CHAPTER 3

RESEARCH METHODOLOGY

3.1. Introduction

The present chapter elaborates the research methodology adopted for the Stability Analysis and HAzard RAting (SAHARA) system for the dump slope structures. Figure 3.1 illustrates the methodology for the development of the SAHARA system. The SAHARA system consists of FoS, XDIS, SSI, Stability Rating, PoF, and water table impact factor with the assistance of statistical model as stability analysis parameters. The crucial steps and their descriptions in the formulation of the SAHARA system are discussed below.

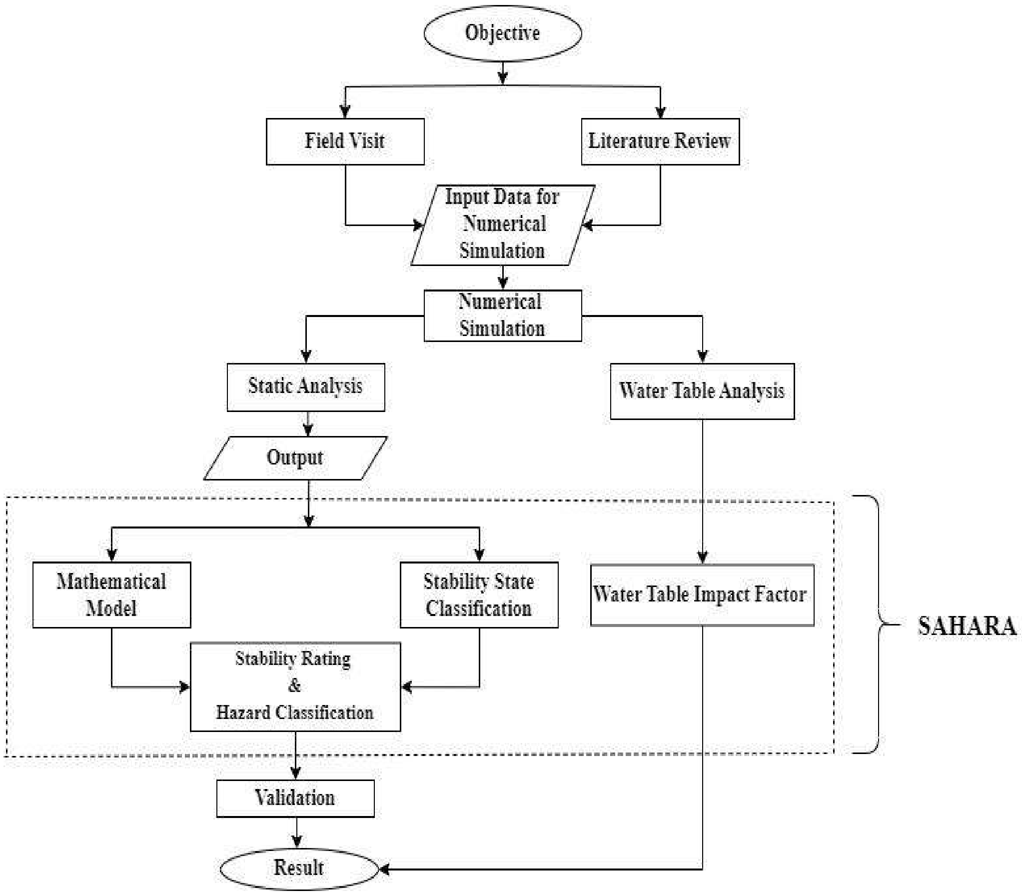


Fig. 3.1 Flow chart of research methodology

3.2. Identification of the Crucial Parameters Governing Dump Slope Stability

Field visits and literature reviews revealed that many factors contribute to the stability of the dump slope structures. However, the degree of the influence of each parameter is different, and every parameter cannot be specifically quantified and simulated through modelling. The interplay of geometrical and geotechnical parameters plays a key role in deciding the configuration of the dump slope. The geometrical factors include the total dump height, bench slope angle, inter-ramp slope angle, overall slope angle, and bench width. Further, the major geotechnical factors include grain size, density, friction angle, and cohesion of dump material.

Therefore, principal parameters governing stability were decided based on scientific studies (Gupta et al. 2018a, b, 2019). In large-size dump slope structures, sub-benching improves stability. It was observed that the effect of the inter-ramp and overall slope angle could be reduced by maintaining the width, height and slope angle of the intermediate benches. Therefore, importance has been given to bench width and bench height in the design of the giant dump slope structures. The presence of the different grain sizes majorly influences the shear strength properties. In geotechnical parameters, density is adopted along with the shear strength parameters (cohesion and friction angle) of OB to assess the behaviour of the developed displacement. Thus, in this study, seven stability governing parameters have been incorporated for the static analysis, i.e., total dump height, bench height, bench slope angle, bench width, density, cohesion, and friction angle.

