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Effect of cracks on the stability of dump slope

Maintaining the stability of overburden dumps in opencast mines is a major challenge. Instability in dump slope occurs because of many inherent factors, cracks formed by mining activities, and natural climatic conditions etc. have been considered in this study. Numerical simulation of the dump slope has been performed using RS2 (Rocscience) software based on the finite element method (FEM). In simulation, the effect of cracks by considering the crack inclination, crack location from the crest of the dump slope, and effect of crack length and crack inclination at critical failure surface location has been analyzed. It has been found for the given conditions that cracks at a distance less than 7.5m from the crest of the slope for inclination 30° to 50° have the least stability and crack at critical failure surface location for inclination 40°, and 50° have a significant effect on the stability of the dump slope for all the considered crack length.

Keyword: *Dump slope, crack, finite element method, numerical modelling*

1. Introduction

Currently the production of coal has substantially increased to achieve the rising demands of industries as well as domestic purposes, in which the share of opencast mining is more than underground mining in order to ensure the maximum recovery of the coal (Behra et al. 2016). Due to the increased production stress on opencast mining method, a considerable volume of overburden waste material is generated and stacked as a dump slope within or outside the pit termed as internal or external dumps, respectively.

The stability of the dump slope is a primary concern for a mining engineer from the production and safety point of view of men and machinery (Verma et al. 2013). The stability of the dump slope depends on certain factors like, the geometry of the dump slope, strength properties of the dump material, presence of water, and generation of tension crack (Kainthola et al. 2011, Verma et al. 2013). Rainfall infiltration increases the pore water pressure and reduces the frictional strength of the dump material. The infiltration of rainwater may enhance the flow of dump material, leading to the formation of the tension cracks on the dump slope. Shock and vibration generated due to poor blasting are also one of the reasons in the formation of tension crack (Verma et al. 2013). Cracks formed in an overburden dump slope of an opencast mine is shown in Fig.1. Wu et al.(2012) described that moisture loss is a critical factor for crack formation in the soil and the rate of moisture loss near the surface is more than that of the deep soil, thus the shrinkage deformation near the surface is higher than that of the deep soil, which results in the formation of crack. Morris et al. (1992) demonstrated that high temperature alone does not form deep and wide cracks during the wet season. However, high temperature in dry seasons develops wide, deep cracks in soils when the groundwater table reduces to significant depth in the soil profile. Zhang et al. (2012) mentioned that oblique crack induces more displacement than the vertical crack in the slope because oblique crack is closer to the slope surface. Cho et al. (2014) found in his work that tension crack at the crest of the waste dump was the starting point of the circular failure path. Fan et al. (2005) have performed the numerical analysis and identified the influence of fracture depth, fracture width, and the location of the fracture on the slope surface during transient seepage on the stability of the dumpslope.

Stability analysis must be performed in order to understand the possible effects of the location and orientation of the cracks on the overall stability of the dump slope. There are many limit equilibrium methods for stability analysis of dump slopes such as; ordinary method of slices by Fellenius (1936), Bishop’s modified method (Bishop 1955), Morgenstern and Price’s method (Morgenstern and Price 1965), Spencer’s method (Spencer 1967) and Janbu’s generalised procedure of slices (Janbu 1968). There are certain limitations associated with all the limit equilibrium methods since the sliding mass is divided into a number of slices, which demands further assumptions related to the interslice forces. The assumptions related to the interslice forces are the main characteristics, which differentiate one limit equilibrium method with the other (Duncan 1996, Griffiths and

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Fig.1 Cracks in the dump slope of an opencast mine

Lane 1999). On the other hand, the finite element method (FEM) has certain advantages over traditional limit equilibrium methods, e.g., there is no need to presume the shape and location of the failure surface. Since there is no concept of slices in this approach, there is no need for assumptions about interslice forces. In this study, the shear strength reduction (SSR) technique is used for the calculation of factor of safety (FOS) (Griffiths and Lane 1999).

The main objective of this paper is to identify the effect of cracks in the stability of the dump slope by performing numerical analysis using RS2 software based on the FEM. In this study effect of crack inclination, crack location from the crest of the dump slope and crack length and crack inclinationat critical failure surface location of crack has been considered, and based on that stability of the dumpslope has been analyzedby observing their FOS.

