CHAPTER 8

RESULTS AND DISCUSSIONS

8.1. Introduction

Operating a large opencast mine is challenging due to the need to accommodate a massive volume of OB dump material within an ever-shrinking space. The challenge of material handling forces mine operators to design a large-size multi-bench dump slope structure. Numerical models can precisely simulate the dump slope behaviour and explain their explicit behaviour. However, it requires a higher level of technical competence. Moreover, it consumes significant time to project the stability state of the dump slope structure. These limitations elude an immediate solution. The stability rating and hazard classification is a suitable alternative to the numerical simulation for assessing the stability of the dump slope structures.

The previous works related to the dump slope stability rating and associated hazard classification mainly pertained to the qualitative classification of slope stability and associated hazard. A few works aimed to develop FoS or PoF based classification system. No classification is available to quantify the rating of hazard governing parameters. Therefore, a reliable system of Stability Analysis and HAzard RAting (SAHARA) was developed for the dump slope structure in this study.

8.2. Numerical Simulation

It was observed that the instability zone initiated from the middle benches and propagated in the upper benches with the increase in the total dump height. The loading effect increased by increasing the dump height. The bottommost bench was least affected as there was sufficient confining stress due to the large bench width. However, the increased dump height with fixed bench width at the middle benches magnified the loading effect.

For a given bench geometrical parameters, increase in dump height resulted in lower overall slope angle. This resulted in instability propagating from the middle towards the top benches.

The instability zone moved from the middle benches towards the bottom benches for increased bench height and slope angle. For a given total dump height, increase in the bench height and bench slope angle resulted in higher overall slope angle causing increased loading effect due to the addition of further dump material. The pre-fixed bench width was insufficient to provide adequate confining stress. Thus, the instability zone moved towards the bottom benches.

The confining stress decreased, and the overall slope angle increased by reducing the bench width. Thus, the loading effect transferred from the top to bottom benches. When the bench width was significantly smaller than the bench height, the multi-bench dump slope structure behaved as a single bench, and the whole dump slope structure became unstable following a circular slip surface.

On reducing the shear strength of the dump material, the resisting force decreased due to weak bonding and frictional force, and the driving force increased due to the loading effect. After crossing the threshold or when the driving force became more significant than the resisting force, the dump structure failed and adjusted itself at the natural angle of repose.

8.3. Prediction of Factor of Safety of Dump Slopes

The statistical model possessed an R^2 of 0.98 and a standard error of 4.7%. This lies within the ±6% limit suggested by Duncan JM (1996) and Ozer and Bromwell (2012). Hence, it can be used for all practical purposes (Knight 2015; Igwe et al. 2022). The formulated statistical model of this study may be utilized for all practical applications, as the error limit of the present study is below the validated threshold value.

8.4. Effect of Water Table on the Stability Indicators

A detailed study was carried out to evaluate the effect of the water table on dump slope structures of total height varying from 30 – 270 m. Dump slopes of 30 - 60 m height exhibited a significant change in the maximum normalized horizontal displacement and shear strain ratio when exposed to the maximum possible water head of 100% of the total dump height. This normalized displacement/strain ratio indicates the relative change in the horizontal displacement (XDIS)/shear strain increment (SSI) observed in the dump slopes having phreatic surface up to a particular height expressed in terms of percentage of total dump height with respect to the maximum XDIS/SSI observed without water table. On the contrary, notable displacement and strain prevailed in medium (90 – 150 m) and large (180 – 270 m) dump slope structures. The maximum XDIS and SSI observed in low height dumps were below the design limit but it was significantly above the design limit for medium and large dump slope structures at similar height of the water table.

With the increase in the water table, low height dump slopes witnessed their vertical settlement in the boundary region away from the slope face. However, with the increasing height of the dump, the settlement tendency shifted towards the crest of the benches. Such characteristic behavior was attributed to the significant increase in body force in this condition. The instability initiated from the toe of the bottommost bench and created a plane of weakness up to the last point of the water table at the top of the boundary due to the differential density along the phreatic surface and the porewater pressure.

8.5. Stability Rating and Hazard Quantification

The dump slope instability hazard was quantified considering the uncertainty in the geotechnical properties of the dump material. The lognormal probability distribution function was found to be most suitable for the dataset developed in this study. This is similar to the findings of Griffiths et al. (2011), USACE (1999), Gui et al. (2000), Wang et al. (2010), Li et al. (2019) and Adriansyah et al. (2021). This distribution function possessed the highest reliability index among the several examined distribution functions. The magnitude of the reliability index was also within the range for the optimally expected performance of the geotechnical design as prescribed by Wang et al. (2010).

