

Assessment of an Open Cast Coal Mine Slope Stability at Mohanpur Block, Raniganj Coalfield, West Bengal, India



Agami Pramanik, Avishek Adhikary, and Supriya Pal

Abstract A large open cast coal mine always needs a stable side slope to prevent collapse due to excessive overburden pressure. The present study was undertaken to assess the stability of slope of an open cast coal mine located in Mohanpur block in the Raniganj coalfield area in West Bengal, India. The pseudo-static approach of stability analysis was performed using Plaxis 3D software package under strength reduction technique. A Mohr–Coulomb constitutive model was considered for the simulation of geological materials under drained and undrained conditions. The average overall depth of the mine slope was considered as 144 m. The slope was designed following the coal mine regulations of mechanized open cast mining (CMR 2017) [1], Ministry of Labor and Employment, Govt. of India. The maximum vertical deformation and safety factor were examined to ascertain the optimized slope angle of the Mohanpur open cast pit. Three trial slopes were considered using three different slope angles. The slope angle of 40° was selected as the design slope as the safety factor as well as vertical deformation was found to satisfy the permissible limits under seismic accelerations considered in the present study.

Keywords Slope stability analysis · Open cast coal mine · Optimized slope angle · Pseudo-static approach · Plaxis 3D

A. Pramanik (✉) · A. Adhikary · S. Pal
Department of Civil Engineering, National Institute of Technology Durgapur, Durgapur 713209,
West Bengal, India
e-mail: pramanikagami44@gmail.com

A. Adhikary
e-mail: avishek.adhikary31@gmail.com

S. Pal
e-mail: supriya070478@gmail.com

1 Introduction

Optimum design of the open cast mine pit slope is important from both stability and economic point of view. Hence, the aim of the design of an open cast mine is to provide the best possible outline of excavation with respect to safety, ore recovery and financial return [2]. The most crucial part of the design is to find the optimum slope angle which depends upon the strength parameters of the overburden soil/rock materials involved. Also, it is known that the sloping walls of the large mines are generally steeped in nature with alternate flat and sloping portions known as step/bench and batter, respectively. These act as an extra safeguard toward sliding/slipping of loose sloping mass soils/rocks. Generally, the height of each batter varies in between 10 and 15 m, and the width of the bench is 20–40 m. The scientific studies of open cast mine pits force the use of sound geotechnical practice in their design for the sake of cost-effective and safe mining.

For many decades, limit equilibrium methods were used in solving geotechnical engineering and particularly slope stability problems. In this method, the safety factor (SF) is calculated as the ratio of the existing shear strength to the shear stress at equilibrium [3]. However, the design of mine slopes is quite complex in nature. Therefore, the simple limit equilibrium method is no longer considered by the scientists/researchers for precise design of mine slopes. In this case, the application of finite element method (FEM) has proven better analysis tool for the stability analysis of the open cast pit slopes and safe design of mines. FEM is more refined and powerful because no assumption needs to be made about the location, direction and shape of slip surfaces. Failure naturally occurs through sections on which soil's shear strength is not capable of sustaining the applied shear stresses [4, 5]. Also, the stress, displacements in different planes throughout the cross section can be found out easily. But in the framework of large-scale mining slopes, obtaining realistic input information and interpreting the results are the trickiest aspects of numerical modeling [6].

The primary objective of the paper is to analyze the open cast mining slope of Mohanpur block under seismic accelerations with the help of Plaxis 3D software and to find out how the design parameters of the mine are responsible in the stability of the slope. The geometric modeling of the slope was performed using the Plaxis software package, and thereafter, seismic excitation was considered in the structure globally. The safety analysis of the slope was then carried out to obtain the safety factor. In this paper, different trial slopes with varying angle of inclinations were considered to evaluate the optimum slope angle considering a benchmark factor of safety (FOS) of 1.5.

2 Problem Statement and Numerical Model

Open cast mining involves the extraction of ore from seams relatively near the surface by means of an open pit. Construction of an open pit mine requires the information of the ore underground. Drilling of boreholes in the ground is required followed by plotting each hole location on the map. The data collected through the holes provide an idea of the extent of the ore's body under the Earth surface. In this study, a typical cross section of an open cast mine at Mohanpur block in Raniganj coalfield is taken into account. The geometric features are indicated in Fig. 1.

