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SLOPE STABILITY ANALYSIS OF BHANEGAON OPENCAST COAL MINE, NAGPUR AREA, WESTERN COALFIELDS LIMITED - USING NUMERICAL METHODS.

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Abstract - Coal is a major source of raw material in power generation of the country and its contribution is about 90% for power generation. For last four decade we have been tapping easily mineable coal reserves in the country. Major part of India's coal production comes from opencast coal mines. Though, coal deposits close to the surface are depleting fast in the country, but there is no way out other than mining coal deposits through opencast mining lying at greater depths. At greater depth problem of slope stability is prominent. Further, if, the deposit is located close to the water reservoir, then it aggravates the problem of slope stability due to ground water movement. It has been observed that irrespective of the type of slope, majority of the slope failures are due to ground water hydrostatic pressure built up. Bhanegaon opencast mine is 33 km from Nagpur which is close to the confluence of two rivers i.e. Kanhan and Pench on rise side of the deposit. In this mine, destabilization of benches on rise side of the property are being regularly experienced. Slope stability analysis shows that ground water seepage is the cause of such failures. In Bhanegaon Opencast Mine, analysis has been conducted to analyse the cause of slope destabilization. In the present scenario limit equilibrium method and two dimensional finite element and finite difference approach have been used to simulate and analyse the slopes.

In Present study rise side of the opencast have been analysed for slope stability. It has been analysed with Limit Equilibrium and Numerical Methods with overall slope angle and water saturation levels. Study shows that reduction of hydrostatic pressure by draining water improves the slope stability drastically as compared with other alternatives.

Keywords - Slope Stability, LEM, FEM, FDM, Hydrostatic Pressure, Bhanegaon, Destabilization

I. INTRODUCTION

To meet the increasing demand of coal for power and steel sector, there has been ample exploitation of coal reserves through surface and underground coal mines. The major problem associated with the opencast mines are huge quantities of overburden material to be removed and thereby requiring a larger surface area for storage. Due to larger output of coal opencast mines have become popular. Since coal deposits closer to the surface are exhausting, therefore coal deposits are being mined at greater depths by opencast mining which involves handling and storage of huge quantities of overburden.

As we go deeper, we need to keep a proper check on the stability of benches and the factors which may cause instability. Past review of accidents in opencast mines are mainly due to destabilization of slopes caused by factors such as water mainly.

The Bhanegaon Opencast mine is situated in Bina block of Kamptee Coalfields. This block falls in Nagpur District of Maharashtra State which lies in Latitude 21°16'37'' to 21°15'36'' and Longitudes 79°10'12'' to 79°08'41''. Bhanegaon Open cast mine is under the administrative control of Western Coalfields Limited (WCL) of Nagpur Area. This Project is located very close to the confluence of Pench and Kanhan Rivers. The mine is surrounded on three sides by these rivers. In this coal deposits there are five coal seams, dipping at an angle 13° to 14° away from the confluence. There are instances of slope failure on the rise side of the mine.

In this paper, the slope stability analysis of the rise side of the mine has been done considering the effect of water present in the mine. Modelling has been done using three methods namely LEM, FEM and FDM. The stability of the mine is focused mainly considering the effect of water permeating through the rise side of the mine due to the presence of confluence of two rivers. Due to the presence of water, the shear strength of the material reduces, hence leading to reduction in overall strength of the material.

II. STABILITY ANALYSIS METHODS

It is important to carry out slope stability analysis for mining activities and other steep slopes in the hilly region. Numerical methods can be used to analyse these slopes and draw a conclusion about their stability in different conditions. The following analysis techniques were adopted in the study.

2.1 Limit Equilibrium Method

The Limit Equilibrium method is the most common approach for analyzing slope stability. LEM assumes the slope to fail over a slip circle under the influence of gravity. The shear strength is fully mobilized at the failure surface. There are a number of methods developed by the researchers to calculate Factor of Safety (FOS) using the limit equilibrium method. Most common out of them are ordinary method of slices, Bishop's Slip circle method and Janbu corrected method.

2.2 Finite Element Method

Finite element method is a numerical method for solving engineering problems. This method carries out the analysis of the entire slope at each node and their results are synthesized to get the complete analysis of the object. Each node can be analyzed for various outputs like stress-strain, displacement, yielded elements or any other characteristics depending on the type of application. The inter-relating behavior of all the nodes gives the behavior of the entire object. The slope stability analysis of the slope using the FEM is done with the help of software Rocscience Phase 2.0. It is a two dimensional program which calculates the stress – strain of the model along with its displacement and presents a user friendly output in the form of coloured contours.