3.3. Formulation of Numerical Models

The general layout of the numerical model of the dump slope structure is presented in Figure 3.2, where boundary conditions parameters are a, b and d, and the rest are the geometrical parameters of the dump slope structure. During the numerical simulation study, the load increases on the model's base as the dump height increases. It becomes prominent after a particular dump height and reduces the stability of the dump slope structure. Therefore, boundary conditions (a, b & d) were increased twice (Table 3.1) when the dump height (g) crossed 200m (Gupta et al. 2018a). The base of the dump slope was competent and did not consider the presence of any weak material on the floor. The meshing of (1m x 1m) was done to analyze affected zones. Material properties are assigned to the dump benches and foundation based on the standard laboratory tests. In the last step, the model was solved under gravity, and the strength reduction method determined the safety factor. In this method, the shear strength of the material (Equation 3.1) was progressively reduced (if initially stable) in small increments until a failure state was found or increased (if initially unstable) to bring the slope to a state of limiting equilibrium. Therefore, the cohesion (C) and friction angle (φ) were reduced (or increased) using trial values of the factor 'F^{trial}' (Equations 3.2, 3.3) through a series of iterations until the slope failure state (or a limiting condition) was observed following Mohr-Coulomb failure criterion (FLAC, 2011).

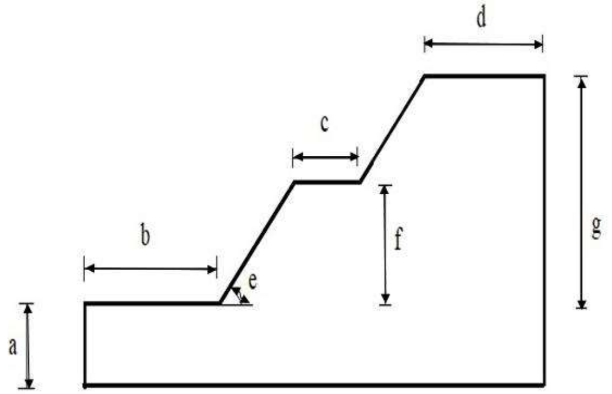


Fig. 3.2 Slope model parameters
(**a:** thickness of foundation/floor, **b:** left side boundary, **c:** bench width, **d:** right side boundary, **e:** bench slope angle, **f:** bench height, **g:** total dump height)

$$\tau = c + \sigma_n tan\varphi \qquad (3.1)$$

$$c^{trial} = \left(\frac{1}{F^{trial}}\right) \mathrm{c} \tag{3.2}$$

$$\varphi^{trial} = \arctan\left(\frac{1}{F^{trial}} \tan\varphi\right) \tag{3.3}$$

Table 3.1 Boundary conditions

Dump Height (m)	**a**	**b**	**d**
≤ 200	50 m	100 m	200 m
> 200	100 m	200 m	400 m

3.4. Laboratory Characterisation of Dump Materials

The 19 samples of the dump material were collected in the same volume from different sections of the overburden dump of different mines (Sample no. 1-19, Annexure I), India, and subjected to sieve analysis (IS, 1985), proctor compaction (IS, 1983) & triaxial test (IS, 1993) after reducing the size of the sample to the requisite amount following coning and quartering.

The grain size analysis test determines the percentage of different sizes of grain contained within the dump material, which governs their strength, permeability, and other properties. Grain size analysis was performed as per the Indian standard (IS, 1985). For this test, about 1000gm of the sample was oven dried for 24 hours. The oven-dried dump sample was washed with water on a 75-micron sieve. The dump sample retained on the sieve was again dried and used in the sieve analysis. The sieve arrangement was made to make the coarser sieve above the finer sieve and the pan below the finest sieve. The entire assembly of the sieve was placed on a sieve shaker and was appropriately covered. The dump sample retained on each of the sieves was weighed to obtain the grain size distribution of the dump material.

The proctor compaction test evaluates the optimum moisture content at which a given dump material becomes the densest and achieves its maximum dry density. The dump material exerts its maximum bodyweight at this density at a slope structure. The Proctor compaction test (IS, 1983) was carried out by dividing the dump sample into three equal parts. In the first stage, the mould was filled with one part of the soil and compacted with 25 evenly distributed blows with the standard rammer. This process was repeated for the second and the third parts of the sample, taking due precaution to scratch the top of the previously compacted layer with a spatula to avoid stratification and achieve homogeneity. Then the mould was detached with compacted soil on it from the base plate. After this, the weight of compacted soil along with the mould was noted. This procedure was repeated by the incremental addition of water in the sample and repeating the experiment to measure its density in each case until it got optimised.