- Maximum height of each lift at OB portions = 12 m (top soil of 3 m).
- Maximum height of each lift at coal seam portions = 6 m,
- Minimum exposed width of each berm = 30 m,
- Angle of slope of one stage with above configuration = 70°, 50° and 40°.
- First working bench of 50 m exposed width at 22 m height from the pit bottom.
- Second working bench of 50 m exposed width at 44 m height from the pit bottom.
- Third working bench of 50 m exposed width at 76 m height from the pit bottom.
- Forth working bench of 50 m exposed width at 108 m height from the pit bottom.

The overall depth of the mine is 144 m. The coal layers are indicated in hatch lines. The top soil was observed up to a depth of 6 m below ground surface, and rest of the overburden in the slope comprises sandstone and shale.

2.1 Assumptions of Models

The primary assumption is that the major cause of slope failure occurred due to the development of excessive shear stress in the structure. The mine slope is analyzed here numerically based on the self-weight/overburden pressure and varying earthquake load for different earthquake excitations. The boundary condition in X and Y direction is set as "Normally fixed" and free in the negative Z direction (here, upward direction is taken as positive Z) in the numerical model of the slope stability analysis. The linear-elastic perfectly-plastic Mohr–Coulomb model is considered in the geo-material modeling in the analysis. The geo-material properties such as Young's modulus (E), the cohesion (c), the friction angle (φ), Poisson's ratio (ν) and unit weight of soil (γ), used in the model as input parameters, were evaluated through experiments performed at the Soil Mechanics and Foundation Engineering laboratory, Department of civil engineering, National Institute of Technology Durgapur, West Bengal, India. In this case, dilatancy angle was taken as zero, since it is close to zero for clay and for sands with a friction angle less than 38°. The slope is analyzed for both drained and undrained conditions. At the undrained condition, instant pore water pressure is generated even above the groundwater table. It is done to find the SF in a worst case scenario when all the soil pores are blocked and water cannot drain out through them.

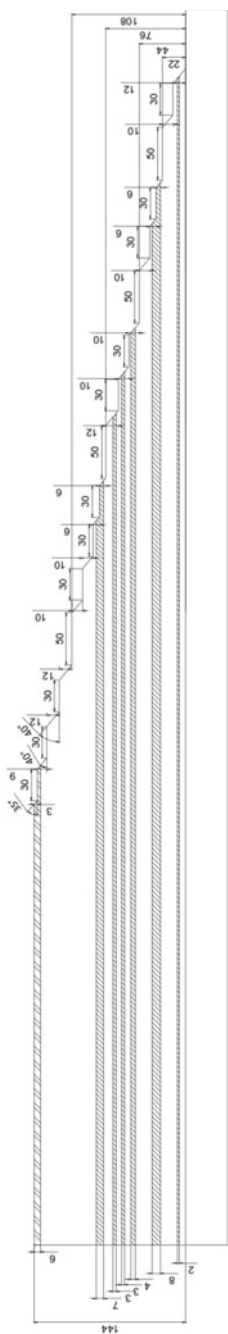


Fig. 1 Sectional layout of open cast coal mine at Mohanpur block (all dimensions are in m)

2.2 Material Properties

Table 1 provides the properties of pit slope materials.

3 The Shear Strength Reduction (SSR) Technique

Computation of safety factor in Plaxis was performed considering phi-c reduction technique at each stage of slope modeling. In this calculation, the load advancement number of step procedure is followed. The incremental multiplier M_{sf} is used to specify the increment of the strength reduction of the first calculation step. The strength parameters are reduced sequentially at each step until all the steps have been performed. The final step results in a fully developed failure mechanism. Otherwise, the calculation is repeated with a higher number of additional steps. Once the failure mechanism is obtained, the factor of safety is estimated based on following expression:

$$SF = \frac{\text{Available shear strength}}{\text{Shear strength at failure}} = \sum M_{sf}(\text{value of } M_{sf} \text{ at failure}) \quad (1)$$

The SSR technique is widely applied in stability studies of open pit slopes. This is so because it contains all the benefits of limit equilibrium analyses, and at the same time, it allows the user to assess the displacement of the slope that are often critical in the evaluation of open pit stability [7].