2.3 Finite Difference Method

FDM method divides the solution domain into finite discrete points - to which a set of governing equations are applied – and replaces the partial differential equations with a set of differential equations. These equations include the differential equations of stress – strain, displacement, etc. The solutions obtained by FDM are not exact but approximate. However, if the discretization is made very fine, the error in the solution can be minimized to an acceptable level.

FLAC (Fast Larangian Analysis of Continua) is a 2D FDM program developed by Itasca, which utilizes an explicit finite difference formulation that can model complex behaviours, such as problems that consist of several stages, large displacements and strains, non-linear material behaviour, or unstable systems. FLAC is used for analysis, testing, and design by geotechnical, civil, and mining engineers. It is designed to accommodate any kind of geotechnical engineering problem that requires continuum analysis. FDM divides the problem into small time steps and predicts the stresses and strains of the next time step based on the present time step using finite difference formulation such as forward, backward and central differences. The FOS of the slope can be calculated by using the Shear Strength Reduction technique. The strength of material is progressively reduced by a factor termed as Strength Reduction Factor (SRF) till the solution becomes non - convergent. The maximum value at which convergence was achieved is termed as critical SRF or FOS.

III. FIELD AND LABORATORY INVESTIGATIONS

The slope stability analysis was performed for the rise side of Bhanegaon opencast mine. The area is covered by a thick blanket of loose soil on the rise side of the mine. The first 5 meters of the surface consists of Black Cotton soil which is initially removed by using scrappers. The Kamthi formation generally overlies the coal containing Barakar formation and is characterized by the presence of loose soil and weathered rocks. The loose and saturated thickness (20m to 57m) of alluvial deposit (mixed with Black Cotton soil and sludge) with Kamthi Formation having high transmissivity, may create stability problem. The Barakar formation consists of the coal and has a lower permeability than the one existing above. The strike of the bed in the block is generally NW- SE and dip at 9° to 14° due SW with gradient ranging from 1 in 4 to 1 in 6. The strike length extends over 300 meters. The rise side of the mine has been divided into different vertical sections and the one which is most critical has been modelled in the software and analyzed for its stability in terms of FOS. Different geotechnical properties have been determined in the laboratory and the data has been used as inputs in the softwares.

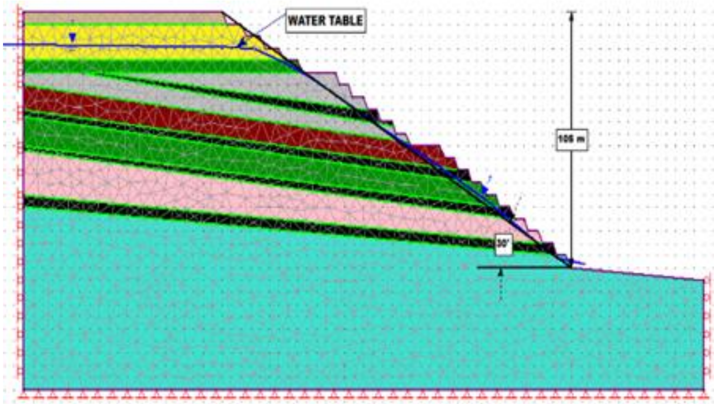

Figure 1: Geometry of existing slope of rise side of the mine.

The samples obtained from rise side of the mine were taken from various locations along different vertical sections to represent the slope. Different geotechnical tests were performed to extract the values of cohesion, friction angle, tensile strength etc. Samples from five different vertical sections of the mines from rise side were collected. Visual inspection and as per the prevalent condition of the site Section C-C’ was found to be the most critical section. Hence the section C-C’ has been modelled in the respective softwares and analyzed for its stability. Figure 1 shows the geometry of the rise side of the mine. Similarly Figure 2 shows the different sections over which the samples were collected.

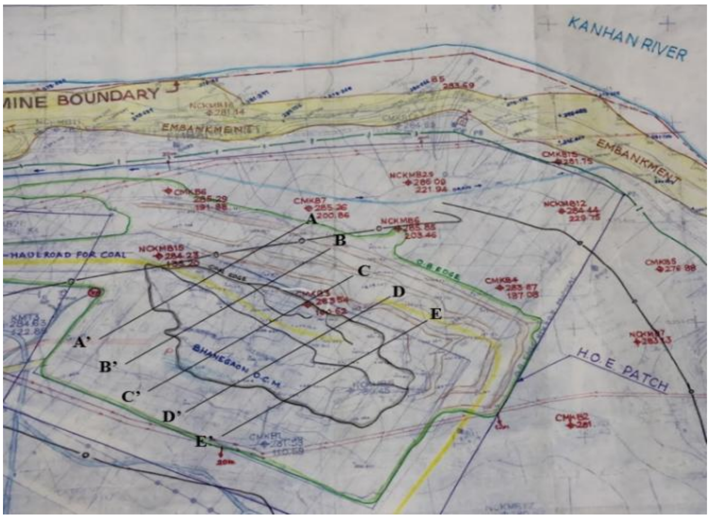

Figure 2: Different sections take along the rise side of the mine.

