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Raghu N. Singh
University of Nottingham, raghu_singh@uow.edu.au

Abdhul Ghani Pathan
Mehran University of Engineering and Technology, Pakistan

David J. Reddish
University of Nottingham

Anthony S. Atkins
Staffordshire University

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GEOTECHNICAL APPRAISAL OF THE THAR OPEN CUT MINING PROJECT

Raghu N Singh¹, Abdul Ghani Pathan², David J Reddish¹ and Anthony S Atkins³

ABSTRACT: This paper is concerned with a slope stability appraisal of the proposed open cut mining operations in the Thar lignite field in Sindh, Pakistan. The Thar coalfield covers an area of approximately 9 000 km² and is estimated to contain 193 billion tonnes of lignite resources. The design of safe high wall slopes is necessary to ensure mine safety and overall economical viability of the mining operations. In the Thar lignite field, the presence of three main aquifers induces pore pressure in the rock mass surrounding the lignite seams and makes high wall slopes potentially unsafe. It is, therefore, necessary to dewater the rock mass before commencing mining excavations. A proposed mine dewatering scheme to facilitate rock mass dewatering surrounding the mining excavations and a description of the slope stability analysis of the high wall using the software "SLIDE" version 5 is outlined. Three computer models with slope angles of 28°, 29° and 30°, incorporating a plane failure mode, were analyzed to investigate the stability of pit slopes. The generalized stratigraphy of borehole RE-25 has been used for the development of the computer models. The main conclusions of this study are that the slope angle of 28° is quite acceptable for a Stability Factor (SF) ≤ 1.3 whereas the excavated slopes with slope angles ≥ 29° are not safe against the plane failure for SF > 1.3. This assessment was followed by a slope stability analysis incorporating circular failure modes. Five models incorporating various slope angles ranging from 23° to 27° and one model incorporating combined slope angles of 23° in dune sand and 26° in the rest of the strata were developed and analysed. The main conclusions from this study are that the dune sand layer (having a thickness of 48 m) is acceptable for a SF of 1.3 at slope angle ≤ 23°, while the rest of the strata is acceptable for SF = 1.3 at slope angles ≤ 26°. The overburden to lignite extraction ratio for this slope design has been calculated as 3:1 or 3 m³ of overburden over 1 t of lignite.

INTRODUCTION

The design of the high walls of an open pit mine is one of the most important aspects in surface mining planning because slope stability calculations are necessary to ensure the safety of excavated slopes coupled with the economic viability of the mining operations. The main objective of this preliminary study is to determine the overall slope angle that is safe during the working life of the mine and this will determine the optimum pit limit. A slope stability analysis was carried out on various models for a geological section of block-I at the Thar lignite deposit. Various slope angles of between 23° and 27° have been investigated using a SF = 1.3. Slide software version 5 was used for the development of models and slope stability analysis using a plane and circular slip surface search. The proposed mine dewatering scheme to ensure stable slopes surrounding the mining excavations is described.

THAR LIGNITE FIELD

Pakistan now possesses the seventh largest lignite resource in the world with 193 billion tonnes of lignite/coal reserves mainly concentrated in the Thar region in the eastern part of Sindh Province, about 400 km east of Karachi as shown in Figure 1. The Thar coalfield covers an area of approximately 9000 km², where lignite/brown coal beds lie at depths of between 130 m and 250 m. The cumulative seam thickness varies between 1.45 m and 42.6 m and the maximum thickness of an individual seam is 28.6 m. The Geological Survey of Pakistan (GSP) and the United States Geological Survey (USGS) under the Coal Resources Exploration and Assessment Program (COALREAP) first discovered this lignite field in 1994.

¹ Nottingham Centre of Geomechanics, Department of Civil Engineering, Faculty of Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, UK

² Dean, Faculty of Engineering, Mehran University of Engineering and Technology, Jamshoro 76062, Sindh, Pakistan

³ Faculty of Computing, Engineering and Technology, Staffordshire University, Octagon Beaconside Stafford ST18 0AD, U. A.S.Atkins@staffs.ac.uk

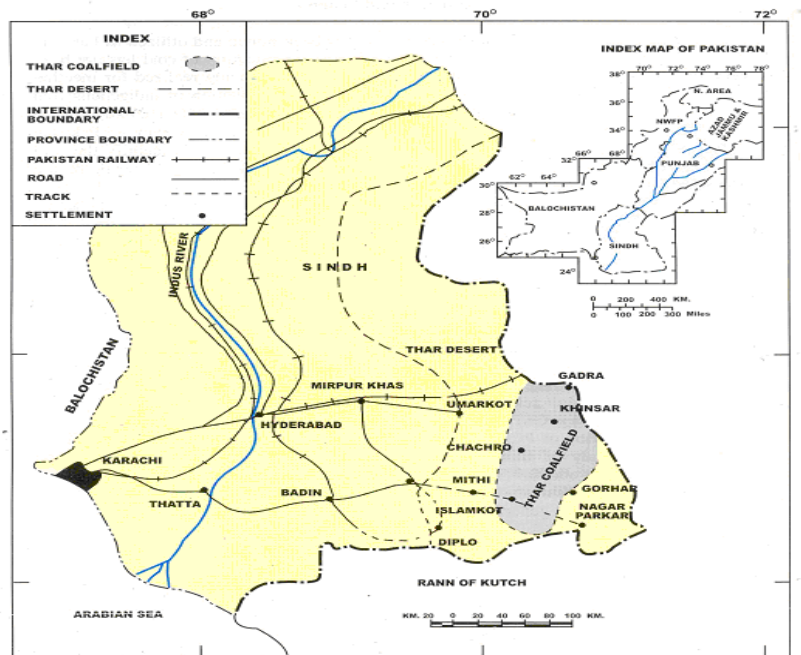


Figure 1 - Location of Thar lignite field, Sindh, Pakistan (R.W.E. Power International, 2004)