2. Finite element modelling

The RS2 software is used in the simulation of the dump slope, which is based on FEM. FEM assists in the computation of stresses and displacements in the dump slope (Rai et al. 2012). SSR methodis used for the calculation of FOS of the dump slope (Griffiths and Lane 1999; Dawson 1999; Matsui and San 1992). It automatically determines the critical failure surface without any prior assumptions about the shape or location of the failure surface (Griffiths and Lane 1999). Mohr-Coulomb failure criterion is used to model the dump slope. In the dump slope stability analysis with the SSR method, a series of iterations are performed with an increasing trail factor of safety (F_{trial}) for a single numerical simulation. The actual shear strength properties of the dump slope, cohesion (c), and internal friction angle (ø) are reduced for each trail as given in the Eq.(1) and Eq.(2). The trail factor of safety is increased until the new shear strength properties of the dump material brings the slope into a state of just stable equilibrium, at this stage the trail safety factor is considered as FOS of the dump slope (Rai et. al. 2012; Griffiths and Lane 1999; Matsui and San 1992; Gupta et. al. 2014; Cai et al. 2003; Dawson 1999).

$$C_{trial} = \frac{C}{F_{trial}} \quad ...(1)$$

$$ø_{trial} = \arctan\left(\frac{\tan ø}{F_{trial}}\right) \quad ...(2)$$

3. Generation of dump slope model with crack

The overall height of the dump slope ranges up to 90m depending upon the material characteristics. However, the single bench height has been kept as 30m in Indian coal mines. Therefore a base dump slope of 30m height and 37° slope angle is developed using FEM based RS2 software, as shown in Fig.2. The strength properties used in the modelling of dump slope are given in Table 1. Two sets of dump slope models have been developed one with the varying crack inclination and varying crack location from the crest of the

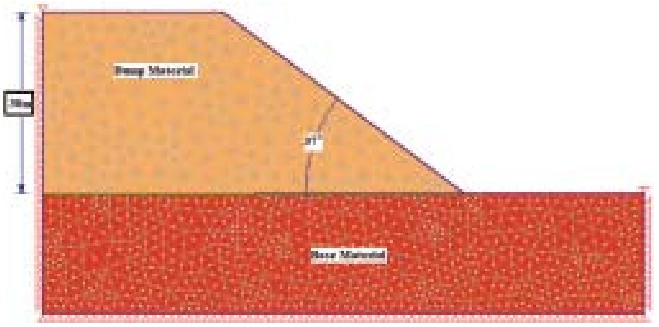

Fig.2 Base model of dump slope with 30m dump height and 37° slope angle

TABLE 1: PROPERTIES USED FOR NUMERICAL SIMULATION

	Properties (Unit)	Dump material	Base material
1.	Cohesion (MPa)	0.071	1
2.	Friction angle	29°	36°
3.	Unit Weight (MN/m^3)	0.02	0.027
4.	Young's modulus (MPa)	80	2000

dump slope, and the second at the critical failure surface point on top of the dump with varying crack length and crack inclination. The base model is used to analyse the effect of crack on the stability of the dump slope.

3.1 Cracks with varying inclination and location from the crest of the slope

A set of models have been developed to identify the effect of inclination and location of the crack, on the stability of the dump slope. The range of the crack location is aken from 5m to 20m at an interval of 2.5m, which is measured from the crest of the dump slope. The inclination of the crack has a range from 10° to 50° at an interval of 10°. The crack length of 8m has been fixed for all the developed models. The angle is measured anti-clockwise from a vertically downward direction, as shown in Fig.3. Dump slope model with crack for a particular location is developed each for all the

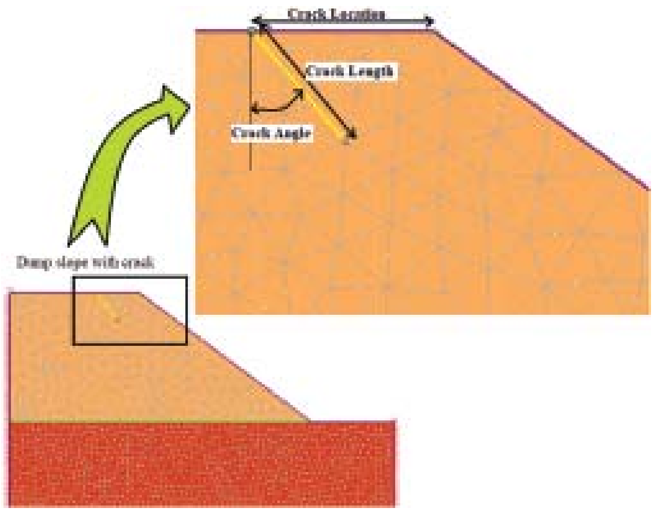

Fig.3 Orientation of crack in the dump slope

inclination (10° to 50°) of crack. Thus, a total of 35 models are developed by using the combination of crack inclination and the location of the crack.

