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Sustainability Analysis of Waste Dump in Mine No. 4 of Golgohar, Sirjan, for Purpose of Increasing Waste Dump Volume

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Abstract

The stability of waste dumps is a significant and at times critical issue in the development of surface mines. Due to insufficient space for waste disposal, environmental concerns, and various other factors, Mine No. 4 at Golgohar Sirjan is not capable of establishing a new waste dump. Given the existing limitations of the mine, the investigation has focused on increasing the dump capacity through the implementation of benches. In this research work, the stability of the waste dump has been investigated using the limit equilibrium method with the Slide3D software, along with a Monte Carlo simulation approach for probabilistic analysis. The results obtained from these methods have been compared with each other. The acceptable safety factor considered for this assessment ranges from 1.15 to 1.2. By adding benches to the eastern waste dump of the mine, a displaced volume equivalent to 36,715.565 cubic meters has been added to the capacity. The constructed model is based on the topography of the area, with dimensions of 1850 meters in length, 1750 meters in width, and 160 meters in height. The results indicate that the safety factor of the waste dump has been calculated as follows using the Spencer, Janbu, and Bishop methods respectively: 1.26, 1.199, and 1.226. Mine No. 4 needs to extract 983.58 million tons of waste to produce 73 million tons of iron ore. In total, by discharging 428 million tons of waste in the northeastern and eastern dumps and adding a bench, a volume of 555.571 million tons of waste is available for disposing of the remaining waste. Considering the remaining waste volume, space must be allocated for waste disposal to Mine No. 4.

1. Introduction

Today, waste dump stability is considered the foremost issue in mining, especially in surface mines [1]. With the expansion of surface and deeper mining operations, the amount of generated waste will also increase, and this increase will lead to larger waste dumps; on the other hand, due to the scarcity of horizontal space available for waste disposal, it will threaten the stability of waste dump [2, 1]. The purpose of constructing a waste dump is to dispose of and retain low-value materials with minimal cost. Long-term sustainability and environmental issues related to the waste dump must also be considered [3]. Various factors contribute to the failure of a waste dump such as the geology and hydrogeology of the dump area, gravitational forces, sub-surface water seepage, stress, and erosion of the dump due to water intrusion, dump slope angle, nature of the dumped materials, changes in material cohesion [1]. The failure of a waste dump can lead to serious issues such as environmental impacts, damage to property, harm to the health and safety of workers and nearby community residents, as well as economic consequences. It can even result in the early closure of the mine [4]. Various research studies have been conducted regarding the stability analysis of waste dump slopes in mines. Bahrami Rad (2008) employed numerical methods and limit equilibrium techniques to calculate the stability of waste dump slopes in Mine No. 1 of the Golgohar iron mine. The analysis results indicated that the waste dump construction stages are equipped with the necessary safety measures [3]. Kainthola *et al.* (2011) assessed the stability of waste dump slopes

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in the Western Coalfield Limited Mine, Nagpur, India, using a two-dimensional finite element code. They eventually proposed an economically viable and safe dump slope angle and height [5]. Adamczyk *et al*. (2013) conducted a study on the waste dump of the open-pit mine Osielec in Poland. They analyzed the final waste dump stability using the limit equilibrium method, and proposed a stable slope angle and height for the ultimate dump [6]. Yaya *et al*. (2017) employed numerical modeling along with geophysical monitoring to assess the stability of the waste dump in the northwest region of the Westwood mine. The results indicated that the waste dump is stable [7]. Zug *et al*. (2018) conducted a stability analysis of a waste dump slope in a specific mine in Tibet using a three-dimensional numerical method. The results of this analysis demonstrated the stability of the waste dump [8]. Shamsaldin Saeed *et al*. (2020) utilized the limit equilibrium method under static loading conditions to calculate the stability of waste dump No. 1 in the Golgohar Sirjan mine for both global and local failure modes. The results of their analysis demonstrated the stability of the waste dump in both scenarios [9]. Vinales *et al.* (2021) have investigated the stability of 1959 waste dump slopes in a lead and zinc mine in southeastern Spain using a combination of satellite-based InSAR (Interferometric Synthetic Aperture Radar) and finite element modeling. The results indicate that out of the studied slopes, 43 were unstable, while 1756 waste dump slopes were considered stable [4]. Vong Nguyen *et al*. (2022) conducted a numerical stability analysis to prevent waste dump sliding in the Janina coal mine in Poland under the influence of rainfall. Based on the results, they proposed selected measures to prevent sliding for the waste dump in the Janina mine under rainfall conditions [10]. Sarpong *et al.* (2023) calculated the stability of three waste rock dumps in gold mines in Ghana using limit equilibrium analysis. Ultimately, they presented the conditions for the deformations of the waste rock dumps [11]. Vishvakiran (2023) has utilized the SLOPE/W software to calculate the stability of waste dump slopes in surface coal mines in India. As a result, recommendations for ensuring the stability of the slope have been provided [12]. The Golgohar Iron Ore Complex is one of Iran's major iron ore deposits, located about 60 kilometers southwest of the city of Sirjan in the Kerman Province. This complex consists of 6 separate iron ore anomalies. Golgohar Mine No. 4 is one of the iron ore mines in this region, situated approximately 3.5 kilometers east of Mine No. 1 [13]. Recently, due to mine expansion and increased production, Golgohar Sirjan Iron Ore Mine No. 4 is currently facing the challenge of insufficient space for waste disposal. In this research, an attempt has been made to design a safe and stable waste dump for the disposal of remaining waste from Mine No. 4 by employing the limit equilibrium method.

2. Case Study

Mine No. 4 is located on a 606-hectare site in the Golgohar region, and holds an iron ore reserve of approximately 98.707 million tons, with an open-pit extraction method. However, about 16.434 million tons of iron ore in Mine No. 4 cannot be extracted using the open-pit method. Approximately 9.273 million tons of iron ore were extracted from Mine No. 4 before 2016 and from 2016 onwards, around 73 million tons of iron ore have been extracted from Mine No. 4 over a span of 21 years using the open-pit method (Table 1) [14].

Table 1. Overall reserve status Reserve Status of Mine No. 4 (total reserve, extracted, remaining) [14].

Title	Iron ore (tons)
Total mine reserve	98.707.000
Pre-2016 extraction	9.273.000
Post-2016 extraction	73.000.000
Remaining reserves	16.434.000

The extraction of mineral material and waste from Golgohar Sirjan Mine No. 4 for the purpose of producing 73 million tons of iron ore required the removal of 983.58 million tons of waste. From the beginning of the project (since 2016) until the end of March 2023, approximately 12.400 million tons of iron ore and 273.640 million tons of waste have been extracted. The remaining amount of mineral material and waste for the extraction of Mine No. 4 from the end of March 2023 (beginning of April 2023) until the completion of the project is 60.600 million tons of iron ore and 637.082 million tons of waste (Table 2) [15].

Table 2. Overall status of mineral material and waste in Mine No. 4 (total mineral material and waste, extracted, remaining) [15].

Title	Extractive material	Amount (million tons)
Total mineral and waste material	Iron ore	73
	tailings (stone and alluvium)	983.58
Mined and waste material extracted until the end of March 2023	Iron ore	12.400
	tailings (stone and alluvium)	273.640
Remaining mineral and waste material from the beginning of April 2023 until the end of the project.	Iron ore	60.600
	tailings (stone and alluvium)	637.082

There are three waste dump sites in Mine No. 4 including the northeastern, eastern, and southern waste dumps. Currently, the waste dump capacity of the northeastern and southern sides is fully utilized, and there is no possibility of further waste disposal in these areas. Therefore, the only available area for waste disposal is the eastern waste dump (Figure 1) [14].