The Geological Survey of Pakistan (GSP) and Deep Rock Drilling (DRD) have completed a detailed assessment of coal resources in eight blocks of the Thar coalfield. The area covered by this exploration program is 730 km², containing some 19.344 billion tonnes of reserves. This represents 89% of Pakistan's total recoverable reserves. The eight blocks explored in the Thar coalfield are shown in Figure 2. Analysis of the Thar lignite indicates a relatively low heating value, between 9.4 and 12.7 million Btu per tonne. The most appropriate large-scale application of the lignite is for power generation, and worldwide more than 90% of lignite and brown coal is used for this purpose (Ahmad and Farzana, 2001).

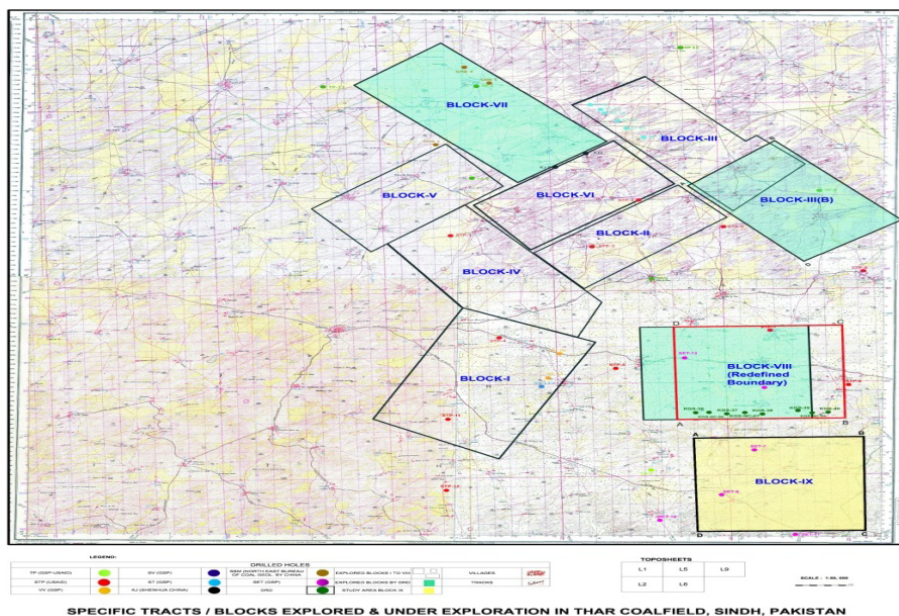


Figure 2 - Eight exploration blocks in Thar lignite field (after DRD 2010, private communication)

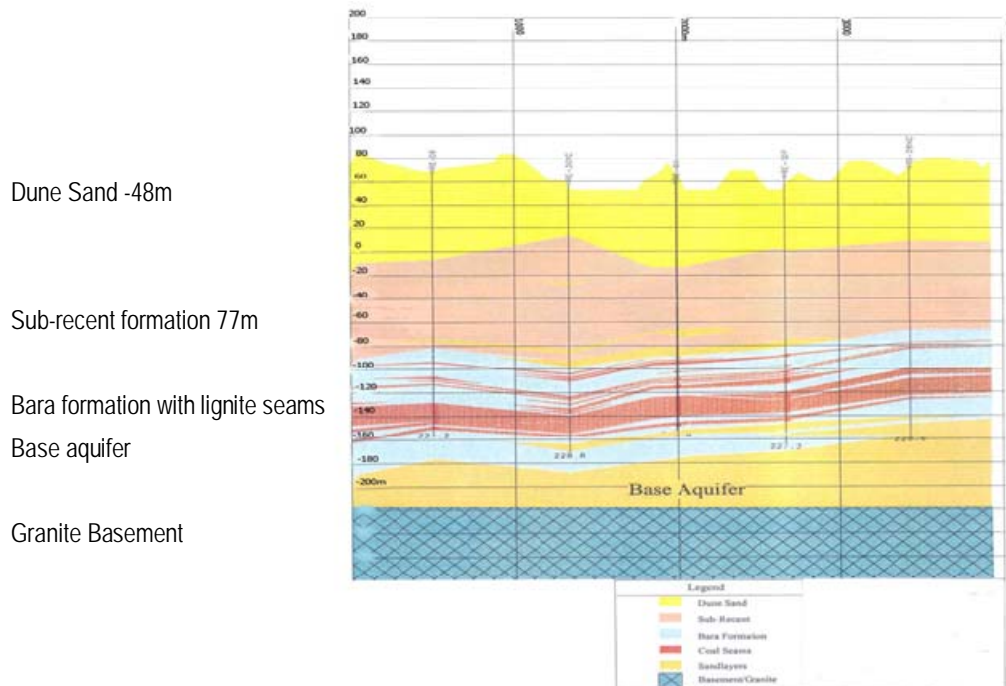
Chemical analysis of some 2000 coal samples has been undertaken, and the rank of coal has been determined, ranging from lignite-B to sub-bituminous-A. The weighted average composition of lignite-B at Thar is presented in Table 1.

