FEM Comparison of crack response to blasting ground vibrations and environmental changes

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One of the negative effects of blasting at open pit mines is induced seismic wave or ground vibrations. These vibrations can in some cases have high magnitude and cause damage to the nearby structures. Those cases rise question of causal connection between blasting operations and damage to structure, and hence blasters liability for damage.

One of the approaches for solving this question is crack response monitoring which states that the causality exists if the cracks in the structure respond to ground vibrations and if this response is higher than the response to other, non-blasting related factors.

This article is the criticism of interpretation of crack monitoring results since even in those cases when blasting influence is considerably smaller than other influences it can not, and should not be neglected because is the fact that it exists.

A FEM analysis is used to compare crack responses to blasting ground vibrations and environmental influences considering the stress state (expressed by stress intensity factor) around the crack tip and to determine equivalent crack responses in the form of crack opening.

Key words: *structures, blasting vibrations, crack responses, FEM analysis, SIF*

1. Introduction

According to the traditional approach [1], causality between the blasting operations at open pit mines and damage to the nearby structures, and hence blasters liability, exists only it ground vibrations peak particle velocity was higher than the regulatory limit and if the particular damage appeared during the passing of the blast induced seismic wave. In other words, if damage existed prior to the blast there is no liability. However, a problem arises when the particular structure is already damaged and hence weakened or its resistance degraded. In that case, a new, crack response monitoring approach is used. This approach was suggested by C.H. Dowding at all, and is now widely accepted in vibration caused damage research [2,3,4,5]. The crack response is in the form of changes in crack width and causality is determined based on the magnitude of this response. If the magnitude of crack response is smaller than the response to other, non-blasting related influences, the seismic wave and resulting ground vibration have no potential to cause damage to the structure so there is no liability.

A number of researches [6,2,3,5] point out the significant influence of non – blasting related factors such as daily temperature changes, variations in the air humidity, foundation settlement and human everyday house activities. Results of these researches indicate that the influence of blast induced vibrations to structures is much smaller compared to other non-blasting related factors and when that is the case, the blasting influence should not be taken into account. However, even in those cases when blasting influence is considerably smaller than other influences it can not, and should not be neglected because the fact is that it exists.

The basic difference between non-blasting and blasting related influences is the time of their duration and hence the time of the stressed state of the constructive elements of the structure. Environmental changes, as non-blasting related influence, are slow processes lasting several hours or days. During that time, the stresses arise in accordance to the excitation and have sufficient time to redistribute within the constructive element. Due to the low speed of excitation, resulting stresses can be considered, and are static.

On the other hand, blasting ground vibrations are short term excitations that give rise to dynamic stresses in the constructive elements of the structure. The duration of excitation, in the order of several seconds, does not allow redistribution of the stresses and they remain concentrated, primarily on the crack tip.

Considering all of the previously mentioned, the basic hypothesis of the paper is that regardless of the considerably smaller magnitude of crack response to blasting ground vibrations, stresses arising from this influence can have the same or even higher value than stresses from environmental influences, and hence, the probability of damage is higher.

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2. Crack responses

In order to perform the comparison of blasting and non-blasting related influences two sets of crack responses were recorded. The first set is the crack in the wall of the structure in order to monitor and record the changes in the crack width. The thermograph and hydrograph were set on the same location to measure and records the changes in air temperature and humidity. The particular monitoring covered 37 hours, from 9 PM on Wednesday to 10 AM on Friday. This time frame was chosen in order to cover full range of daily temperature changes. The results of monitoring are given in figure 1.

