CHAPTER 4

Safety Chart for the Identification of Stability of Internal Dragline Dumps

4.1 General

The strong demand for output in dragline mines leads to significant levels of overburden removal and coal extraction, which ultimately raises the dragline dump's steepness and height. The stability of the dragline dumps must therefore be monitored or identified with greater care. The most important factors that must be properly considered for the identification of slope stability are geometrical and strength parameters. Strength parameters are material characteristics that cannot be altered, but geometrical parameters can be set so that the dump slope can safely contain the optimum amount of overburden material. Numerous studies have been conducted to quickly determine the stability of slopes using statistical approaches and classification techniques, but few have been performed for stability analysis of the dump slopes. As a result, a safety chart has been created in this chapter to make it simple to determine whether the dragline dump slopes are stable or not. Only the three geometrical parameters that were determined to be the most important after doing a sensitivity analysis of all the geometrical parameters were taken into consideration for the safety chart.

4.2 Monte-Carlo methods

A person with a basic understanding of probability can apply the Monte-Carlo method, which is a very handy tool for the probabilistic analysis of complicated engineering problems (Basahel and Mitri, 2019). This method incorporates the uncertainties of the strength parameters into the simulation of the dump slope by assigning random strength parameter values to samples from a defined range of the given strength parameter (Papadopoulos and Yeung, 2001).

The dump material does not have consistent strength properties throughout the entire mine as a result of the heterogeneity of the dump materials and the dumping process; consequently, a probabilistic approach has been developed to take into account the variability of strength property. Using a probabilistic strategy makes sense in light of these uncertainties. Since they can effectively account for the uncertainty in geomaterial properties, these approaches are gaining recognition for slope stability analysis over time (Ray et al. 2020 and Singh 2019). This study makes use of the RS2 (Version 9.0) software, which incorporates a Monte Carlo simulation technique to account for the variability of strength properties (cohesion and angle of friction), which randomly distributes the properties within their defined range among the number of samples (trials) assigned to a dump slope model, and calculates the FOS (Basahel and Mitri, 2019; Papadopoulos and Yeung, 2001; Tobutt, 1982; Hammah et al., 2009). El-Ramly et al. (2002) provided a viable framework for probabilistic analysis based on the Monte Carlo simulation as well as principles related to uncertainties of rock and soil parameters. The number of allocated samples or the quantity of deterministic computations affects how accurate the Monte Carlo approach is (Basahel and Mitri, 2019; Hammah et al., 2009). Sample size should be chosen so that it delivers greater accuracy while taking up less time because increasing sample size takes more time.

4.3 Finite Element Modelling of Dump

The finite element method has capability of simulating complicated geometrical parameters of an OB dump, such as the height of the dump, the slope angle of the dump, the inclination of the floor, the hydrological conditions, and the interface between the dump and the foundation. The dragline dump slope is designed using the Mohr-Coulomb elastic and perfectly plastic model, which is represented as follows: where c and φ are the cohesion and angle of friction, and σ_1 and σ_3 are the major and minor primary stresses. The FOS of the dump slope is calculated in this work using the shear strength reduction (SSR) technique (Bowman and Gilchrist, 1978; Sharma et al., 2011; Chakraborty and Goswami, 2016). Duncan (1996) claims that SSR provides the FOS value as a factor F by which the slope's actual shear strength is split gives a new shear strength, bringing the slope into a condition of shaky equilibrium. The real shear strength parameters of cohesion (c) and friction angle (φ) are decreased on each trial (Gupta et al., 2014; Kanungo et al., 2013; Matsui and San, 1992) in the SSR technique, which simulates dump slope in a series of trials with rising F^{trial}.

$$c^{trial} = \frac{1}{F^{trial}}\, c$$

$$\varphi^{trial} = \tan^{-1}\left[\, \frac{1}{F^{trial}} \tan\varphi \right]$$

where c_{trial} and φ_{trial} are the reduced trial values of the dump material, cohesion and friction angle, respectively, and F_{trial} is the trial safety factor value. The FOS of the dump slope is the trial safety factor at which failure occurs (Mbarka et al., 2010). Tools used in geomechanics are typically deterministic in nature (a single set of input parameters gives single output), such as stress analysis (e.g., finite element analysis). Therefore, the statistical method is employed to cope with the unpredictability of the input parameters in order to produce a trustworthy design approach (Valley and Duff, 2019; Vanmarcke, 1980). The RS2 V9.0 software from Rocscience, a finite element method-based tool for assessing the stability and deformation using SSR approach, has been used to run simulations. Numerous researches have evaluated the FOS and other deformation parameters for soil and rock slope using the application of SSR in conjunction with the finite element approach (Dawson et al., 1999; Griffiths and lane, 1999). A built-in probabilistic analysis tool (Monte Carlo simulation) in RS2 V9.0 accepts a variety of input factors, including joint and material attributes. To calculate the likelihood of failure and FOS, the statistical distribution of all the input parameters must either be known or assumed. Material attributes are provided as mean, relative minimum, and relative maximum in this probabilistic analysis approach. The model automatically creates a predetermined number of sample models with the same geometry after receiving a set of input parameters, and it randomly distributes the attributes within their preset range to all the samples (El-Ramly et al., 2002). While calculation time also increases with an increase in the number of samples, Monte Carlo simulation accuracy rises as the number of generated samples does (Basahel and Mitri, 2019). Since there was little change in the FOS when the sample number was above 100, but a large increase in computation time, therefore 100 samples were assigned in this situation to precisely compute the FOS along with the allowable computation time.