IV. SLOPE STABILITY ANALYSIS

The slope stability analysis was conducted for the rise side of the mine considering the most critical section. Numerical methods were adopted to determine the FOS of the existing slope and optimized slope.

4.1 Stability Analysis of Existing Benches of Mine

The existing state of mine shows that, few of the benches on the rise side about 20 meters below the surface are prone to sliding. There is a very high risk of failure of these benches due to movement of water through the benches having high permeability. To find out stability of the existing area, numerical models have been prepared using three different approaches to study the present state of stress - strain, displacement, plasticity etc.

4.2 Stability Analysis of the Optimized Slope.

In the present context, optimized slope mean, the one which has sufficient stability, viz FOS = 1.30. The existing slope has been modified by making various changes to the slope angle and lowering of water table. Before modifications the FOS of the slope was in the range of 0.8 to 0.9. A standard value of FOS 1.30 has been considered to optimize the slope. This FOS of 1.30 will ensure the slope to be stable and withstand forces arising due to hydrostatic pressure. It has been observed that section C-C’ bears the least stability. In Table 1 geo-mechanical properties have been shown foe various formations. A comparison of FOS obtained in different softwares for different cases has been presented in Table-2.

Figure 3 shows the optimized slope of the rise side with the slope angle changed from 31° to 27° and water table lowered to 23 meters depth. Table 2 represents the various conditions of the mine and its respective FOS. The FOS is the largest when the mine is completely drained and the overall slope angle has been flattened to 27°. Slide (LEM based software) does not reveal stability status when water is present in the slope. In Table 2 the case V has been considered to be the optimized condition of the slope. Case VI presents a very high safety factor considering the slope to be entirely drained. A percentage wise comparison has been shown in Table 3 pertaining to the variation in FOS in different Methods. The stability of the slopes are mainly affected due to steep slope angles and presence of water. The water penetrates through the pore spaces and reduces the effective strength of the material.

Table 1. Material Properties of the mine.

	Black Cotton Soil	Loose Soil	Coarse Grained Sandstone	Alluvial Soil	Coal	Medium Grained Sandstone	Clay Soil	Sandy Shale
Unit Weight (KN/m^3)	17.5	18	27	18.3	12	27	17.7	24
Friction Angle (in degrees)	33	28	27	25	30	35	20	14
Cohesion (kPa)	10	20	2700	6	1000	2700	7	3000
Young's Modulus (MPa)	25	16.5	1910	4.2	2000	1910	2.68	1110
Poisson's Ratio	0.28	0.3	0.28	0.34	0.3	0.28	0.38	0.29
Tensile Strength (kPa)	0	0	500	0	400	1000	0	800

Table 2. FOS obtained for different cases of the rise side of the mine.

Analysis of Rise Side Slope of Bhanegaon Opencast Mine				
		Phase 2.0	**Slide**	**FLAC/Slope**
Case I	Initial geometry of mine	0.92	0.883	0.842
Case II	Water Table Lowered by 10 meters	1.27	0.881	1.05
Case III	Slope Angle Changed from 31° to 27°	1.07	1.17	0.9
Case IV	Totally Drained	1.27	0.848	1.11
Case V	Slope Angle Changed to 27° and Water Table Lowered by 10 meters	1.31	1.16	1.16
Case VI	Slope Angle changed to 27° and WT Totally drained	1.72	1.17	1.48

Comparison of FOS values we can see that there is an increase in the value of FOS to more than 30% from the one obtained in the initial condition of the mine. Here the comparison is done only for the existing and optimized condition. For the intermediate cases the results were almost similar to the above except in the case of LEM.