Table 1- Showing the composition of Thar lignite [after Thomas, et al., 1994)

S.No.	Parameter	% composition
1.	Moisture (as received)	46.77 %
2.	Fixed Carbon (AR)	16.66 %
3.	Volatile Matter	23.42 %
4.	Ash (AR)	6.24 %
5.	Sulphur	1.16 %
6.	Heating Value	5,774 btu/lb

STRATIGRAPHY AND LITHOLOGY OF THAR LIGNITE FIELD

Lignite seams in the Thar area are found in the Bara formation of the Paleocene/Eocene age. The Bara formation is some 95 m thick consisting of sandy/silty claystone and a sandstone formation overlying the basement granite lying at a depth of 100 m to 220 m. The basement rock is very light grey, weathered, medium compacted-granite containing fine to coarse quartz grains. The overlying Bara formation consists of layers of carbonaceous clay stone, sandy claystone and silty claystone. Carbonaceous claystone is medium light grey to brown in colour containing carboniferous petrified roots, carbonaceous materials and rare sandy resin globules. The olive grey to dark-grey claystone containing petrified plant roots and pyretic resin globules overlies this sediment.

**Figure 3 - Stratigraphy of Thar lignite field (based on R W E Power International, 2004)**

There are number of coal seams of varying thickness ranging from 3 m to 21 m at an average depth of 170 m. The Bara formation is overlaid by the sub-recent formation comprising inter-bedded carbonaceous sandstone, siltstone and claystone up to 65 m thick, at a depth of 52 – 125 m. The recent formation overlying the sub-recent formation consists of some 50 m of thick dune sand. This sand is fine to medium grained, yellowish grey in colour, containing sub-rounded and moderately sorted grains of ferromagnesian minerals. Figure 3 shows the stratigraphic section and lithology of the Thar coalfield.

OUTLINE OF THE PROPOSED ROCKMASS DEWATERING SCHEME

Mine dewatering arrangements comprise of four main elements namely, surface drainage ditch, dewatering wells to the top aquifer, dewatering wells for intermediate aquifer, dewatering well for the base aquifer as shown in Figure 4.

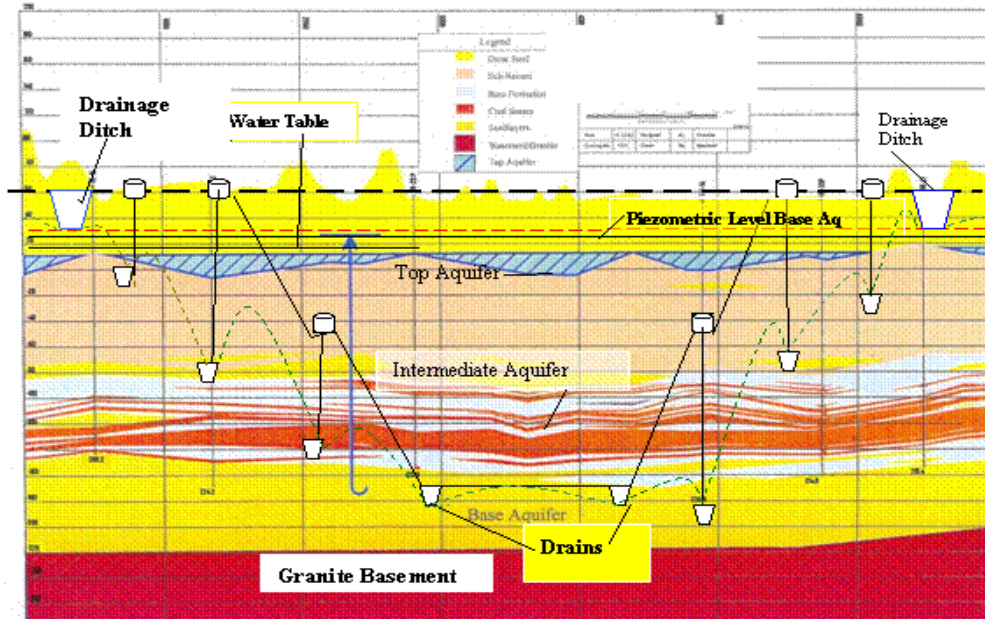


Figure 4 - Ground water regime and dewatering arrangement of Thar lignite prospects

Design of surface drainage ditch

A review of the rainfall data from the Mithi district indicates that the maximum daily rainfall of around 100 mm/day occurs during the months of July or August. It is expected that this will lead to a certain amount of flooding during unexpected rainfall, meaning that the entire operation of the mine may completely close down for a period of one to two days. The peak flow to the surface drainage system for Thar mine has been calculated using the rational formula in a previous publication (Pathan, *et al.*, 2007) as 7.5 x 10⁴ L/s. Pumping rates from the three aquifers at the Thar prospect have been calculated using the equivalent well approach by Pathan *and Singh* (2008) and are as follows:

- Pumping out rates from top aquifer is calculated = 116 m³/d;
- Pumping out rates from the intermediate aquifer r = 147 m³/d;
- Pumping out rates from the bottom aquifer r = 1.34 x 10⁶ m³/d.