According to Kanungo et al. (2013), boundaries for the dump models are fixed from the model's lateral sides and base while employing a uniform-type mesh and six-noded triangular elements. Because there was little change in FOS below 1 m, but a large increase in computation time, 1 m was chosen as the element size for the dump. Given that the coal rib's width at roof level is only 2 m, the element size of the mesh chosen for it is 0.5 m to better discretize it. The outcome of the simulation is shown as the mean FOS value across all 100 sample models produced by the basic model. The assumptions of these finite element models in simulation of internal dragline dumps are: (1) Depending on the number of elements generated for each model, each one requires a substantial amount of computing time. The simulation of one model takes about 20 to 30 hours. (2) During the retreat of the mining operation, the coal-rib is partially excavated, and when one cut is finished, its thickness is quite low. The coal-rib that is thought to be buried beneath the dump debris is therefore thought to be crushed and failed (Rai et al., 2012). As a result, it is not taken into account in the dragline dump model. (3) The finite element model does not take the dragline machine's weight into account.

4.4 Material Properties

Based on the Mohr-Coulomb failure criterion, cohesion (c) and the internal angle of friction (φ) are used in this study as the material's strength parameters. Table 4.1 lists the characteristics of dump material and how it interacts with the foundation in the Jayant, Dudhichua, Bina, Khadia, Amlohri, and Nigahi projects of NCL, India (Sharma et al., 2015; Sengupta et al., 2014). A mixture of broken white sandstone, very soft sandstone, yellow clay, and coal dust make up the dump interface material. This mixture can cause a plane of failure on the dragline dump's inclined foundation (Sengupta and Roy, 2015; Sengupta et al., 2016), and Kasmer (2006) also identified the interface layer as a point of weakness in his study. To account for the variety of strength qualities of the mines listed in Table 4.1 as well as the variability of strength attributes of individual mines, a probabilistic numerical simulation was conducted. Since simulation involves probabilistic analysis, properties are taken in relative minimum and relative maximum, as indicated in Table 4.2, of the properties specified among the six mines of Table 4.1. This is done in order to establish the range.

Table 4. 1 Material properties of projects of NCL

Name of The Project	Dump Property		Interface Property	
	Cohesion (KPa)	Friction Angle (°)	Cohesion (KPa)	Friction Angle (°)
Jayant	75	25	40	21
Bina	70	27	60	23
Khadia	75	30	58	29
Nigahi	65	28	40	21
Dudhichua	75	35	40	25
Amlohri	65	27	30	20

Table 4. 2 Material properties used for probabilistic analysis

Material Property	Cohesion (KPa)			Angle of friction (°)		
	Mean	Rel. Min	Rel. Max	Mean	Rel. Min	Rel. Max
Dump	71	65	75	29	25	35
Dump Interface	45	30	60	23	20	29
Coal Interface	1.3	0.8	1.8	35	33	38

4.5 Sensitivity Analysis

The height of the dragline dump, the slope angle of the dump, the width and height of the coal rib, the strength characteristics of the dump, and the interface material are only a few of the geometrical and geotechnical factors that affect the stability of the dragline dump. By carrying out a sensitivity analysis, it is possible to priorities these characteristics in terms of importance. Sensitivity analysis helps identify the key parameters by analyzing the output (FOS) of the model by changing one parameter while holding the others constant (Rai et al., 2012; Tatang et al., 1997; Castillo et al., 2008). As a result, sensitivity analysis reveals how a model reacts when an input parameter is altered. A dimensionless index I (sensitivity index), which measures the relationship between the relative change in a model's output and the corresponding change in an input parameter, is used to express sensitivity (Figure. 4.1). The sensitivity index was defined by Lenhart et al., (2002) and stated in the following equation:

$$I = \frac{(y_2 - y_1)/y_0}{2\Delta x/x_0}$$

$$\Delta x = x_2 - x_1$$

$$I = \frac{(y_2 - y_1)/y_0}{(x_2 - x_1)/x_0}$$

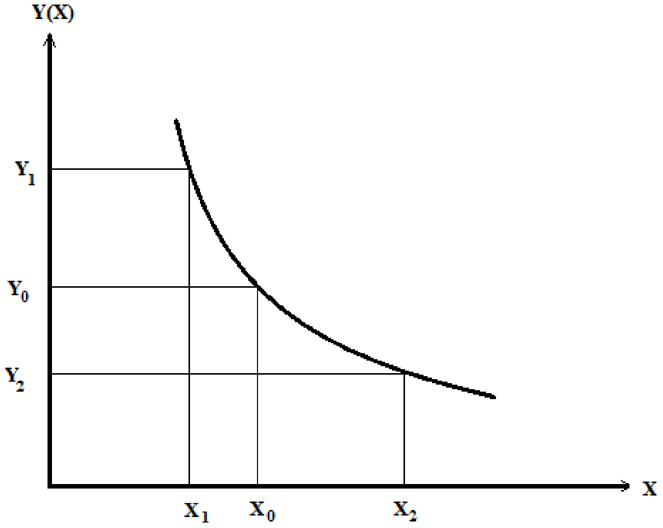


Figure 4. 1 Relation between output (y) and input (x) parameters

The sensitivity index's sign indicates whether or not the input and output parameters are co-directional. The input parameter is co-directional to output if the sign is positive, which means that output rises with an increase in input or falls with a drop in input. According to Figure. 4.2, there are nine geometrical characteristics in the dragline dump, each of which has a different level of influence on the stability of the dragline dump. The most sensitive geometrical parameters are identified with the aid of sensitivity analysis, which is used to generate the sensitivity index. The following are all the geometrical parameters:

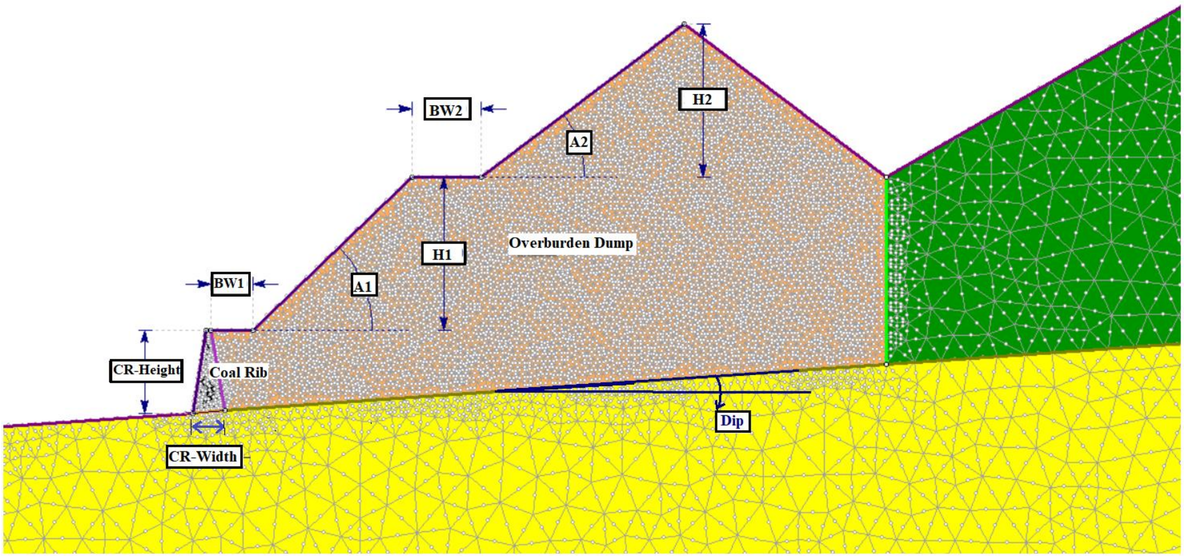


Figure 4. 2 Geometrical parameters of the internal dragline dump

4.6 Probabilistic Analysis

A1, H1, and CR-Height are the three most sensitive geometrical parameters employed in the probabilistic analysis, and they have respective ranges of 30° to 50°, 25m to 45m, and 10m to 20m. While A1 and H1 display the range of values found in the research region with an expanded upper or lower value to know their upper or lower limit with guaranteed stability of the dump, the CR-Height is the thickness of the coal seam, which ranges from 13 to 20 meters. As shown in Table 4.3, six data are collected for each of the three parameters at a predetermined interval within the selected range. The six values of the three geometrical parameters are used to simulate various model combinations. The mean value assigned to all the geometrical parameters of the base model is shown in Table 4.4. There are 216 combinations possible when each of the three parameters is used six times

(6*6*6= 216). The properties listed in Table 4.2 are used to simulate and model each of these combinations.

Table 4. 3 Values assigned for the three most sensitive parameters

S. No.	A1 (°)	H1 (m)	CR-Height (m)
1	30	25	10
2	34	29	12
3	38	33	14
4	42	37	16
5	46	41	18
6	50	45	20

Table 4. 4 Mean values of the nine geometrical parameters for the base model

Parameters	Mean Value (Unit)
CR-Height	15m
CR-width	7m
BW1	10m
A1	37°
H1	33m
BW2	15m
A2	33°
H2	28m
Dip	4°

4.7 Safety Chart

Four data, such as the values of the three parameters and their respective FOS, are accessible for each combination following simulation of all 216 models. As depicted in Figure 4.3, the parameters A1, H1, and CR-Height are used as three axes (scales). If the parameter values are thought of as the three vertices of a triangle on the axes, a triangle is produced by pointing the values of the three parameters on their axes of the chart for a certain combination of a model. In Figure 4.3, the combination of A1 = 38°, H1 = 37m, and CR-Height = 18m is displayed, and the point between the circle is showing both the center of the circle and the in-center of the triangle. The in-center of the triangle symbolizes the FOS of the specific model. The 216 models are also displayed on the graph, and each point represents the FOS of the dump slope created by the unique combination of the three geometrical parameters in each model. To illustrate the pattern of variation in FOS across all models, various zones are generated (Figure 4.4). The zones are divided into three categories: safe zone (FOS ≥ 1.2), vulnerable zone (1 ≤ FOS ≤ 1.19), and fail zone (FOS < 1). The vulnerable zone separates the failure zone, and it is made sure that the fail points don't cross over into the vulnerable zone. The safe zone and the vulnerable zone are kept apart so that the safe zone and vulnerable points don't cross over.