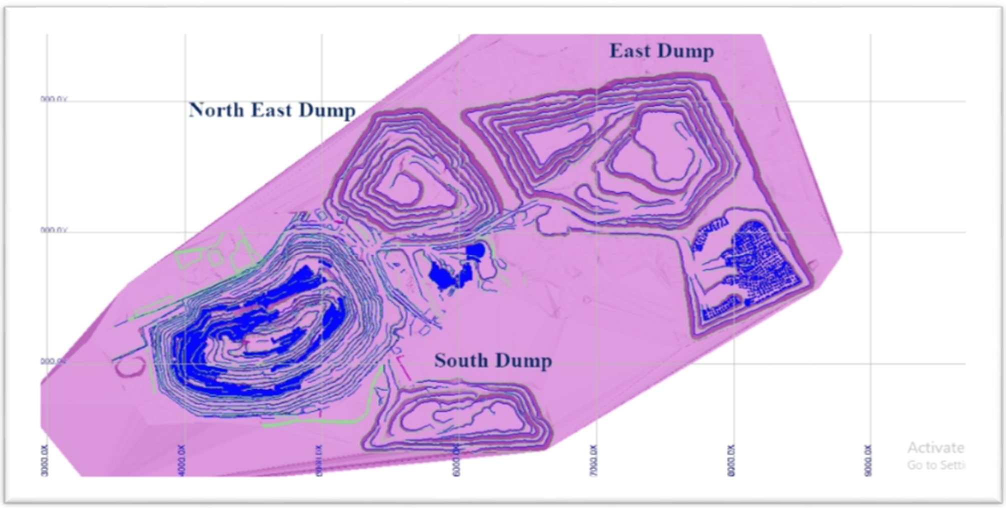


Figure 1. A view of the current tailings dump of Mine No. 4 (end of March 2023).

From the beginning of the project (before the year 2016) until now, the extracted waste at the sites of the northeastern, southern, and eastern waste dumps has been disposed of. The capacity of the northeastern and southern waste dumps has been filled, and the amount of waste discharged in these dumps is 100 million tons and 20 million tons, respectively. The northeastern waste dump has received 100 million tons of waste, with 80 million tons discharged before the year 2016 and 20 million tons discharged since 2016. The amount of material deposited in the eastern waste dump until the end of March 2023 is 326.500 million tons, and as a result, a total of 446.500 million tons of waste has been discharged in all waste dumps (Table 3). The remaining capacity of the eastern waste dump (active waste dump) is 41 million cubic meters displaced (equivalent to 33 million cubic meters in situ), as stated in Table 4 [15].

Table 3. Volume of waste discharged in waste dumps from start of operation until March 2023 [15].

Waste dumps	Discharged volume (cubic meters)		tonnage (tons)
	Displaced	In-situ	
Northeast dump	55.000.000	44.000.000	100.000.000
Eastern dump	183.840.090	147.072.072	326.500.000
Southern dump	12.500.000	10.000.000	20.000.000
Total	251.340.090	201.072.072	446.500.000

Table 4. Remaining volume of mine dump No. 4 [15].

Waste dump	Total displaced volume (million cubic meters)	Remaining volume (million cubic meters)		Tonnage (million tons)
		In-situ	Displaced	
Eastern dump	225	33	41	73.5

3. Stability Analysis using Limit Equilibrium Method

In the limit equilibrium method, it is assumed that soil or rock mass slides on a failure plane. When examining a stable slope, the shear strength involved at equilibrium is less than the available shear strength. Thus the Safety Factor (SF) is defined as follows:

SF = Available shear strength / Required shear strength for stability

This method is used to assess the stability of slopes in two models: structural control (wedge, planar failures, and overturning), and non-structural control (circular failure). For this purpose, several sections are considered for analysis, and in the most critical section, stability is examined. The safety factor related to this surface (minimum safety factor) is considered the slope's safety factor.

As part of the stability analysis using the limit equilibrium method, there are several aspects that require more attention, particularly the selection of the analysis method. This is because slope failure, in addition to stress concentration, depends on the specific properties and discontinuity conditions. Once the type of failure is determined, an appropriate stability analysis method is chosen, and the stability analysis is performed [16].

The first step in assessing stability is to construct a model of the studied area. The subsequent step in evaluating stability is the selection of the analysis method. Available analysis methods include Spencer, Janbu, Bishop, GLE, and others [2]. In this study, three methods - Spencer, Janbu and Bishop - have been utilized, and the safety factor has been determined for each method.

3.1. Assumptions of slope stability assessment using Spencer, Janbu, and Bishop methods

In this report, three deterministic analysis methods - Spencer, Janbu, and Bishop - have been used for slope stability analysis. Therefore, in this section, we will explain the assumptions of these methods.

The Spencer method, introduced in 1967, is based on the assumption of static equilibrium with high accuracy. It assumes that there is a constant value of total inter-slice forces and that the inclination angle is similar across the failure surface. While initially designed for analyzing circular failure surfaces, this method can be easily extended to non-circular failure surfaces by introducing an extended rotational friction center.

The assumptions considered for the Bishop method are as follows:

- The sliding occurs on the circular failure surface around the center of the circle. Therefore, this method cannot be directly used to assess the safety factors of non-circular surfaces, unless the method of rotational friction center is employed.
- Forces acting on the lateral surfaces of the horizontal slices are assumed. This means that shear stresses between the adjacent slices are not accounted for explicitly.
- The entire normal force acts at the base of each slice.

While the Bishop method may not fully satisfy static equilibrium, the safety factors obtained from this method closely match (within about 5% difference) the safety factors calculated using more precise methods like the finite element method.

In the simplified Janbu method, an assumption is made that the shear forces between the slices are zero, which leads to the lack of equilibrium of anchors. Although the Janbu method introduces a correction factor to account for this lack of equilibrium, its advantage lies in its applicability to non-circular failure surfaces as well, unlike other methods like Spencer [17].

4. Geomechanical Properties of Waste Dump

For the purpose of assessing the stability of a waste dump, input data must be defined for analytical and numerical software. These data can be broadly categorized into two parts: the physical properties of the materials and the mechanical properties of the waste materials.

Physical properties include parameters such as moisture content, particle size distribution, and density. Among these, density has a significant influence on the analysis.

Mechanical properties encompass characteristics like internal friction angle, cohesion, Poisson's ratio, and modulus of deformation of the waste materials. Among these, the internal friction angle and cohesion hold great importance in assessing the stability of the waste dump. This is because they play a crucial role in determining the behavior of the materials under various loading conditions and ultimately affect the potential for slope failure [2].

The geo-mechanical properties of the tailings of Mine No. 4 in Golgohar, Sirjan including density, internal friction angle, and cohesion have been measured, and their values are provided in Table 5.

Table 5. Values of density, cohesion, and internal friction angle of Mine No. 4 tailings dump.

Parameters	Unit	Amount of
Density	kN/m³	20
Cohesion	kPa	21
Internal friction angle	Degree	27

5. Model Construction and Analysis

To assess the stability of the Mine No. 4 tailing dump in Golgohar, Sirjan, a tailings dump model was designed in the Surpac software using an appropriate slope angle and height. The volume of added benches was calculated within the model. Subsequently, the model was analyzed using the slide3D software. Given that the environment mainly consists of soil and fine-grained materials, the analysis considers circular failure surfaces. Due to the dry nature of the tailings materials and the absence of groundwater, completely dry conditions are assumed for the assessment. Additionally, as there are no external forces acting on the tailings dump, the evaluation is solely based on the weight of the tailings materials. Typically, a safety factor of 1.15 to 1.2 is considered acceptable for slope stability assessments.

5.1. Stability analysis of eastern tailings dump final design in Mine No. 4, Golgohar, Sirjan

Initially, the stability of the final design of the eastern tailings dump in Mine No. 4 was analyzed in terms of slope stability. If the safety factor of the tailings dump exceeds the acceptable safety factor (FS > 1.15 to 1.2), benches can be added to it. The eastern waste dump of Mine No. 4, with a displaced volume of 183,840,090 cubic meters, has bench slopes ranging from 33 to 30 degrees and benches with a height of 20 meters. Figures 2 to 4 illustrate the stability analysis of the eastern tailings dump using the Bishop, Janbu, and Spencer methods. The results related to the safety factor of the eastern tailings dump using these three methods are presented in Table 6.