DESIGN PARAMETERS FOR SLOPE STABILITY ANALYSIS

A slope stability analysis was performed for the geologic section shown in Figure 5, which is the generalized geology of borehole RE25. The thickness of various strata layers is given below:

- Dune Sand = 48m
- Siltstone = 77m
- Sand = 9m
- Siltstone = 13.5m
- Claystone1 = 2.7m
- Lignite = 4.6m
- Claystone2 = 11.5m
- Lignite = 3m
- Claystone3 = 4.2m
- Lignite = 27.8m

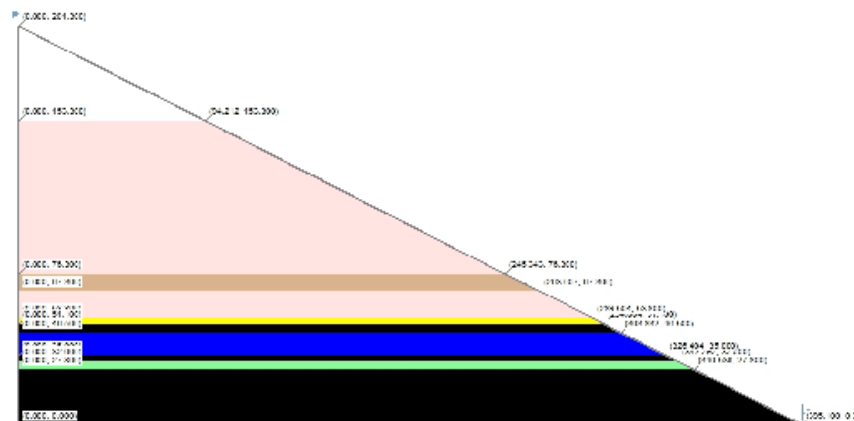


Figure 5 - Stratigraphy of Block-4 of Thar lignite field, Pakistan (After Pathan *et al.*, 2007)

The following design parameters shown in Table 2 were used for the slope stability analysis:

Table 2 - Showing the input design parameters after Pathan, Singh and Shah (2006)

Stratum	Formation	Density, γ (kN/m^3)	Angle of internal friction (ϕ_0)	Cohesion, c (kN/m^2)
Dune Sand	Recent	17	30	0
Siltstone	Sub-recent	21	14	200
Sand	Sub-recent	17	30	0
Claystone1	Bara	16.9	27	120
Claystone2	Bara	18.8	23	200
Claystone3	Bara	19.4	25	40
Lignite	Bara	11.8	30	200

DESIGN PARAMETERS FOR STABILITY ANALYSIS USING PLANE FAILURE SURFACES

Three computer models of pit slopes, with slope angles 28° , 29° and 30° , have been investigated against plane failure. The computer software "Slide" version 5 was used for the design of slopes. An example of one model with a slope angle of 30° is shown in Figure 6 incorporating the orientation of a potential failure plane. The following parameters were used in all the models:

- Analysis technique = Bishop;
- Surface Type = Plane, Non-circular;
- Search Method =Block;
- Number of surfaces = 5000;
- Left angle start = 135° ;
- Left angle end = 135° ;
- Right angle start = 45° ;
- Right angle end = 45° .

Plane of failure was added in each model and the coordinates of the plane were entered at the prompt line.

RESULTS AND DISCUSSIONS OF THE PLANE FAILURE ANALYSIS

All the computer models were analyzed for a slope stability assessment against plane failure along potential slip plane. Figures 6, 7 and 8 show the results of a 'Block Search' indicating the 'Global Minimum' slip surfaces for 28° , 29° and 30° slopes respectively using the Bishop Analysis technique. Figure 6 also indicates the safety factors for the Global Minimum slip surface. Figure 6(a) indicates the safety factor of 1.331 for the slope angle of 28° , whereas the safety factors for slope angles of 29° and 30° are 1.292 and 1.266 respectively as shown in Figure 6(b and c). These results clearly indicate that the excavated slopes with slope angles $\leq 28^\circ$ are acceptable against plane failure for $SF \leq 1.3$, whereas the excavated slopes with slope angles $\geq 29^\circ$ are not acceptable against plane failure for $SF \leq 1.3$.