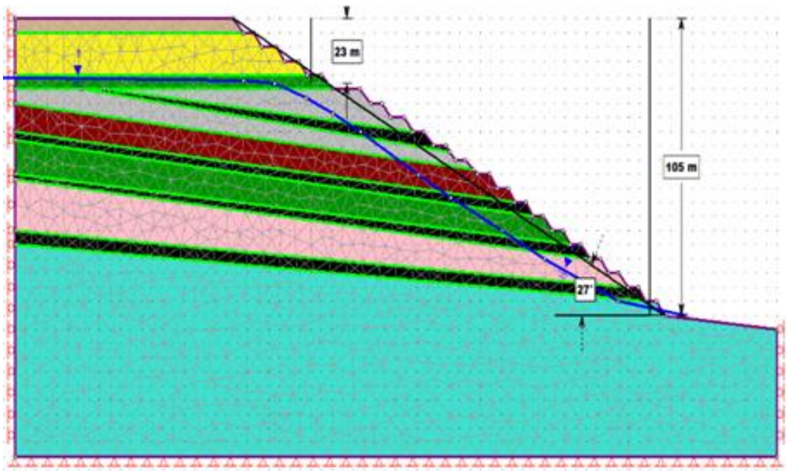

Figure 3: Geometry of optimized slope - rise side after lowering Water Table and flattening overall slope angle.

Table 3. Comparison of FOS values obtained for existing and optimized slope.

Method of Analysis	FOS of existing slope	FOS of optimized Slope	% Change
Limit Equilibrium Method	0.88	1.16	31.8 %
Finite Difference Method	0.842	1.16	37.7%
Finite Element Method	0.92	1.31	42.3%

V. RESULTS AND DISCUSSIONS

The stability analysis of the rise side of Bhanegaon Opencast Mine was done using three approaches by considering various combination of slope angles and hydrologic conditions. The analysis produced results related to stress-strain, displacement and plasticity.

5.1 LEM Analysis

Limit equilibrium analysis was done using a two dimensional limit equilibrium software for evaluating the FOS of the failure surface. The program Slide, which is a part of Rocscience software was used to evaluate the slope. The slope was analysed with Ordinary Method of Slices, Simplified Bishop Method and Janbu Corrected Method. The FOS for existing slope obtained using Slide ranged from 0.881 to 0.885 and for the optimized slope the FOS ranged from 1.14 to 1.16. Figures 4 and 5 shows the results of the existing and optimized slope. The LEM shows the profile of the slip surface. Initially the FOS was below 1.00, which shows failure of slope. After optimizing the slope the FOS changed to 1.16, which is still below the minimum required value of 1.30. Also, it was observed that LEM gives improper results when water is present in the slope. Hence the results obtained from LEM does not give correct picture of stability condition of the mine. Also LEMs give very little information about the deformational behaviour of the slope. To understand more about stability status of the slope the deformational properties of the slope are important. Hence, further analysis of the slope using FDM and FEM have been taken up.

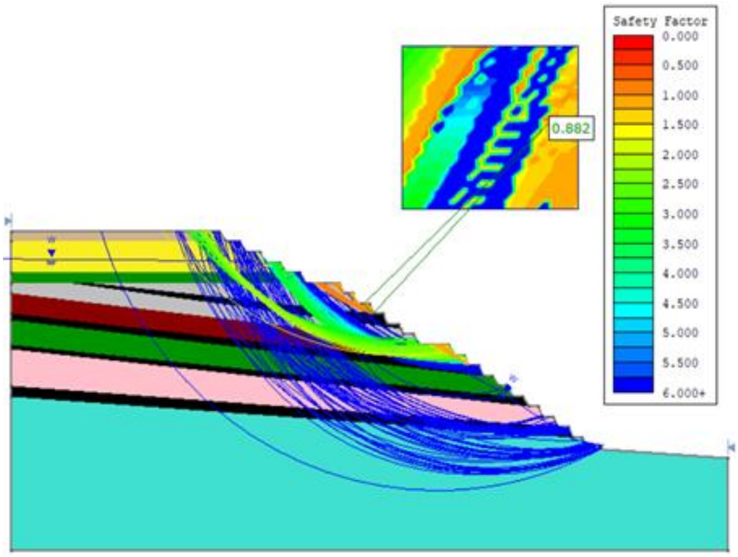

Figure 4: Slip circle obtained using Bishop's Method for existing slope. (FOS = 0.882)