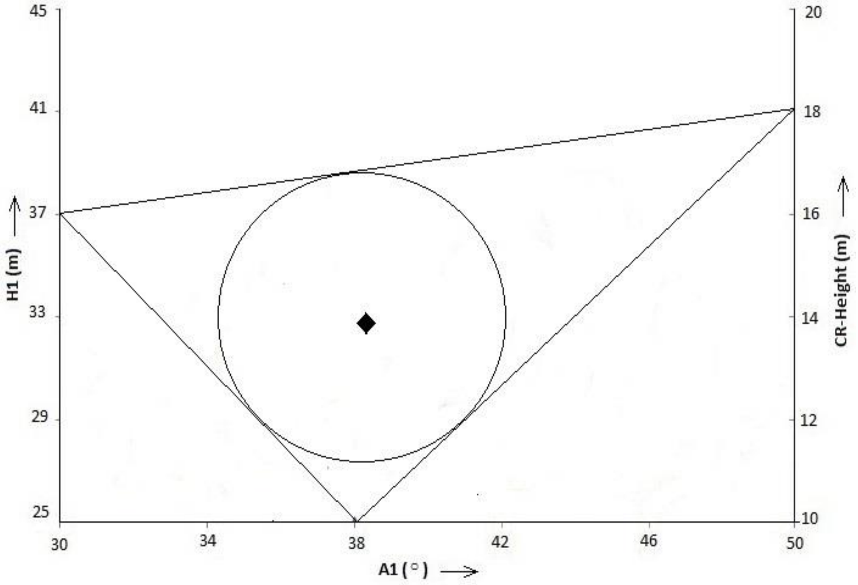


Figure 4. 3 The in-center of a particular combination of the three parameters

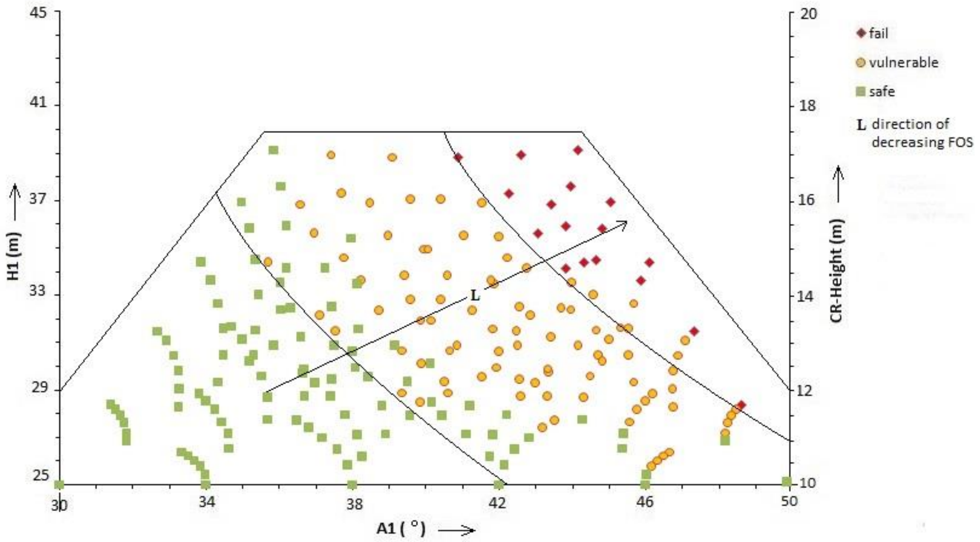


Figure 4. 4 The in-center of all 216 models and their range of FOS

4.8 Result and Discussion

4.8.1 Sensitivity analysis

The finite element method is used to simulate the dump slope model. Figure 4.2 displays a discretized image of the dragline dump slope model. Nine geometrical parameters are subjected to sensitivity analysis; one parameter is changed, while the other eight are left unchanged. The sensitivity index is calculated using the dragline dump simulation results shown in Table 4.5, and the parameters are then categorized as being high, medium, or very low sensitive in accordance with the sensitive indices established by Lenhart et al., (2002).

Table 4. 5 Parameters used in sensitivity analysis for internal dragline dump slope and their sensitivity index

Parameters	x_0	Range $(x_1 - x_2)$	Sensitivity Index (I)
CR-Height	15 m	10 – 20 m	-0.337
CR-width	10 m	5 – 15 m	0.116

BW1	12.5 m	5 – 20 m	0.135
A1	38°	28º – 48º	-0.573
H1	32.5 m	20 – 45 m	-0.264
BW2	10 m	10 – 25 m	0.114
A2	35 °	25º – 45º	-0.083
H2	25 m	15 – 35 m	-0.109
Dip	4.5 °	2º – 7º	-0.03

4.8.1.1 Coal-Rib Height

The thickness of the coal seam is known as coal-rib height, and it varies from mine to mine in the Singrauli coalfields. For the sensitivity study, the coal-rib height is adjusted from 10 to 20 meters with a 1-meter interval. As the height of the coal ribs rises, the safety factor declines. A linear relationship between the coal-rib height and the factor of safety is depicted in Figure 4.5 (a). The element of safety is rapidly decreasing as a result of the coal-rib height increasing in tandem with the overall height of the dump. This parameter's sensitivity index is 0.337, which is in the high sensitivity range. The stability of the dump will be significantly affected by even a modest change in this setting.

4.8.1.2 Coal-Rib Width

The coal rib's top width is held constant at 2 meters, and it varies from 5 to 15 meters with intervals of 1 meter. The safety factor is growing along with the width of the coal rib. The broader coal-rib will make the dump slope safe, but a significant amount of coal will be lost. A linear relationship between the coal-rib width and the factor of safety is depicted in Figure 4.5 (b). The coal-rib width's sensitivity index, which is 0.116, falls into the medium sensitivity category.

4.8.1.3 Berm Width at coal-rib roof level (BW1)

The coal-rib roof level berm width ranges from 5 to 20 meters with a 1.5-meter spacing. The relationship between Berm width and factor of safety is depicted in Figure 4.5(c). The factor of safety improves as the berm width increases; however, the rate of increase has dropped from 14 to 20 meters of berm width. The Berm width's sensitivity index, which is 0.135, falls into the medium sensitivity category.

4.8.1.4 Height of the bench from the coal-rib roof to Dragline sitting level (H1)

The bench rises from the coal-rib roof level to the Dragline sitting level at a range of 20 to 45 meters with an interval 2.5-meter interval. After doing a sensitivity analysis, it was shown that as bench height is raised, the safety factor actually decreases. A relationship between H1 and the safety factor is seen in Figure 4.5 (d). With a sensitivity level of 0.264, the discussed bench height falls into the more sensitive category.

4.8.1.5 Slope Angle of the bench between the coal-rib roof and dragline sitting level (A1)

The angle is varied from 28º to 48º with an interval of 2º. Figure 4.5 (e) shows the relation that factor of safety is increasing with the increase in slope angle. The factor of safety for A1=28º is 1.38 and for A1=48º is 1.03, which shows a sharp decrease in the stability. The sensitivity index of Slope Angle of the bench between the coal-rib roof and dragline sitting level is 0.573, which lies in a high range of sensitivity. Thus, it is one of the critical parameters; a small change in this may lead to a significant impact on the stability of the dump slope.

