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A Framework for Geotechnical Hazard Analysis in Highwall Mining Entries

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Highwall mining involves driving a series of parallel entries with web pillars in between. These entries are driven by using a continuous miner with attached conveying system to extract locked up coal behind the highwall slope when the open cut coal mine reaches its ultimate limit. These entries are driven unmanned, unventilated and unsupported. Therefore, a detailed knowledge of structural features ahead of operations is essential in assessing the stability of these entries. Highwall mining operations can greatly benefit from accurate structural mapping of rock mass defects. The stability of these entries can be suitably assessed for any major roof failure by adopting discrete fracture network based structural modelling to characterize and delineate the regions of possible major roof failures to prevent damage to the conveyor and burial of the expensive continuous miner. In this paper, a generalized framework is described based on photogrammetric survey, digital mapping and discrete fracture network based structural modelling to characterise such failures for an Indian highwall mining operation. A sensitivity analysis is undertaken to demonstrate the significance of structure persistence in the geotechnical assessment. Such analysis would provide more insight into designing highwall mining layouts and in predicting possible impending highwall failures, and indirectly facilitates reducing machine downtime for better management of highwall mining operations.

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A Framework for Geotechnical Hazard Analysis in Highwall Mining Entries

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Abstract

Highwall mining involves driving a series of parallel entries with web pillars in between. These entries are driven by using a continuous miner with attached conveying system to extract locked up coal behind the highwall slope when the open cut coal mine reaches its ultimate limit. These entries are driven unmanned, unventilated and unsupported. Therefore, a detailed knowledge of structural features ahead of operations is essential in assessing the stability of these entries. Highwall mining operations can greatly benefit from accurate structural mapping of rock mass defects. The stability of these entries can be suitably assessed for any major roof failure by adopting discrete fracture network based structural modelling to characterize and delineate the regions of possible major roof failures to prevent damage to the conveyor and burial of the expensive continuous miner. In this paper, a generalized framework is described based on photogrammetric survey, digital mapping and discrete fracture network based structural modelling to characterise such failures for an Indian highwall mining operation. A sensitivity analysis is undertaken to demonstrate the significance of structure persistence in the geotechnical assessment. Such analysis would provide more insight into designing highwall mining layouts and in predicting possible impending highwall failures, and indirectly facilitates reducing machine downtime for better management of highwall mining operations.

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Keywords: highwall mining; structural mapping; structural modelling; discrete fracture networks; hazard analysis

1. Introduction

Highwall mining operations offer the opportunity to improve coal extraction rates significantly provided geotechnical risks are managed properly. These risks include slope failure as well as roof collapse within

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the highwall entries induced by local failure, potentially resulting in loss of the continuous miner and conveying system. The Guidelines for Open pit Design [1] presents detailed recommendations for the management of uncertainty and risk in open cut slope design and the work described in this paper takes place within this framework. In this paper, we describe a framework that uses photogrammetric survey, digital mapping and analysis, stochastic structural modelling for the stability analysis of structurally controlled failures at an end user site in India. This study uses data previously acquired at an Indian coal mine site [2].

2. Site details

The site was part of an Open-Cast operation of a Coal Mining Company in India (hereafter, site referred to as OC II). The Coal Company started mining temporary entries into the highwall of OC II to access longwall operations. These entries will eventually be replaced by permanent entries once mining in OC II is complete. Fig. 1 shows the general layout of mining operations, with the highwall being around 125 m high with an overall slope angle of approximately 35º to 40º in the vicinity of the temporary entries (from the floor of I seam) and 10 m benches have been mined with bench face angles up to 80º. Significant bench erosion was observed at higher elevations. Table 1 details structural data for the region of interest in OC II [3].

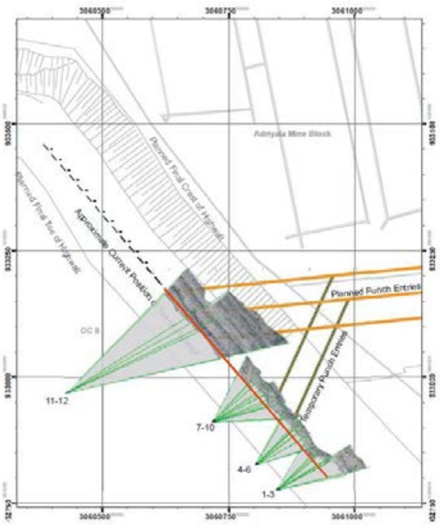
Table 1. Structural data for region of interest in OC II [3].