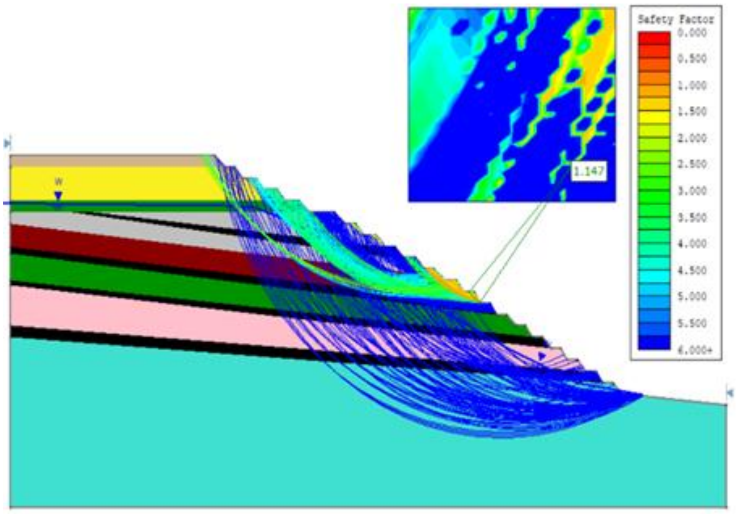

Figure 5: Slip circle obtained using Bishop's Method for the optimized slope. (FOS = 1.147)

5.2 FDM Analysis

The software FLAC/Slope was used for the analysis of slope using FDM.. Duncan and Christopher (2001) suggested norm was used to find out the stability of the slope (Table – 4). The output obtained are in terms of velocity and displacement vector as shown in Table 5. The FOS for the existing slope is 0.842 whereas for the optimized slope FOS is 1.16. Figures 6 and 7 show the results obtained in FLAC/Slope for the existing and optimized slope resp.

Table 4. Stability status based on norms (Duncan and Christopher, 2001)

Parameter	Status of Parameter	Status of Stability
Displacement and Velocity	Increasing displacement and velocity	Unstable State
Displacement and Velocity	Steady displacement and decreasing velocity	Stable State
Displacement and Velocity	Constant displacement and velocity	Failure
Velocity (ms^{-1})	Below 1e-6	Indicates Stability
Velocity (ms^{-1})	Above 1e-5	Indicates Instability

Table 5. Shear Strain Rate, Velocity Vector and FOS in existing and optimized slope.

Parameter	Existing Slope of Rise Side	Optimized Slope of Rise Side.
Shear Strain Rate (s^{-1})	5.00E-05 to 7.50E-04	2.50E-06 to 3.00E-05
Maximum Velocity Vector (ms^{-1})	2.172E-02	1.018E-03
FOS	0.842	1.16

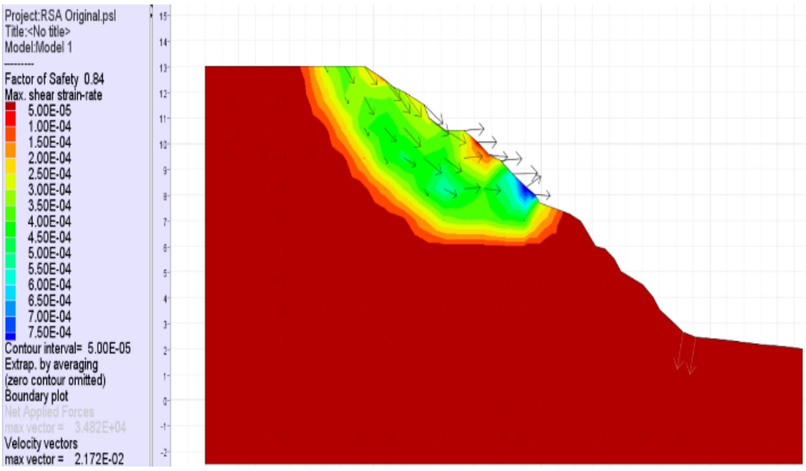

Figure 6: Slip circle obtained in FLAC/Slope for existing slope on rise side (FOS = 0.84)

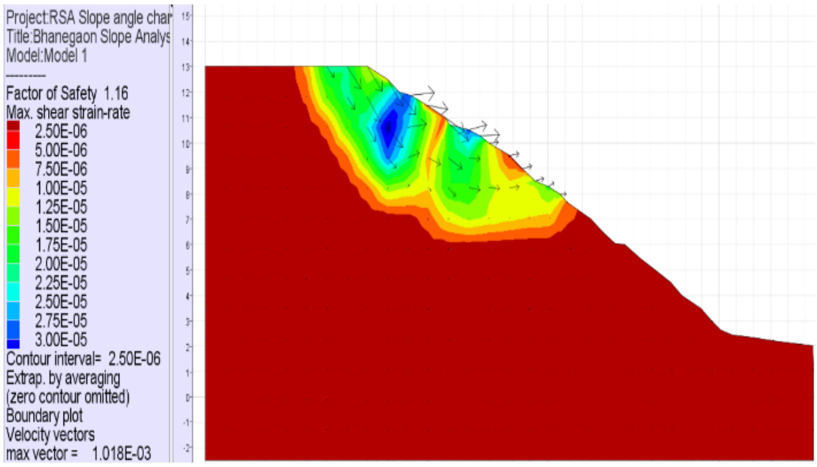

Figure 7. Slip circle obtained in FLAC/Slope for optimized slope of rise side. (FOS = 1.16)

Thus, comparison of FDM results for existing and optimized slope, it is found that there is a reduction in the velocity vector as well as the shear strain rate, but it does not totally satisfy the other norms given by Duncan and Christopher, hence we carry out FEM analysis for existing and optimized rise side slope.