Table 1 Geotechnical properties of pit slope materials

	Sandstone and shale materials	Coal samples	Top Soil
γ (kN/m ³)	24.71–26.53	15.83–16.65	19.11–20.37
c (kN/m ²)	94–132	62–76	17–22
Φ (°)	33–35	18–20	28–32
E (MN/m ²)	457–546	79–101	165–176
μ	0.30–0.31	0.39–0.40	0.32–0.34

where

γ = Unit weight of the material

Φ = Angle of friction

c = Cohesion

μ = Possion's ratio

E = Modulus of elasticity

4 Results and Discussions

In the present work, the angle of the slope was optimized by trial and error method. Three trials were made with three different slope angles, viz. (i) 70°, (ii) 50° (iii) 40°. In Plaxis 3D, dynamic loading can be considered in a pseudo-static way [9] by specifying global acceleration which is taken into account for different earthquake zones as given in Table 2. The results are given below:

4.1 70° Slope Angle

Initially, the slope angle was chosen 70°. Pseudo-static stability analysis of the slope was done using Plaxis 3D software in three stages. The drainage conditions of the materials were set to “undrained”. The horizontal seismic coefficient for Zone III was included in the numerical analysis. The safety factor (SF) was found out to be 1.12 following SSR technique in Plaxis 3D model (Fig. 2).

Table 2 Horizontal Seismic Coefficient for Different Earthquake Zones [8]

Earthquake zones	Zone II	Zone III	Zone IV	Zone V
Horizontal acceleration coefficient	0.02	0.04	0.05	0.08

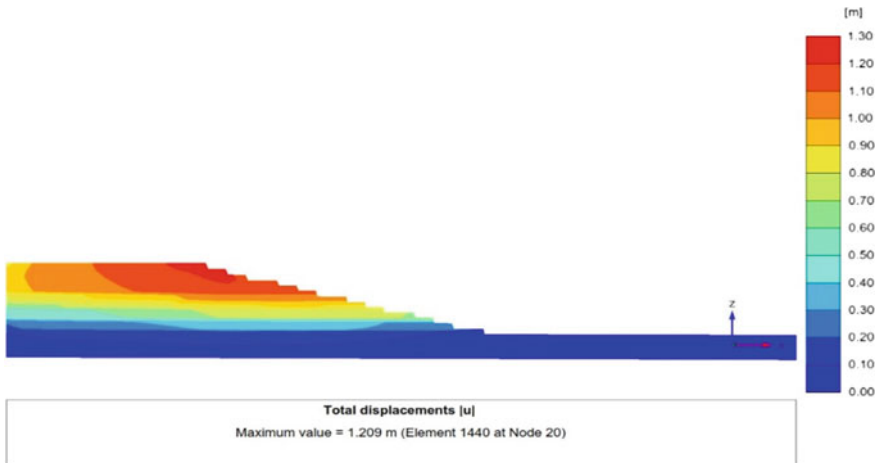


Fig. 2 Total vertical displacement of mine slope (angle of inclination of 70°) at Mohanpur block using Plaxis 3D software

