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OPEN PIT SLOPE STABILITY ANALYSIS IN SOFT ROCK FORMATIONS AT THAR COALFIELD PAKISTAN

Slope Stability Analysis is one of the main aspects of Open-pit mine planning because the calculations regarding the stability of slopes are necessary to assess the stability of the open pit slopes together with the financial feasibility of the mining operations. This study was conducted to analyse the effect of groundwater on the shear strength properties of soft rock formations and determine the optimum overall slope angle for an open pit coal mine at Thar Coalfield, Pakistan. Computer modelling and analysis of the slope models were performed using *Slide* (v. 5.0) and *Phase2* (v. 6.0) software. Integrated use of Limit Equilibrium based Probabilistic (LE-P) analysis and Finite Element Method (FEM) based shear strength reduction analysis was performed to determine the safe overall slope angle against circular failure. Several pit slope models were developed at different overall slope angles and pore-water pressure ratio (Ru) coefficients. Each model was initially analysed under dry conditions and then by incorporating the effect of pore-water pressure coefficients of Ru = 0.1, 0.2, and 0.3 (partially saturated); finally, the strata were considered to be fully saturated. It was concluded that at an overall slope angle of 29 degrees, the overall slope will remain stable under dry and saturated conditions for a critical safety factor of 1.3.

Keywords: Open Pit Slope Stability; Pore Water Pressure Coefficient; Overall Slope Angle; Thar Coalfield; Soft Sedimentary Rocks; Computer Modelling

1. Introduction

Mining involves risks, especially in the design of pit slopes [1]. Open pit slope design is essential for successful mining operation as the mining depths of open pits are continuously

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increasing [2]. Safety of the excavated slopes is a primary component of every open pit mine, and the design of safe slopes for an open pit mine requires extensive planning [3]. Slope stability calculations are necessary to analyse the stability of the excavated slopes along with the economic feasibility of the mining project. The primary phase of Slope Stability Studies is to define the overall slope angle (OSA) that remains safe over the entire working life of the pit and governs the optimal final contour of the pit [4]. This research work is centred on the stability assessment of open-pit coal mine slopes at Thar Coalfield, Pakistan. The rock layers overlying and interbedding the coal seams at Thar Coalfield have low strength values. Therefore, the slope design in these soft sedimentary rocks is crucial to ensure the stability of slopes.

The quantitative parameter for slope stability assessment is the Factor of Safety (FOS), which is the ratio of soil/rock resistance force to the sliding force. The resisting and sliding forces are both a function of the Geomechanical properties of the rockmass and the overall slope geometry [5]. The allowable guidelines for the safety factor for open pit slopes were proposed by [6] and are presented in Table 1.

TABLE 1

Allowable FOS guideline [6]

Slope Description	Acceptable Safety Factor	Consequence of Failure
Bench Slope; small bench (<50 m), temporary slopes, not adjacent to haulage roads	1.3	Not serious
Any slope of a permanent or semi-permanent nature	1.6	Moderately serious
Medium-sized (50-100 m) and high slopes (<150 m) carrying major haulage roads or underlying permanent mine installations	2.0	Very serious

Several research studies have been carried out to assess the slope stability in open pit mines. Studies have been conducted by a wide range of field engineers and researchers for both practical as well as academic purposes. Halatchev and Gabeva used the Monte-Carlo simulation technique to investigate the impact of seismic forces on the stability of slopes. The Geomechanical properties of the rockmass and hydraulic conductivity of the formations were also incorporated into this probabilistic model [7]. Sullivan studied the effect of water over slope deformations. The open-pit hydrogeology was discussed in relation to the pore-water pressures and their significance in slope design [8]. Yang et al. also investigated the influence of water on slopes, considering the deformations within the rockmass and partial pore-water pressures [9].

Pathan et al. [10] conducted rock and soil mechanic investigations in block VIII at the Thar coalfield and concluded that most of the strata are mainly composed of sand with an average content of 67.68 %. The laboratory study on rock and soil samples from drill hole GT-01 revealed that the strata in block VIII are very weak. The average uniaxial compressive strength (UCS) value is 3.59 MPa, average tensile strength value is 0.68 MPa, average young's modulus value is 0.234 GPa, and average cohesion is 129.19 kPa, and average friction angle is 55.47 degrees. Slope stability analysis, based on the probabilistic approach, was carried out using *Slide* software. The possibility of failure was investigated for the slopes in an open pit coal mine, block-VIII, Thar coalfield and it was found that the probability of failure was zero percent at a slope angle of 17 degrees [10].

The probability of failure of a cohesive slope using both simple and more advanced probabilistic analysis tools was investigated by Griffiths and Fenton [11]. The influence of local averaging on the probability of failure of a test problem was thoroughly investigated. In this simple approach, the classical slope stability analysis techniques were used, and the shear strength was treated as a single random variable. Stacey et al. [12] conducted a numerical stress analysis approach to assess the stability of slopes. The stress analysis was performed as a two-dimensional stress analysis for 400-1200 metres of the pit depth, incorporating the effect of in situ stresses at various Poisson's ratios.

Carranza [13] conducted an analysis to determine the optimum slope angle of a future mining site based on both limit equilibrium and elastoplastic continuum approaches. Popescu et al. [14] discussed the hazards related to slope instability and highlighted the potential risks associated with slope failure. The effectiveness of the probabilistic approach for stability analysis of slopes was presented as a case study.

An effective dewatering scheme for an open pit coal mine at Thar Coalfield was proposed by Singh et al. [15] in which a simplified rockmass dewatering system was to be installed along the perimeter of a future mine. A computer model was developed using *Slide* Software against the planar and circular modes of slope failure at varying slope angles. For Planar failure, the study concluded that slopes with an OSA of 28 degrees are safe at a safety factor of less than or equal to 1.3. The analysis of the slope models developed against the circular failure revealed that a Dune sand formation with an average thickness of 48 meters is safe and stable at an OSA of 23 degrees for a safety factor of 1.3. The strata underlying the Dune sand formation are also found to be safe at an OSA of less than or equal to 26 degrees for a safety factor of 1.3.

Hammah et al. [16] focused on comparative analysis to compute the probability of failure for slopes by using numerical methods such as the Finite Element Method (FEM) and Shear Strength Reduction (SSR) and statistical simulations such as the Point Estimate Method (PEM) and Monte Carlo Simulations. The conclusions revealed that the numerical analysis is relatively complex compared to statistical methods for estimating the probability of failure of slopes. El-Ramly et al. [17] investigated the Shek Kip Mei cut slope failure in Hong Kong, using a Monte Carlo-based Probabilistic approach and @Risk computer software. Based on a probabilistic back-analysis of the failure, the slope was regraded to a lower angle.

Eberhardt et al. [18] discussed the potential mechanisms of slope failures by rock slope stability assessment based on advanced computer-based techniques for the conventional and numerical methods. Daiatana et al. [19] illustrated "how a deterministic slope stability package can be made into a probabilistic software package or used in a probabilistic manner". In addition, the probability distribution of the safety factor was obtained for a specific slip surface.