5.3 FEM Analysis

After analysing the slope using the above two methods, we proceed to FEM analysis of the slope. In FEM a two dimensional analysis of the slope is conducted using the software Rocscience Phase 2.0. In this software the model is divided into 3 node triangular mesh in which the outputs are stress, strain, plasticity etc. Mohr Coulomb Failure criteria is adopted for the analysis of slope and the SRF was used to calculate the critical SRF, and displacement.

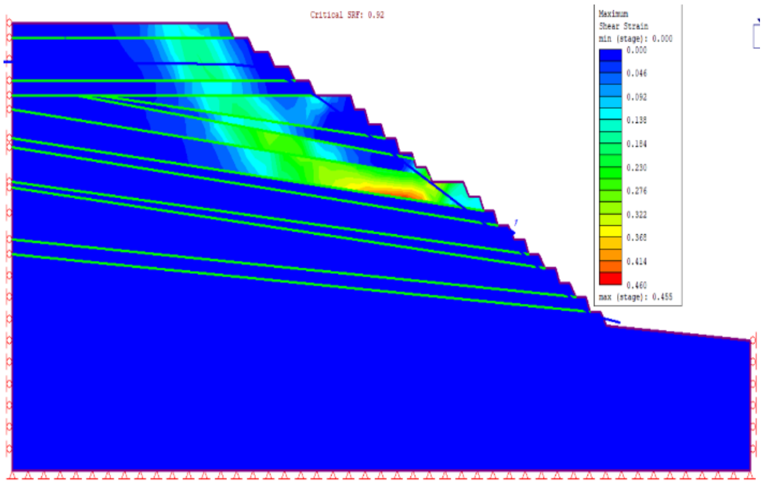

Figure 8. Distribution of strain on existing slope (max shear strain = 0.455)

Figure 8 and 9 shows distribution of strain in the existing and optimized slope. The highest shear strain value of 0.455 is observed between 6th to 10th benches at a distance of 40 to 50 meters below from the surface of the slope. Whereas in the case of the optimized slope of the mine maximum shear strain reduces to 0.281 which is prevalent at a distance of 40 meters below from the surface of the rise side of the slope.

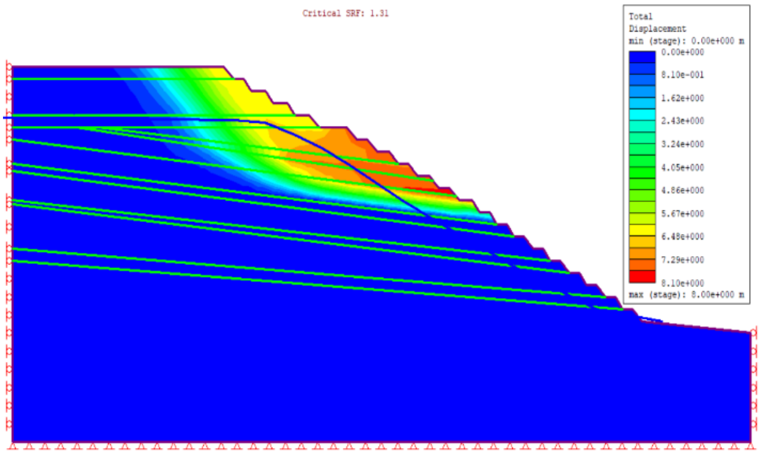

Figure 9. Distribution of strain on optimized slope (max shear strain = 0.281)

FEM analysis gives plot between the maximum displacement and SRF. As SRF increases, strength properties decreases. The maximum value of the SRF for which the solution converges is termed as Critical SRF or the FOS. The FOS obtained for the existing slope is 0.92 with a maximum total displacement of 11.027m, whereas the FOS for the optimized slope turns out to be 1.31 with a maximum displacement of 9.405m. Figures 10 and 11 shows displacement contour and the graph between SRF and Maximum total displacement resp. for existing condition of the mine.