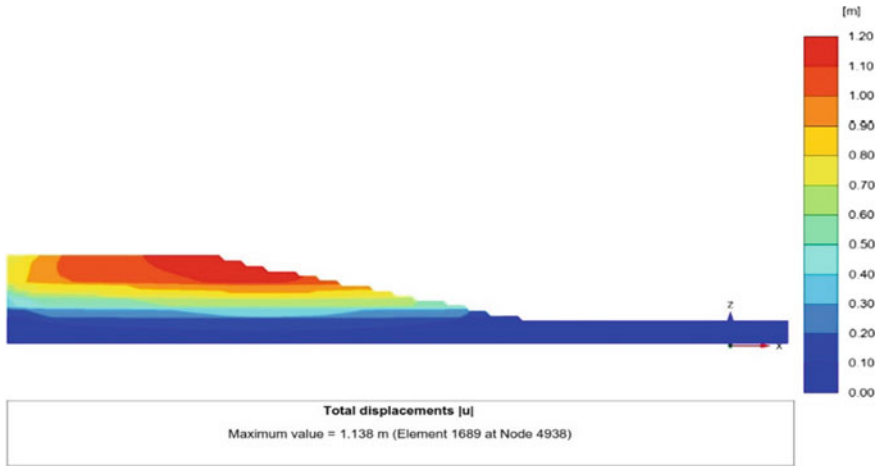


Fig. 3 Total displacement along X-axis of mine slope (50°) at Mohanpur block in Plaxis

Table 3 Results for open pit slope at Mohanpur block (70° and 50° slope)

Zone 3 (undrained condition)		
Slope	70° slope	50° slope
Safety Factor	1.12	1.21

4.2 50° Slope Angle

As the SF is less than 1.5 for 70° slope, next trial was made with the reduced slope angle of 50°. Pseudo-static stability analysis of the slope was carried out in Plaxis 3D in the same manner as stated above keeping all the parameters same as previous analysis. In this case, the safety factor (SF) was obtained as 1.21 (Fig. 3 and Table 3).

4.3 40° Slope Angle

From the above results, it is clearly seen that the safety factor was less than 1.5 for both 70° and 50° angle. This clearly states that such steep slope angles are not appropriate for this mine pit. Therefore, the slope angle is further reduced to 40°, and the slope stability analysis is done. Results are given in Table 4 as depicted.

Therefore, it is clearly seen that with the reduction of slope angle to 40°, the design of slope satisfies the required critical factor of safety as well as nominal vertical displacement of the slope is observed. Thus, this slope can be applied in the field to get a safe working condition without the risk of collapse of the slopes due to excessive overburden pressure (Figs. 4 and 5).

Table 4 Results for open pit slope stability analysis at Mohanpur block (40° slope)

Eartquake zones	Factor of safety and horizontal displacement							
	Zone 2		Zone 3		Zone 4		Zone 5	
Horizontal acceleration coefficient	0.02		0.04		0.05		0.08	
Drainage	Drained		Undrained		Drained		Undrained	
SF	2.187		1.889		1.903		1.679	
Horizontal displacement (m)	0.196		0.17		0.25		0.324	