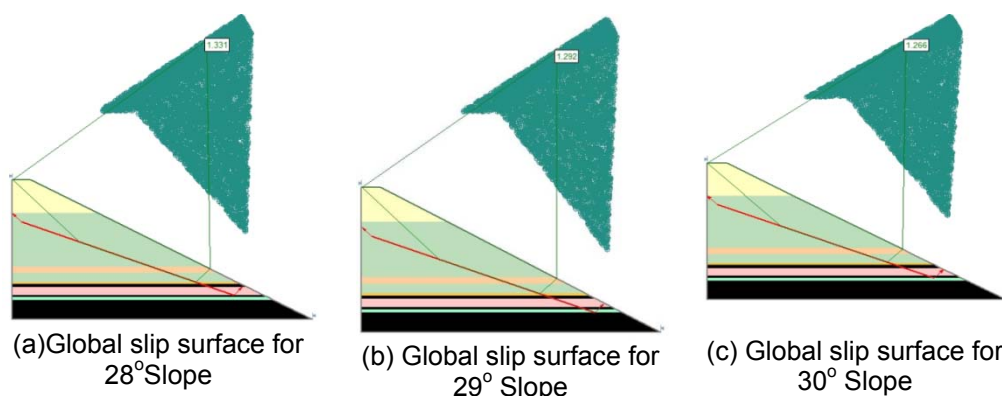


Figure 6 - Slope stability analysis of open pit slope in Thar lignite mine predicting plane failure

Figure 7 (a to c) shows all slip surfaces with various safety factors for slope angles of 28° , 29° and 30° respectively. Figure 8 has been generated to filter the slip surfaces for $SF \leq 1.3$. No slip surface is shown in Figure 8(a) for the slope angle of 28° which means that the excavated slopes having the slope angle \leq

28° is safe for SF ≤ 1.3. However, Figures 8(b) and 8(c) show some slip surfaces, indicating the potential plane failure for slope angles of 29° and 30° respectively.

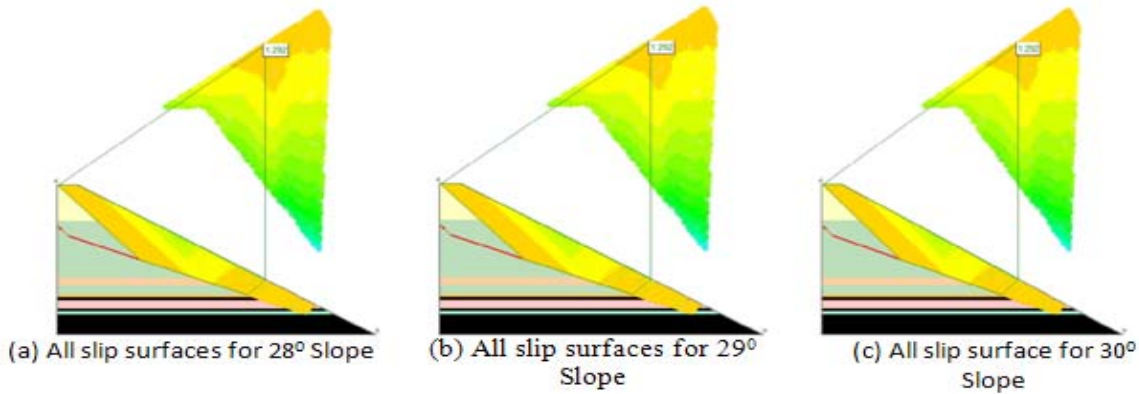


Figure 7 - Slope stability analysis of open pit slope in Thar lignite mine showing plane failure

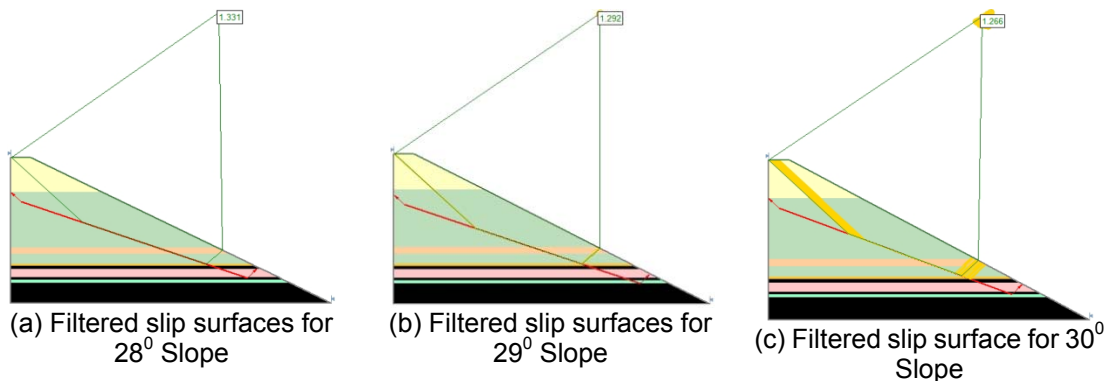


Figure 8 - Slope stability analysis of open pit slope in Thar lignite mine predicting Plane failure

Stability Factor vs Location for 28° to 30° slopes indicating plane failure mode

Figure 9 shows the graph for various safety factors plotted against the horizontal location for slope angles of 28°, 29° and 30°. All the data points for a slope angle of 28° are above the minimum stability factor = 1.3, which means the pit slope with an inclination of 28° is quite safe for SF ≤ 1.3. However, some data points plotted for slope angles of 29° and 30° lie below the minimum safety factor of 1.3, therefore it can be concluded that the excavated slopes with slope angles ≥ 29° are not safe against the plane failure at SF ≤ 1.3.