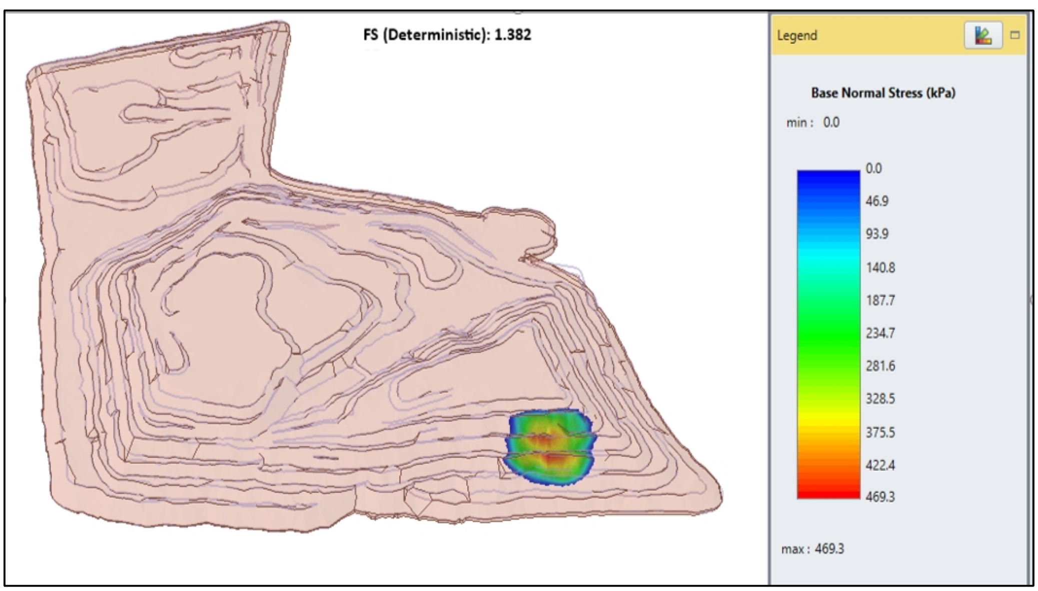


Figure 2. Stability analysis of eastern tailings dump final design in Mine No. 4 using the Bishop method.

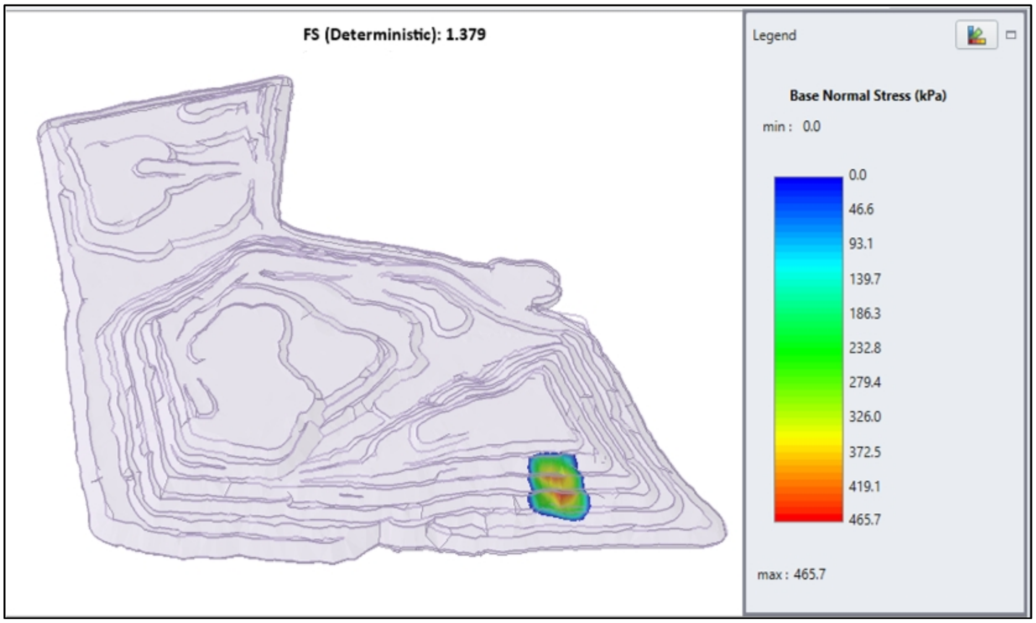


Figure 3. Stability analysis of eastern tailings dump final design in Mine No. 4 using Janbu method.

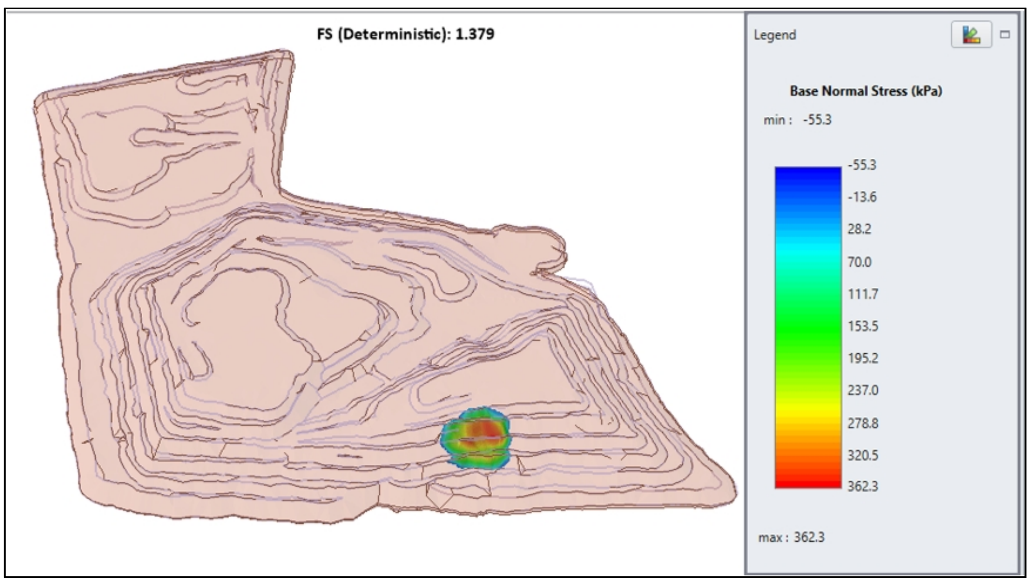


Figure 4. Stability analysis of eastern tailings dump final design in Mine No. 4 using Spencer method.

Table 6. Calculated safety factor of final design of eastern waste dump of Mine 4 using analytical method.

Analysis method	Safety factor
Bishop	1.382
Janbu	1.379
Spencer	1.379

The final results of the stability analysis of the eastern waste dump of Mine No. 4 indicate that the safety factor of the eastern waste dump is greater than the acceptable safety factor (1.3 > 1.15-1.2). Thus the bench can be added to the final design of the eastern waste dump.

5.2. Stability analysis of eastern waste dump of Mine 4, Golgohar, Sirjan, with addition of bench

Figure 5 depicts the sections to which benches have been added. In the Surpac software, for Section A, three benches with a slope angle of 31 degrees and a height of 20 meters have been added, resulting in a total volume of 7.546.110 cubic meters. In Section B, four benches with a slope angle of 31 degrees and a bench height of 20 meters have been added, resulting in a total volume of 29.169.455 cubic meters (Figure 6). The constructed model is based on the topography of the area, with dimensions of 1850 meters in length, 1750 meters in width, and 160 meters in height. Figures 7 to 9 display the stability assessment of the eastern waste dump of Mine 4 with the addition of benches using the Bishop, Janbu, and Spencer methods. The results related to the safety factor of the eastern waste dump of Mine 4 with the addition of benches using the Bishop, Janbu, and Spencer methods are provided in Table 7.

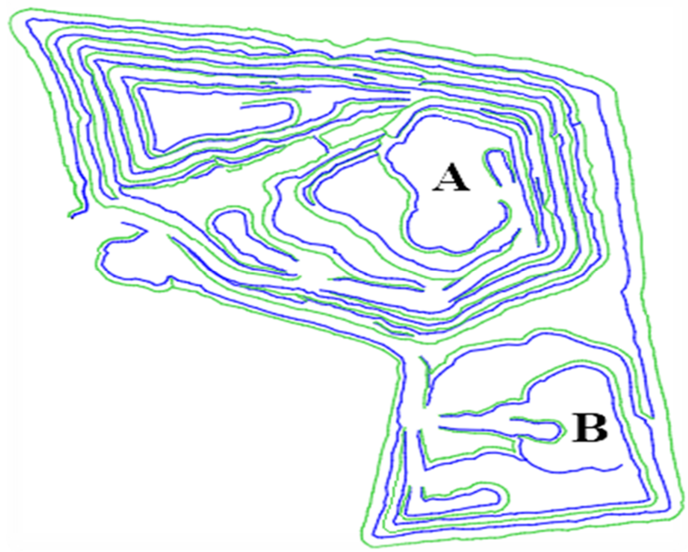


Figure 5. Location of additional benches added to eastern waste dump of Mine 4.

Table 7. Calculated safety factor of eastern waste dump of Mine 4 using analytical method with addition of benches.

