



The effect of blasting on bench stability by the numerical modelling in basanthnagar limestone quarry

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Abstract. The study of blast effect on bench stability is indispensable, because the overall stability of the quarry's slope is directly linked to it. For this purpose, a study is conducted in a limestone quarry. Before the stability analysis, a fragmentation evaluation is carried out by two methods, by the Kuz-Ram model and the Digital Image analysis method using the WipFrag program, this part of the work aims to establish a more efficient blast design that assures a better fragmentation and a higher stability for the quarry's structure. Afterwards, a numerical stability analysis approach is adopted, by employing the Finite Element Method (FEM) through the Phase² software. A 2D numerical model of the quarry's profile is constructed, on which simulations are carried out for two cases: 1- static conditions; 2- Dynamic conditions using the proposed blast design. This analysis goals are to define the possible deformation that the blasting process could engender to the benches and its effect on bench's stability as an individual case and on the overall stability of the slope in general.

1. Introduction

Drilling and blasting is a preferred method of rock excavation world-wide due to low initial investment, cheap explosive energy, easy acceptability among the blasting engineers and, possibility to deal with different shapes and sizes of openings. Although, drill and blast method has witnessed significant technological advancements, it has inherent disadvantage of deteriorating surrounding rock mass due to development of network of fine cracks in it leading to safety and stability problems [1]. Blasting is usually required to produce easily excavated broken rock, while leaving surrounding rock masses as undamaged and stable as possible [2]. However, it is a well-known fact, that, presently only a meagre percentage of total explosive energy is being utilised in fragmenting and displacing the rock mass [3].

Bench stability dictates overall slope stability and affects utilization of haul road above and below it [4]. Risk of failure is directly related to the stability of a bench, and this in turn is related directly to the danger of rock collapse, which could threaten personnel and machinery at the foot of the pit wall or bench [5].

2. Methodology

The object of the present paper is the analysis of the blasting process's effect on bench stability in a limestone quarry. The Basanth Nagar limestone quarry (limestone deposit) is subject to this study. For this matter, numerical modelling, by means of the Finite Element method (FEM), is the adopted approach. Before the stability analysis, a fragmentation evaluation is conducted by a comparative study between a Kuz-Ram fragmentation prediction and a Digital Image Analysis. The objective of this part of the work is the improvement of the blasting design for a more satisfying fragmentation, a more tolerable oversized fragments rate from the overall blasted rock volume, and for a better bench stability, ergo, a better overall slope stability in the quarry.

Firstly, Kuz-Ram simulations were run, while introducing a modification to the blast design to find a combination of blast parameters that allows the lower possible oversized fragments percentage and mostly an optimal usage of the explosives. Once this new blast design is set, it is applied in the field, the resulted muck-piles are analyzed by the Digital image analysis method. The results of this



analysis are compared to those obtained by the Kuz-Ram model, for both the old and the modified blast design.

2.1. The Kuz-Ram Model

Cunningham introduced the third generation of the Kuz-Ram models in 2005 [5], in which new equations for both the mean size and the uniformity were introduced, while the adapted Rosin-Rammler function (2) stayed unchanged. This removes some of the deficiencies of the previous models and takes into account new blast parameters like initiation and delay. There are also explicit calibration factors when the model is calibrated for different blasting sites [6]. The model equations were presented as follows:

$$x_{50} = A_t \cdot A \cdot Q^{1/6} \left(\frac{115}{RWS} \right)^{19/30} / q^{0.8} \cdot C(A)$$

Where: x_{50} is the median fragment size, cm; A_t is the (delay) timing factor; A is the rock factor (varying between 0.8 and 22, depending on hardness and structure); Q is the mass of explosive in the hole, kg; RWS is the weight strength relative to ANFO, 115 being the RWS of TNT; q is the powder factor, kg of explosive per cubic metre of rock [5-6].