Factor of safety and horizontal displacement

Zone 2

0.02

Drained

2.187

0.196

Zone 3

0.04

Undrained

1.889

0.17

Zone 4

0.05

Drained

1.903

0.25

Zone 5

0.08

Undrained

1.679

0.324

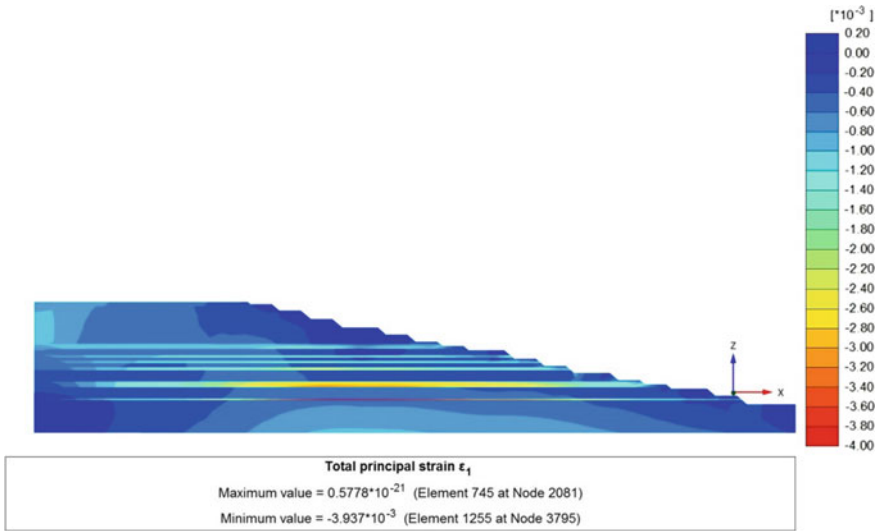


Fig. 4 Total principle strain of mine slope (40°) at Mohanpur block in Plaxis

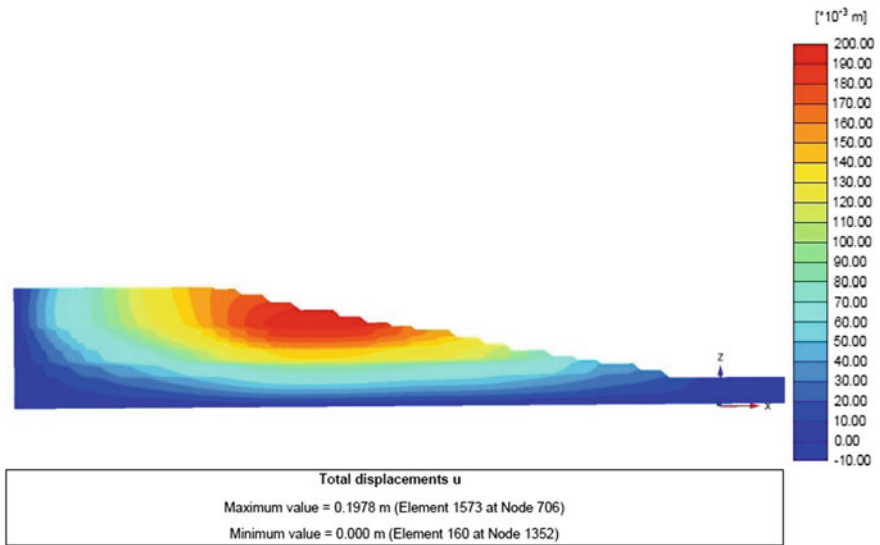


Fig. 5 Total vertical displacement of mine slope (angle of inclination of 40°) at Mohanpur block using Plaxis 3D software

5 Conclusions

In the present study, a number of trials were performed with varying slope angles of the open cast mine in order to design the side slopes which can withstand the overburden pressure without showing signs of collapse. It was observed that keeping all other parameter same, the factor of safety decreases with increase in seismic acceleration coefficient.

The safety factor is less for undrained condition in comparison with drained condition of the slope mass. Assuming that all the drainage paths are blocked, in undrained condition, instant pore water pressure is generated within the soil/rock even above the water table making it a worst case scenario. Therefore, the factor of safety was found decreased in undrained condition.

There is no well-defined failure surface was observed in the mine slopes. As the mine is not homogeneous, coal seams are much weaker than the surrounding sandstone and shale. Therefore, strain is higher in the coal seams. And there is no continuity within the parting.

Displacement is higher in drained condition than undrained condition of the sloping mass. In drained condition, the pore water pressure in the soil/rock mass is completely dissipated, and therefore, settlement is more. However, in the undrained condition, instant pore water pressure is generated, and therefore, it takes long time to settle. So, the displacement is higher in drained condition than undrained condition of the soil.

References

1. Coal Mine Regulation [Part II, Sec 3 (i)], Ministry of Labour and Employment, Govt. of India (2017)
2. Read, J., Stacey, P.: Guidelines for Open Pit Slope Design. CSIRO Publishing, Australia (2009)
3. Duncan, J.M., Wright, S.G.: Soil Strength and Slope Stability. Wiley (2005)
4. Duncan, J.M.: State of the art: limit equilibrium and finite-element analysis of slopes. *J. Geotech. Eng.* **122**(7), 577–596 (1996)
5. Griffiths, D., Lane, P.: Slope Stability analysis by finite elements. *Géotechnique* **49**(3), 387–403 (1999)
6. Hustrulid, W., McCarter, M., Van Zyl, D.: Slope Stability in Surface Mining, Society for Mining, Metallurgy & Exploration (SME) (2001)
7. Hoek, E.: Fundamentals of Slope Design, Keynote address, Slope Stability 2009, Santiago, Chile, 9–11 (2009)
8. Earthquake Resistant Design of Structures IS 1893:2016 [Part I]
9. PLAXIS 3D Reference manual