The triaxial test (IS, 1993) was conducted to assess the shear strength of dump material in terms of cohesion and angle of internal friction. In the Triaxial tests apparatus, three tests were conducted for each sample in undrained conditions without any sample saturation prior to the application of load. In this test, about 1000gm of dump sample (passed from the 4.75mm sieve) was dried in the oven for 24 hours. The weight equivalent to maximum dry density multiplied by the volume of the mould was taken. Then, water equivalent to the optimum moisture content was added to the sample and thoroughly mixed. The dump sample was then put in the mould and properly compacted. A compaction machine did the final compaction of the dump sample. The compacted dump sample obtained was taken out from the mould by unscrewing the knot and covered with a seamless rubber membrane. The sample prepared in this manner was tested in the triaxial testing machine. The specimen had a diameter of 38mm with a height of 76mm.

The material content and the size of the rock blocks influenced the geotechnical properties of the soil-rock mixture. The friction angle increases and cohesion decreases with the increment in rock content in the soil-rock mixed dump material (Zhou et al. 2020). Moreover, it possesses a larger slope angle than the natural angle of repose due to the large size of the rock blocks that improves the stability of the waste rock slope structure (Gao et al. 2017, 2018). British Columbia Mine Dump Committee and Piteau Engineering Ltd. (1991) found that the bench slope angle could be steeper than the average angle of repose (i.e.,37°) when dump material consists of appreciable fines or cohesive material or very large and angular boulders. In contrast, cohesion increases with the increment of clay or fine particles (Bishwal et al. 2017). Hence, the proportion and size of the grains affect the geotechnical properties of dump material. Thus, the geotechnical properties as input parameters for parametric study were decided by keeping the significance of the grain size contribution in geotechnical properties.

3.5. Parameters for Assessment of Dump Slope Stability

The factor of safety is one of the most preferred dump slope stability analysis parameters. It provides the overall stability state condition of the slope structure. However, in the case of large-size multi-bench slope structures, if one bench fails, it does not mean that the whole slope structure has failed. Therefore, it is a tedious task to identify the affected or vulnerable part of the slope structure using FoS. Thus, in this study, maximum Horizontal Displacement (XDIS) and Shear Strain Increment (SSI) were deployed along with FoS to pinpoint the most affected zone. The most vulnerable zone possesses max. XDIS and SSI magnitude and their position depend on the cumulative effect of stability governing parameters. The brief descriptions of the performance assessment parameters are as follows:

- **Factor of Safety (FoS):** the ratio of resisting forces to driving forces that controls material flow in a dump structure.
- **Horizontal Displacement (XDIS):** the movement of the material along the X-axis direction.

- **Shear Strain Increment (SSI):** the incremental shear strain rate that a slope structure would develop in a specific state of instability.

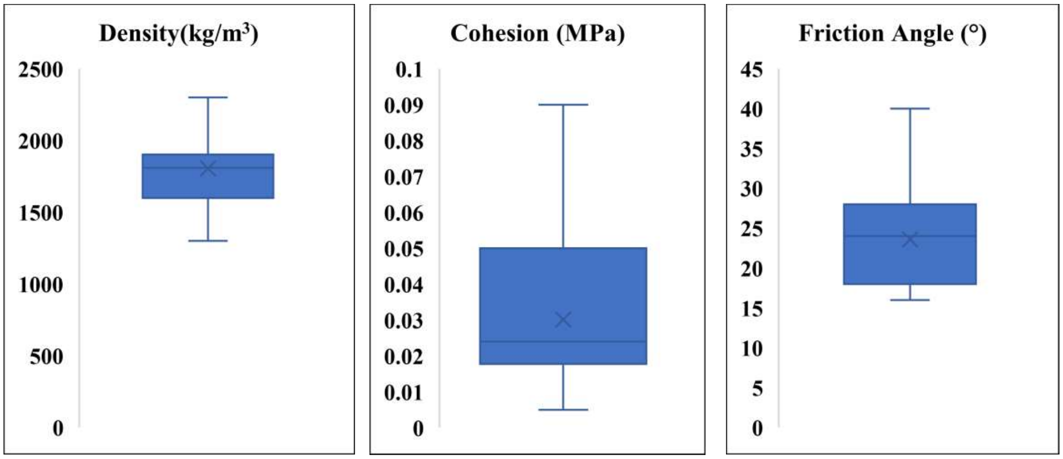
3.6. Parametric Study of Dump Slope Stability