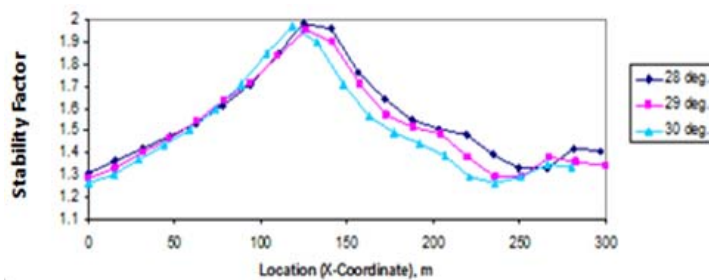


Figure 9 - Stability factor along X-direction for plane failure from 28° to 30° slope angles

DEVELOPMENT OF COMPUTER MODELS USING CIRCULAR SLOPE FAILURE SURFACES

For the circular slope stability analysis, the computer software “Slide”, version five, was used to create five models incorporating various slope angles ranging from 23° to 27° and one model incorporating a combined slope angle of 23° in dune sand and 26° in the rest of the strata. Slope stability analysis was performed on the geologic section shown in Figure 5 and design parameters as indicated in Table 2 were used.

Following parameters were used for the development of models:

- Analysis technique: Simplified Bishop Method;
- Surface type: Circular and composite;
- Grid spacing: 20 x 20;
- Radius increment: 10.

Interpretation: Minimum surfaces and filter surfaces for $SF \leq 1.3$ Figures 10 (a) and (b) show the minimum surfaces and filter surfaces respectively for a factor of safety ≤ 1.3 and slope angle of 27° .

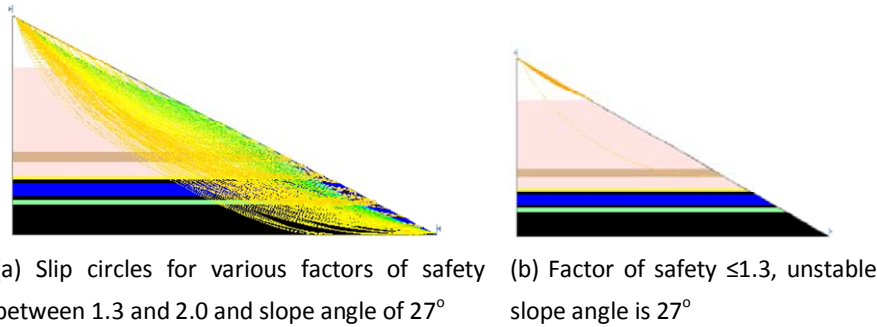


Figure 10 - Slip circles for various factors of safety, and slope angle of 27°

RESULTS AND DISCUSSION OF SLOPE STABILITY ANALYSIS USING CIRCULAR SHAPE OF FAILURE SURFACE

A slope stability analysis was executed for five slope angles ranging from 23° to 27° using Slide Version 5.0 Software. Slip circles for $SF \leq 1.3$ were generated along the excavated slope for various slope angles. In a preliminary analysis, no slip circle was observed (diagram not shown), which means that for the excavated slope angle of 23° with a factor of safety ≥ 1.3 no slip was observed.

Figures 11 (a) to (c) show the development of slip circles in the dune sand region, which indicates the possible failure of the excavated slope in dune sand. It can be concluded from these results that the dune sand zone is not safe for $SF < 1.3$ with slope angles greater than 23° . In Figure 11(d), an additional slip circle is observed, extending from the surface down to the sand layer of the strata, which indicates the possible failure of the excavation in this strata region. It is, therefore, concluded that the overall slope of the excavation is not safe for $SF \leq 1.3$ with the slope angle greater than 26° . In view of the above discussion it can be concluded, that the dune sand zone is safe for the slope angle $\leq 23^\circ$ and rest of the strata is safe for slope angle $\leq 26^\circ$. It was decided to analyze the stability of the combined slope angles of 23° and 26° . The results of this slope analysis, with combined angles of 23° in dune sand and 26° in rest of the strata, showed that there is no slip circle. This means that the combined slope is safe for $SF \leq 1.3$ and slope angles $\leq 23^\circ$ in dune sand and $\leq 26^\circ$ in the rest of the strata.