The first model's equation in (Eq.13 in [5]) refers to x_m , the mean particle size and should be interpreted as the median fragment size x_{50} . The Kuz-Ram papers should be read with care as there are formula errors [6].

$$R_x = \exp \left[-0.693 \left(\frac{x}{x_m} \right)^n \right]$$

Where: R_x is the mass fraction retained on screen opening x ; n is the uniformity index, usually between 0.7 and 2.

$$n = n_s \cdot \left[\left(2 - \frac{30B}{d} \right) \right]^{1/2} \cdot \left[\left(\frac{1+S/B}{2} \right) \right]^{1/2} \cdot \left(1 - \frac{W}{B} \right) \cdot \left(\frac{L}{H} \right)^{0.3} \cdot \left(\frac{A}{6} \right)^{0.3} \cdot C(n)$$

Where: n_s is the uniformity factor, S = spacing, m; B = burden, m; W = standard deviation of drilling, m; d = hole diameter, mm; L = charge length affecting fragmentation, m; H = bench height; $C(A)$ and $C(n)$ are the factors used to adapt or 'calibrate' (1) and (3) to specific site conditions. Normally $0.5 < C(A) < 2.0$ [5-6]. The factor $(A/6)^{0.3}$ is missing in equation 14 from [5] but the text and the table 1 in [5] describe its existence. Thus the rock mass properties now influence the uniformity index n [6].

2.2. Digital Image Analysis

Digital image analysis systems have become practical and useful tools for measuring the performance of explosives in breaking rock, determining the validity of blast models. The WipFrag fragmentation sizing system, is one of the programs used adapting this technique, it has been in widespread use for many years now. It is being used in the explosives, mining, and materials handling industries for the purpose of evaluating the efficiency of the comminution process, whether by blasting, crushing, grinding, or inadvertently by material handling processes [7].

During this part of the work, images of muck piles were taken, these images are then processed using the WipFrag software. This process is applied for resulted muck piles using the old blast design, and those resulted from using a proposed blasting design by the authors. Afterwards, the obtained estimations for both designs were compared.

2.3. Finite Element Method (FEM)

In the present study, the finite-element method, through Phase² (version 8.0) was used for the analysis. The Phase² software is a powerful 2D elastoplastic finite element stress analysis program for underground or surface excavations in rock or soil. One of its major features is finite element slope stability analysis using the shear strength reduction (SSR) method. This option is fully automated and can be used with either Mohr-Coulomb or Hoek-Brown strength parameters [8].

3. Casestudy

The case study, the Basanth Nagar limestone deposit, is located 34 km North-East of the Karimnagartown, and 10.5 km South-west of Ramagudam. The geological reserves, according to the limits of the deposit and the exploitation works progress, are estimated at 97 million tons of limestone. These reserves are still sufficient to supply the Its own Kesoram cement plant for more than 50 years for the capacity of 1,000,000 tons of clinker production per year. The Basanth Nagar limestone has a rock specific gravity of 2.6 t/m³; a uniaxial compressive strength (UCS) of about 772.4 kgf /cm² (UCS ≈ 75.75 MPa). The deposit is characterized by a highly fractured rock mass. Figure 1 indicates the location of the Basanth Nagar limestone deposit, the Kesoram cement factory along the mechanical preparation station (crushing, milling, screening... etc.).



Figure 1. Google Earth image of the Basanth Nagar limestone deposit and the Kesoram cement factory.

4. Results and discussion

4.1. Fragmentation evaluation

According to Jimeno et al [9], usually, in the case of rotary percussive drilling, the blastholes are inclined, which, in bench blasting, gives numerous benefits amongst which, a better fragmentation, displacement and swelling of the muck pile, as the burden B value is kept more uniform along the length of the blasthole and the angle of the projection direction of the shot increases (Figure 2); and Lower powder factor as the shock wave is reflected more efficiently in the bench toe and the possibility of increasing burden size with less risk of toe appearance (Figure 3) [9].

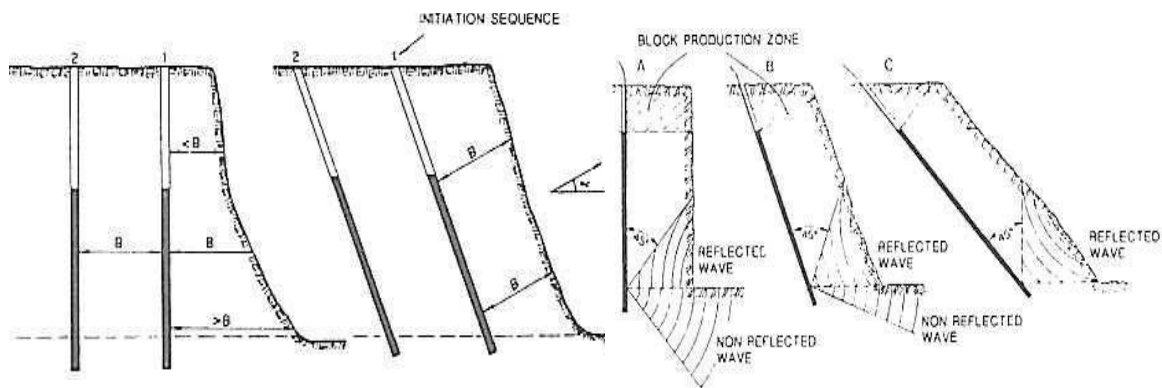


Figure 2. Inclined drilling vs. vertical drilling [9].