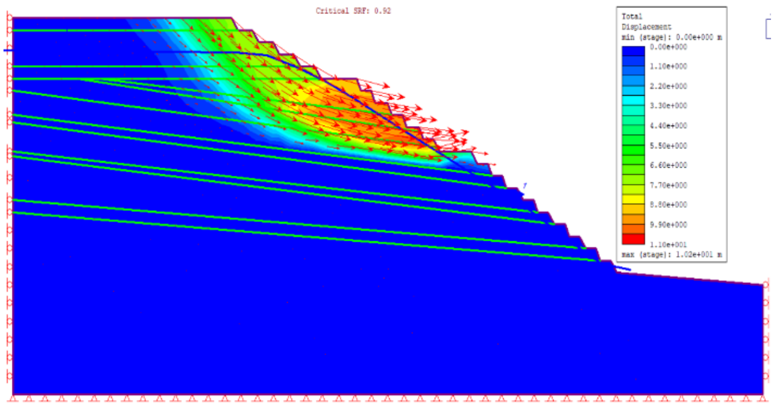

Figure 10. Displacement contour of the existing slope in Phase 2.0 (max Disp. = 11.027m).

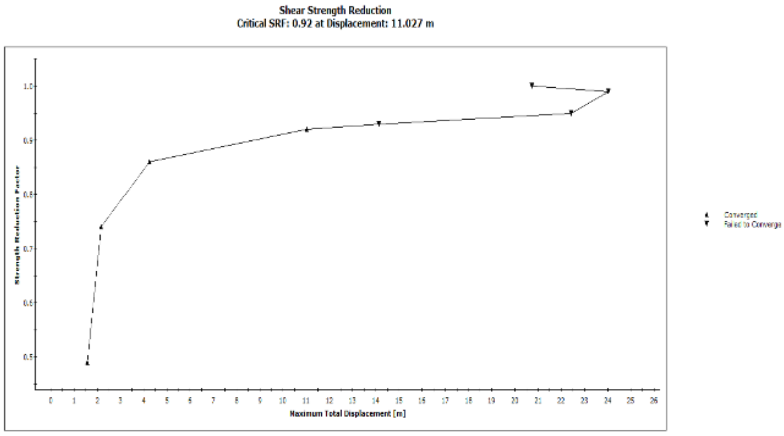

Figure 11. SRF vs max total displacement graph for the existing slope

Figures 12 and 13 show the results obtained in phase 2.0 for the displacement of the optimized slope and the graph between maximum total displacement and SRF respectively.

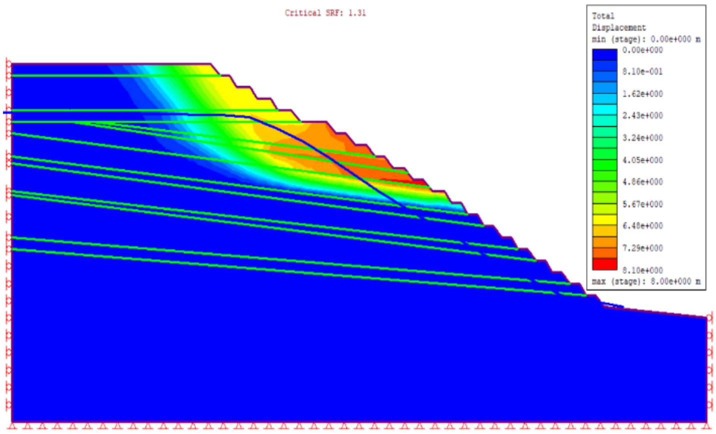

Figure 12. Displacement contour of the optimized slope in Phase 2.0 (max Disp. = 9.4m)

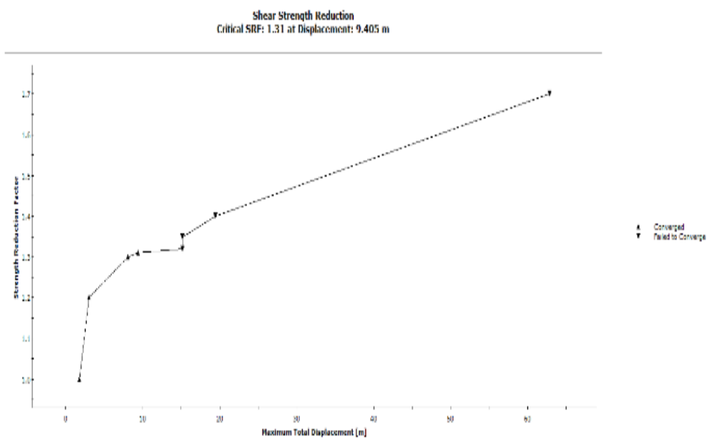

Figure 13. SRF vs Max Total Displacement graph for the optimized slope.