3.2 Cracks with varying inclination and length at critical failure surface

The critical failure surface identified from the simulation of the base modeland used further for detailed analysis by varying the crack length and inclination at critical failure surface location. The critical failure surface meets at 16m from the crest of the dump slope, as shown in Fig.4. The location of the crack is fixed at a critical point, and crack length is varied from 5m to 11m at an interval of 1m. For each crack length, the inclination is varied from 0° to 50°at an interval of 10°. Thus, a total of 42 models have been developed by using the combination of both the length and inclination of crack at the critical failure surface.

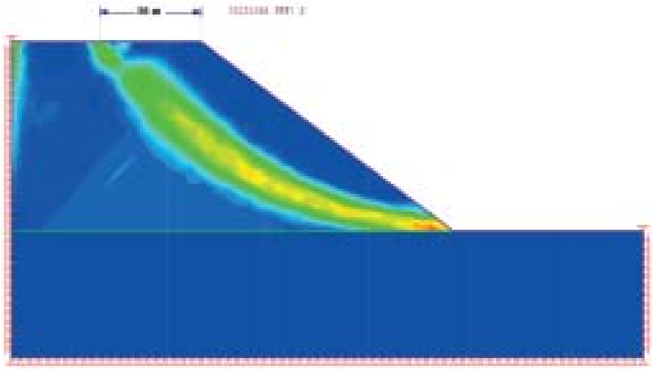

Fig.4 Base dump slope showing the critical failure surface

4. Results and discussion

4.1 Cracks with varying inclination and location of crack from the crest slope

The combination of inclination and the location of the crack is used to understand how they are affecting the stability of the dump slope. A total of 35 dump slopes have been modelled by using the combinations of crack length and inclination. It is evident in the graph, as shown in Fig.5 that FOS is decreasing from the crack inclination 10° to 50°, but the difference in FOS from inclination 10° to 20° is minimal in comparison with others. Numerical simulation results of the dump slope model of 10° to 50° crack inclination for crack location 15m is shown in Fig.6.

The effects of the increase in crack locations for crack inclination 10° is not significant. At location 5m from the crest FOS is 1.97, and at 20m FOS is 2.0, almost a negligible change is found, which defines that there is a very negligible effect on the stability of the dump slope due to the change in location of the crack.

For the crack inclination 20°, there is a small increment in FOS with the increase in the crack location from 5m to 20m. FOS has increased from 1.83 to 1.99 for the crack location 5m to 20m, respectively.

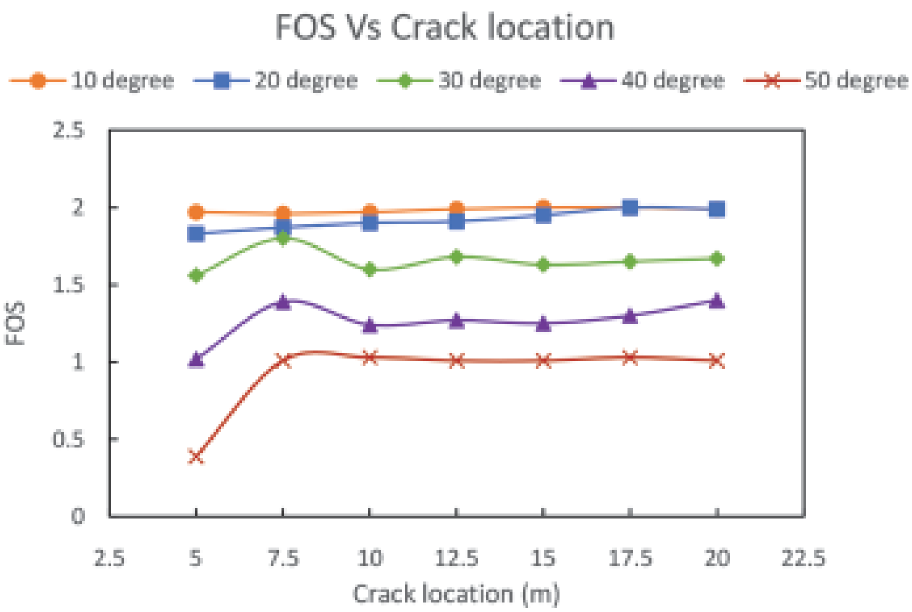

Fig.5 Graph is showing the relation between crack location and crack inclination with FOS

It is found that for the crack inclination 30°, 40°, and 50°, the FOS first increases from the crack location 5m to 7.5m after that remain unchanged from the crack location 7.5m to 20m. Crack location near the slope surface (at 5m) gives a natural slip surface as it gets the least horizontal confinement, as Chang et al. (2019) defined that with the decrease in horizontal confining stress, shear stress increases in dump slope near slope surface and becomes most vulnerable to shear failure. Therefore, the presence of crack near the slope surface makes the dump slope more prone to failure. Horizontal confinement stress away from the slope surface becomes constant; that is why FOS remains unchanged from the crack location 7.5m to 20m.