The review of literature as well as experience gained in field visits showed that the geometrical parameters (dump height, bench height, bench slope angle and bench width) and geotechnical parameters (cohesion, friction angle and density) are the most influential parameters affecting stability of dump slopes. Hence, they form the basis for parametric study. The geotechnical datasets were based on the outcome of the laboratory tests conducted for 19 dump material samples from different coal mines in India and literature. The geometrical datasets were also collected from the field and as well as literature. Cluster analysis of the collected datasets has been performed to determine the maximum, minimum and mean of each parameter. This decided the range and base value of each parameter. The majority of the existing cases and salient regulatory provisions were also considered during the base value decision. Table 3.2 presents the range and base value of the considered critical stability governing parameters. The behaviour of the total dump height, bench height, bench slope angle, bench width, density, cohesion, and friction angle was analysed in the parametric study. No correlation was observed among the considered stability governing parameters in the field. Therefore, they were analysed independently. During the study, the parameter to be optimised was varied throughout the considered range by keeping other parameters constant (i.e., base value).

The range of geotechnical parameters was decided by removing the exceptional and outlier cases from the 87 cases (Annexure I), as shown in Figure 3.3. The density range was 1300 - 2300 kg/m^3, cohesion was 0.01 - 0.09 MPa, and friction angle was 16 - 40°. The geometrical parameters were compiled from the field visits and literature (Figure 3.4) and also decided by removing the outliers. The range of the dump height was 90 – 420 m, bench height was 10 – 50 m, bench width was 5 – 40 m, and bench slope angle was 30 - 50°.

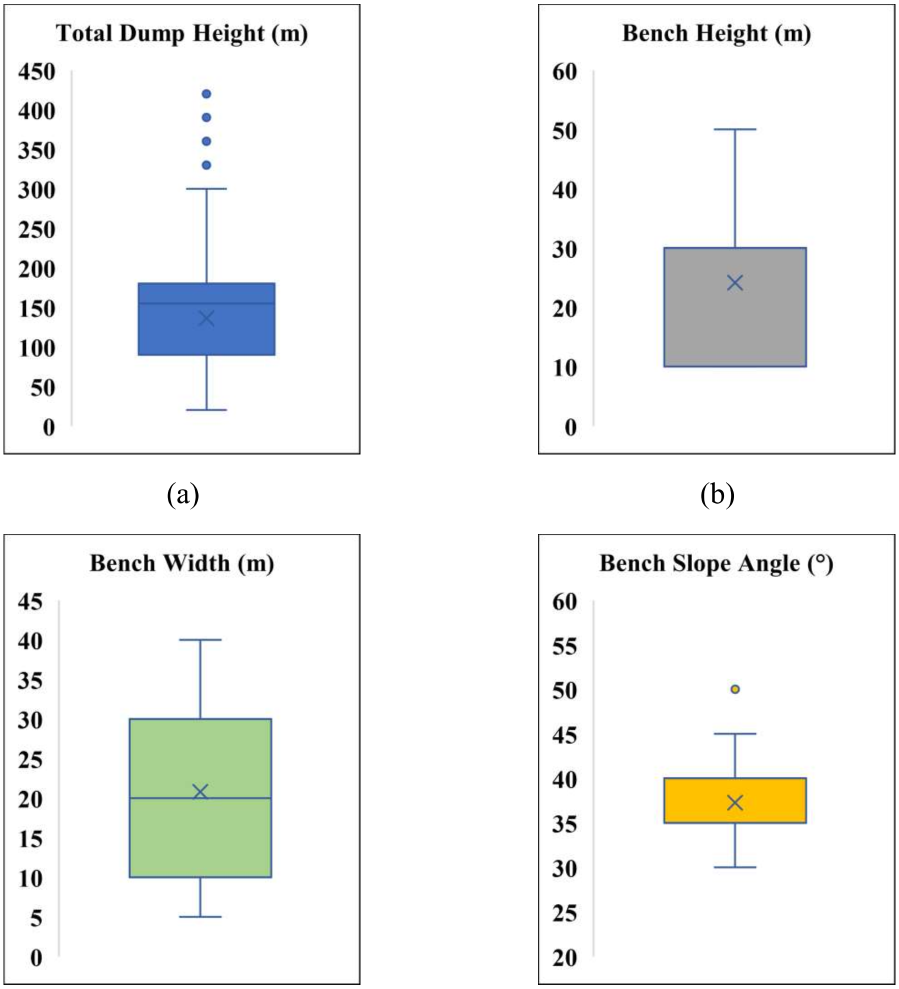
Table 3.2 Range and base value of parameters governing stability (Annexure I)