4.8.1.6 Strata Dip

The strata dip ranges from 2° to 7° with a 0.5° interval. There is a slight reduction in the safety factor when stratum dipping increases. A linear relationship between the factor of safety and strata dip is depicted in Figure 4.5 (f). The stratum dip's sensitivity index, which is 0.03, is in the very low sensitivity category.

4.8.1.7 Berm Width at dragline sitting level (BW2)

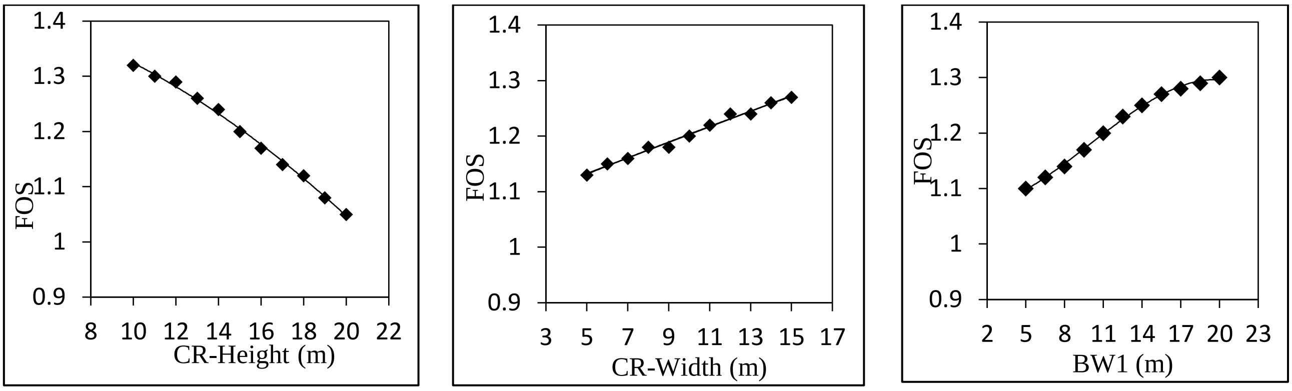
The berm width at dragline sitting level ranges from 10 to 25 meters with a 1.5-meter interval. As the width of the berm increases, so does the safety factor. A linear relationship between the berm width and the factor of safety is shown in Figure 4.5 (g). The berm width's sensitivity index, 0.114, is within the medium sensitivity range.

4.8.1.8 Slope angle between the dragline sitting level and the peak of dragline dump. (A2)

Angles ranging from 25 to 45 degrees are alternated by 2 degrees. There is a very slight decrease in the factor of safety with an increase in slope angle value. A linear relationship between the safety factor and the slope angle between the dragline's resting level and its peak dragline dump is shown in Figure 4.5 (h). The medium sensitive range is represented by the sensitivity index of 0.083.

4.8.1.9 Height between the dragline sitting level and the peak of dragline dump. (H2)

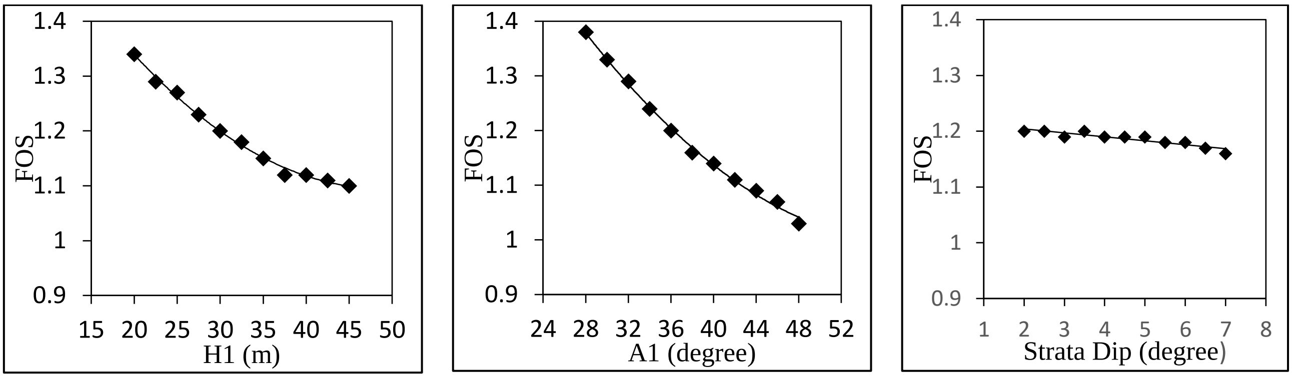
The top bench varies in height by 2 meters, from 15 meters to 35 meters. As height rises, the safety factor declines, however this decline is not very noticeable. The sensitivity index is 0.109, which is in the moderately sensitive category, and Figure 4.5 (i) illustrates a linear relationship between the safety factor and the height of the bench between the dragline sitting level and the peak of the dragline dump.



(a) Effect of CR-Height on FOS.

(b) Effect of CR-Width on FOS.

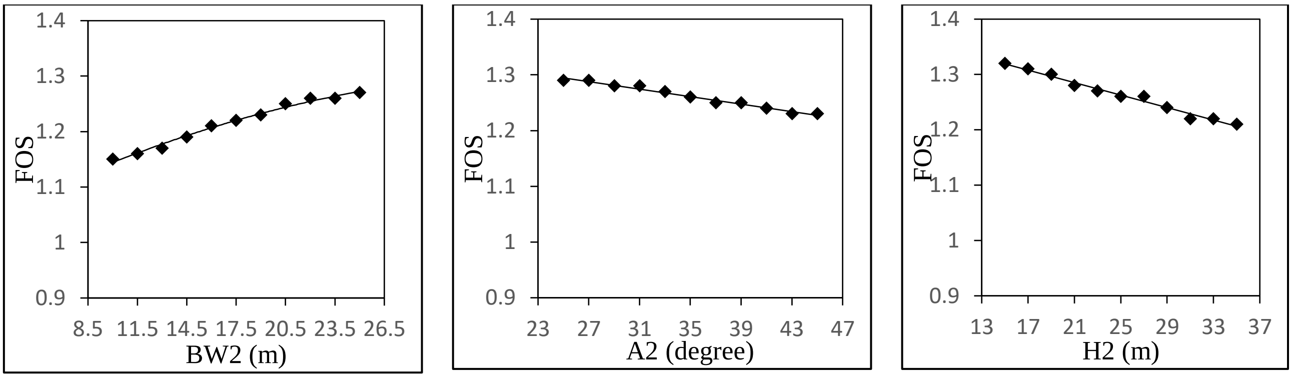
(c) Effect of BW1 on FOS.