4.2 Cracks with varying inclination and length at critical failure surface

Dump slope fails on a critical failure surface. It is essential to know the inclination and length of crack at which the dump slope will fail on critical failure surface location. So, the inclination and length of crack have been varied at the critical failure surface location, which is 16m away from the crest of the dump slope. The length of crack

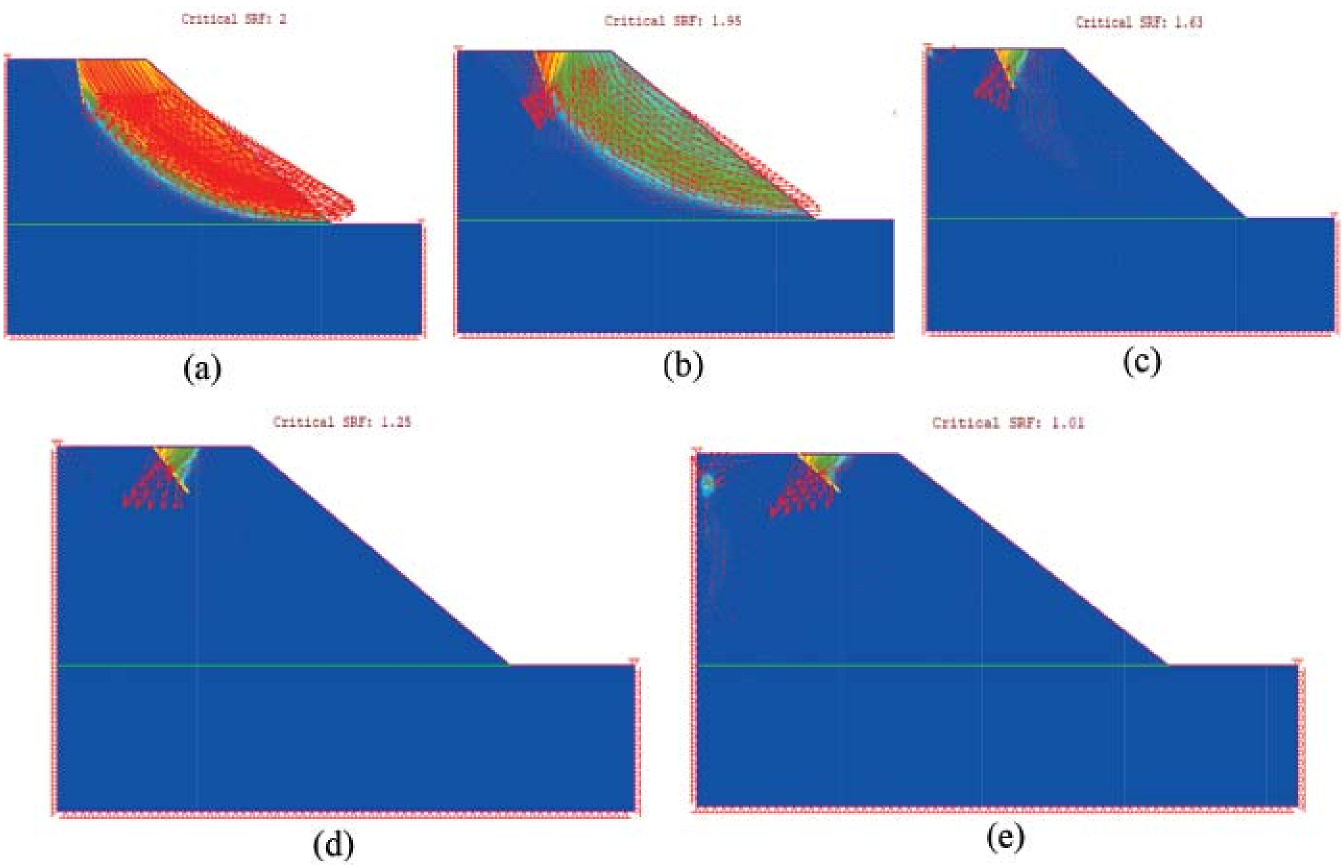

Fig.6 Simulation results with FOS and deformation vector at 15m crack location for crack inclination 10°, 20°, 30°, 40° and 50° in the figure (a), (b), (c), (d) and (e) respectively