Parameters	**Range**	**Base value**
Total Dump Height (m)	90 - 420	180
Bench Height (m)	10 – 50	30
Bench Slope Angle (°)	30 - 50	40
Bench Width (m)	5 - 40	30
Cohesion (MPa)	0.01 - 0.09	0.05
Friction Angle (°)	16 - 40	28
Density (kg/m³)	1300 - 2300	1800



(a) (b) (c)

Fig. 3.3 Statistical distribution of geotechnical parameters (a) density (b) cohesion (c) friction angle for parametric study



(a) (b)

(c) (d)

Fig. 3.4 Statistical distribution of geometrical parameters (a) total dump height (b) bench height (c) bench width (d) bench slope angle for parametric study

3.7. Development of Statistical Model

In this study, the effect of the individual parameter was determined vis-a-vis the stability of the dump slope structure. A statistical model was developed to assess the combined impact of the total dump height, bench height, bench slope angle, bench width, density, cohesion, and friction angle on the stability of the dump slope structure by establishing a relationship between all seven parameters with FoS. A multiple nonlinear regression analysis was conducted to evaluate the coefficients of 7 independent parameters against FoS as the dependent parameter. The coefficient of determination (R^2), standard error, F-value, and P-value were utilized to examine the accuracy of the statistical model (SAS Enterprise Guide, 2017). The R^2 is also called the coefficient of determination. It determines the "Goodness of Fit" and the deviation in the dependent variable from the predicted value by the model. It ranges from 0 to 1. Data fitting increases with an increase in the R^2 value. Standard error indicates the deviation of the observed value from the regression line. The smaller standard error value indicates that observations are close to the fitted line. The F-value helps in establishing the statistical significance among the observations. It varies from zero to an arbitrarily large number. If the F-value is slightly greater than 1, it is enough to confirm the statistical significance of the observations. The P-value is used to analyze the reliability of forecasted dependent parameter from considered independent parameters. Generally, the P-value should be less than 0.05 to accept the significance of parameters.

3.8. Effect of Water Table

The OB dump slope is made up of a soil-rock mixture. The porewater pressure significantly influences the dump material's mechanical properties by altering its shear strength. It was observed that the groundwater level is one of the most sensitive external factors in deciding the stability of the dump slopes (Cai et al. 1998, Wang et al. 2020). Therefore, the water table effect under the drained condition (Figure 3.5) at different heights of the dump slope was studied.

Although the actual phreatic surface may not be a straight line but its actual curvilinear profile in different site-specific conditions and is very difficult to establish. There are different methods to determine the phreatic surface but those were also based on certain assumptions and not purely applicable to dump slope structures. In fact, the phreatic surface can fluctuate and shows a non-uniform pattern. It can be convex or concave depending on the material characteristics (Abramson et al. 2002).

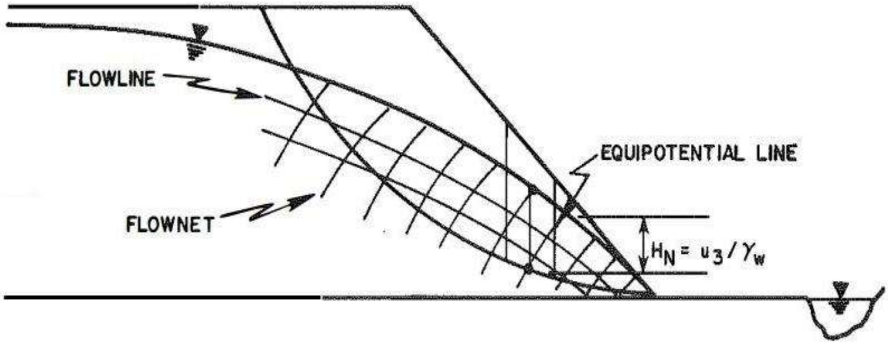


Fig. 3.5 The phreatic surface under drained condition **(**Hopkins et al. 1975**)**

In consideration of the above, a simplified approach of a straight line profile under the drained condition was adopted by considering the fact that such deviation would not affect the end result significantly (Abramson et al. 2002). Numerical modelling provides flexibility to simulate rare physical existing conditions to analyze the worst scenario. Therefore, the effect of the water table was examined at 10, 25, 40, 50, 60, 70, 80, 90 and 100% of the dump slope structure height (Figure 3.6). The total dump height varied from 30 m to 270 m in the interval of 30 m in each stage, with the base value of other parameters as taken in the parametric study (Table 3.3). The water table impact factor was determined to analyse the impact of the water table on the stability of the dump slope structure. FLAC 2D software, version 7.0 (FLAC 2011) was used and pore water pressure was applied using the WATER table and CONFIG gwflow command as pertinent model input. In the water table impact factor, the ratio of FoS, XDIS, and SSI were computed corresponding to the static condition (absence of phreatic surface). Thus, multiplying these factors with site-specific static FoS, XDIS, and SSI would reflect the stability condition of the dump slope structure.