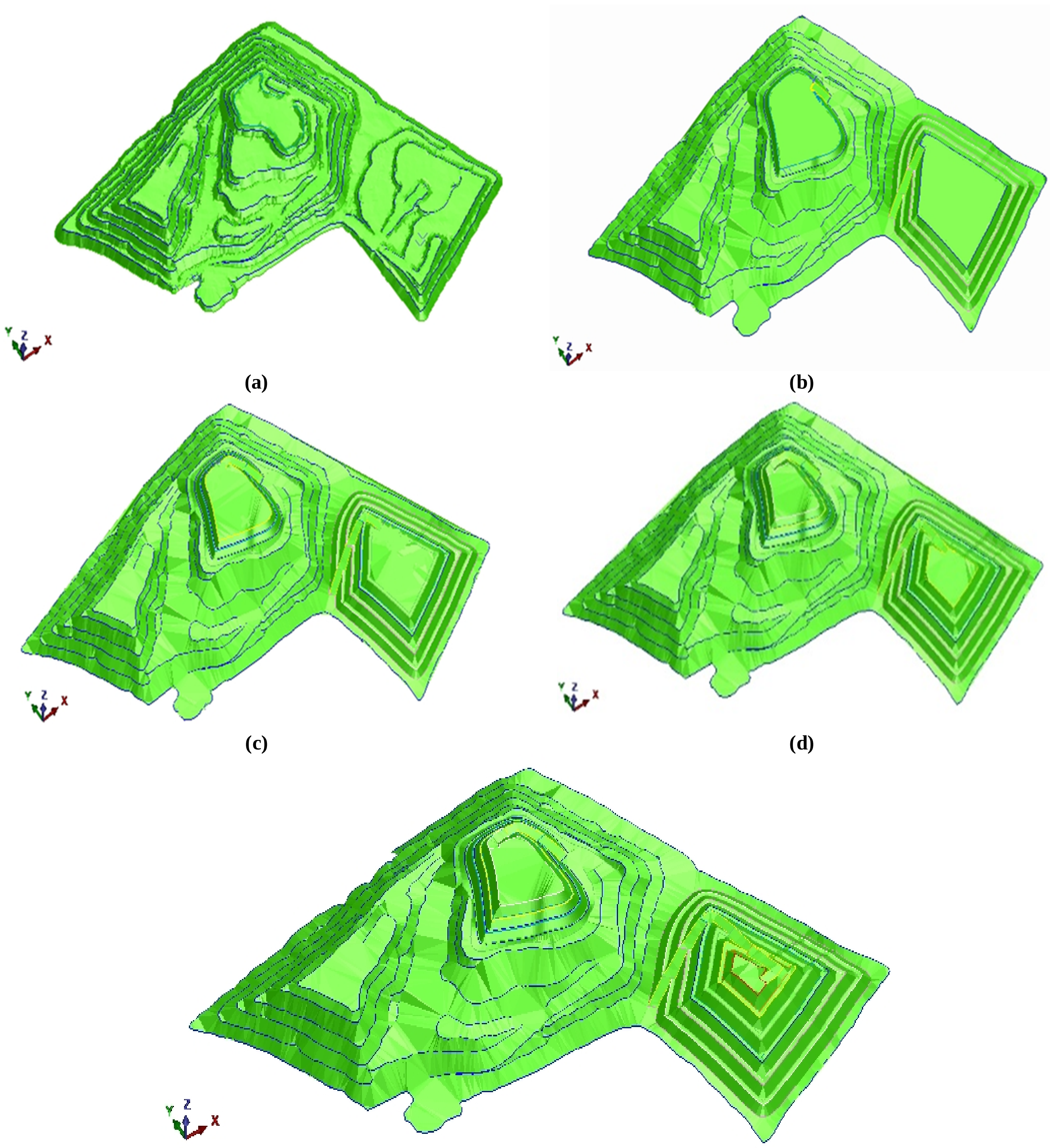
Analysis method	Safety factor
Bishop	1.226
Janbu	1.199
Spencer	1.26

The results obtained from the stability analysis of the eastern waste dump of Mine 4 with the addition of benches using the Bishop, Janbu, and Spencer methods indicate that the safety factor of the eastern waste dump is greater than the acceptable safety factor.

5.3. Volume of eastern waste dump of Mine 4 with addition of benches

The eastern waste dump of Mine 4 has a total displaced capacity of 225 million cubic meters (equivalent to 400 million tonnes). As of the end of March 2023, approximately 183.840 million cubic meters (equivalent to 326.500 million tonnes) of waste material have been discharged from it. A remaining displaced volume of 41.385 million cubic meters (equivalent to 73.500 million tonnes) is available for waste disposal in the eastern waste dump. By adding benches in sections A and B of the eastern waste dump of Mine 4, the total capacity will increase to 36.715.565 million cubic meters (81.508.554 million tons). Considering the stability analysis, which has shown stability, waste can be discharged in the eastern dump.

Mine number 4 needs to extract 983.58 million tons of waste to produce 73 million tons of iron ore. By discharging 20 million tons of waste into the northeastern dump and 408 million tons into the eastern dump, along with the addition of benches in sections A and B, totaling 428 million tons, a volume of 555.571 million tons of waste is available for disposing of the remaining waste. Considering the remaining waste volume, space must be allocated for waste disposal to Mine No. 4.



(e)

Figure 6. Designing stairs in two sections A and B, in the Surpac software (a) final waste dump plan (b) One bench has been added in section A, and one bench has been added in section B (c) After ensuring stability of previous benches, a second bench has been added in sections A and B (d) After confirming stability of previous benches, a third bench has been added in sections A and B (e) After ensuring stability of previous benches, only a fourth bench has been added in section B.

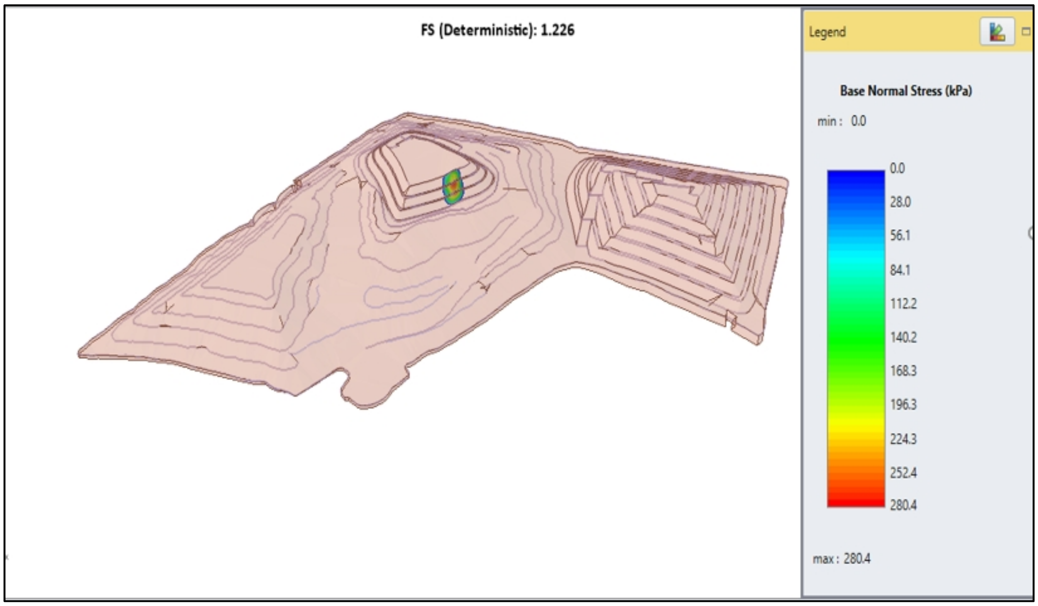


Figure 7. Stability analysis of eastern waste dump of Mine 4 using Bishop method with addition of benches.