Literature confirms that the groundwater affects the stability of the open pit slopes. Therefore, the effect of regional hydrogeology on the stability of the slopes must be taken into consideration while determining the optimum Overall Slope Angle. To address this, the study is focused on the computer modelling and stability analysis of open pit slopes against circular failure in open pit coal mines at Thar Coalfield, Pakistan, incorporating the groundwater conditions. This study integrates the effect of groundwater at various pore-water pressure coefficients on the stability of the excavated slopes against circular failure using computer modelling. Groundwater entrapped within the interstices of the geomaterials exerts pressure on the walls (inner-surfaces) of the interstices, which is known as Pore-water pressure (PWP). The pore-water pressure ratio coefficient (Ru coefficient) expresses the pore-water pressure as a fraction of the vertical earth pressure. The Ru coefficient values range from zero (minimum) to 1 (maximum). A minimum Ru value (Ru = 0) indicates that the formation is dry, having no groundwater and a maximum Ru value (Ru = 1) indicates that the formation is fully saturated.

2. Study Area

2.1. Location, Stratigraphic and Lithological description of Thar Coalfield

Thar Coalfield is situated approximately 400 kilometres east of Karachi, Sindh Province, Pakistan [20]. Thar Coalfield, with estimated total reserves of 175.6 billion tons of Lignite Coal, is spread over an area of approximately 9000 square kilometres. The coal seams are deposited at depths between 130 and 250 metres [21]. Fig. 1 presents the location of Thar coalfield and distribution of coalfield into 13 blocks and features the location of the studied area, i.e., Block-IX Thar Coalfield, Pakistan [22].

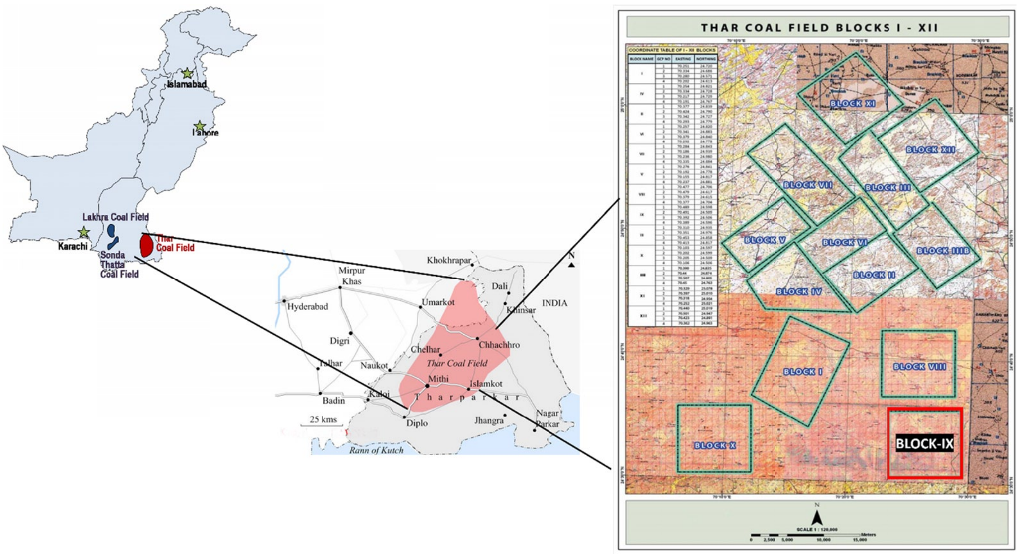


Fig. 1. Location of Thar Coalfield and block wise distribution of Coalfield (TCEB, 2020)

Thar Coalfield was first discovered in 1994 by the Geological Survey of Pakistan (GSP) and the United States Geological Survey (USGS) under the Coal Resources Exploration & Assessment Program (COALREAP) [15]. The coal-bearing formation at Thar is the Bara formation, where the coal deposition is estimated to be from the Paleocene/Eocene era (Fig. 2) [23].

In the Coalfield region, the basement Granite is an unconformity overlain by sediments of Paleocene to Eocene tertiary age Bara Formation (the coal-bearing formation). The lignite coal seams are deposited in this formation. These Coal seams are bounded by the top and bottom

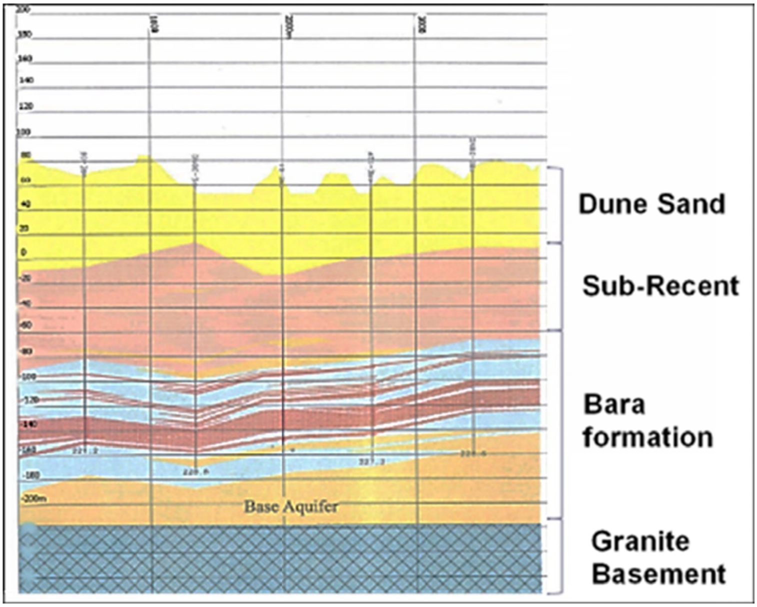


Fig. 2. Stratigraphic Section of the Thar Coalfield Region (RWE, 2004)

aquifers. The Sub-Recent formation rests unconformity on the sediments of the Bara Formation. The stratigraphic column is topped by the Recent Formation Dune Sand. The average thickness of the coal-bearing formation is about 95 metres, composed of siltstone, claystone, and alluvial formation sandstone, which covers a basement granite formation deposited at approximately 100 to 220 metres depth. In the Thar coalfield, the rock formation overlying the coal beds has low compressive strength and is loosely consolidated [10]. Due to the low compressive strength, the rocks overlying, and underlying coal formation are regarded as "soft sedimentary formations". The Top, Middle and Bottom Aquifer Sand layers are present within all three Formations. These Aquifer Sand layers consist of silty to coarse sand with partly substantial fractions of fine gravel matrix with more or less the amount of kaolinite clay. The stratigraphic and lithologic scenario at the Thar Coalfield indicates that the instabilities are likely to be circular in nature and controlled by the significantly weak rock mass strength rather than structures [15].