Table 3.3 Stability governing parameters of water table study

Parameters	
Total Dump Height (m)	30 - 270
Bench Width (m)	30
Bench Slope Angle (°)	40
Bench Height (m)	30
Cohesion (MPa)	0.05
Density (kg/m^3)	1800
Friction Angle (°)	28

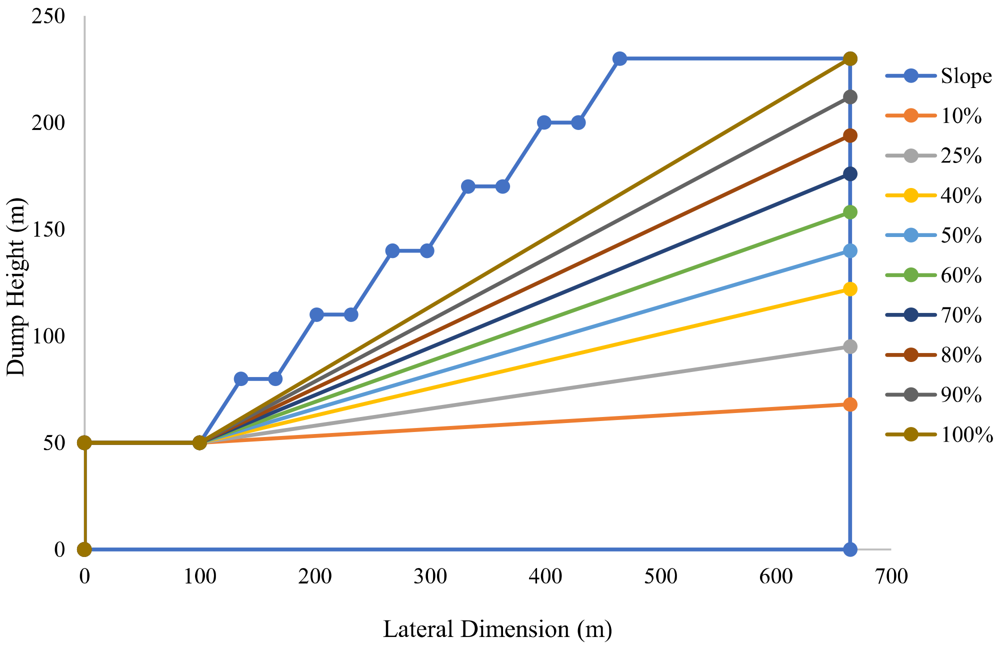


Fig. 3.6 Water table variation in a dump slope structure

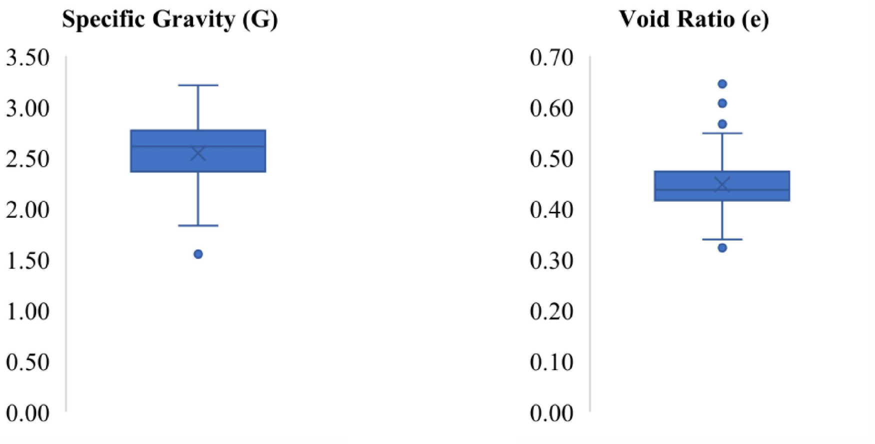
In FLAC software (FLAC 2011), the effective stress analysis with the water table needs dry density (γ(d)) and saturated density (γ(s)) of OB dump material after defining the phreatic surface. The γ(d) will be assigned above and γ(s) will be assigned below the phreatic surface. The average γ(d) (Figure 3.3 (a)) and specific gravity (*G*) (Figure 3.7

(a)) were obtained from the standard laboratory tests and literature review (Chaulya et al. 2000; Gupta and Paul 2016; Priya and Kumar 2018; Rajak et al. 2018). The water density (γ(w)) was taken as 1000 kg/m^3. The void ratio (e), porosity (n) and γ(s) were calculated from Equations 3.4, 3.5, and 3.6, respectively (Lambe and Whitman 1969). The average value of G was 2.54, γ(d) was 1759 kg/m^3, e was 44.7%, n was 30.8%, and γ(s) was 2067 kg/m^3 (Figure 3.7). The difference between γ(s) and γ(d) was 308. Since the γ(d) was 1800 kg/m^3 in the study for the water table, therefore, γ(s) was obtained by adding 308 in γ(d), i.e., γ(s) was taken as 2108 kg/m^3.