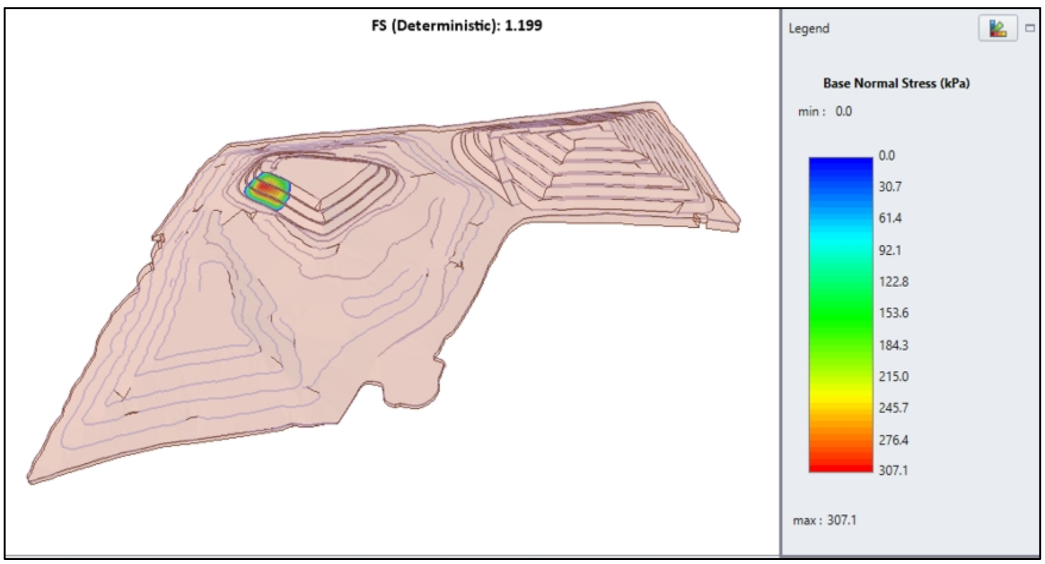


Figure 8. Stability analysis of eastern waste dump of Mine 4 using Janbu method with addition of benches.

6. Probabilistic Assessment using Analytical Method

In deterministic slope stability assessment, by considering a specific value for each parameter and determining a safety factor for slope stability, assumptions are made for the entire slope geometry, even in points close to each other, despite the heterogeneous nature of the soil and its various parameters. These assumptions are used in selecting the model to be used and its imperfect match with the conditions present in the field, as well as human errors in choosing soil parameters or the utilized model. All these factors contribute to the unreliability of the selected safety factor for the analyzed slope. Therefore, in comparison to deterministic assessment, probabilistic assessment, while taking into account uncertainties in input parameters, provides a more efficient method for analyzing slope stability problems and predicting the behavior of rocks and soil more accurately [18].

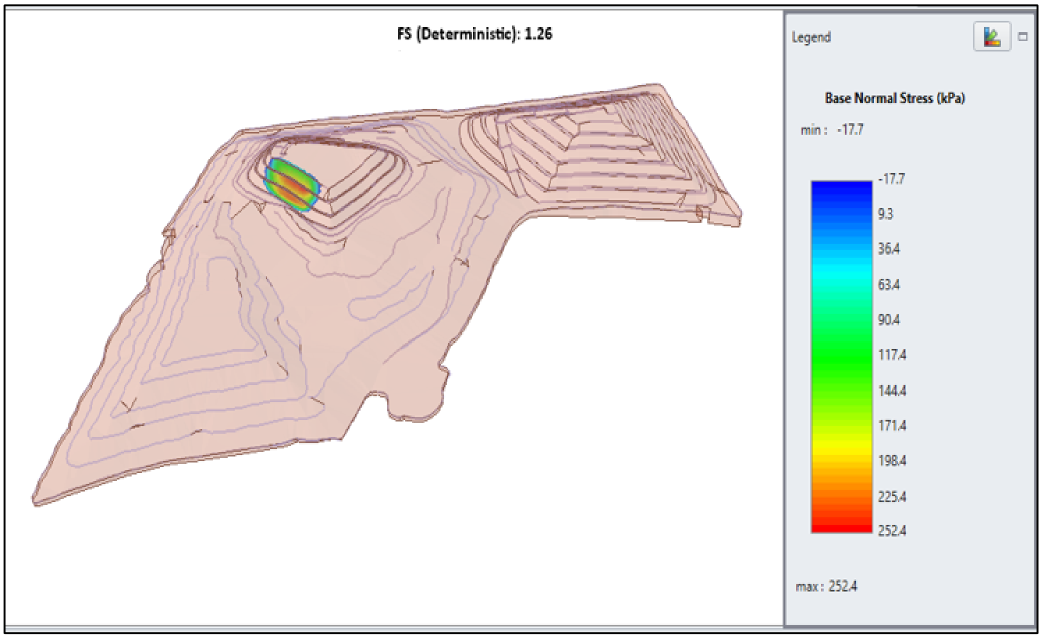


Figure 9. Stability analysis of eastern waste dump of Mine 4 using Spencer method with the addition of benches.

6.1. Probabilistic assessment methods

In all probabilistic methods, modeling the properties of rock and soil will constitute the main part of the probabilistic analysis. In probabilistic methods, the probability of failure is directly calculated based on the probability density function of the variables and by multidimensional integration over the entire failure domain. Usually, due to the complexity of the final probability function and the difficulty of multidimensional integration, determining the exact probability of failure is challenging and often requires numerical approximations. However, in simulation methods and considering the computational power of modern computers, calculating the probability of failure has become easier [19].

In this research work, the Monte Carlo method has been employed due to its high accuracy and the ease of its application. This method has been used more extensively in geo-technical projects because of its simplicity.

6.2. Monte Carlo method

The Monte Carlo simulation is a method that uses a series of random numbers sampled from the probability distribution of variables to simulate the final function. The Monte Carlo method is widely applied today in challenging problems with inherent uncertainty. In the Monte Carlo method, the sampling process is entirely random, with each sample being chosen completely randomly from the distribution interval of input parameters [19].

The various steps of the Monte Carlo method are as follows:

- Determine an appropriate deterministic analytical solution method.
- Specify input data for probabilistic modeling and quantify their variations.
- Random sampling is performed for each parameter based on the probability density function or the data column associated with that parameter.
- Solve the deterministic analytical problem for the set of specified parameters to estimate the performance function.
- The process is repeated through the previous two steps until a sufficient number of simulations are conducted. By using the output values, the distribution of the performance function is obtained, ultimately leading to the determination of the probability of failure [20].

Probabilistic analysis using the Monte Carlo method has been conducted with the Slide3D software, employing three methods: Spencer, Janbu, and Bishop. This software is capable of estimating the probability of failure and the distribution of the safety factor by taking into account the slope model, deterministic and probabilistic material data, as well as the water table level. In the probabilistic analysis performed using the Slide3D software, the input variables' distribution function has been assumed to be normal.

The Monte Carlo method effectively simulates the influence of input variables, which are randomly determined and placed within the function of the performance, on the response and the reliability index. In the Monte Carlo method, for each randomly chosen input data, the probability density function is used to generate random numbers according to the range of its variations. These random numbers are then used to estimate the value of the performance function. This process continues until an estimate of the shape of the reliability index's probability density function is roughly determined, based on which the probability of failure and the reliability index can be estimated. To perform slope stability assessment using this method, a substantial number of repetitive operations are required. From a theoretical standpoint, a larger number of repetitions will lead to more accurate results. However, the question arises as to how many repetitions are necessary for the assessment. The minimum number of iterations required is computationally dependent on the number of random variables and the desired confidence level. The determination of the number of iterations in the Monte Carlo method can be achieved using Equation (1) [20].

$$N = \left[\frac{d^2}{4(1-\varepsilon)^2}\right]^m \qquad (1)$$

In this equation, N represents the number of computational stages in the Monte Carlo simulation method, ε and d correspond to the desired confidence level and the standard deviation of the normal distribution, which are determined from Table (8), and the number of input random variables is denoted by the symbol m.

Table 8. Standard deviation according to confidence levels [21].

Standard deviation	Confidence level
1.282	%80
1.645	%90
1.960	%95
2.576	%99

The parameters of internal friction angle and cohesion have been considered as input variables with normal distribution functions. The number of samples, which is equivalent to the number of computational stages for the assessment, has been estimated to be 15,000 based on Equation (1) and Table (9), with a confidence level of 95%. Various values and parameters that are of interest have been chosen to apply probabilistic analysis using the Monte Carlo simulation method for the entire waste dump, and they are consistent with Table 9.

Table 9. Parameters and values considered for evaluation in probabilistic analysis method.

Parameter		Amount of
Cohesion	Standard deviation	12
	Mean	21
	Relative minimum	15
	Relative maximum	10
	Distribution function	Normal
Internal friction angle	Standard deviation	8
	Mean	27
	Relative minimum	15
	Relative maximum	10
	Distribution function	Normal
Number of repetitions		15000
Type of analysis		Global minimum

6.3. Probabilistic analysis of eastern waste dump of Golgohar Mine No. 4 in Sirjan with addition of bench

Figures 10 to 12 depict the probabilistic modeling of the eastern waste dump of Mine No. 4 in Golgohar, Sirjan, with the addition of the bench using the Bishop, Janbu, and Spencer methods.