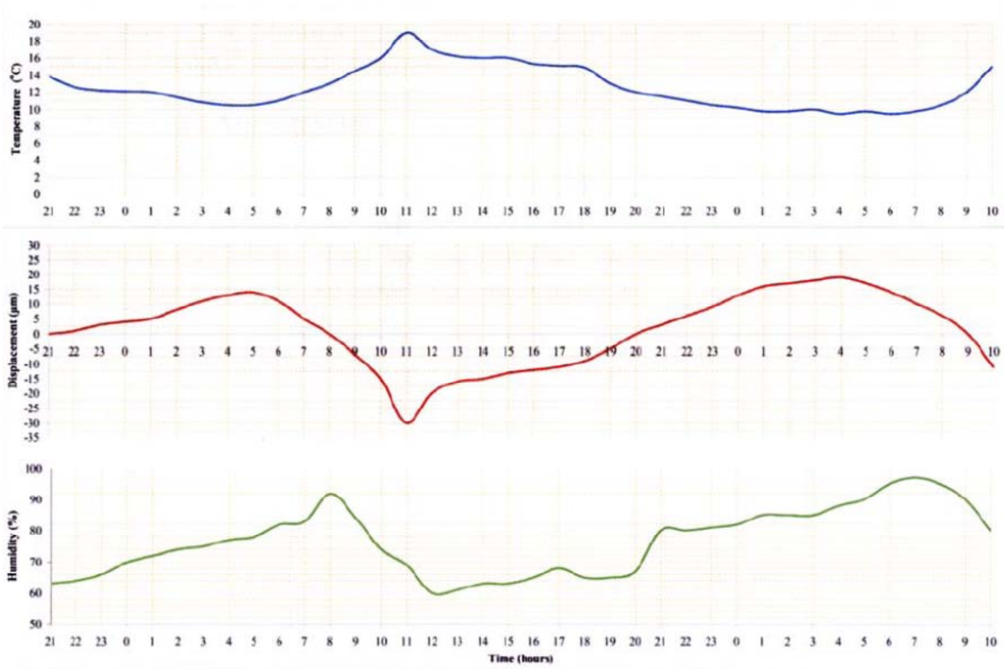

Fig. 1. Crack response to environmental influences.

The second set is crack response to blast induced ground vibrations with peak particle velocity – PPV of 4.93 mm/s. The results of this monitoring are given in figure 2.

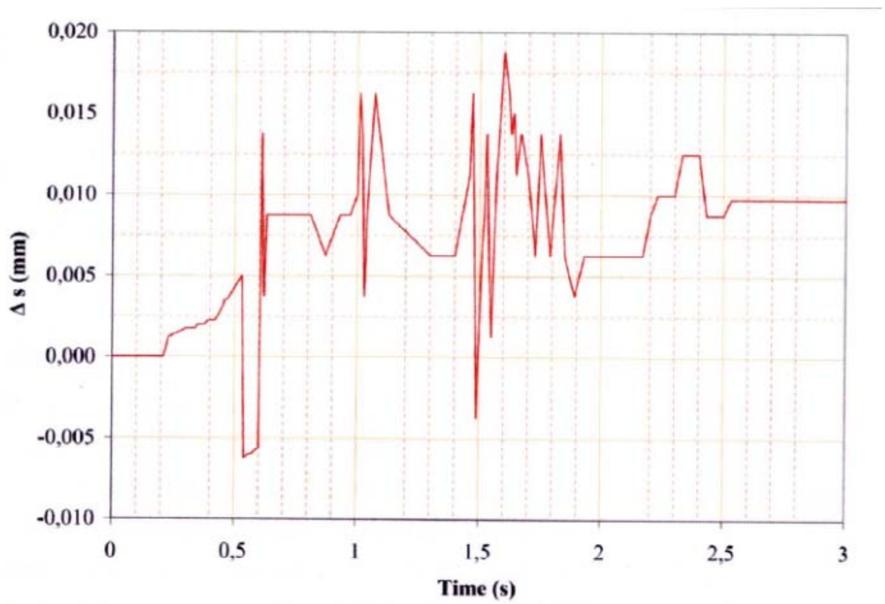

Fig. 2. Crack response to blast induced ground vibrations.

As it can be seen from the figure 1, crack response is in high accordance with the temperature changes. With the increase of the temperature and decrease of humidity the crack closes due to the thermal swelling of the wall and vice versa. Maximum temperature change was 9.5°C from Thursday 11 AM to Friday 4 AM. Corresponding crack response (peak to peak displacement) in the form of crack opening was 50 µm.

It can be seen from the figure 2 that structure motions due to ground vibration excitation lasted less than 2.5 s. Maximum crack response (peak to peak) was 20 µm during 10 ms between 0.6th and 0.61st seconds of motion.