2.2. Hydrogeological description of Thar Coalfield

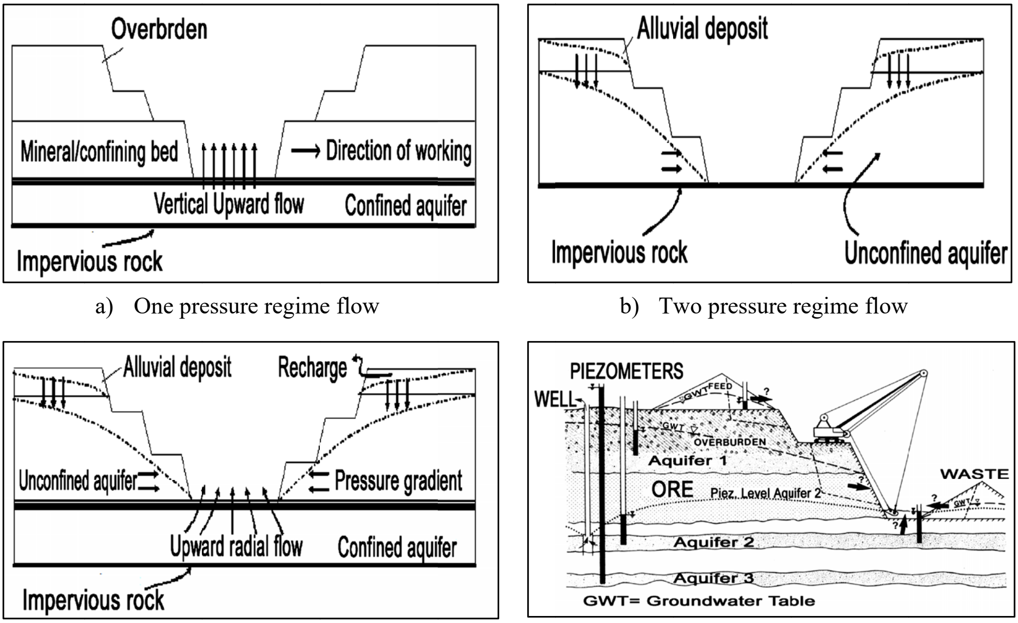
Thar Coalfield hosts three major aquifers [24]. These aquifers are classified based on their depth of occurrence from the surface (topsoil) as follows:

i) Top Aquifer (TA) – Located near the dune sand base having a permeability coefficient of 3×10^{-7} m/sec. This aquifer extends across the Thar region. In the coalfield region, this aquifer has a water head of about 5 metres. Above 10-12 metres from the mean sea level lies the water-table of the top aquifer [25].
ii) Middle Aquifer (MA) – This aquifer is spread in scattered water bodies within the Sub-Recent and Bara formations. The coefficient of permeability for the middle aquifer is

estimated to be ranging between 10^{-5} to 10^{-7} m/sec. The water-table of the middle aquifer varies between 10 to 20 metres above the mean sea level.

iii) Bottom Aquifer (BA) – It is the most predominant of the other two aquifers due to its permeability, lateral extension and its thickness (i.e. about 50 to 60 metres) [25]. The bottom aquifer is located in close proximity to the base of the bottom coal seam, extending down to the basement granite layer. The bottom aquifer is identified to be an artesian type aquifer having 25 metres of the piezometric head above the mean sea level [24].

It is necessary to assess the effect of groundwater and pore-water pressure on the stability of the slopes in open pit mines at Thar Coalfield. Singh et al. [26] suggested the possible common sources of groundwater inflow towards the pit, as shown in Fig. 3.



a) One pressure regime flow

b) Two pressure regime flow

c) Three pressure regime flow

d) Four pressure regime flow

Fig. 3. Different possible groundwater flow regimes in open pit mine at Thar

3. Materials and Methods

The experimental work of this research study was performed as per the methods suggested by the International Society for Rock Mechanics [27] and the American Society for Testing and Materials [28]. The core samples from Borehole KTN-GT-01 and KTN-GT-02 of Block-IX taken from the Thar Coalfield were used. The core samples were acquired, preserved, and tested in As-Received condition. The core samples were well preserved until tested to retain the natural moisture content of the rock/soil. The total number of samples was one hundred and twenty-three, tested for determination of the rock properties.

3.1. Sample Preparation

The samples for the Direct Shear Test were prepared in the Rock Mechanics Laboratory, the Department of Mining Engineering of the Mehran University of Engineering and Technology. The core pieces selected for the sample preparation were of sufficient length so that every piece could be cut into at least four sample discs. As the approximate diameter of the core samples is 64 mm to maintain the suggested (standard for Direct Shear Test) thickness to diameter ratio of 0.5:1, the disc samples with a thickness of 32 mm were cut. The samples prepared for laboratory investigation are shown in Fig. 4.

Fig. 4. Some of the samples prepared for the laboratory investigation

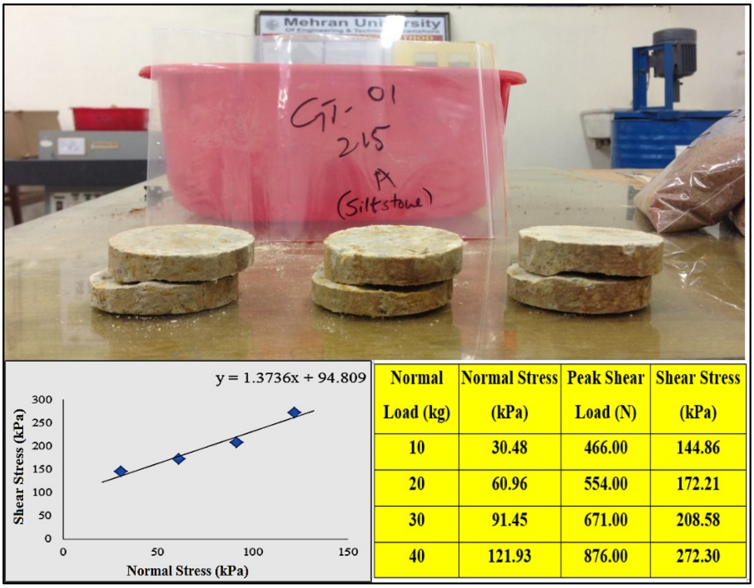
3.2. Density Determination

Non-destructive tests are commonly performed before the destructive ones. Hence the density was determined before the samples were tested under direct shear. Density was calculated by ISRM's suggested standard calliper technique [27].

3.3. Direct Shear Test

The direct shear test was performed using the Laboratory Direct Shear Testing Machine (Model T-665/N), following ASTM D5607–16 for rock samples [29] and ASTM D3080–04 for soil samples [30]. The area of the rock core specimen having a 64 mm (0.064 m) diameter was calculated as 0.003217 m^2. However, the area for soil samples was calculated using the inner dimensions of the shear box, i.e., 60*60 mm^2 equivalent to 0.0036 m^2. A series of tests for various rock and soil samples were performed at normal loads of 10, 20, 30 and 40 kg, equivalent to normal stress values of 30.48, 60.96, 91.45 and 121.93 kPa, respectively for rock samples. For soil samples, however, the normal stress values were 27.24, 54.48, 81.72 and 108.96 kPa at normal loads of 10, 20, 30, and 40 kgs, respectively. The rate of shear displacement was 0.2 mm/min under constant normal stress. The test was stopped after the peak shear stress value was achieved.