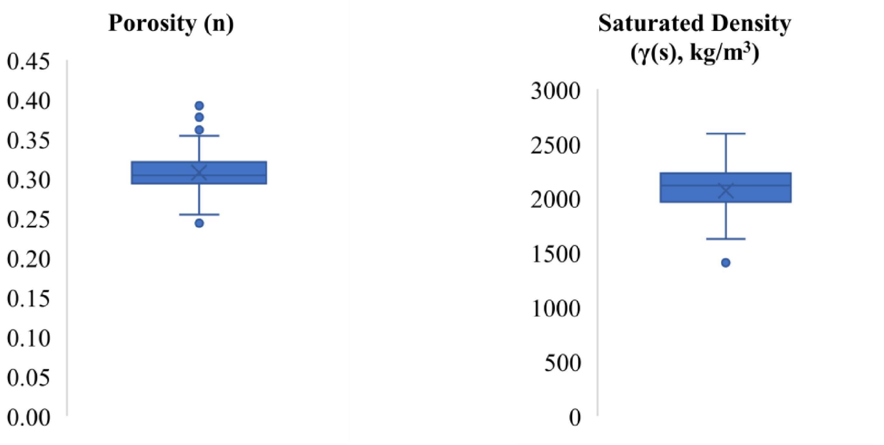
$$e = \frac{G \times \gamma(w)}{\gamma(\mathrm{d})} - 1 \tag{3.4}$$

$$n = \frac{e}{1 + e} \tag{3.5}$$

$$\gamma(\mathrm{s}) = \frac{(G + e)}{(1 + e)} \times \gamma(w) \tag{3.6}$$



(a) (b)



(c) (d)

Fig. 3.7 Statistical distribution of (a) specific gravity, (b) void ratio, (c) porosity, (d) saturated density of OB dump material

3.9. Dump Slope Stability Classification

During the literature review, it was seen that the different safety factor values were considered for the stable dump slope structures. Table 3.4 shows the FoS value adopted in various studies as a stability acceptance criterion. Section 2.3.2 of Chapter 2 also classified the hazards and the consequences based on the FoS. It was also suggested that uncertainty related to the geometry or strength of the waste rock material might vary the FoS by approximately 10% (Miller et al. 1979; Khandelwal and Mozumdar 1992; Hustrulid et al. 2009). It was also noted that a few dump slope structures received failure in due course of time although their FoS were marginally greater than 1. DGMS (2020) also suggests a minimum FoS of 1.30 for a stable slope structure. Therefore, there is a possibility that the dump could fail, even with FoS just greater than one. Thus, this study introduced a Critically Stable state along with the Stable and Unstable states to determine the threshold limit of FoS for analyzing the stability state condition of the dump slope structure. The critically stable state informs about the dump slope prone to failure even with FoS greater than one.

Table 3.4 Factor of safety values for stability analysis

Reference	FoS
Duncan et al. (2014); Cheng and Lau (2014); Chebrolu et al. (2020)	>1
Kardani et al. (2020)	>1.30
Abramson et al. (2002)	1.25 - 1.50
Sakellariou and Ferentinou (2005); Bui et al. (2020)	>1.20

3.10. Development of Stability Rating and Hazard Quantification System

Stability rating and hazard quantification of the stability governing parameters and dump slope structure was done through @RISK software, Version 7.0 (Palisade Corporation 2016) based on stability state classification. The dump material possesses uncertainty in the geotechnical properties throughout the dump slope structure. Therefore, cohesion, friction angle, and density of the dump material were assigned as random variables, and geometrical parameters were considered deterministic parameters. The reliability-based study was conducted to tackle the uncertainty of the geotechnical properties of dump material. The Reliability Index (β) is frequently used for safety and performance measurement of geotechnical design. It is a useful indicator to compute the structure's probability of failure (PoF). The Reliability Index (β) measures the possibility that the safety factor is less than one. The U.S. Army Corps of Engineers (1997) summarized the expected performance level of structure using β and PoF as presented in Table 3.5 (Wang et al. 2010). To obtain the reliability index, the mean and standard deviation were determined using the histogram of FoS for a particular condition. These values were used to calculate the reliability index using Equation 3.7. This equation was not based on the distribution function. Therefore, the considered distribution functions did not affect the result of Equation 3.7 (Christian et al. 1994).

