadows. Adjacent stereo pairs were overlapped by approximately 30% in order to facilitate creating mosaics of multiple 3D images. Georeferencing was achieved by locating the camera positions and three control points in each 3D model using the site's differential GPS system.

3.5 Quality and Accuracy of the Data

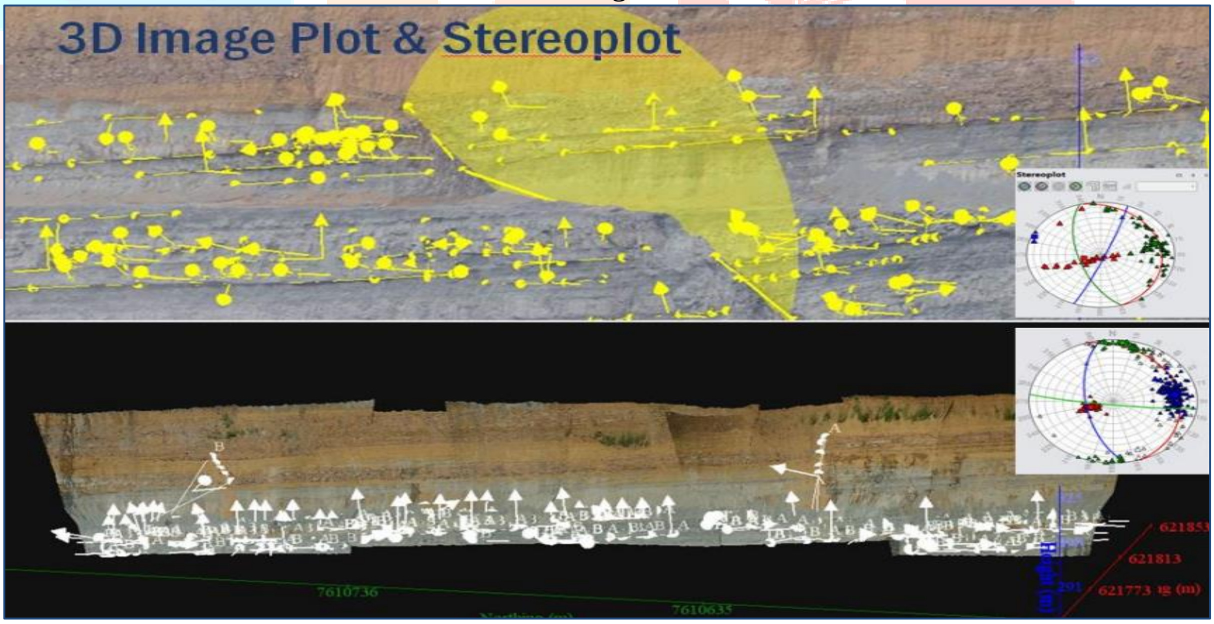
The accuracy of Software mapping is said to exceed +/- 0.5° for dip angle and dip direction within the range of 3-1500m. However, this claim was not verified in the recent investigation. In coal mines, the distance between the photographer on the low wall and the target on the high wall can be several hundred meters, which can decrease the accuracy. Nevertheless, one author has conducted a direct comparison and found that Software-measured data is comparable to, and occasionally even superior to, manually measured data.
The resolution of the camera image is determined by the distance from the mapping wall and the width of the photo coverage, as shown in the graph provided. The image must be captured in RAW format.

3.6 How the Software Data was Used

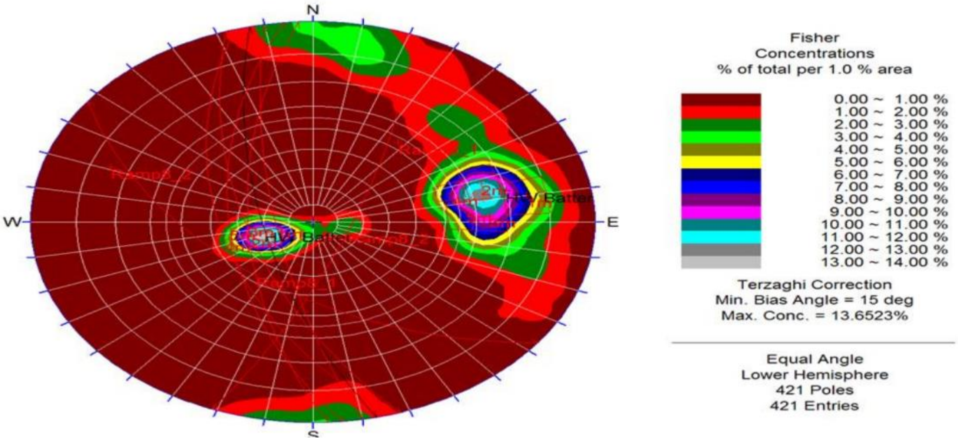
Software was used to identify individual joints, measure their orientation and location, and derive their spacing (Figures 5 and 6). The data were transferred to the program Dips for further analysis. Much of the further analysis could have been done within Siro joint but in this case Dips was the tool of choice and it did not matter that locational information for each structure was lost.