The peak shear stress value was achieved between displacement ranges of 8 to 10 percent of the specimen's original dimensions. The relationship between normal stress and peak shear stress is established using Microsoft Excel 2010. The Cohesion and internal angle of friction were calculated from Mohr-Coulomb's shear strength envelope. Fig. 5 shows a Siltstone sample that failed under direct shear and corresponding Mohr-Coulomb envelope.



Normal Load (kg)	Normal Stress (kPa)	Peak Shear Load (N)	Shear Stress (kPa)
10	30.48	466.00	144.86
20	60.96	554.00	172.21
30	91.45	671.00	208.58
40	121.93	876.00	272.30

Fig. 5. A Sample of Siltstone failed under Direct Shear and its strength envelope

Average values of each parameter (i.e., cohesion, phi, and unit weight) were determined, and the summarised results from the density and direct shear tests are presented in Table 2, along with other geotechnical properties. For the development of slope models, the cohesion, friction angle and unit weight parameters were used as material properties input.

TABLE 2

Geotechnical properties of soil and rock units

Rock Type	UCS (MPa)	ITS (MPa)	PLS (MPa)	C (kPa)	φ (degrees)	γ (kN/m^3)
1	2	3	4	5	6	7
Dune Sand	0.512	0.221	0.026	14.6	40.88	17.34
Sandstone	0.616	0.244	0.04	97.68	45.56	18.45
Siltstone-1	1.326	0.301	0.055	33.28	27.83	16.52
Claystone-1	0.641	0.231	0.032	323.43	58.96	17.29
Siltstone-2	2.052	0.511	0.16	150.56	60.17	20.93
Aquifer Sand-1	0.395	0.194	0.02	18.32	39.6	17.3
Siltstone-3	2.01	0.398	0.09	235.16	47.57	19.06

TABLE 2. Continued

1	2	3	4	5	6	7
Claystone-2	2.24	0.41	0.066	215.21	54.55	19.54
Lignite-1	1.429	0.311	0.043	148.02	50.53	9.86
Claystone-3	1.845	0.321	0.062	340.28	56.33	22.3
Aquifer Sand-2	0.216	0.191	0.022	23.73	31.62	17.82
Lignite-2	2.235	0.403	0.068	133.9	40.14	11.36
Claystone-4	1.104	0.297	0.039	172.1	56.09	19.56
Weathered Granite	—	—	—	277.8	50.5	19.2

UCS = Uniaxial compressive strength, ITS = Indirect Tensile Strength, PLS = Point Load Strength, C = Cohesion, φ = Angle of Internal Friction, γ = Unit Weight

3.4. Simplified Lithological Section

For the development of the computer models and to execute the stability analysis, the obtainable lithology of the area was simplified, as shown in the simplified lithological section (Table 3).

Lithologically, the overall strata is grouped into 7 major units:

1) Dune Sand (Top Aquifer) and alluvial Sandstone of the Recent Formation.
2) Siltstone & Claystone of the Sub-Recent Formation.
3) Aquifer Sand (Middle Aquifer) of the Sub-Recent Formation.
4) Hanging wall Claystone and Aquifer Sand of the Bara Formation.
5) Lignite coal seams of the Bara Formation.
6) Footwall Claystone and interbedded Aquifer Sand (Bottom Aquifer) of the Bara Formation.
7) Basement Granite.

TABLE 3

Simplified lithological section of Block IX (Ref. Drillholes KTN-GT-01 and KTN-GT-02)

Formation	**Simplified Lithology**	**Depth**		**Thickness (m)**
		From	**To**	
Recent	Dune Sand	Zero	52.17	52.17
	Sandstone	52.17	55.78	3.61
Subrecent	Siltstone – 1	55.78	61.37	5.59
	Claystone – 1	61.37	68.93	7.56
	Siltstone – 2	68.93	90.50	21.57
	Aquifer Sand – 1	90.50	99.72	9.22
	Siltstone – 3	99.72	140.21	40.49
Bara	Claystone – 2	140.21	177.44	37.23
	Lignite – 1	177.44	188.88	11.44
	Claystone – 3	188.88	195.50	6.62
	Aquifer Sand – 2	195.50	202.64	7.14
	Lignite – 2	202.64	219.63	16.99
	Claystone – 4	219.63	241.60	21.97
	Weathered Granite	241.60	246.74	5.14
				Total Depth = 246.74 m

The simplified lithological section presented above (Table 3) reveals that the overall slope consists of a combination of soil and rock units having intercalated Lignite coal seams. The top layer is wind-blown silty, very fine-grained Dune Sand of Recent Formation. Due to the blend of fine-grained silts and coarse sand grains, the Dune Sand is slightly cohesive in nature. The cohesion values for dune sand range between 0-57 kPa [10]. Near the Dune Sand base lies a saturated formation, forming a thin upper aquifer. As the depth increases, the Dune Sand becomes weakly cemented Sandstone. Some geologists describe this Sandstone layer as a 'compacted sand lens'. Below this is a 70 to 75 m thick sequence of Siltstones and Claystone of Subrecent Formation, near the base of which is an 8 to 10 m thick aquifer sand layer within which is contained the confined middle aquifer. Underlying the Subrecent Formation lies the fine-grained low permeability Bara Formation. This sequence consists of carbonaceous Claystone with intercalation of Lignite seams which increase in thickness with depth. The main (bottom) Lignite seam is formed by a 10 to 20 m thick unit, the base of which forms the pit floor. The immediate footwall underlying the pit floor consists of Claystone intermixed with Aquifer Sand, combinedly forming the bottom aquifer. The bottom Granite complex consisted of highly weathered Granite of the pre-Cambrian age. The overall coal-bearing strata rest upon this structural platform of the pre-Cambrian era. Generally, the strata dip at less than 2° uniformly throughout the study area, suggesting that there are no major off-sets or other large-scale structures. The geological profile of the modelled slope is presented in Fig. 6.

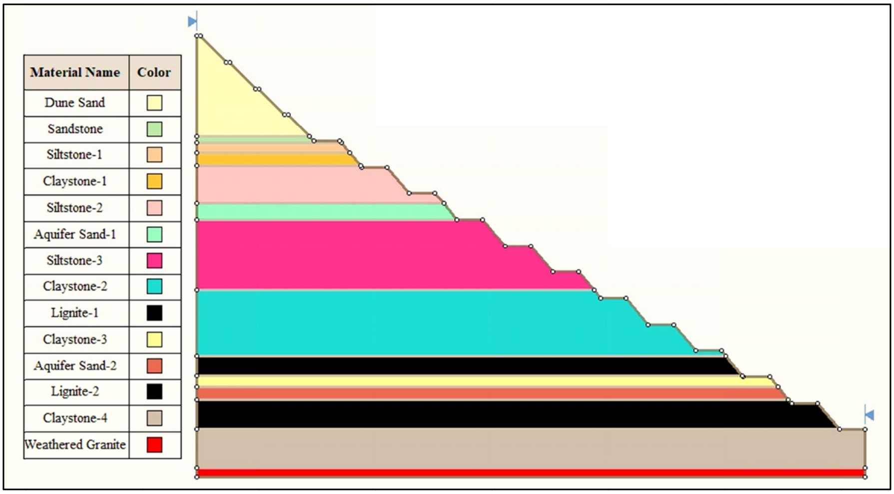


Fig. 6. Geological profile of the modelled slope (reference drillholes KTN-GT-01 and KTN-GT-02)