Joint/Cleat Set	Dip Direction	Dip	Spacing (m)	Persistence (m)
J1	130º	86º	1.5	2.5
J2	050º	14º	1.0	5.0
J3	232º	84º	1.5	1.0
CL1	050º	14º	0.2	0.6
CL2	155º	86º	0.1	1.0
CL3	260º	84º	0.4	0.6

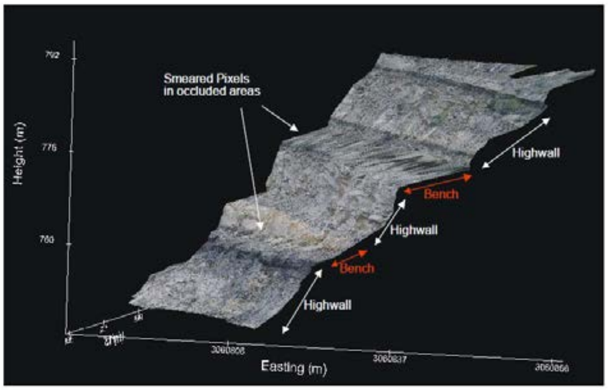
3. Photogrammetric survey

The Sirovision^{TM} system [4] developed by the CSIRO was used for the photogrammetric survey and structural analysis. Thirty stereo pairs over a distance of 500 m were acquired and processed into 12 ‘stacks’ of 3D images (Fig. 1a).

A Nikon D300 DSLR camera with 60 mm lens was used. The distance to the toe of the highwall was approximately 120 metres for images 1 to 10 and 300 metres for images 11 and 12 with camera locations being constrained by site access. Camera locations were surveyed and control points were located along the toe and along the crest of the highwall which supported scaling and geo-referencing of the 3D images. The 3D resolution of the images and the accuracy of measurements made from them, is a function of the distance of the camera to the highwall, the resolution of the camera and the focal length of the lens used. Overall, the spatial resolution of the images collected was of the order of 10 to 30 mm in the areas of interest. The geometry associated with the moderate slope angle of many benches at OC II (35º to 40º) and site access resulted in areas being occluded in the images (Fig. 1b). Note that the use of aerial based (including unmanned aerial vehicle) photogrammetry could alleviate this issue in future surveys.



(a)



(b)

Fig. 1. (a) Approximate camera locations for the twelve stacks. Note that stacks 11 and 12 are more than double the distance from the highwall than the others; (b) Occlusion of upper sections of benches.

4. Structural analysis

The structural analysis described below is taken from [2]. The joint statistics are shown in Table 2. No attempt has been made to measure cleat in the coal seams for this study. JI has a very similar attributes to J1 in the CMRI (2205) report. However, the persistence and spacing of this joint set is greater in this study. J2 and J3 in this study are not represented in the CMRI (2005) report. If these two joint sets are combined, the dip direction of the combined set is 219º, which is similar to the dip direction of J3 in the CMRI (2005) report, although the dip is significantly shallower and the spacing and persistence greater. The bedding was also measured and has a dip of 20º towards 52º. This corresponds with J2 in the CMRI (2005) report.

Table 2. Joint set statistics.

Set No.	No. Joints	Dip (º)		Dip Direction (º)		Fisher K	R90	R99	Persistence (m)	Spacing (m)
		Mean	Standard Deviation	Mean	Standard Deviation					
J1	66	89.2	10.2	138.9	12.8	15.9	31.2	44.8	6.6	8.7
J2	32	61.1	14.3	199.3	11.8	17.1	30.1	43.0	4.5	3.9
J3	14	58.4	10.8	261.0	10.0	25.3	24.6	35.1	3.0	4.0

The observed non-uniform distribution of joints is perhaps representative of actual geological domains (e.g. coarser, cross-bedded, sand stone units with fewer joints than other units) but potentially due to sampling bias as mapping in weathered material is challenging. Occlusion, rubble, blasting damage and damage from mining equipment present further challenges to mapping.