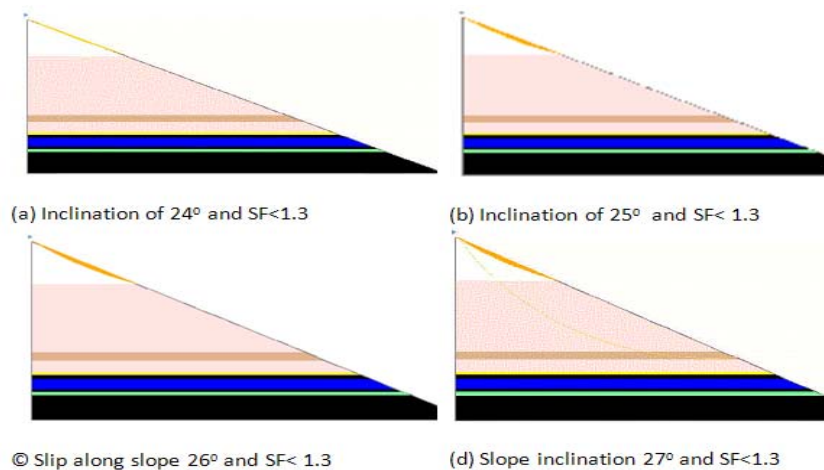


Figure 11 - Slip circles for various stability factors and slope angles

Stability factor versus location for 24° to 27° circular slopes

In order to evaluate the quantitative analysis of the stability of excavated slopes, Stability Factor (SF) vs. location graphs were generated for various slope angles between 23° and 26°. These graphs are shown in Figure 12 (SF1 to SF6). In Figure 12, the SF 1 curve shows the minimum SF of 1.36 and the maximum SF of 2.1, which means the excavated slope of 23° is quite acceptable for the SF ≥ 1.36. It is clear from Figure 12, SF 2, for slope angle 24°, that the initial part of the graph is touching the Y-axis at SF=1.3, which shows that the dune sand zone of the strata is not acceptable at a slope angle of 24°. Figure 12, SF 3 and SF 4 indicate that the initial portion of the graph, comprising of dune sand, lies below FS=1.3, which means that the dune sand layer is not considered stable for slope angles of 25° and 26°. It is also observed from Figure 12, FS 5, that not only does the initial part (comprising of dune sand) of the graph lie below 1.15, but the other portion of the graph, at a location of X= 260 m, also falls below FS=1.3, which means that the overall slope is not considered stable at an inclination of 27°.

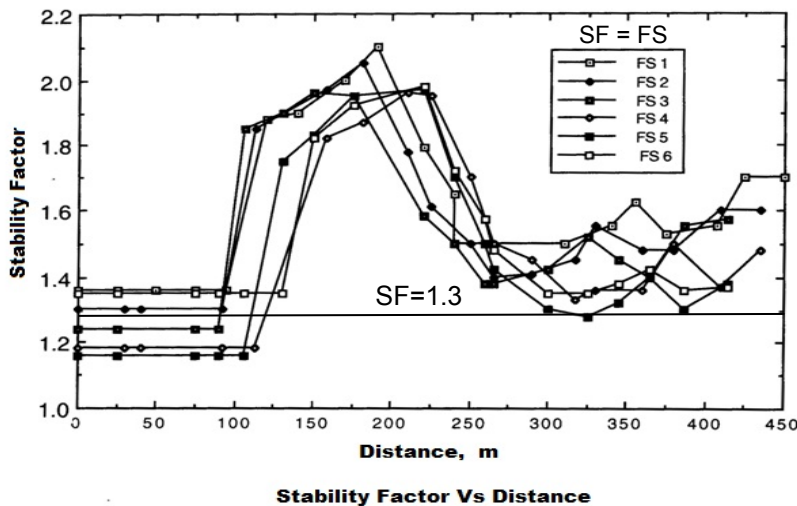


Figure 12 - Stability factor versus location for circular failure surface. Note FS should be SF.

The FS versus location graphs shown in Figure 12, SF 1 to SF 5 reveal that the dune sand layer of the strata is safe for SF=1.3 at slope angles ≤ 23° and rest of the strata is acceptable as safe for SF=1.3 at slope angles ≤ 26°. On the basis of these results it was necessary to evaluate the stability of the combined slope angles of 23° and 26°, therefore an SF vs. location graph was generated for the combined slope as shown in Figure 12 SF 6. It is very clear from the graph SF 6 in Figure 12 that no single point on the graph lies below the stability factor 1.3.

Sensitivity analysis

Table 3 - Sensitivity analysis of slopes at various angles in Dune Sand and other strata for different values of cohesion (C) and internal angle of friction (φ)

STRATA	SLOPE ANGLE	STABILITY FACTOR									
		10% φ	20% φ	30% φ	40% φ	Mean value φ	60% φ	70% φ	80% φ	90% φ	100% φ
Dune Sand	23°	0.2	0.5	0.75	1.05	1.363	1.700	2.20	2.85	3.50	4.65
	24°	0.19	0.35	0.70	1.00	1.307	1.650	2.15	2.70	3.35	4.50
	25°	0.10	0.34	0.68	1.00	1.238	1.62	2.10	2.55	3.20	4.30
	26°	0.10	0.32	0.65	0.91	1.200	1.45	2.00	2.39	3.15	4.25
	27°	0.15	0.28	0.63	0.90	1.136	1.44	1.84	2.36	3.05	4.20
		10% C, φ	20% C, φ	30% C, φ	40% C, φ	Mean value C, φ	60% C, φ	70% C, φ	80% C, φ	90% C, φ	100% C, φ
Other Strata	23°	1.363	1.363	1.363	1.363	1.363	1.363	1.363	1.363	1.363	1.363
	24°	1.307	1.307	1.307	1.307	1.307	1.307	1.307	1.307	1.307	1.307
	25°	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238
	26°	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
	27°	1.136	1.136	1.136	1.136	1.136	1.136	1.136	1.136	1.136	1.136

Due to the poor quality of the geotechnical data obtained to date it was considered appropriate to carry out sensitivity analysis on assumed values of C and φ (average values as given in table 2 ± 10%) for different slope angles. Table 3 shows the sensitivity analysis results for the slopes in dune sand and other

strata for slope angles between 23° and 27° for different assumed values of cohesion and internal angle of friction. Table 3 indicates that pit slopes having inclination of 23° and 24° are safe for the calculated stability factor of 1.3 for the average values of C and ϕ . Table 3 also indicates that the stability factors at 50% ϕ are 1.238, 1.2 and 1.136 for the pit slopes of 25° , 26° and 27° respectively in the dune sand which means that Dune sand slopes, having inclination $> 24^\circ$, are not safe.