Figure 3. Benefits of inclined holes [9].

In bench blasting, the normal blasthole patterns are either square or rectangular, owing to the ease with which the collaring points can be marked out. However, the most effective are staggered patterns; especially those drilled on an equilateral triangular grid, as they give optimum distribution of the explosive energy in the rock and allow more flexibility when designing the initiation sequence and the break direction. This pattern produces the best fragmentation, with a spacing (S) to burden (B) ratio of $S = 1.15B$ for vertical blastholes and $S = 1.15B \cdot \cos \alpha$, where α is the angle with respect to the vertical in inclined holes [9].

So, as a second modification in the blast design, staggered pattern is adopted to replace the currently used square pattern, as for the S/B ratio, it has been varied and simulations were run by the Kuz-Ram (for each of the previously mentioned inclination angles), for the following S/B ratios:

$S = 1.05B \cdot \cos(\alpha)$; $S = 1.10B \cdot \cos(\alpha)$; $S = 1.15B \cdot \cos(\alpha)$ (Table 1). Based on the results obtained by the Kuz-Ram

simulations for the uplisted combinations charge lengths and burden to spacing ratios, the following combination is chosen: $\alpha = 10^\circ$; $S = 1.05B \cdot \cos \alpha$; using a staggered pattern. This new combination of blast parameters allowed a 2.50 percent decrease in the oversized fragments percentage (22.8% to 20.3%), while keeping the same powder factor, but a very low increase in the predicted average size of fragments of only 1 centimeter (72 cm to 73 cm).

Table 1. Hole and charge lengths corresponding to each dip angle.

	Units	Values			
Borehole dip angle	°	0	5	10	15
Hole length	m	16	16.06	16.24	16.56
Charge length	m	13.45	13.51	13.69	14.01
Burden	m	4	4	4	4
$S = 1.05B \cdot \cos \alpha$	m	4.20	4.18	4.13	4.05
$S = 1.10B \cdot \cos \alpha$	m	4.40	4.38	4.33	4.25
$S = 1.15B \cdot \cos \alpha$	m	4.60	4.58	4.53	4.44



The proposed design has also permitted a considerable decrease in the overall used charge of explosives, estimated to 172.8Kg (3762.88kg to 3590.70kg); add to this a decrease in the overall length drilled per blast operation, 487.20 meters instead of 512 meters (24.8 m), the modifications applied to the blasting design are summarized in table 2 along with the new total explosives charge weight and total drilled length.

Table 2. Proposed blasting design vs. old blasting design

	Unites	Old design	Proposed design
Pattern type		Square	Staggered
Hole Diameter	mm	110	110
Charge length	m	13.45	13.69
Burden	m	4	4
Spacing	m	4	4,13
Bench Height	m	15	15
Drilled length	m	512	487.2
Borehole dip angle	(°)	0	10
Powder Factor	Kg/t	0.19	0.19
Number of holes per row		32	15
Number of rows		1	2
Total length drilled	M	512	487.2
Volume of rocks to blast	m ³	7440	7440
Charge weight per hole	Kg/hole	117.59	119.69
Total charge weight per blast	Kg	3762.88	3590.70
Charge Weight per delay	Kg/delay	352.77	359.07

Employing the proposed blast configuration, two blasts were realized, the resulted muck piles were analyzed using the WipFrag Software (uploading images, scale setting, manual editing of the net). The same steps were followed in the analysis of muck piles images resulted of two blasts using the old blast design. The results of the analysis are shown in table 3 with a comparison to results obtained by the Kuz-Ram model.

Table 3. WipFrag image analysis results for the proposed and the old blasting designs.