The quantification of slope instability hazard was done based on the probability of stable, critically stable, and unstable states for each governing parameter. The increase in the total dump height, bench height, bench slope angle, and density enhanced the driving forces inside the dump slope structure due to an increased loading effect under gravity and resulted in increased cases of critically stable and unstable dumps. In contrast, the resisting force in the dump slope structure increased due to the improvement of the shear strength of the dump material. Therefore, the increment of cohesion and friction angle enhanced the stable state cases. The stability condition improved with the increase in bench width as it increased the confinement to the slope surface. Out of seven control variables, increase in values of six variables led to the transition of stable cases of dump structures to the critically stable state. However, it ultimately transformed into unstable state. However, with the increase in bulk density of dump material, the transition of stable cases was limited up to the critical state only. The sensitivity of these parameters on the transition trend was different owing to their varying impact on the stability of the dump slope structure. The probability of failure did not increase significantly with the density for its considered range as its impact was smaller than the remaining parameters. These findings corroborate the studies of Nguyen and Chowdhury (1984).

The rating of each input parameter was suggested based on the coefficients of the regression analysis. The study established that bench slope angle had a significant impact on the stability of the dump slope structure, followed by friction angle, bench height, bench width, and cohesion. These findings are also supported by Sharma et al. (2017).

Although the total dump height is a crucial parameter, the statistical study could establish only a moderate effect as the bench slope angle was maintained near the angle of repose with a low overall slope angle (< 25°). The angle of internal friction proved to cause a more significant impact as compared to the cohesive strength of dump material, as also supported by Poulsen et al. (2014) and Sharma et al. (2017).

The stability rating and hazard quantification study showed that for the variation in cohesion 0.01-0.09MPa, friction angle 16-40° and density 1300-2300 kg/m^3, it is possible to have a stable dump slope structure for total dump height, bench height, bench width and bench slope angle up to 180 m, 30 m, 30 m, and 37.5°, respectively. The provisions of CMR (2017) with regard to maximum bench height, bench slope angle and overall slope angle also support these projections for a long-term stable dump slope structure. The findings of the British Columbia Mine Dump Committee. and Piteau Engineering Ltd. (1991) related to the bench slope angle of the dump material also coincided with the outcomes of the study.

8.6. SAHARA System

Table 8.1 summarises the range of FoS, XDIS, SSI, Stability Rating, and PoF for stable, critically stable, and unstable states of dump slopes. The dump slope structure was stable for the long term when it possessed safety factor greater than 1.30, max XDIS less than 10 mm, and max SSR less than 0.25% with stability rating greater than 75.4.

Table 8.1 Range of performance measuring parameters based on stability states

Stability States	**Performance Measuring Parameters**				
	FoS	XDIS (mm)	SSI (%)	Stability Rating	PoF (%)
Stable	>1.30	<10	<0.25	75.4-100	0-0.12
Critically Stable	1-1.30	10-100	0.25-3	64.1-75.4	0.12-41.3
Unstable	<1	>100	>3	0-64.1	41.3-100

This study suggested the minimum acceptable limit of the FoS to be greater than 1.30 for the long-term stability of a large dump slope structure. This threshold limit of the safety factor is also supported by Hawley and Cunning (2017), Gupta et al. (2019), and the Directorate General of Mines Safety (DGMS 2020).

Pappin and Bowden (1998) and Haiwang and Wen (2012) suggested FoS of 1.16-1.20 for the stable behavior of dump slopes when exposed to seismic loading conditions. The risk of instability is low for slope movement less than 20 mm (Pappin and Bowden 1998) or horizontal displacement less than 15 mm (State of California 2008). Mukhlisin et al. (2011) advised FoS greater than 1.30 whereas Gusman et al. (2018) mentioned the cut-off FoS of 1.25. The threshold value provided by Zhu and Xiao (2020) was 1.20. These threshold values of FoS and maximum horizontal displacement for stable performance of dump slopes exposed to seismicity and porewater pressure (due to rainfall, water table or moisture content) are also satisfied by the proposed design limits.

The present study recommended that for the stable state, the maximum shear strain increment (SSI) should be less than 0.25%, while it can vary between 0.25 to 3% for the critically stable condition of slope. Maximum SSI greater than 3% led to the unstable state condition. The findings of Hawley and Cunning (2017) support the strain limits as projected in this study for the stable dump slope structures.

The study of slope instability hazard for the experimentally developed set of databases showed PoF less than 0.12% for stable slope structures which is also supported by Wang et al. (2010).