Sensitivity curves of cohesion (C) and angle of internal friction (ϕ) for different strata layers with combined slope angles are shown in Figure 13 indicating that stability factor for the mean values of cohesion (C) and internal angle of friction (ϕ) in dune sand and other strata is 1.345 which means it is safe for stability factor of 1.3.

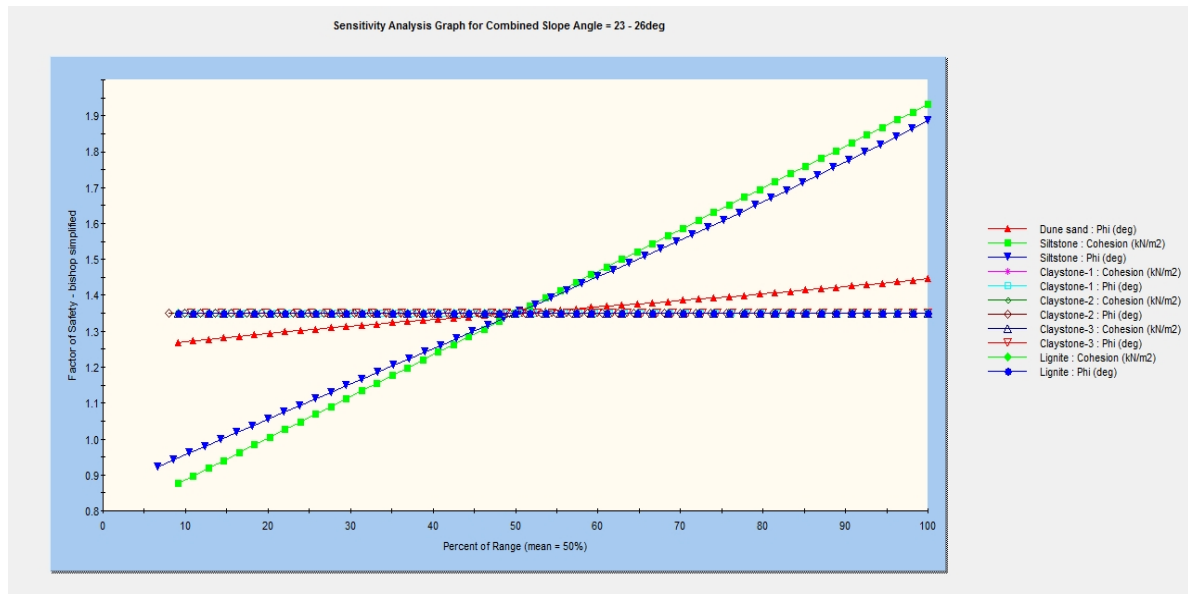


Figure 13- Showing the sensitivity of cohesion (c) and angle of internal friction (ϕ) for combined slope angle $\alpha = 23^\circ - 26^\circ$

CONCLUSIONS

The computer software package SLIDE version 5 has been conveniently used to carry out a slope stability analysis of the high walls of the open cut operations in the Thar Coalfield. Three, computer models with slope angles of 28° , 29° and 30° incorporating plane failure modes have been used to analyze the stability of the pit's high wall slopes. This model assisted in concluding that the slope angle of 28° is safe for a factor of safety ≤ 1.3 whereas the excavated slopes with slope angle $\geq 29^\circ$ are not safe against the plane failure for $SF \geq 1.3$. The analyses using the circular failure mode were carried out on five models for various slope angles ranging from 23° to 27° and one combined model containing a slope angle of 23° in dune sand and 26° in the rest of the strata, and concluded that the dune sand layer, which is 48m thick, is safe for $SF \leq 1.3$ at slope angle 23° , while the rest of the strata is safe for the stability factor of 1.3 for slope angles 26° . Sensitivity analysis indicated that the stability factor for sand dune slope range from 0.2 to 4.65 for angle of friction variation from 10% to 100 % ϕ values.

It may also be noted that the sensitivity analysis of slopes at various angles in Dune Sand and other strata, for different values of cohesion (C) and internal angle of friction (ϕ), revealed that the slopes with inclination $\leq 24^\circ$ are safe whereas the combined slope is safe for inclination of 23° in dune sand and 26° in rest of the strata. The overburden to lignite extraction ratio for the present slope design was estimated as 3:1 or 3 m³ of overburden to be removed to recover 1 t of lignite (Pathan, *et al.*, 2007).

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