3.5 Modeling and the Slope Stability Analysis Procedures

The safe overall slope angle is determined by the integrated use of two computer software, i.e., *Slide* (version 5.0) and *Phase2* (version 6.0). The *Slide* software is a limit equilibrium-based slope modelling and stability analysis software which was used for the limit equilibrium-based probabilistic (LE-P) analysis. *Phase2* software is a finite element method (FEM) based software package. Slope models at different OSA and pore-water pressure coefficients were developed using *Slide* software. The probabilistic slope stability analysis using the Monte Carlo simulation feature in *Slide* software was performed to investigate the overall slope failure possibility for an open pit lignite mine at Block-IX, Thar coalfield. The slope geometry, stratigraphy and rock/soil properties were incorporated into the computer models to determine the critical slip surfaces. The number of samples used for the simulation was 1000, and the analysis type was 'overall slope'. The finite element method (FEM) based slope stability analysis is then performed to compute a critical strength reduction factor for each slope model. In FEM, the critical strength reduction factor (SRF) is equivalent to the safety factor of the overall slope [16]. The FEM analysis is performed using *Phase2* software.

Slide software was used for the development of slope models. To develop the computer models for the slope stability analysis, the first step was to set up the limits of the drawing region in which the model will be created. Then project settings were set, and the probabilistic analysis option was selected. The model had two types of boundaries that needed to be added, external boundaries and material boundaries. The next step was to define the random variables, which would be incorporated into the analysis. Four properties, i.e., cohesion, angle of internal friction, unit weight and the pore-water pressure coefficient, were considered random variables in this study. Then the model was saved, and the probabilistic analysis was carried out using *Slide* software. The results of the analysis were obtained by selecting the "Interpret" option.

A total of thirty-five (35) slope model variants were developed at different overall slope angles, as presented in Fig. 7. The mean safety factor (FS), probability of failure (PF) and reliability index (RI) based on normal distribution were determined from the probabilistic analysis. The analysis was carried out for the overall slope. The slope models developed in *Slide* software were then exported to *Phase2* software (version 6.0) for FEM analysis. The FEM analysis was performed for the computation of critical SRF and corresponding maximum total displacement within the slope. This study incorporates three hydrogeological scenarios within the slope models to analyse the stability of the overall slope against circular failure. Each model was developed and analysed for the following groundwater conditions with both analysis techniques, i.e., LE-P and FEM techniques.

- **Dry** – Assumed that the formation is completely dry (hence Ru = 0),
- **Partially Saturated** – formation is assumed to be partially saturated at three different pore-water pressure ratios (Ru = 0.1, 0.2, 0.3),
- **Saturated** – Ground Water Surface / Water-Table Method (Ru = 1) formation is assumed to be fully saturated.

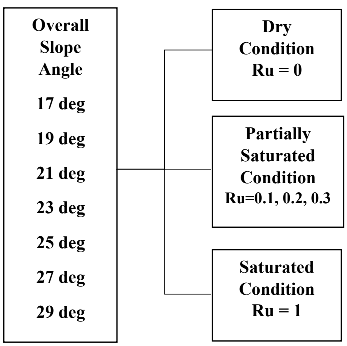


Fig. 7. Overall slope angles analysed under three different groundwater conditions

4. Results and Discussion

The results of the LE-P slope stability analysis based on the global minimum slip surfaces are displayed beside the slip centre dialogue box, as mentioned in Figs 8a and 8b. Global Minimum slip surface is the slip surface having the lowest safety factor out of all the slip surfaces analysed within that particular analysis. Global minimum results include FS (deterministic), FS (mean), PF and RI (normal).

- FS (deterministic) is the safety factor calculated by the Global Minimum slip surface, from the regular (non-probabilistic) slope stability analysis.
- FS (mean) is the mean (average) safety factor obtained from the probabilistic analysis.
- PF is the probability of failure which is simply equal to the number of analyses with a safety factor of less than 1.3, divided by the total number of samples, and it is calculated as follows:

$$PF = \frac{\text{Number of samples failed}}{\text{Total Number of Samples}} \times 100\% \tag{1}$$

- The Reliability Index (RI) is an indicator of the number of standard deviations which separate the mean safety factor from the critical safety factor (i.e., 1.3). Since the normal distribution is used in this probabilistic analysis, therefore the Reliability Index is calculated using equation-2. The recommended Reliability Index is greater than or equal to 3, which indicates a satisfactory pit slope in terms of safety. RI less than 3 shows an unsatisfactory safety level for the pit slope [31].