5. Structural modelling

The CSIRO developed structural modelling software known as *Siromodel* [5] was used with the aforementioned structural data. The discrete fracture network (DFN) generator in Siromodel supports several models but given the scarcity of information regarding spatial distribution of the joints and for the purposes of this study, the established *Baecher* model [6] was used.

5.1. Simulations based on measured trace lengths

Synthetic fracture networks were generated and input parameters adjusted to ensure agreement between synthetic and mapped joint traces given the modelling assumptions (e.g. hexagonal fractures). The structure parameters in Table 3 were determined to achieve agreement to within 10 % of mapped parameters.

Table 3. The joint set parameters used in Siromodel.

Dip (°)	σ(Dip) (°)	DD (°)	σ(DD) (°)	Trace length (m)	Number of joints in simulation volume	Joint representation
89	10	139	13	8	2500	hexagon
61	14	199	12	5.5	2500	hexagon
58	11	261	10	3.6	2500	hexagon

Bedding layer data was acquired from [4]. Average values were used for depth of cover, thickness, and orientation, with size being assumed to be persistent throughout the region of interest (Table 4).

Table 4. Bedding properties used in Siromodel [2].

Seam	Depth of cover, m	Thickness, m	Dip (°)	DD (°)	ϕ (°) (±10%)	C (kPa)
I	124.5	5.95	20	52	25	0
II	147	3.55	20	52	25	0
IIIA	192	1.35	20	52	25	0
III	219.5	11.6	20	52	25	0
IV	234.5	3.9	20	52	25	0

Due to lack of data, conservative values were used for friction angle and cohesion and standard deviation of 10 % was applied. These values are, of course, extremely significant in the assessment of daylighting wedge or block stability [7]. Fig. 2 shows an idealised model and DFN realisation of the section of the highwall simulated with the inclusion of nine benches in this analysis. For the purposes of this demonstration, ten tunnel entries have been included in the modelling, confined to seam IV.