The plasticity analysis of the existing and optimized slope in FEM is shown in Figures 14 and 15 resp. Results for both slopes are almost similar. The failure in tension is indicated by a symbol O, whereas the failure in shear is indicate by the symbol X. The upper 20 m zones of the slope are occupied by the shear elements. These shear elements extend towards the benches of the slope. The presence of these elements show that the slope is prone to sliding failure towards the dip side. High concentration of the tension elements is observed dipping towards the dip side just below the zone of shear elements. The presence of tensile zones suggests that the material is weak in tension and may initiate formation of tension cracks and lead to high permeability of water. These cracks further worsens the stability condition of the rise side slope of Bhanegaon Opencast Mine. Thus, plasticity result suggest that the slope is vulnerable to both the types of failure that is shear and tensile.

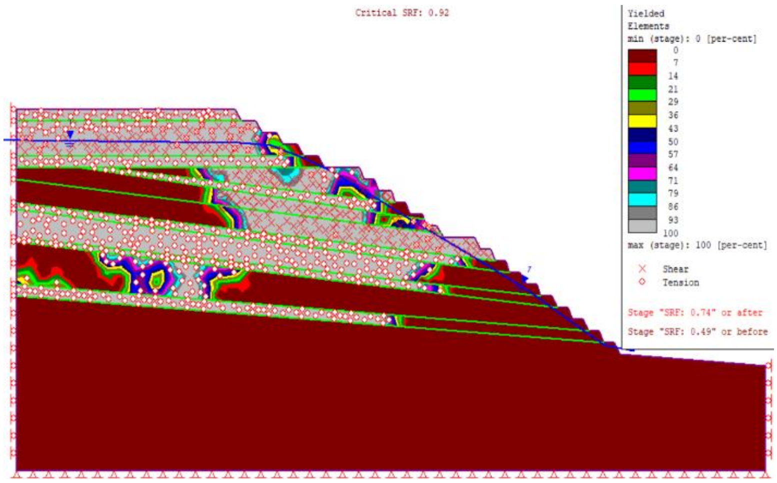

Figure 14. Plasticity values and distribution on the rise side of the existing mine.

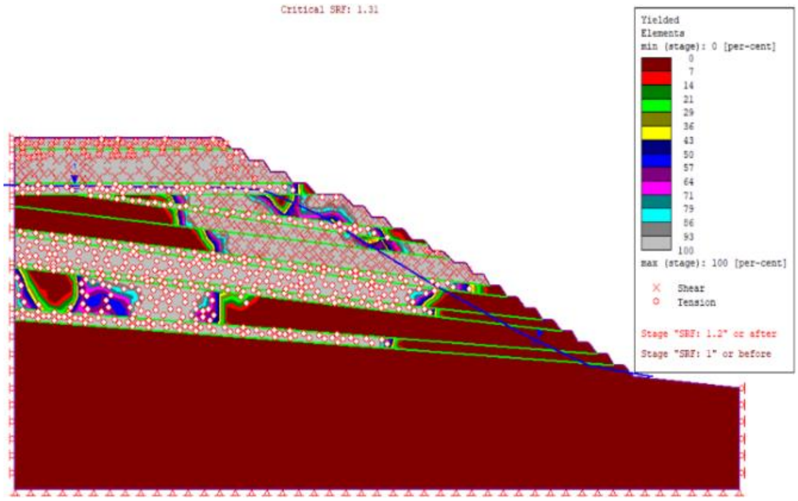

Figure 15. Plasticity values and distribution on the rise side of the optimized mine.

VI. CONCLUSIONS

From the present study of slope stability analysis of rise side of Bhanegaon Opencast Mine, following conclusions are drawn.

- The LEM analysis fails to deliver a convincing solution when water is present in the slope. The FOS obtained, is not acceptable when water is present in the slope, as it gives erroneous results.
- Water plays an important role in deciding the slope stability of the mine. It has been observed that for undrained conditions of slope FEM and FDM gives almost similar results.
- The analysis using FDM indicates a maximum velocity vector of 2.172E-02 and 1.018E-03 for the existing and optimized slope respectively. It shows that the velocity vector is reducing as the saturation level of slope reduces. This amounts to increase in stability of rise side slope.
- In case of failure of existing slope, the toe will be undergoing displacement above 11.047 m and in case of optimized slope the displacement is 9.405m. This helps in monitoring the slope stability.
- Amongst the overall slope angle and hydrostatic pressure, the hydrostatic pressure seems to be more sensitive in stabilizing the slope. Ten percent lowering of water table from its initial position lead to an increase of FOS by 37 % whereas the slope angle when flattened by 10 % increases the FOS by only 16 %.

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