The results obtained from the Monte Carlo probabilistic analysis are described below:

- **Deterministic safety factor**

The deterministic safety factor is the same as the safety factor estimated for the minimum sliding surface in regular (non-probabilistic) assessment. The deterministic safety factor is a value obtained when all input data are exactly equal to their mean values [21].

- **Mean safety factor**

The mean safety factor is the average safety factor calculated from the probabilistic analysis. Generally, as the number of iterations in the simulation becomes large, the mean safety factor approaches the deterministic safety factor [21].

- **Probability of failure**

According to Equation (2), the probability of failure is simply equal to the number of assessments with safety factors less than one, divided by the total number of simulations [21].

$$PF = \frac{\text{number of breaks}}{\text{number of samples}} \times 100\% \qquad (2)$$

- **Reliability index**

The reliability index is also one of the common factors that is assessed after probabilistic analysis. This index is defined as a characteristic representing the number of standard deviations between the average safety factor and the critical safety factor. The reliability index can be estimated for both normal and log-normal distributions of safety factor results. Assuming that the distribution function of the safety factor is normal, this index is calculated using Equation (3) [21]. A negative value of the reliability index indicates that the safety factor is less than one, and when the reliability index is equal to zero, it signifies that the average safety factor is one [22].

$$\beta = \frac{\mu_{FS} - 1}{\sigma_{FS}} \qquad (3)$$

The symbol β represents the reliability index μ_{FS} which is the average safety factor, and σ_{FS} represents the standard deviation of the safety factor.

Figures 13 to 15 depict histograms of the safety factor distribution function calculated from probabilistic analysis of the eastern waste dump of Mine No. 4 by applying the Bishop, Janbu, and Spencer methods with the addition of the bench. According to the figure, the left-hand portion (blue section) of the graph represents the probability of slope failure with a safety factor of less than one.

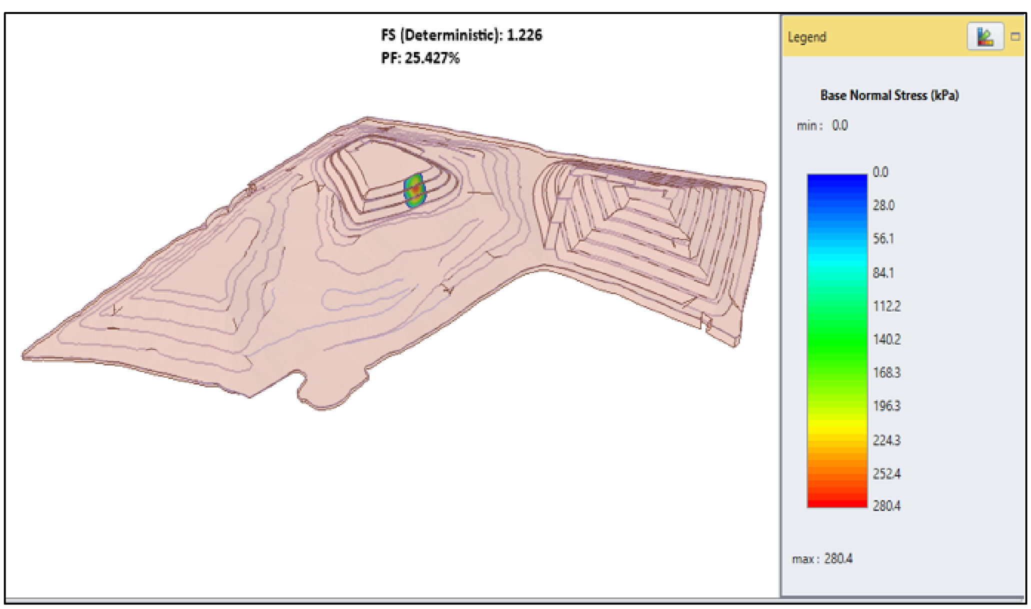


Figure 10. Probabilistic modeling of eastern waste dump of Mine No. 4 with addition of bench using the Bishop method.

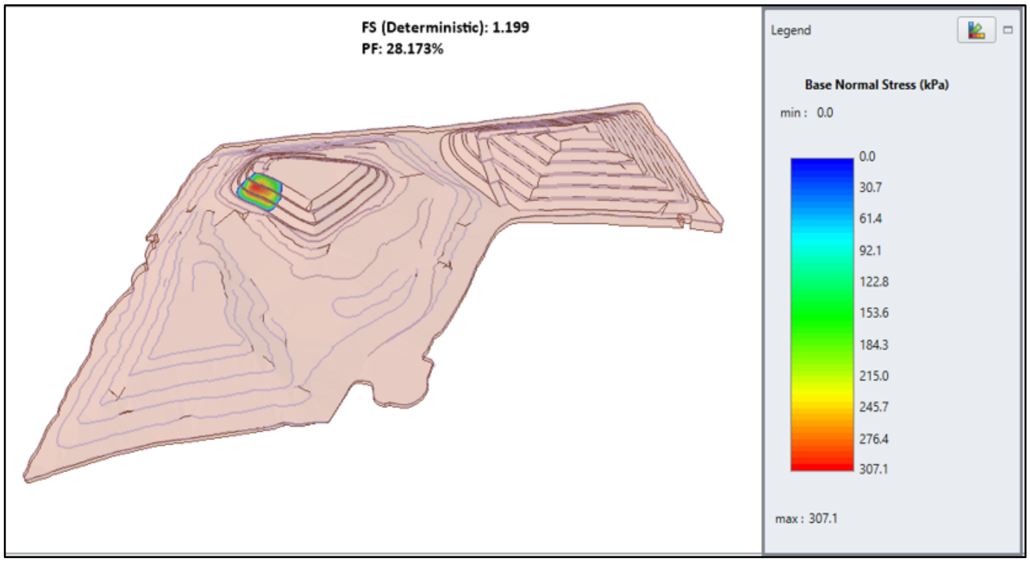


Figure 11. Probabilistic modeling of eastern waste dump of Mine No. 4 with addition of bench using Janbu method.

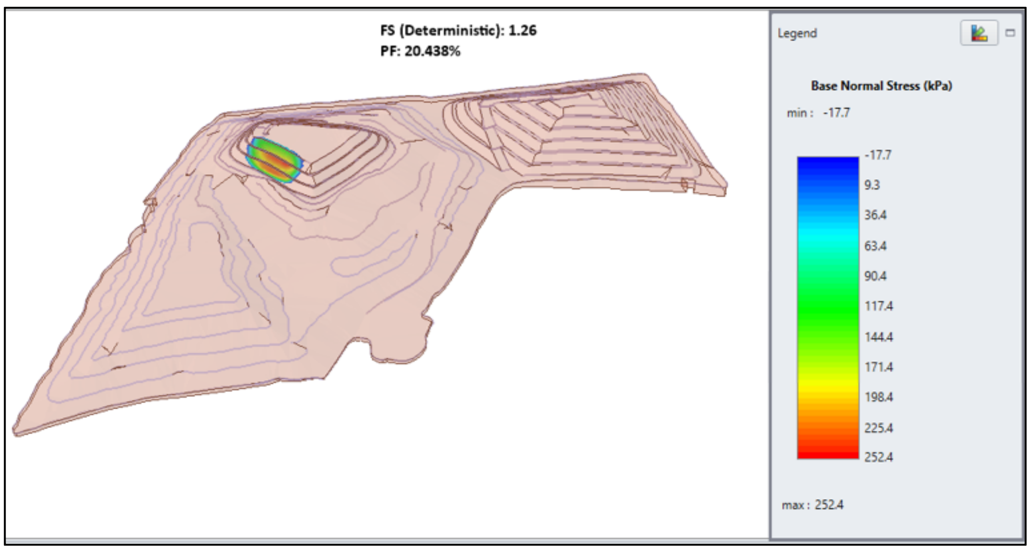


Figure 12. Probabilistic modeling of eastern waste dump of Mine No. 4 with addition of the bench using Spencer method.