(d) Effect of H1 on FOS.

(e) Effect of A1 on FOS.

(f) Effect of Strata dip on FOS.



(g) Effect of BW2 on FOS

(h) Effect of A2 on FOS.

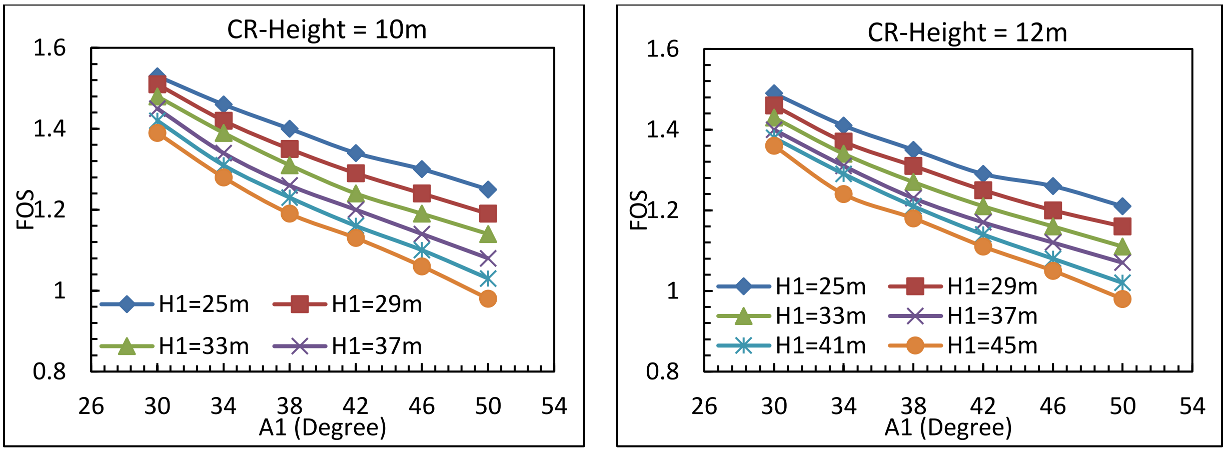
(i) Effect of H2 on FOS.

Figure 4. 5 Sensitivity analysis of the nine geometrical parameters

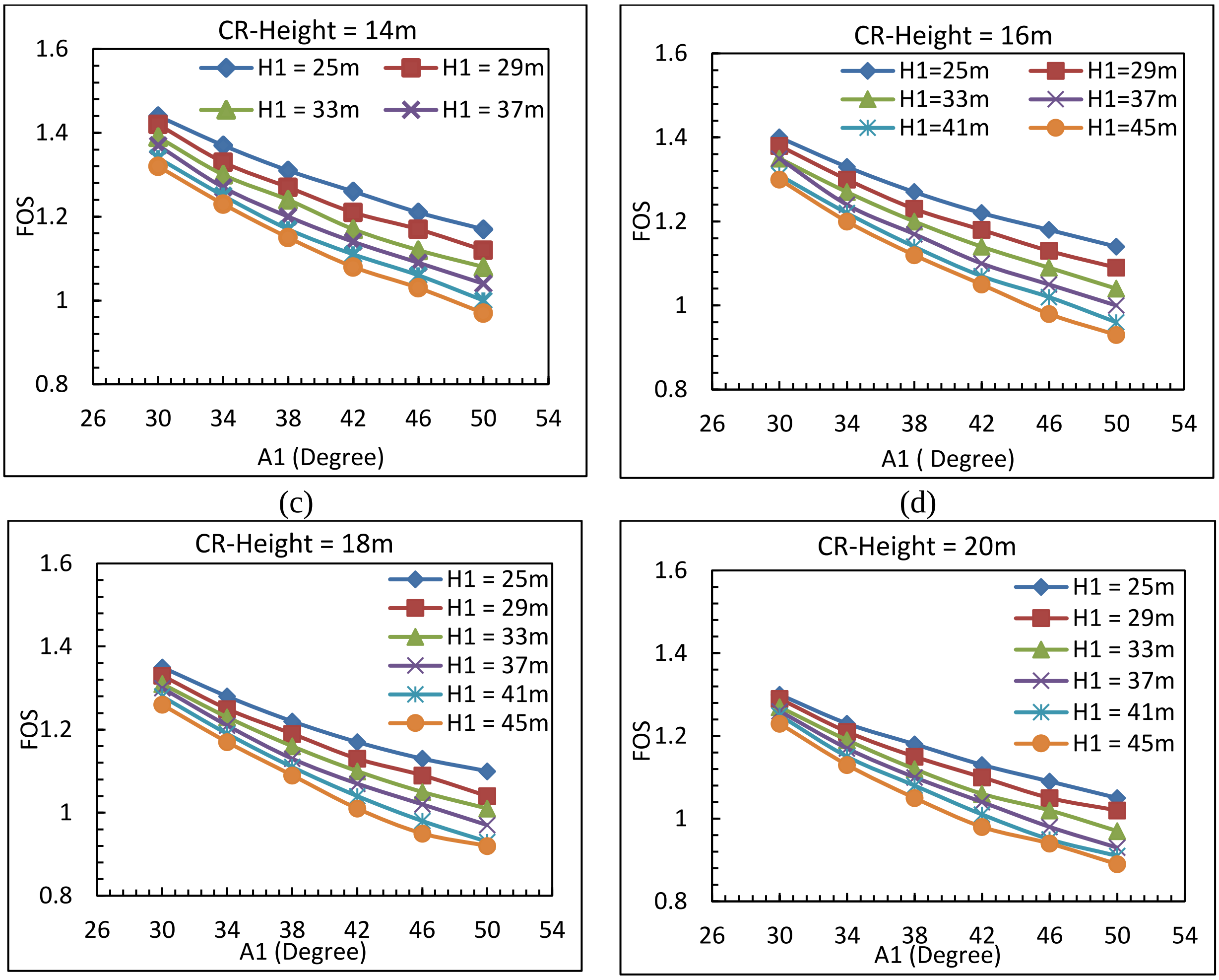
Table 4.5 summarizes the sensitivity index for nine parameters. The three most sensitive parameters out of the nine geometrical parameters are the height of the bench between the coal-rib roof and dragline sitting level, the slope angle of the bench between the coal-rib roof and dragline sitting level, and the height of the coal-rib. Medium sensitive parameters include those related to coal rib width, berm width at coal rib roof level, berm width at dragline sitting level, slope angle between the dragline sitting level and the peak of the dragline dump, and height between the dragline sitting level and the peak of the dragline dump. The least sensitive metric is strata dip.