	Blast number	1200 mmpassing percent (%)	Percent oversize (%)	Mean percent oversize (%)	Mean size of materials (mm)
Old design	1	74.35	25.65	30.73	658.90
	2	64.19	35.81		
	Kuz-Ram	77.2	22.80	22,80	720.00
Proposed	1	88.88	11.12	15.13	276.55

Design	2	80.86	19.14		548.91
	Kuz-Ram	79.7	20.30	20.30	730.00

4.2. Stability analysis

Figure 4 shows the constructed numerical model of the Jebel Medjounes quarry's slope with a 66.5m height and slope angle varying from 80° to 85°. The Mohr-Coulomb failure criterion has been chosen for the analysis. A mesh graded (6 noded triangles) with 257133 nodes has been used.

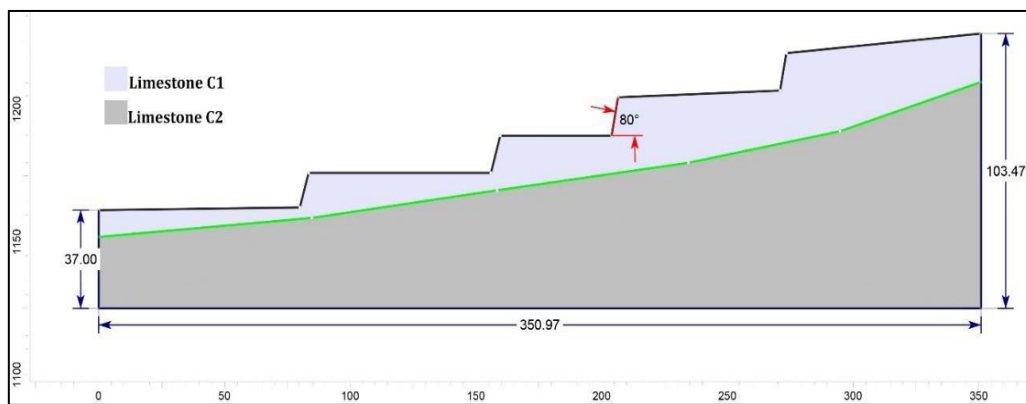


Figure 4. Numerical model of the studied profile

The geotechnical properties used for the analysis are listed in table 4. The model comprises two limestone layers, the first one is the main (ore), and the second layer is a marly limestone which isn't mined.

Table 4. Geotechnical properties of materials for the numerical model.

Parameter	Name	Unit	Materials	
			Limestone C1	Limestone C2
Unit weight	γ_{sat}	MN/m ³	0.026	0.025
Young's modulus	E_{ref}	MPa	27000	19000
Poisson's ratio	ν		0.4	0.3
Friction angle	Φ	(°)	48.5	35
Cohesion	C	MPa	1.64	0.85
Dilation Angle	ψ	(°)	18.5	5
Failure criterion			Mohr-Coulomb	
Mesh and element type			Graded, 6 noded triangles	

Another important feature when doing an SSR analysis is the ability to plot maximum deformation (displacement) versus SRF, as the SRF is increased, the strength properties are decreased; and as the strength decreases the maximum displacement increases. At some point, the slope will fail, deformations will increase rapidly, and the finite element analysis will not converge. It is this point of non-convergence that defines the critical SRF. The plot of the Shear Strength Reduction Factor versus the maximum displacement, in both static and dynamic loads, are presented in Figure 5, show the points of convergence of the numerical analysis towards a solution in each case.