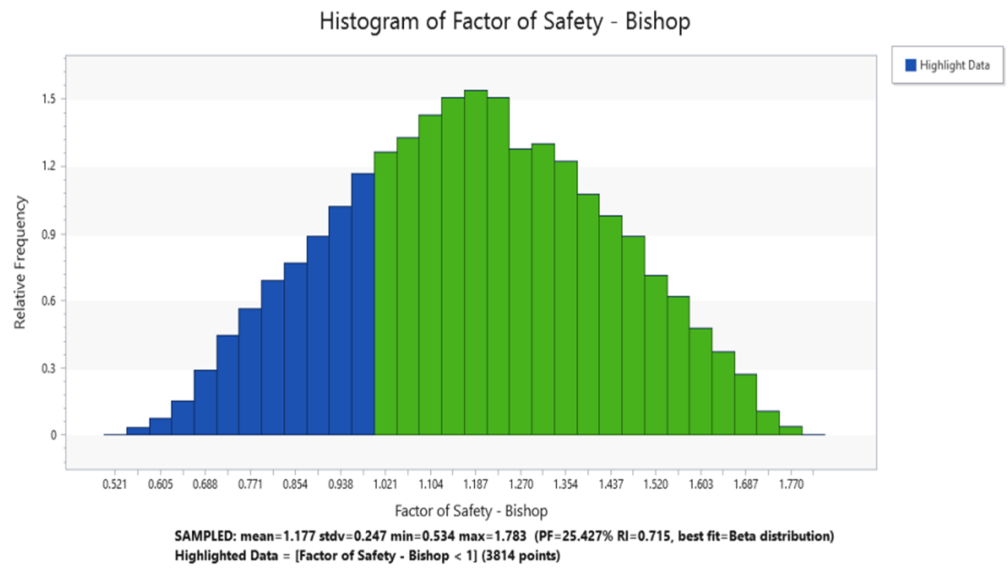


Figure 13. Graph represents probabilistic distribution function of safety factor for eastern waste dump of Mine 4 using the Bishop method with addition of bench.

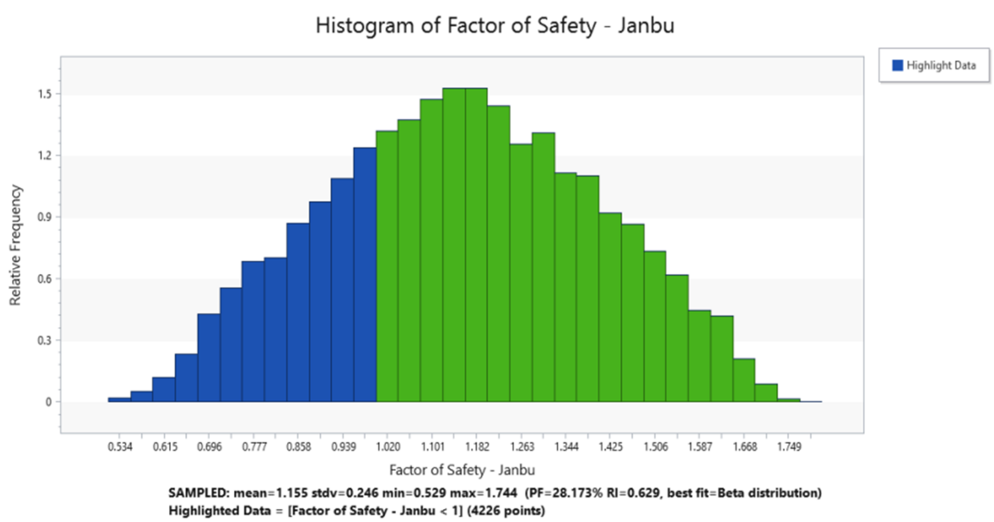


Figure 14. Graph represents probabilistic distribution function of safety factor for eastern waste dump of Mine 4 using Janbu method with addition of bench.

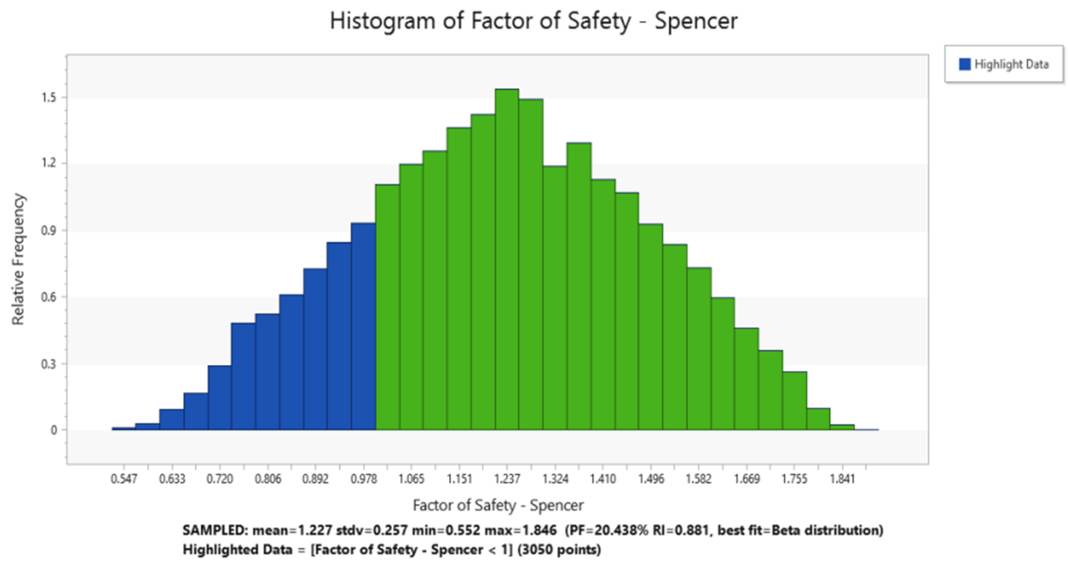


Figure 15. Graph represents probabilistic distribution function of safety factor for eastern waste dump of Mine 4 using Spencer method with addition of bench.

The probability of failure of the waste dump can be calculated using the cumulative probability of failure curve. Figures 16 to 18 illustrate the cumulative probability of failure curves obtained from probabilistic analysis of the eastern waste dump of Mine 4 using the Bishop, Janbu, and Spencer methods with the addition of the bench.

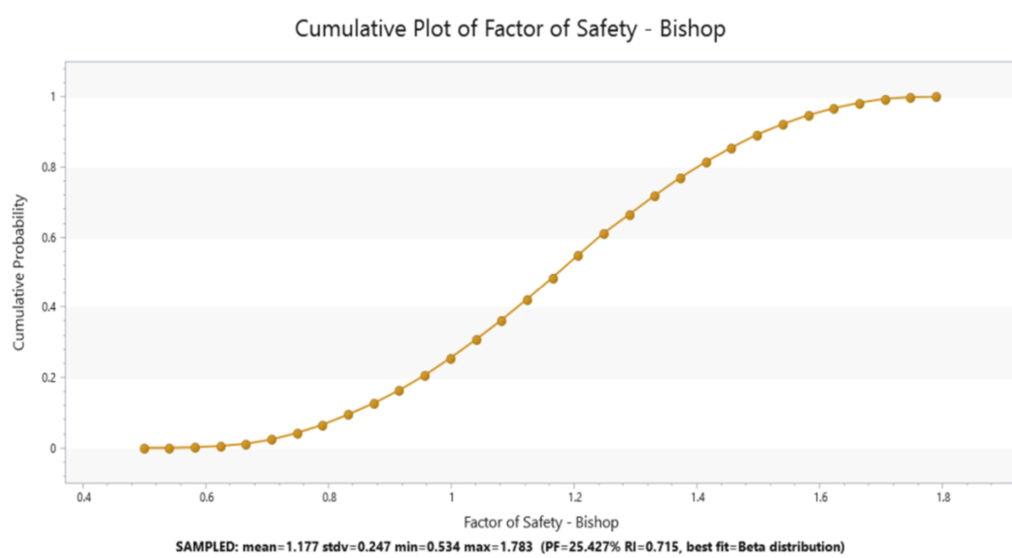


Figure 16. Graph depicts cumulative probability of failure curve for eastern waste dump of Mine 4 using Bishop method with addition of bench.

Based on Figure 16, at a safety factor of 1, the cumulative probability is 0.25427 or equivalently 25.427%. This value corresponds to the probability of failure parameter.