4.8.2 Probabilistic Analysis

In the probabilistic analysis, 216 simulated dump slopes are modelled using different combinations of the three geometrical parameters that are most sensitive, and their stability is examined by plotting graphs between the three geometrical parameters and factor of safety, as seen in Figure 4.6. The safest dump slope model has CR-Height = 10m, H1 = 25m, and A1 = 30°, whereas the most unsafe dump slope model has CR-Height = 20m, H1 = 45m, and A1 = 50°, and its FOS is 0.89. For coal rib heights between 10 and 20 meters, the safety factor falls as the slope angle and height of the bench from the coal rib roof to the dragline sitting level increase. While observing the graphs in Figure 4.6 from coal-rib heights of 10 to 20, it is evident that the entire graph is moving downward on the FOS-axis (with a scale of 0.8 to 1.6), indicating that the factor of safety is declining as coal-rib height rises.



(a) (b)



(c) (d)

(e) (f)

Figure 4. 6 Graphs showing FOS Vs A1 and H1for (a) CR-Height = 10m, (b) CR-Height = 12m, (c) CR-Height = 14m, (d) CR-Height = 16m, (e) CR-Height = 18m, (f) CR-Height = 20m

4.8.3 Safety Chart

All of the graphs in Figure 4.6 are intended to be incorporated into the safety chart. On the safety chart, as indicated in Figure 4.4 by line L, the trend of the factor of safety is decreasing from the left-bottom to the right-top, and the values of all three axes are increasing comparatively in the same direction. As a result, it is clear from the figure that the safety factor is falling as the values of all three geometrical parameters rise. By the range of factor of safety allocated to each zone, such as fail zone (FOS < 1), vulnerable zone ($1 \leq$ FOS ≤ 1.19) and safe zone (FOS ≥ 1.2), the chart is separated into three distinct zones. Figure 4.7 depicts fail, vulnerable, and safe zones as A, B, and C, respectively. We can quickly determine the safety status of any dragline dumps by using the chart. By selecting the best values for slope angle and bench height for a specific coal-rib height or thickness of the coal seam, both of which are located in the safe zone, the safety chart can also be used in building the dragline dump profile.

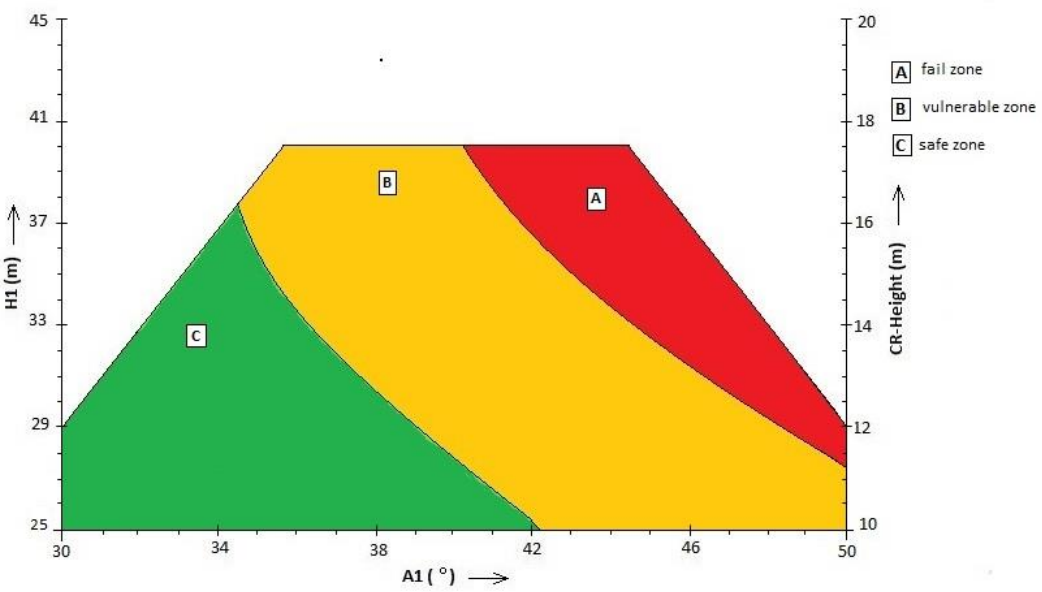


Figure 4. 7 Safety chart with three zones: safe, vulnerable, and fail

There are certain limitations associated with the safety chart: (1) This chart is applicable for the range of strength properties defined in this study, (2) The weight of the dragline has not been considered and (3) The chart is applicable only for the dry condition.