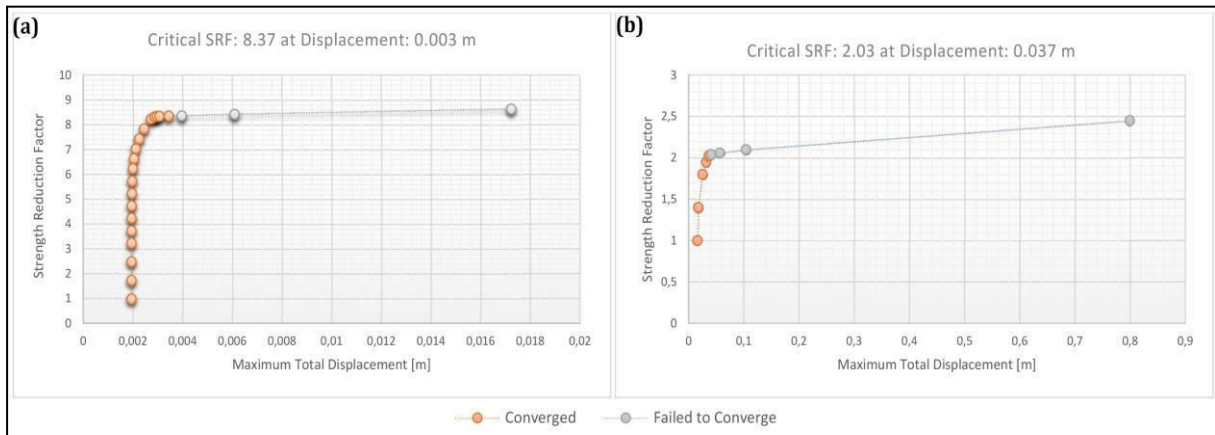


Figure 5. Strength reduction factor vs. Maximum total displacement in the case of (a) static load and (b) dynamic load

The critical Strength Reduction Factor (Critical SRF) is the maximum value of SRF for which the model remains stable (i.e. the analysis converges). This is the uppermost green data point on the graph. For the static load the critical SRF = 8.37 at a displacement equal to 0.003 m (figure 5(a)), and for the dynamic load the critical SRF = 2.03 at a displacement equal to 0.037 m (figure 5(b)). The analysis as it is demonstrated in the plots failed to converge beyond the mentioned displacement values. We can notice through figure 6(a) that the maximum shear strain in the static load is located in the upper most part of the model (upper bench) and lower bench's toe, however in the dynamic load, as figure 6(b) shows that the maximum shear strength is only focused in the upper bench.

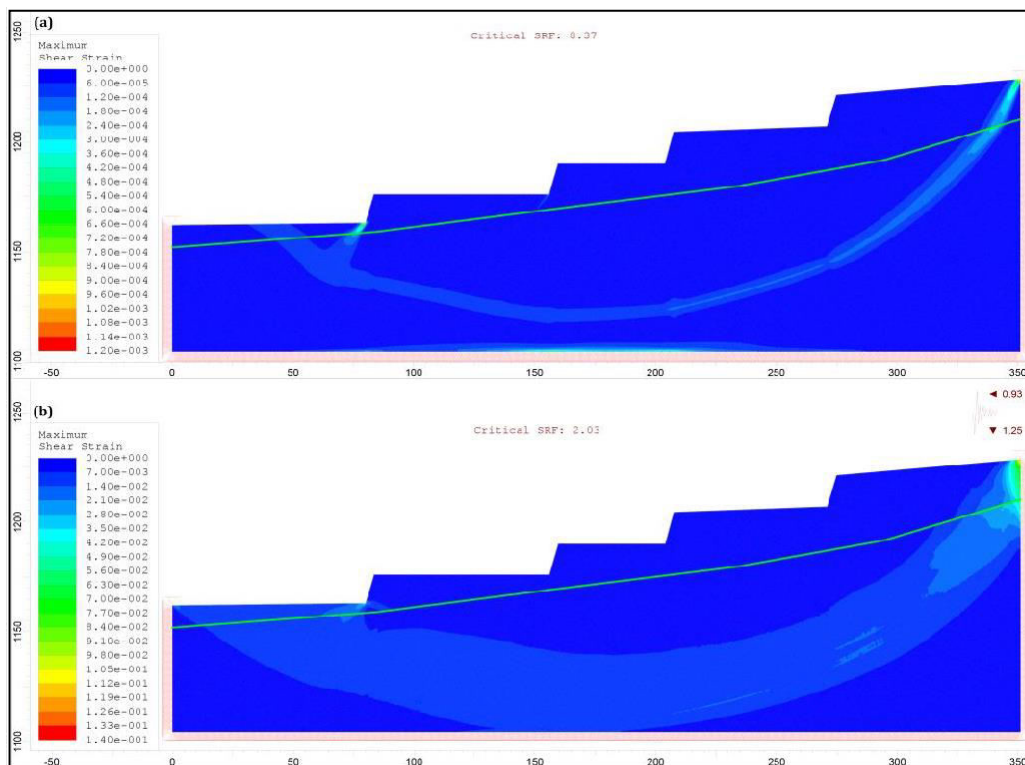


Figure 6. Maximum shear strain in the case of (a) static load (b) dynamic load.