The support of the mine and the mine owner used for this case study is gratefully acknowledged. The impetus for this study came from the necessity for a business decision and the support of Indian Mining to develop this methodology in support of that business decision is gratefully acknowledged

Defining Fault



Stereographic Face Map



Concentrations of Poles

3.7Analysis of Software Data

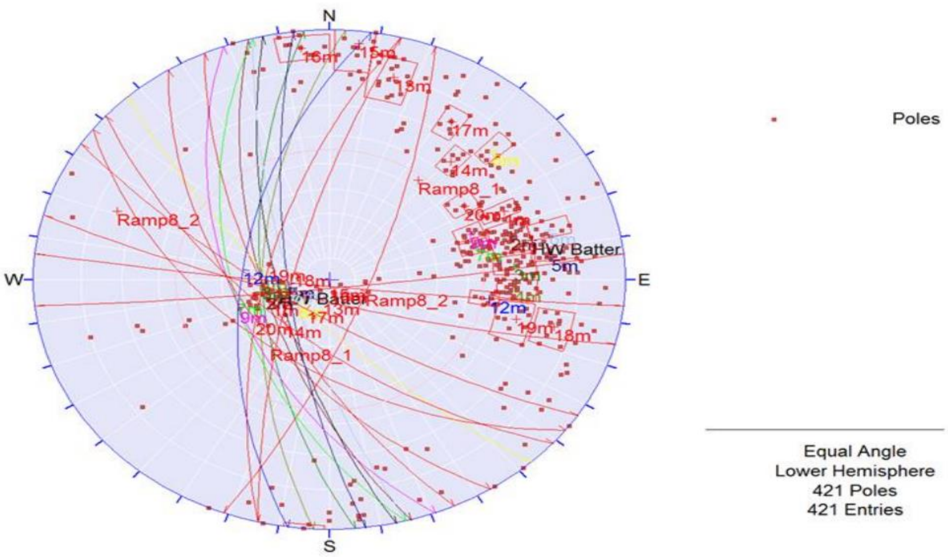
The results obtained from the Software mapping are shown in Figure 8. A superficial reading of the stereo plot indicates that the poles are clustered around 64°-degree average dip and at dip directions that diverge less than 20° from the highwall dip direction. However, there is a wide variation in dip angles.

Accepting the average values could lead to the conclusion that a batter angle of 65° is optimal. However, when explored closely, it is possible to identify various subsets of the average.

These subsets were investigated further.

The poles were sub-grouped into smaller clusters, from which several subsets were identified.

These subsets are likely to give rise to small-scale wedge and planar failures. By identifying these more hidden potential failures and estimating their volume a better appreciation of an optimal slope angle can be made. Figure 8 shows the joint subsets that were used in subsequent analyses.



Equal angle lower hemisphere stereoplot of mapped structures

An alternative method of displaying the mapped data is shown in Table 3. Here the data is arranged to show what percentage of joints have orientations within specified departure intervals from the highwall dip and dip direction. This way distribution of critical joint planes can be better understood.

HW Dip	70
HW Dip Dir.	257

		Dip Direction (+/- 20 HW Dip Direction)											
		-20	-15	-10	-5	5	10	15	20				
	Dip	>237 <242	>242 <247	>247 <252	>252 <257	>257 <262	>262 <267	>267 <272	>272 <277	Sum	%	Cum	Cum %
-40	>30 <35	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	1	0.5%	1	0.5%
-35	>35 <40	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	1	0.5%	2	1.0%
-30	>40 <45	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1	0.5%	3	1.5%
-25	>45 <50	0.0%	0.0%	0.5%	1.0%	0.5%	1.0%	0.0%	0.0%	6	3.1%	9	4.6%
-20	>50 <55	0.5%	0.0%	2.0%	2.0%	2.6%	0.5%	0.5%	0.0%	16	8.2%	25	12.8%
-15	>55 <60	1.0%	0.5%	3.1%	4.1%	3.1%	4.1%	1.5%	1.5%	37	18.9%	62	31.6%
-10	>60 <65	1.5%	1.5%	1.5%	6.1%	2.0%	3.1%	3.1%	5.1%	47	24.0%	109	55.6%
-5	>65 <70	1.0%	3.1%	4.1%	4.1%	3.6%	2.6%	3.1%	1.0%	44	22.4%	153	78.1%
5	>70 <75	0.0%	0.5%	0.5%	2.6%	2.6%	3.1%	1.0%	0.5%	21	10.7%	174	88.8%
10	>75 <80	0.5%	0.0%	0.0%	2.0%	0.5%	2.0%	1.5%	0.5%	14	7.1%	188	95.9%
15	>80 <85	0.5%	0.0%	1.0%	0.0%	0.0%	1.0%	0.0%	0.5%	6	3.1%	194	99.0%
20	>85 <90	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.5%	2	1.0%	196	100.0%
	Sum	10	12	26	43	29	35	22	19				
	%	5.1%	6.1%	13.3%	21.9%	14.8%	17.9%	11.2%	9.7%				
	Cum	10	22	48	91	120	155	177	196				
	Cum %	5.1%	11.2%	24.5%	46.4%	61.2%	79.1%	90.3%	100.0%				