Table 3.5 Expected performance level based on Reliability Index and Probability of Failure (U.S. Army Corps of Engineers 1997)

Reliability Index	Probability of Failure	Expected Performance Level
1.0	0.16	Hazardous
1.5	0.07	Unsatisfactory
2.0	0.023	Poor
2.5	0.006	Below average
3.0	0.001	Above average
4.0	0.00003	Good
5.0	0.0000003	High

$$\beta = \frac{E[FoS] - 1}{\sigma[FoS]} \tag{3.7}$$

E[FoS]: mean of safety factor
σ[FoS]: standard deviation of the safety factor

In @RISK software, the first preeminent step was to assign the probability distribution function to the random variable, and it was done using β. The next foremost step was to evaluate the PoF as a hazard through the iteration process with due consideration of the geotechnical variability. It was observed that the Latin Hypercube sampling method is widely used in the uncertainty analysis of complex systems due to minimal iterations, performance time, and associated error with a high confidence level (Helton and Davis 2003; Chrisman 2014; Garcia-Alfonso and Cordova-Esparza 2018; Data Science Genie 2022). Latin Hypercube Sampling is a statistical method used in experimental design and uncertainty analysis, particularly in the field of computer experiments and simulations. It aims to efficiently sample a multi-dimensional parameter space while ensuring a more even distribution of samples compared to traditional random sampling methods. This method was adopted in the iteration process to generate samples for each uncertain geotechnical parameter through the selected probability distribution function. The impending hazard (i.e., PoF) corresponding to the range of stability governing features was categorized based on the stability states.

The weightage of the input features was obtained from the regression model coefficients to determine the rating of the input features. The variation of the weightage throughout the range of stability governing parameters was done as FoS varied and assigned as a rating.

It is proposed that the dump slope structure would collapse if any stability governing parameters moved beyond the threshold limit or toward the instability condition. Since the dump slope structure was the main system and stability governing parameters were the independent components of the system. Hence, the failure of any one component would lead to the failure of the entire system. Therefore, the dump slope structure was considered to have a series system configuration as per the reliability. The rating and the PoF of the entire system were determined based on the series system hypothesis. The PoF of the dump slope as a series configuration was determined from Equation 3.8 (Obregon and Mitri 2019).

$$PoF = 1 - \prod_{i=1}^{N} (1 - PoF_i) \tag{3.8}$$

PoF: probability of failure of the system
N: total number of components
PoF_i: probability of failure of ith component

3.11. Model Validation

The accuracy of the developed Stability Analysis and HAzard RAting (SAHARA) system of the dump slope structure was analyzed through existing and proposed dump slope structures. The first mine "X" was India's largest and Asia's second largest opencast coal mine (GlobalData 2021; Mining Technology 2021). The second mine “Y” was from the highest OB generating subsidiary of Coal India Limited, India. The third mine “Z” belonged to the second highest coal producing subsidiary of Coal India Limited, India (Coal Controller's Organization 2022).

In the existing dump slope, the Mine “X” mega opencast coal mine of Chhattisgarh, India, was considered. Three internal dump slopes of the Mine “X” opencast coal mine were considered. In the planned dump slopes, one was from Mine “Y” opencast coal mine of Singrauli, Madhya Pradesh, India. The two dump slopes were from the Mine “Z” opencast coal mine of Chhattisgarh, India where one dump slope was proposed for pure dump material, and the other was planned for fly ash and OB mixed dump slope.

The proposed dump slopes had uniform benches, and existing ones possessed heterogeneous benches. Therefore, bench height, slope angle, and width were easily defined for the SAHARA system in uniform benches. In the case of non-uniform dump slopes, prone to failure bench or bench with extreme instability geometrical parameters were utilized to define the bench configuration.

3.12. Summary

This chapter discusses the approach to designing the stability analysis and hazard rating of the dump slope structure. Numerical modelling outcomes were utilized to develop the statistical model. The statistical model was valid for the defined stability governing parameters and their range. In numerical modelling, the base of the dump slope structure was competent and free from loose materials. All dump slope models were internal dump slope structures. In addition to the FoS, XDIS and SSI were adopted to pinpoint the affected zone in the large-size dump slope structure. The change in the FoS, XDIS and SSI due to the presence of the water table was also determined through numerical modelling. The critically stable state was introduced along with the stable and unstable states to avoid the chances of failure even though the slope has FoS greater than one. The associated hazard of the stability governing parameters and dump slope structure was quantified due to uncertainty of the geotechnical properties through @RISK software. The proposed scheme was validated by examining the existing and planned dump slope structures.