$$RI = \frac{\mu_{FS} - 1}{\sigma_{FS}} \tag{2}$$

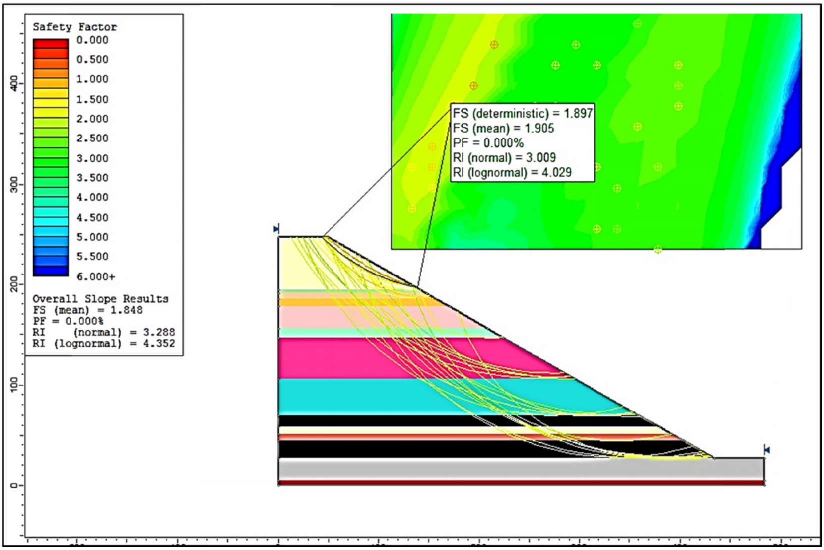


Fig. 8a. Slope Model for dry slope at OSA 29 degrees

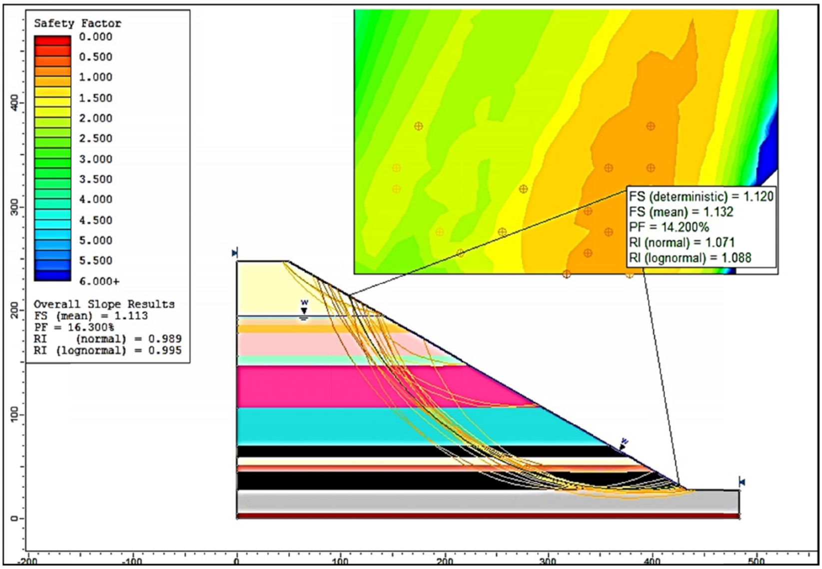


Fig. 8b. Slope Model for fully-saturated slopes at OSA 29 degrees

The FEM analysis determines the shear strength reduction factor (SRF) for slope, which is displayed on the middle-top of the result window, as shown in Fig. 9a. Due to effective stresses, the shear strength properties of the decreasing slope material. As a result of this decrease in shear strength, the shear deformation increases eventually, increasing the total displacement within the slope. This maximum deformation (total displacement) within the slope is plotted versus the SRF for each slope model (Fig. 9b shows an example of such a relationship).

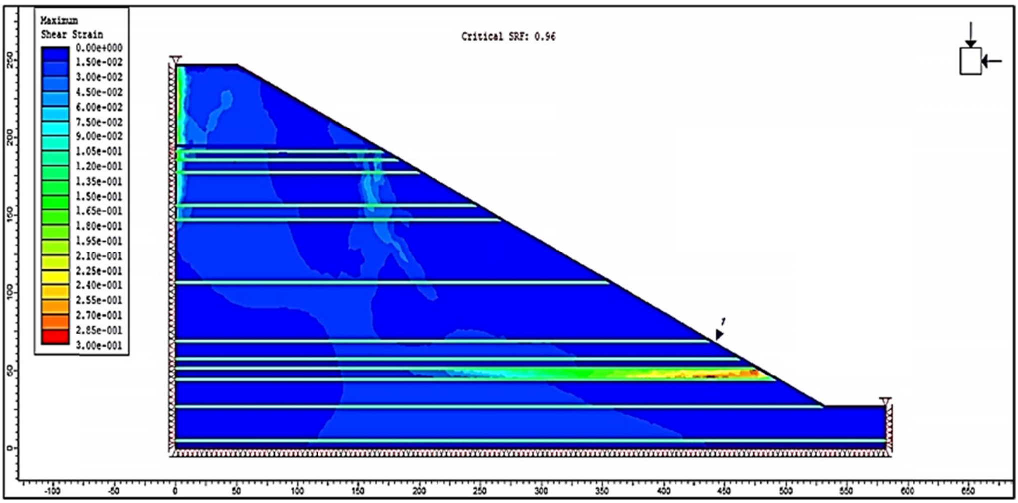


Fig. 9a. FEM analysis of slope model having OSA 23 deg. At Ru = 1

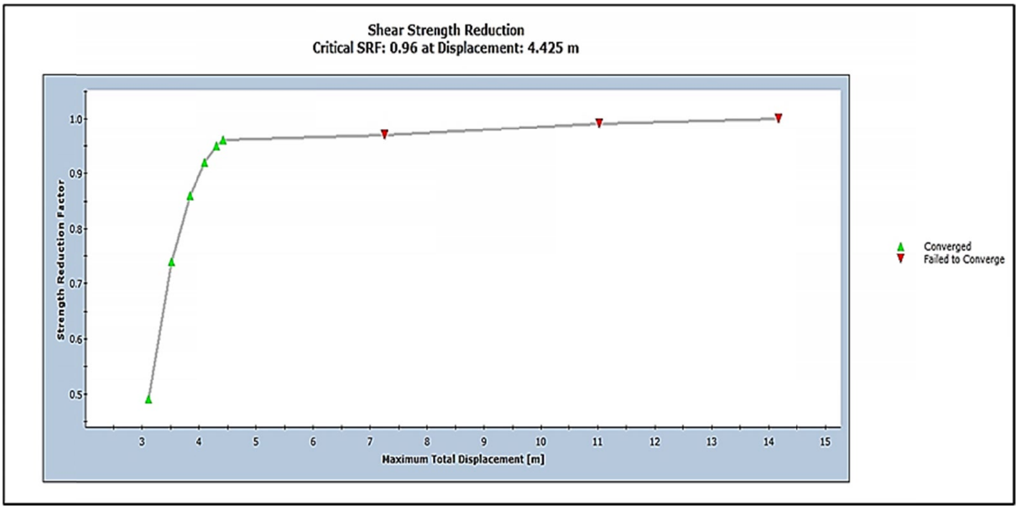


Fig. 9b. Max. Total displacement vs SRF at OSA 23 deg. and Ru = 1

Fig. 9b shows the point where the slope will probably fail, and nodal displacements will rapidly increase. Hence the FEM analysis will not converge. This point marks the non-convergence, and at this stage, the critical SRF is determined. Figs 10a-10e presents the summarised results from Limit Equilibrium Probabilistic (LE-P) and Finite Element Method (FEM) based slope stability analyses. The factor of safety (FOS), shear strength reduction factor (SRF), probability of slope failure (PF) and reliability index (RI) at different overall slope angles are expressed for each groundwater scenario mentioned in Fig. 7.

Table 4 presents the factor of safety (FS) and strength reduction factors (SRF) at various groundwater conditions and overall slope angles. The factor of safety and strength reduction factor values are separately plotted versus overall slope angles to determine the optimum overall slope angle in each case (Figs 11a and 11b).

TABLE 4

FS and SRF values at various overall slope angles

OSA (deg)	Dry		Partially Saturated						Fully Saturated	
	FS	SRF	FS			SRF			FS	SRF
	Ru = 0	Ru = 0	Ru = 0.1	Ru = 0.2	Ru = 0.3	Ru = 0.1	Ru = 0.2	Ru = 0.3	Ru = 1	Ru = 1
17	3.011	3.1	2.884	2.758	2.63	2.95	2.74	2.37	1.999	1.44
19	2.728	2.76	2.61	2.491	2.372	2.66	2.47	2.1	1.75	1.25
21	2.488	2.5	2.379	2.269	2.151	2.4	2.23	1.9	1.555	1.1
23	2.28	2.28	2.204	2.127	2.025	2.21	2.05	1.75	1.396	0.96
25	2.076	2.09	2.075	2.013	1.943	2.01	1.89	1.61	1.249	0.82
27	1.897	1.9	1.889	1.828	1.741	1.82	1.74	1.44	1.12	0.7
29	1.739	1.75	1.738	1.738	1.646	1.7	1.59	1.28	1.004	0.59