4.9 Validation

For the purpose of validating this chart, several findings from published articles have been used (Figure 4.8). Internal dragline dump of the Dudhichua project of Northern Coalfields Limited, with dimensions of A1 = 41o, H1 = 37m, and CR-Height = 20m, was examined by Sengupta and Roy (2015). They came to the conclusion that the FOS = 1.26 and the dump's in-center lie in the vulnerable zone of safety chart, as shown in Table 4.6. Roy and Sengupta's (2014) analysis of internal dragline dumps for two Northern Coalfields Limited projects—Nigahi, with dimensions of A1 = 40°, H1 = 35m, and CR-Height = 15m—led them to the conclusion that the parameters are in the vulnerable zone of safety and that the FOS is 1.08; Khadia, with dimensions of A1 = 40°, H1 = 34m, and CR-Height = 18m, reached a similar conclusion. Internal dragline dumps of the Jayant project of Northern Coalfields Limited with dimensions of A1 = 50o, H1 = 35m, and CR-Height = 18m were examined by Sharma and Roy (2015), who came to the conclusion that the FOS = 0.94 and the in-center of the same three geometrical parameters lie in the failed zone (FOS 1.0) of safety chart. The internal dragline dump of the Amlohri project of Northern Coalfields Limited, with dimensions of A1 = 40°, H1 = 35 m, and CR-Height = 14 m, was examined by Sengupta et al. (2016), who came to the conclusion that the FOS = 1.2 and the center of the same three geometrical parameters lie in the vulnerable zone of the safety chart.

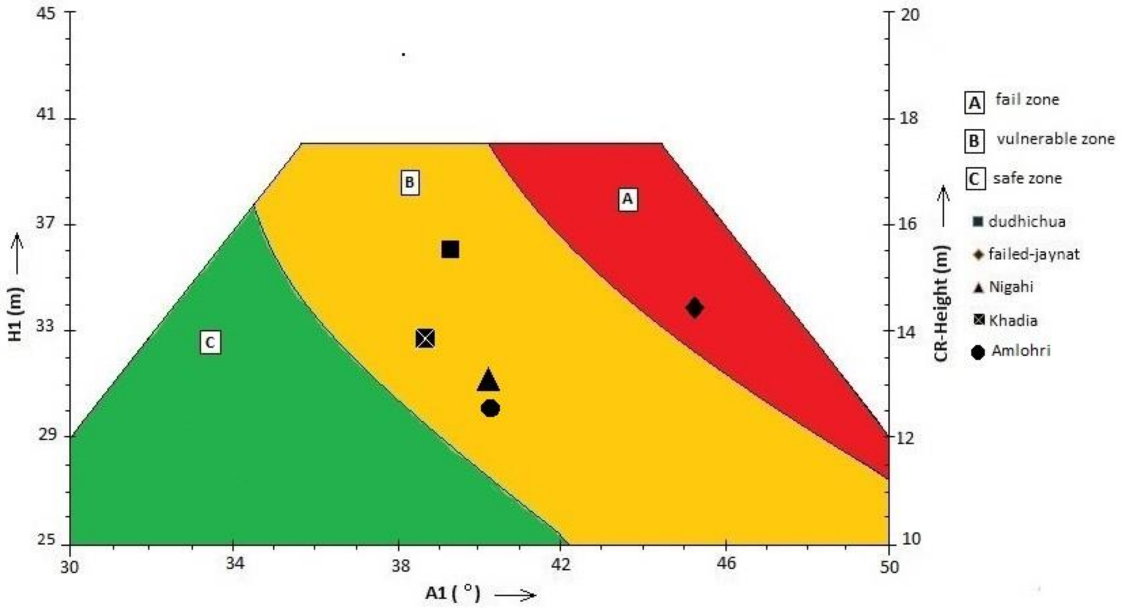


Figure 4. 8 Validation of safety chart on previous studies

Table 4. 6 Validation results of the safety chart

S. No.	Mine	A1 (º)	H1 (m)	CR-Height (m)	Safety Zone
1.	Dudhichua	41	37	20	Vulnerable
2.	Nigahi	40	35	15	Vulnerable
3.	Khadia	40	34	18	Vulnerable
4.	Jayant	50	35	18	Fail
5.	Amlohri	40	35	14	Vulnerable

4.10 Summary

A safety has been proposed based on three most critical parameters of internal dragline dump slope. Variability of strength properties has been included with the help of the probabilistic analysis method. The safety chart presented in this paper will be helpful to understand the stability of any dragline dump. Following are some inferences made in light of the results:

- Coal-rib Height, Slope Angle and Height of the bench from the coal-rib roof to Dragline sitting level are the three highly sensitive geometrical parameters; a small change in any of them will significantly impact the stability of dump slope.
- The medium-sensitive parameters are the coal-rib width, the berm width at coal-rib roof level and dragline sitting level, the slope angle, and the height of the bench above the dragline sitting level; a small change in any one of these parameters will have little effect on the stability of the dump slope, but a large change in any one of these parameters could result in instability.

- Among all geometrical characteristics, strata dipping is the least sensitive, and any alteration within its prescribed range in the research will have little impact on the stability of the dump.
- Based on the combination of dragline slope profiles, a safety chart has been presented for the detection of dragline dump instability. This type of chart is primarily created to aid investigators during the initial investigation and enable them to concentrate more on the vulnerable slopes. Based on how slope profiles behave, the stability chart is classified into three regions: safe, vulnerable, and fail.
- In order to maximize the quantity of overburden while maintaining the safety of the dragline dump profile, the chart also provides guidance on how to combine the parameters of coal-rib height, slope angle, and height of the bench from the coal-rib roof to dragline sitting level.