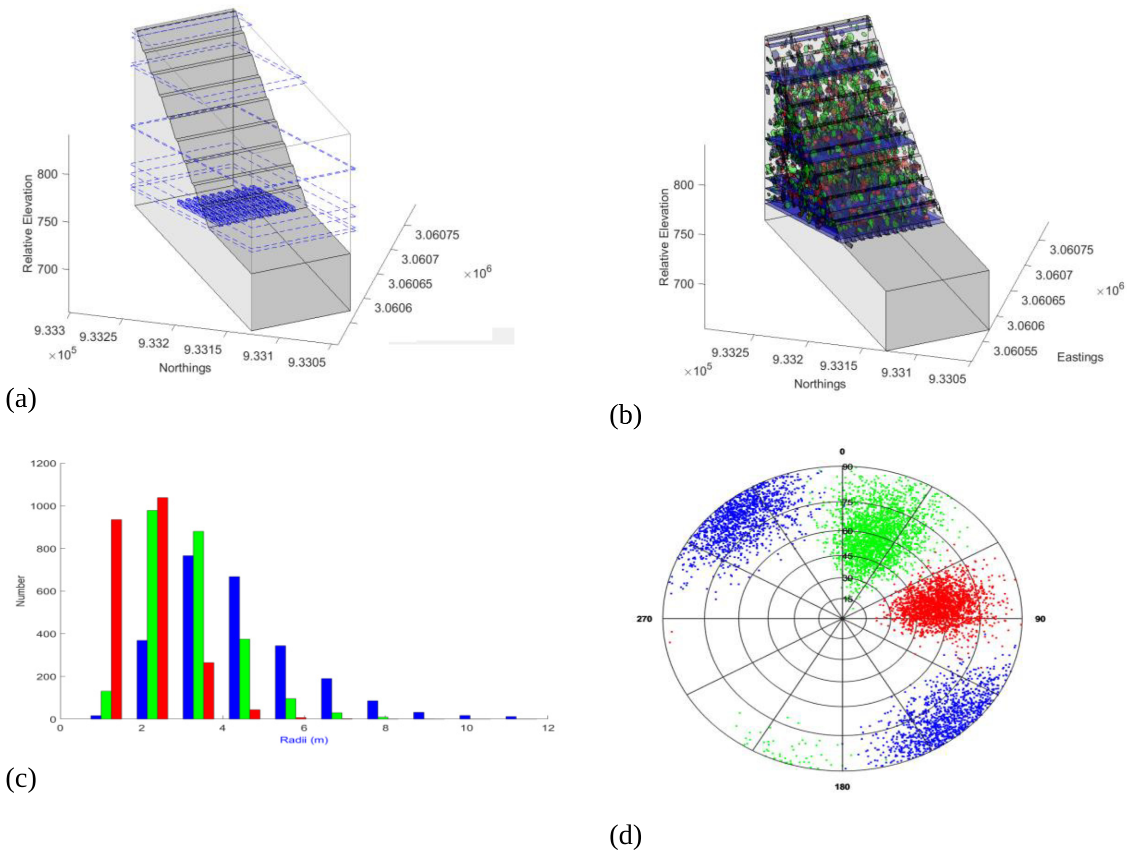


Fig. 2. (a) Idealised Model of the highwall with bedding layers and entry geometries shown; (b) Example realisation of a DFN used in this analysis; (c) Histogram of joint radii for DFN realisation in (b); (d) Lower hemisphere stereonet for DFN realisation shown in (b).

One hundred DFN realisations were performed in a Monte Carlo simulation, with the polyhedral modelling algorithm utilised in Siromodel [8] being used to detect polyhedra (i.e. blocks) which form from the intersection of the polygons comprising the DFN. It was observed that only a few polyhedra (typically less than 10) were detected for each realisation and an analysis of the cumulative results showed that the 90th percentile block volume is less than 10 m^3. A 3D spatial analysis revealed that across the entire highwall, less than 3 % of simulations predicted hazard formation. No increased occurrence of hazards was detected in the regions of the entries.

5.2. Simulations assuming the presence of significant under-estimation of trace lengths

The preceding analysis assumes that the structural mapping has captured the salient characteristics of the discontinuities in the rock mass. There are a number of issues and sampling biases that the practitioner needs to be aware of [9, 10]. Assessing the significance of these issues through techniques such as sensitivity analyses is extremely important to ensure confidence in geotechnical analysis is maintained. One of the more critical parameters associated with slope stability is structure size [11, 12]. A conservative analysis of the significance of this parameter has been conducted assuming the trace lengths are much larger than mapped. Using the typical interburden thickness as a guide, mean trace lengths of each of the three joint sets has been set to 25 m and the Monte Carlo simulation repeated. Fig. 3. shows an example realisation (where red blocks indicate Type I (unstable), yellow type II (stable given friction) and green type III (kinematically stable)) and Fig. 4 the geotechnical analyses based on these realisations.