Figure 7 illustrates that the maximum displacement occurs at the top and bottom bench, the displacement contours highlight the failure zone. The maximum displacement values obtained in

the static and dynamic loads are respectively 0.003m (3mm) and 0.037m (37mm).

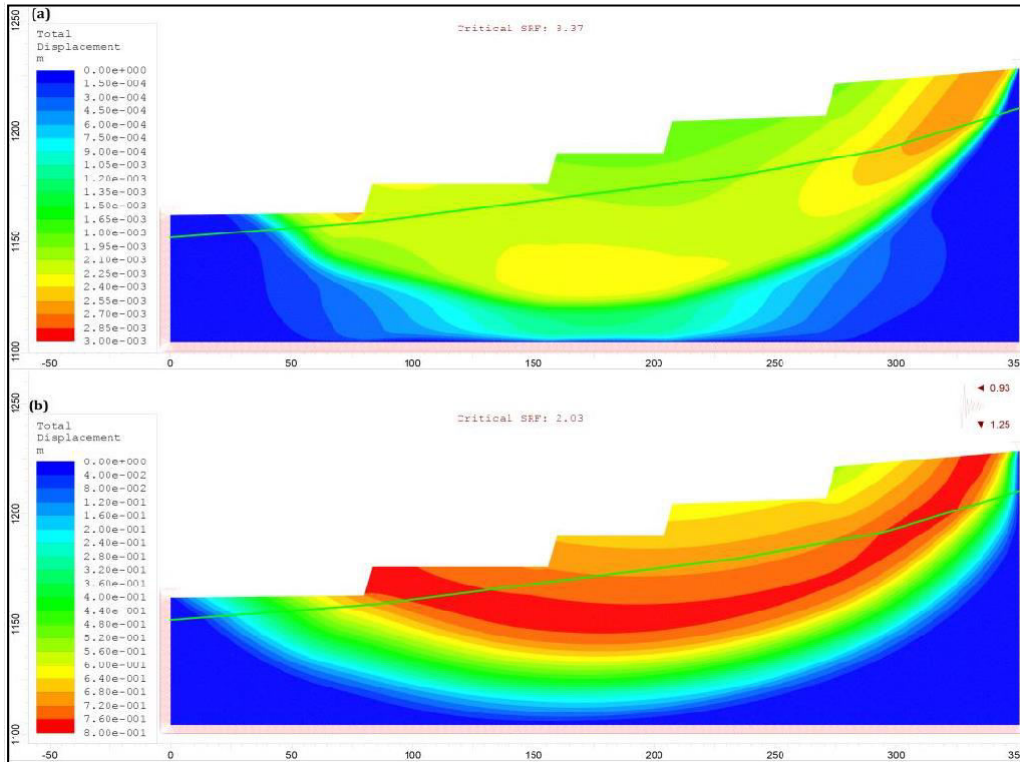


Figure 7. Total displacement in the case of (a) static load (b) dynamic load.

The direction of displacement, on the other hand, is vertically downward for the uppermost bench and horizontally downward for the lowermost bench, suggesting a possible mass detachment from the slope. Therefore, the deformation occurs both vertically from the upper part of the model where the failure happens and horizontally towards the out of the model's exterior boundaries in the direction of the free face.

5. Conclusion

In this paper, the stability of a numerical model of a slope made of four benches has been simulated by the finite element method considering both static and dynamic conditions at which the rock mass is subjected. The results obtained by this method have been analyzed. The critical factors of safety issued by the numerical analysis are 8.37 and 2.03 for the static and the dynamic loads respectively. The results obtained for the dynamic conditions, $SRF = 2.03$ and total displacement of 0.037m, indicate that the slope could be a stable even during the blasting process, especially for the middle benches, in exception of a slight deformation zone that is highlighted by the displacement contours, in the upper bench of the model the maximum displacement in this zone is estimated to about 4cm in the direction of the free face (out of the model's boundaries) and downwards for the vertical displacement.

It is important to point out that although the possible deformation that the seismic loading could generate is a small zone, its effect on the safety factor is significant, where it dropped from $SRF = 8.37$ to $SRF = 2.03$. It is then possible to assume that slightly bigger charge would have induced a larger deformation zone.

During the first part of this work, it has been established that inclined drilling has substantial advantages over vertical drilling, it has been demonstrated that with a 10 degree inclination considerable economical savings could be achieved, whereas a decrease in the total charge of explosives to be used and the total length to be drilled.

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