~50%

<<HW Slope

HW Dip Direction

~50%

Dip and dip direction distribution in relation to dip and dip direction of highwall

3.8 Rockfall Volume Estimation Procedure

Joint sets that were identified from the Software data were transferred to Vulcan and wedge solids were created within software based on the intersection of planes orientated in accordance with the identified joint sets and the highwall (Figure 10). The volumes of those wedges were calculated and tabulated in order to permit a semi-quantitative comparison of the likely rockfall volumes for a range of batter angles.

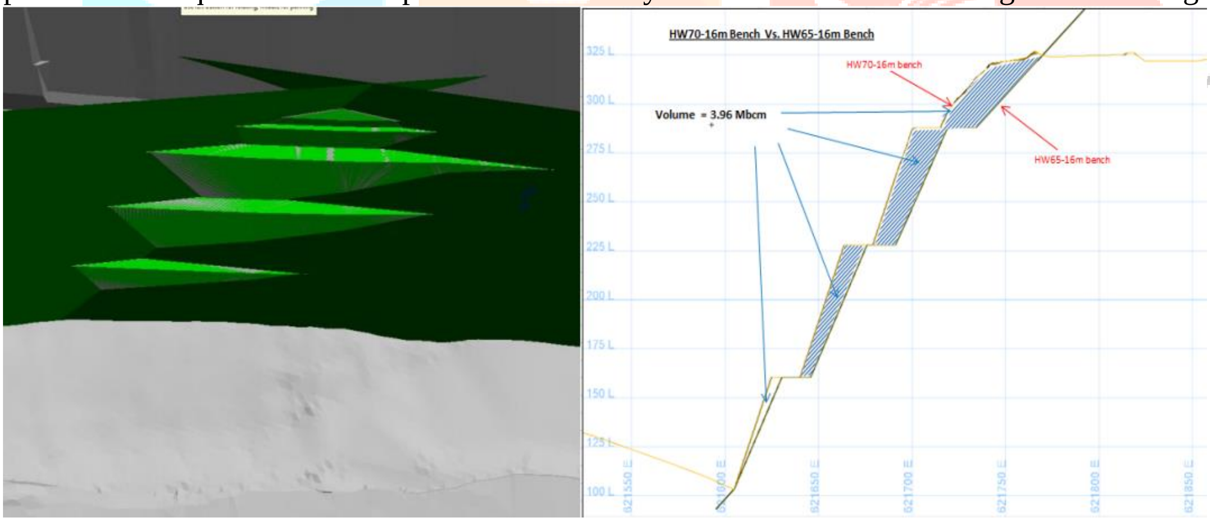


Figure 10.Typical wedges formed on high wall face

Results

The results of the analysis indicated that:

- Wedge failures will occur in all circumstances of highwall batter angle and joint orientations considered (at highwall angle of 70°/257°).
- Reducing the batter angle from 70° to 65 ° reduces the proportion of joints exposed at face from 78.2% to 55.6% (by 22.4%) but the total wedge volume drops approximately only 4% from 500kbcm to 350kbcm.
- Overall probability of a deep seated failure is quiet low (12.6% and 6.6% for non-buttressed and buttressed highwall respectively with strength reduction factors varying from 1.29 to 1.40.
- Reducing the highwall batter angles from 70° to 65° increased the strength reduction factor from 1.28 to 1.38 while the probability of failure decreased from 12.6% to 8.5% at the expense of approximately 4Mbcm additional excavation.

- Increasing berm width from 16 m to 25 m increased the strength reduction factor from 1.28 to 1.40 at the expense of additional wedge failures in the order of 200kbcm.
- A dragline spoil buttress at the pit bottom decreased the probability of failure from 12.5% to 6.6%.

Conclusion

There is no doubt that with additional time the method described in this case study could be improved. However, the authors are not aware of any other examples where this approach has been used to assist in a design decision of this nature. The approach taken here meant that over a few days, making use of some pre-existing laboratory data, the mapping was done, the data analysed and a long running discussion as to whether it would be worthwhile flattening the highwall batter angle from 70° to 65° was resolved.

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