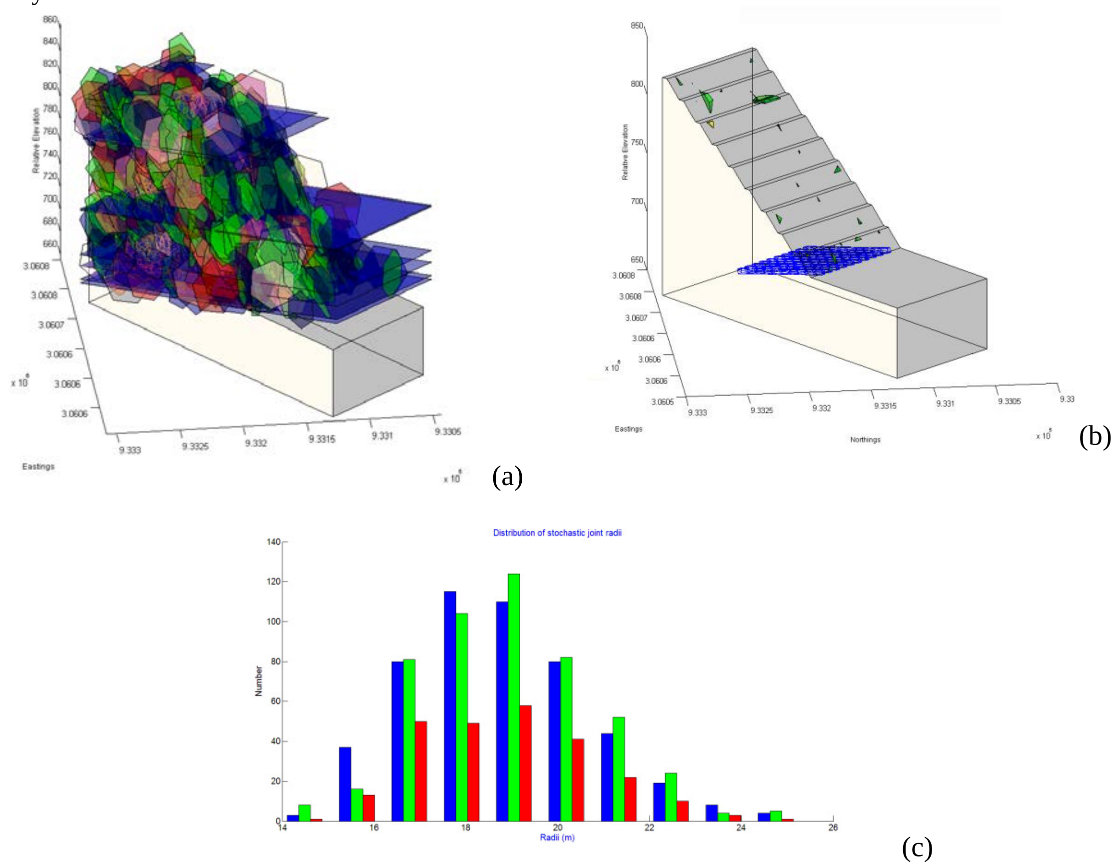


Fig. 3. (a) Example realisation of a DFN used in this analysis; (b) polyhedral model for this realisation; (c) histogram of joint radii for this realisation.

Many more polyhedra are now predicted with the 90th percentile block volume being 36 m^3 (95 % confidence interval for this parameter lies between 12 to 89 m^3). The cumulative hazard map shows the locations and stability type of all kinematically free blocks detected for every DFN realisation, where red indicates Type I (unstable), yellow type II (stable given friction) and green type III (kinematically stable). The hazard density map shows that across the entire highwall there are regions where up to 50 % of simulations predict block formation but less than 11 % predict Type I and II blocks. This is particularly so for the region around seam II where the seam thickness is conducive to the formation of blocks but they are almost exclusively Type III (i.e. kinematically stable) due to the bedding dipping into the wall. The structural modelling in this analysis has not discriminated between in-seam and interburden joint characteristics (a contributing factor to these results). Of particular note is Fig. 4(c) which highlights the increased occurrence of hazards in the regions of the entries.

5.3. Simulations representing interburden shale bedding

Another sensitivity analysis was conducted to determine the effects of shale bedding in the interburden above the Seam IV entries. For this Monte Carlo simulation, the original DFN parameters were used (i.e. joint traces as mapped in the field). One metre spacing was assumed for the shale bedding with orientation and friction angle identical to those assumed for the seam bedding. Although the presence of the shale bedding was seen to contribute to block formation relative to the analysis discussed in Section 5.1, less than 1 % of simulations predict formation at any given location. There was also no significant incidence of Type I or II block formation associated with the entries.