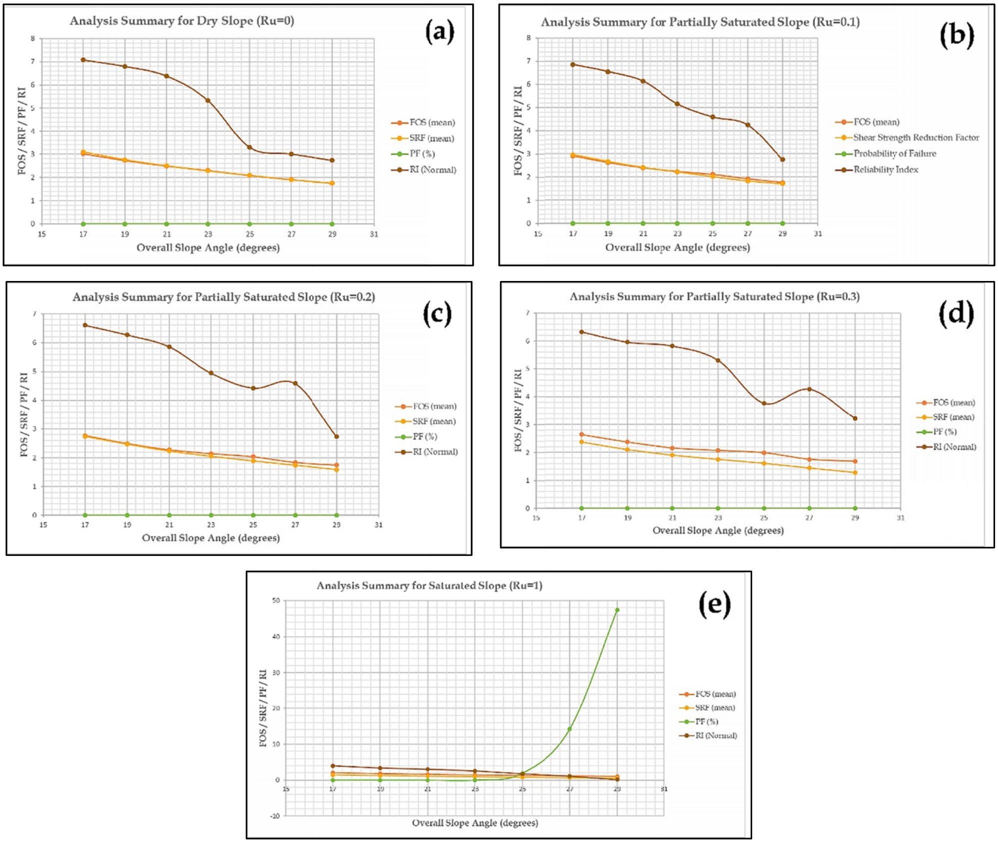


Fig. 10. Summarised results from the LE-P and FEM Slope Stability analyses

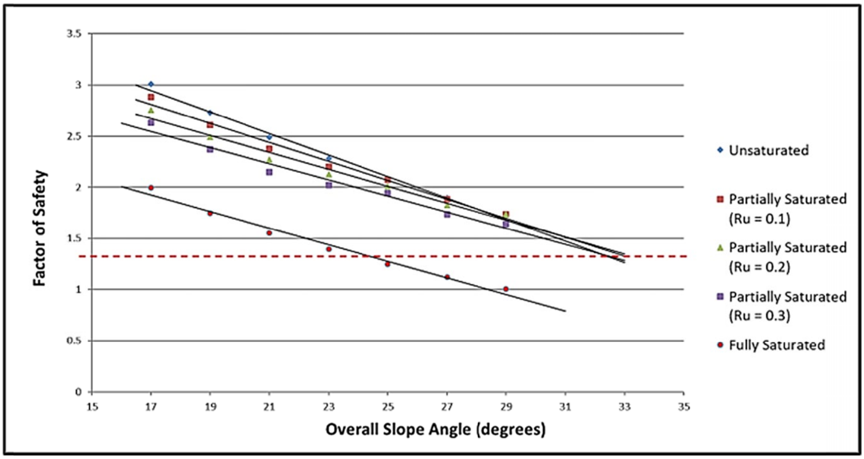


Fig. 11a. Relationship between the Factor of Safety and Overall Slope Angle

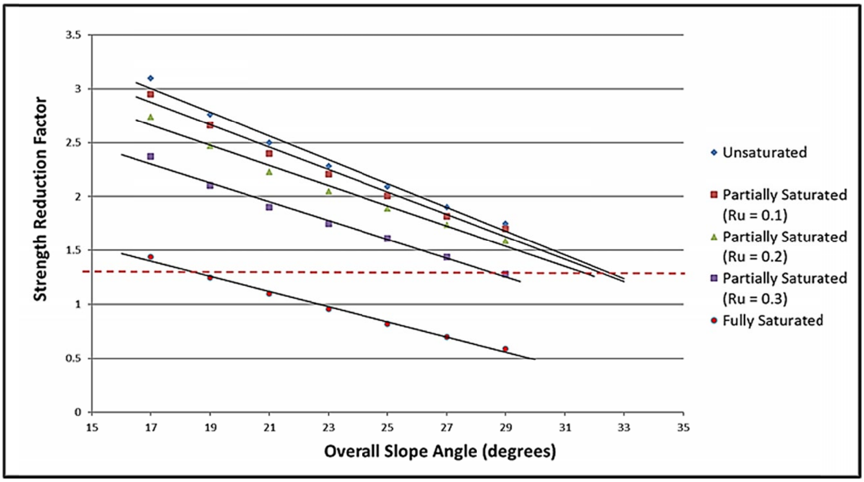


Fig. 11b. Relationship between the Strength Reduction Factor and Overall Slope Angle

5. Conclusions

The mine planning engineers still rely on historical data to set the design criteria and then update them based on their present performance. Stability analysis of open pit slopes involves a higher degree of uncertainty due to the rock behaviour and hydrogeological situation of the strata. Based on three different hydrogeological situations, 35 slope models were developed and analysed in this study. Two different analysis methodologies were used, i.e., limit equilibrium based probabilistic (LE-P) technique and finite element method (FEM) based shear strength reduction technique, to determine the optimum overall slope angle for an open pit coal mine at Thar coalfield. The following conclusions have been made for each hydrogeological scenario:

- For dry strata, LE-P analysis shows that the overall slope angle of 33 degrees will remain stable at a safety factor of 1.3 against circular failure (Fig. 11a). FEM analysis also shows the optimum overall slope angle of approximately 33 degrees to be safe for dry conditions (Fig. 11b).
- Partially saturated formation with a gradual increase in the pore-water pressure ratios (i.e., Ru = 0.1, 0.2 and 0.3) shows a decrease in the stability which can be observed from the orientation of linear trendlines for Ru = 0.1, 0.2 and 0.3 (Figs 11a and 11b). In this case, LE-P analysis suggested a safe OSA of 33 degrees, whereas the FEM analysis recommended that an OSA of 29 would be safe.
- For dry and partially saturated situations, LE-P analysis determined the probability of failure equal to zero and a reliability index of approximately ≥ 3, which justifies the FS values to be reliable.
- Finally, the strata were assumed to be fully saturated and based on LE-P analysis, the optimum OSA is concluded to be 24 degrees. Under fully saturated conditions, the probability of slope failure remains zero for the rest of the slope models, except for the slope models having 25, 27 and 29 degrees, which justifies the suggested optimum OSA of 24 degrees. However, the FEM analysis shows that due to saturated conditions, the SRF

of the formation is greatly influenced, and relatively lower SRF values are obtained. The decrease in SRF values is due to an increase in seepage forces. Therefore, in a fully saturated situation, the FEM analysis indicated an optimum OSA of 19 degrees to be safe.