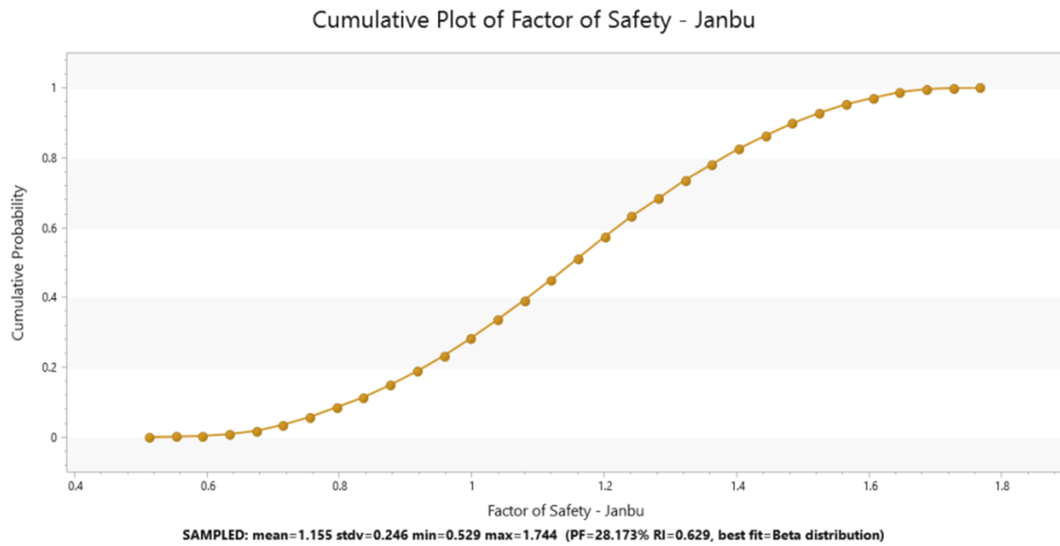


Figure 17. Graph depicts cumulative probability of failure curve for eastern waste dump of Mine 4 using Janbu method with addition of bench.

Based on Figure 17, at a safety factor of 1, the cumulative probability is 0.28173 or equivalently 28.173%. This value corresponds to the probability of failure parameter.

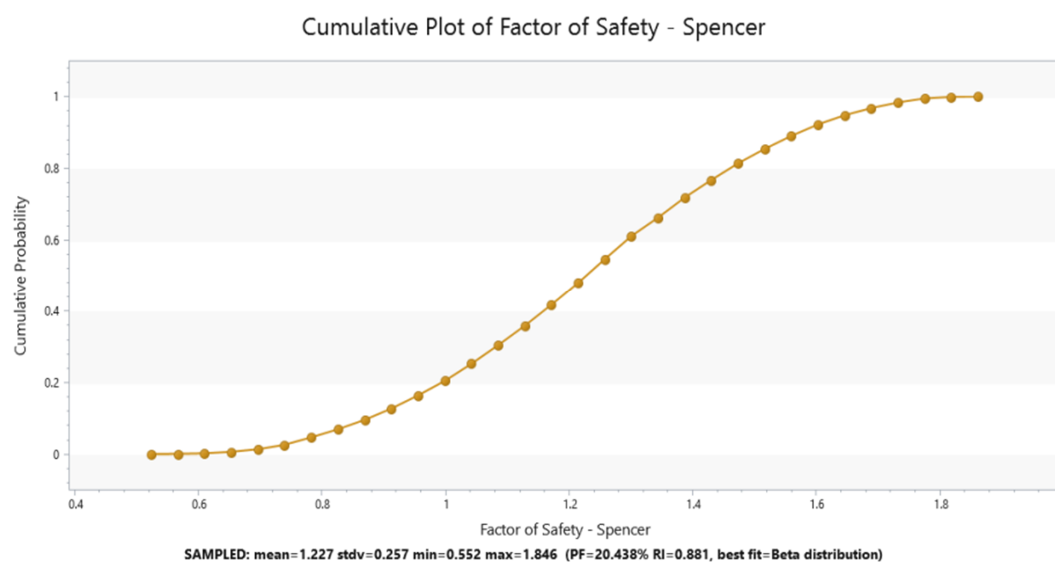


Figure 18. Graph depicts cumulative probability of failure curve for eastern waste dump of Mine 4 using Spencer method with addition of bench.

Based on Figure 18, at a safety factor of 1, the cumulative probability is 0.20438 or equivalently 20.438%. This value corresponds to the probability of failure parameter.

The final results obtained from probabilistic analysis for the eastern waste dump of Mine 4 with the addition of the bench using the Monte Carlo simulation method, as well as the analytical method, along with the Spencer, Janbu, and Bishop methods, presented in Table 10.

Table 10. Results obtained from probabilistic analysis of eastern waste dump of mine with addition of bench.

Eastern waste dump of Mine 4	Calculated parameter	Calculation method		
		Bishop	**Janbu**	**Spencer**
Eastern waste dump of Mine 4 with the addition of benches	Definite safety factor	1.226	1.199	1.26
	Mean safety factor	1.177	1.155	1.227
	Probability of failure (%)	25.427	28.173	20.438
	Reliability index	0.715	0.629	0.881
	Type of distribution function	Normal	Normal	Normal

Considering the potential variability in soil and rock characteristics within certain sections of the eastern waste dump of Mine 4, it was deemed necessary in this study to utilize a probabilistic analysis method for assessing the stability of the eastern waste dump. Given Table 11, the deterministic safety factor and the average safety factor for the stability of the eastern waste dump were computed using the Bishop, Janbu, and Spencer methods. These values are closely similar to each other, indicating that the input parameters of density, cohesion, and internal friction angle have been relatively accurate for analyzing the stability of the eastern waste dump.

7. Conclusions

The stability assessment of the waste dump of Mine No. 4 at Golgohar, Sirjan, has gained significant attention due to recent concerns arising from the limited available for waste disposal. The stability analysis of the eastern waste dump of Mine No. 4 at Golgohar, Sirjan, has been conducted by the addition of the bench and without considering groundwater conditions and seismic loads. The three-dimensional limit equilibrium method has been utilized to determine the stable slope for the waste dump. Based on the results obtained from the evaluations, the safety factor of the eastern waste dump of Mine No. 4, with the addition of the bench, using the Spencer, Janbu, and Bishop methods, is 1.26, 1.199, and 1.226, respectively.

Probabilistic analysis of the stability of the eastern waste dump of Mine No. 4, with the addition of the bench has been conducted using the Monte Carlo method through the Slide3D software. The objective of employing the probabilistic approach is to provide an estimation of the probability of slope failure for the waste dump and to compare it with the actual values.

Mine number 4 needs to extract 983.58 million tons of waste to produce 73 million tons of iron ore. By adding 7 benches in sections A and B, approximately 81 million tons of waste can be dumped. About 555 million tons of waste remain for waste disposal. Considering the remaining waste volume, space must be allocated for waste disposal at mine number 4.

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تحلیل پایداری انباشت باطله معدن 4 گل‌گهر سیرجان به‌منظور افزایش حجم انباشت باطله

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چکیده:

پایداری انباشت باطله معدن مسئله مهم و گاهی بحرانی در توسعه معادن سطحی است. معدن شماره 4 گل‌گهر سیرجان به علت کمبود فضای کافی برای تخلیه باطله و مشکلات زیست‌محیطی و سایر عوامل امکان ایجاد انباشت باطله جدید را ندارد، باتوجه‌به محدودیت‌های موجود معدن به بررسی افزایش حجم با اضافه‌کردن پله پرداخته شده است. در این تحقیق برای پایداری انباشت باطله از روش تعادل حدی با نرم‌افزار Slide3D و با روش شبیه سازی مونت‌کارلو برای تعیین تحلیل احتمالاتی استفاده گردید و نتایج آن‌ها با هم مقایسه شده‌اند. ضریب ایمنی مورد قبول در این ارزیابی 1/2-1/15 مدنظر گرفته شده است. با اضافه‌کردن پله در انباشت باطله شرقی معدن ظرفیتی معادل 36/715/565 مترمکعب نابرجا اضافه شده است. مدل ساخته شده از توپو گرافی منطقه دارای طول 1850متر، عرض1750متر و ارتفاع160متر می‌باشد که نتایج حاصل نشان می‌دهد ضریب ایمنی انباشت باطله معدن با سه روش اسپنسر، جانبو و بیشاپ به ترتیب 1/26، 1/199 و 1/226 است معدن شماره 4 برای تولید 73 میلیون تن سنگ‌آهن نیاز به 983/58 میلیون تن باطله برداری بوده، در مجموع با تخلیه‌کردن 428 میلیون تن باطله در انباشت شمال شرقی و شرقی با اضافه‌کردن پله به میزان 555/571 میلیون تن باطله معادل 312/821 میلیون مترمکعب حجم نابرجا برای دفع باطله باقیمانده است، باتوجه‌به حجم باقیمانده باطله معدن باید فضای را برای دفع باطله به معدن شماره 4 تحویل داده شود.

کلمات کلیدی: پایداری انباشت باطله، روش تعادل حدی، نرم‌افزار Slide3D،روش شبیه‌سازی مونت‌کارلو، معدن گل‌گهر سیرجان.