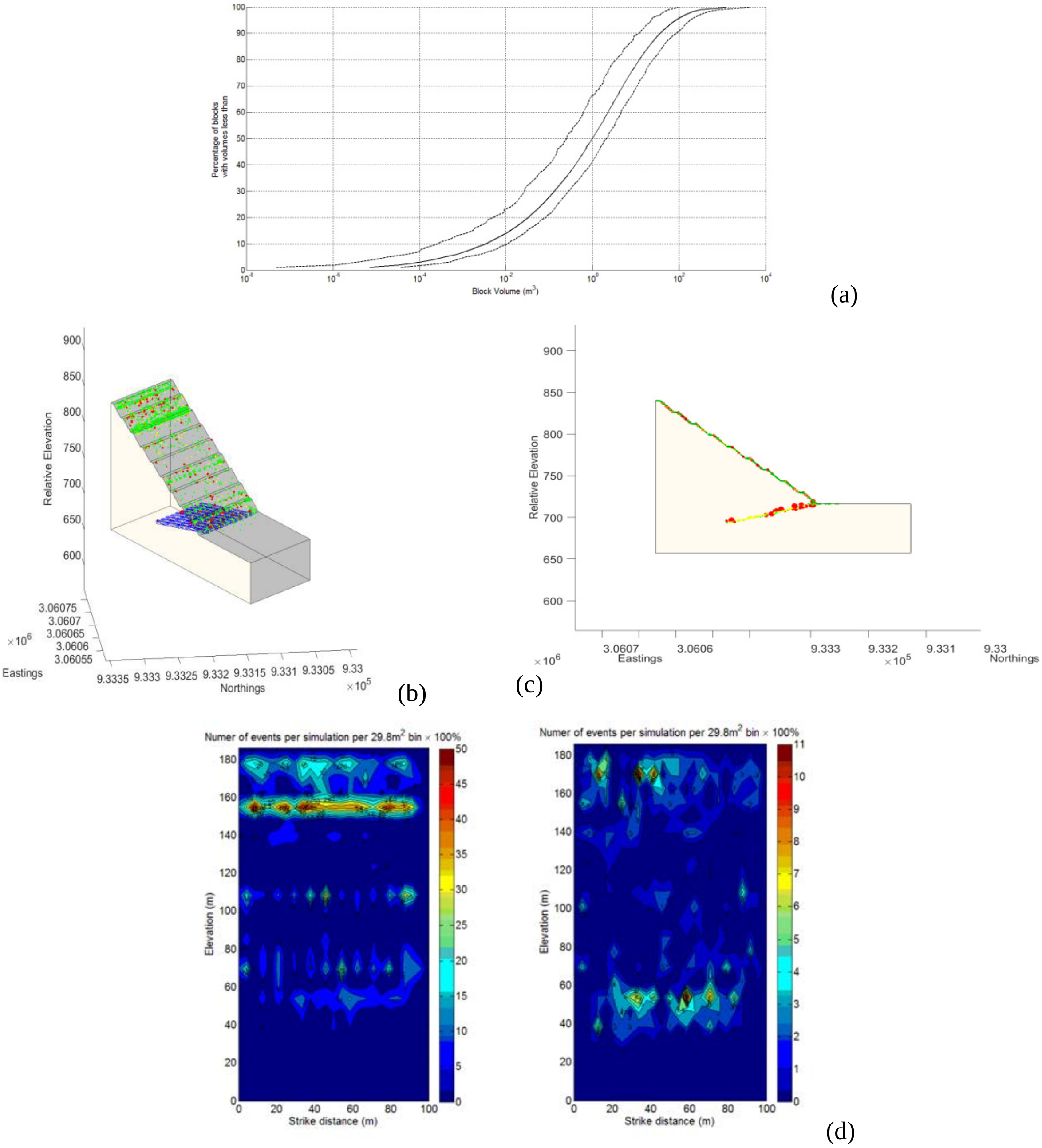


Fig. 4. Several geotechnical analyses based on the Monte Carlo simulations for the more conservative scenario; (a) Cumulative block size distribution for kinematically free blocks; (b) Cumulative Hazard map; (c) Cumulative Hazard map view along strike showing the increased hazards associated with the entries; (d) Hazard density map for all blocks (left) and only Type I and II blocks (right). The vertical axis shows elevation above the lowest level in the model, so the bottom of the highwall corresponds to elevation of 60 m.

6. Conclusions

A generalised framework for assessing geotechnical uncertainty for highwall mining is described. A case study is undertaken using digital mapping and probabilistic structural modelling for the stability analysis of structurally controlled failures in highwall mining operations. It has been demonstrated through a case study that sensitivity analyses, particularly focussing on structure persistence, are vital for an improved understanding of the significance of sampling bias and parameter uncertainty. Such analysis would provide more insight into designing highwall mining layouts and in predicting possible impending highwall failures, and indirectly facilitates reducing machine downtime for better management of highwall mining operations.

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