Practically, this situation (fully saturated) never exists because an effective dewatering system is necessary to be installed by the mining operators to keep the water table below the coal seams. Various techniques have been suggested and implemented practically, and some were presented by [24,25,32]. The top stratum Dune Sand of Recent Formations is considered dry throughout the analysis (i.e., in all three situations). This is due to the location of the top aquifer being below the Recent Formation (Dune Sand) stratum.

Following the conservative design approach and considering the safety of the slope as a priority, this study suggests an overall slope angle of 29 degrees to be safe against circular slope failure.

Recommendations

In this study, only the overall slope angle is considered. Hence it is recommended that this work can be expanded upon to design bench-face slope angles with multiple assumptions. Such as all the benches having constant bench heights or if the situation is different (i.e., all the benches having different heights). The analyses were performed with *Slide* and *Phase2* software which are two-dimensional-based analyses software. These analyses can be carried out using any three-dimensional slope stability analysis software.

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Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

[1] H. Chiwaye, T. Stacey, A comparison of limit equilibrium and numerical modelling approaches to risk analysis for open pit mining. Journal of the Southern African institute of Mining and Metallurgy **110**, 10, 571-580 (2010).

[2] J. Sjöberg, Large scale slope stability in open pit mining: a review. Luleå tekniska universitet, 1996.

[3] K.A. Mahdi Nekouei, Modified stability charts for rock slopes based on the hoek-brown failure criterion. Archives of Mining Sciences **58**, 3, 747-766 (2013). DOI: https://doi.org/10.2478/amsc-2013-0052

[4] J.D.St George, Probabilistic methods applied to slope stability analysis. ResearchSpace@ Auckland, 1991.

[5] M.G. Navid Hosseini, Investigating the slope stability based on uncertainty by using fuzzy possibility theory. Archives of Mining Sciences **59**, 1, 179-188 (2014). DOI: https://doi.org/10.2478/amsc-2014-0013

[6] S. Priest, E. Brown, Probabilistic stability analysis of variable rock slopes. Transactions of the Institution of Mining and Metallurgy, Section A: Mining Industry, IMM **92**, A1-A12 (1983).

[7] R. Halatchev, D. Gabeva, Probabilistic analysis of seismic impact on open pit slope stability, International Journal of Mining, Reclamation and Environment **31**, 3, 167-186 (2017).

[8] T. Sullivan, Hydromechanical coupling and pit slope movements. [In:] Proceedings of the 2007 International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, 2007: Australian Centre for Geomechanics, pp. 3-43.

[9] T.-H. Yang, F.-C. Zhang, Q.-L. Yu, M.-F. Cai, H.-Z. Li, Research situation of open-pit mining high and steep slope stability and its developing trend [J]. Rock and Soil Mechanics **5** (2011).

[10] A. Pathan, R. Singh, R. Stace, Geotechnical Assessment of Block VIII at Thar Coalfield, Pakistan, in 23rd World Mining Congress, pp. 11-15. Montreal, Canada, 2013.

[11] D. Griffiths ,G. A. Fenton, Probabilistic slope stability analysis by finite elements, Journal of Geotechnical And Geoenvironmental Engineering **130**, 5, 507-518 (2004).

[12] T. Stacey, Y. Xianbin, R. Armstrong, G. Keyter, New slope stability considerations for deep open pit mines. Journal of the Southern African Institute of Mining and Metallurgy **103**, 6, 373-389 (2003).

[13] C. Carranza-Torres, Analysis and design of slopes for Rajo Sur, an open pit mine next to the subsidence crater of El Teniente mine in Chile.

[14] M.E. Popescu, A.C. Trandafir, A. Federico, Risk Assessment of Slope Instability Related Geohazards. [In:] Numerical Methods for Reliability and Safety Assessment: Springer, 243-269 (2015).

[15] R.N. Singh, A.G. Pathan, D.J. Reddish, A.S. Atkins, Geotechnical appraisal of the Thar open cut mining project 2011.

[16] R. Hammah, T. Yacoub, J. Curran, Probabilistic slope analysis with the finite element method, 2008.

[17] H. El-Ramly, N. Morgenstern, D. Cruden, Probabilistic assessment of stability of a cut slope in residual soil. Geotechnique **55**, 1, 77-84 (2005).

[18] E. Eberhardt, Rock slope stability analysis-utilization of advanced numerical techniques. Earth and Ocean scienes at UBC, 2003.

[19] Y. Daiatana, D. Fredlund, W. Stolte, A probabilistic slope stability analysis using deterministic computer software. [In:] Conference on probabilistic methods in geotechnical engineering 267-274, (1993).

[20] I. Siddiqui, S.H. Solangi, M.K. Samoon, M.H. Agheem, Preliminary studies of cleat fractures and matrix porosity in Lakhra and Thar coals, Sindh, Pakistan. Journal of Himalayan Earth Sciences **44**, 2, 25-32 (2011).

[21] F.I. Siddiqui et al., Lignite resource estimations and seam modeling of Thar Field, Pakistan. International Journal of Coal Geology **140**, 84-96 (2015).

[22] T.C. a. E.B. (TCEB), Thar Coal – A new horizon for investment in Pakistan. Sindh, Pakistan **1**. January (2020).

[23] G. RWE Power International, Thar mining project, bankable feasibility study and site assessment report., Sindh Coal Authority, Province Sindh, Pakistan, **1**, December 2004.

[24] A. Pathan, R. Singh, A. Shah, Hydrogeological Studies and The Design of Mine Dewatering System for the Proposed Open Cut Lignite Mine at Thar, Pakistan.

[25] R. Singh, R. Stace, A. Pathan, A. Doulati, A. Atkins, Hydrogeological assessment of the Thar lignite prospect. [In:] International Mine Water Association (IMWA) 2010 Conference **2010**: CBU Press, 441-445. (2010).

[26] R. Singh, A. Atkins, A. Pathan, Determination of ground water quality associated with lignite mining in arid climate, (2010).

[27] E.T. Brown, Rock characterization, testing & monitoring: ISRM suggested methods, (1981).

[28] ASTM D5607-02 Standard Test Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constant Normal Force, W. C. ASTM International, PA, (2002).

[29] Standard Test Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constant Normal Force, A. International, (2016). [Online]. Available: https://www.astm.org/d5607-16.html

[30] A. D-02, Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. ed: ASTM International USA, (2002).

[31] Rocscience. Probabilistic Analysis Tutorial, (2020).

[32] R. N. Singh, A. ATKINS, A.G. Pathan, Water resources assessment associated with lignite operations in Thar, Sindh, Pakistan. Archives of Mining Sciences **55**, 3, 425-440 (2010).