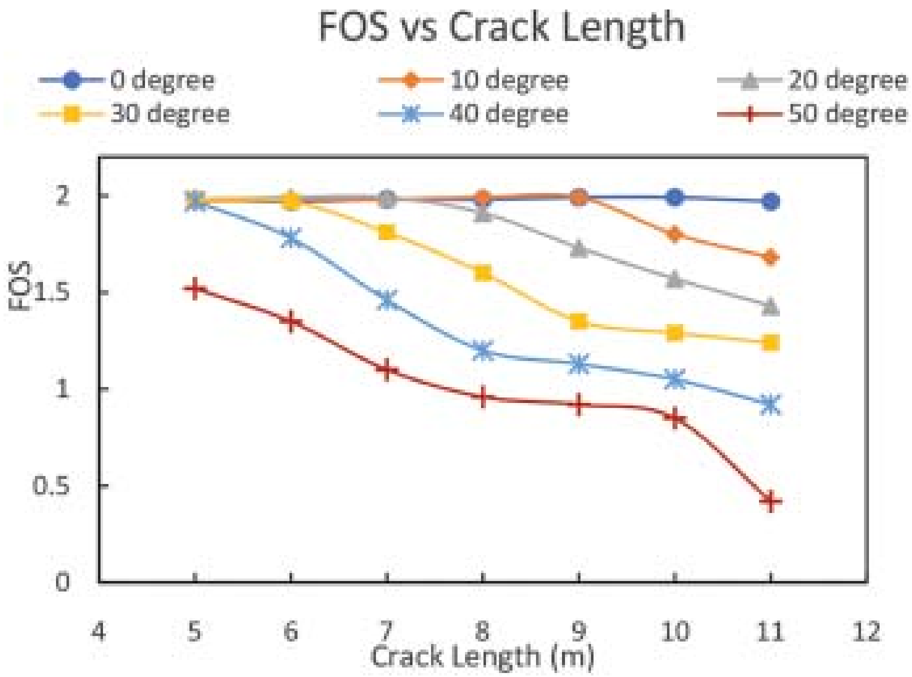

Fig.7 Graphis showingthe relation between crack length and crack inclination with FOS

ranges from 5m to 11m at an interval of 1m, and the crack angle ranges from 0° to 50° at an interval of 10°. Thus a total of 42 models have been generated using the combination of inclination and length of the crack.

For the crack angle 0°, there is a negligible change found in FOS for all the length of cracks ranging from 5m to 11m, as shown in Fig.7. Since, the crack is vertical and touching the critical failure surface only on the top of the dump. Thus, the crack is not able to create any weak shear surface for the dump material to fail.

For crack angle 10°, there is almost no change in FOS for the crack lengthfrom 5m to 9m, but FOS has decreased for the crack length 10m and 11m to 1.8 and 1.68, respectively.

FOS has decreased from 7m to 11m length of crack for the crack inclination 20°, but there is no effect on FOS from crack length 5m to 7m for the crack inclination 20°.

For the crack inclination 30° to 50°, FOS is decreasing for 5m to 11m crack length, and FOS is decreasing with the increase in the inclination of crack. Cracks with crack inclination 30° to 50° are oriented in such a way that they are almost following the path of critical failure surface and creating a weaker plain of failure, which leads to the decrease in FOS with the increase in inclination from 30° to 50°. The length of cracks adds more volume of dump material on a weak plain, making the dump slope more prone to failure.Thus with the increase in crack angle, FOS is decreasing, which is also confirmed by Zhang et al. (2012) in his researchthat oblique cracks make dump slope more prone to failure in comparison to vertical cracks.

5. Conclusions

In the present study, the effect of cracks with different sizes, location, inclination, and their behaviour at critical failure surface location have been analyzed. A combination of varying crack inclinations and crack locations have been used to model 35 dump slopes and another combination of crack length and crack inclination at critical failure surface location are used to model 42 dump slopes to analyse their effects on the stability of dump slope, and the following conclusions have been drawn:

- With the increase in the inclination of crackfrom a vertical position, FOS is decreasing for all crack locations (5m to 20m), but the decrease in FOS from crack angle 10° to 20° is minimal.
- Crack located near the slope surface at a distance of 5m from the crest of slope bears the least FOS for a particular inclination of crack, and FOS remains unchanged from 7.5m to 20m.
- FOS is decreasing with the increase in crack length (5m to 11m) for the crack inclination 30°, 40°, and 50° when the crack location is at the critical failure surface.
- There is a negligible effect of the length of crack on FOS at the critical failure location for 0° and 10° crack locations.

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