3. FEM comparison

3.1 Model

The model for the FEM analysis was created in accordance with fracture mechanics recommendations [7, 8, 9, 10]. Due to symmetry of the problem, a 2D half model was considered. The geometry of the model is given in figure 3.

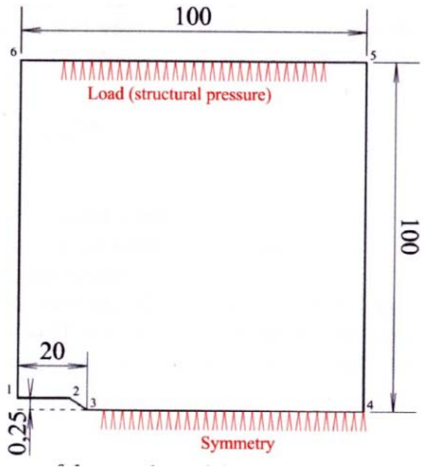

Fig. 3. Geometry of the crack model and applied loads (measures in mm).

The element type was solid, 8 node quadrilateral element (PLANE82) and the plain stress with thickness condition was assumed. The used material was linear, elastic and isotopic with Young's modulus, Poisson's ratio and density corresponding to concrete (E=30GPa, v=0.2 and γ= 2.4t/m^3 respectively).

The crack tip was defined as concentration point with 32 elements around the circumference and radius of first row of elements of 2.5 mm. The model was mashed with 8 node quad elements and the mash was denser around the crack tip and coarse in the rest of the model.

3.2 Loads

It is impossible to model all the variables that contribute to crack response (ground vibrations, soil/structure interaction, interaction between constructive elements, inertia of the structure, thermal conductivity and sensitivity to moisture of the materials etc.) Even if it was possible to model this, the analysis would require an enormous processing power and significant amount of time. Because of that, only structural pressure was applied as load, along the line 5 – 6. An independent analysis was undertaken to determine the magnitude of the structural pressure that would result in corresponding crack response, the analysis showed that structural pressure of σ=11 MPa results in 50 µm crack opening for non-blasting influence, and σ=2.1 MPa results in 20 µm crack opening for blasting related influence. The loads were applied in load steps with time steps corresponding to the duration of the particular influence. The load steps were used to allow the load to increase from zero to full value in accordance to the time of exposure. The time step for non–blasting influence analysis was 61200 s (17 hours) with substep of 500 s. The time step for ground vibration influence analysis was 10 ms with substep of 0.1 ms.

In addition, a symmetry boundary condition was applied along the line 3 – 4, and all the degrees of freedom were constrained for the keypoint 4.

3.3 ANALYSIS

A transient analysis of the model was performed in order to track the results over time. The result of interest was stress intensity factor (SIF) for crack opening mode **(K_1)** as it can determine stress state near the crack tip caused by a remote load.

As said, stresses resulting from the environmental influences were, due to the duration, considered static and ANSYS code built in macro was used to calculate SIF. On the other hand, blast induced ground vibration influence and resulting stresses are dynamic so dynamic SIF was used as the measure of the influence. Dynamic SIF was calculated according the equation (1)

$$K_{I-din} = \sqrt{\frac{GE}{1-v2}} \ , \ (Pa\ m^{1/2}) \tag{1}$$

where

G - Energy release rate J/m^2

E - Young's modulus of elasticity

v - Poisson's ratio

Energy release rate was calculated from the stored values of strain energy. Strain energy values were calculated for every substep of the analysis using ANSYS code. According to the virtual crack extension method energy release rate can be calculated as [7]

$$G = -\frac{U_{a+\Delta a} - U_a}{B\Delta a} \ ,(J/m^2) \tag{2}$$

*w*here

$U_{a+\Delta a}$ - strain energy for the crack length extended for Δa (J)

U_a - strain energy for the crack length a (J)

B - thickness of the model (m)

Δa - crack extension (m)

a - crack length (m)

In order to calculate energy release rate, a second analysis was performed for the crack length extended for 1% of its original length (nodes in the vicinity of the crack tip were scaled in the X direction by scale factor of 1,01).

3.4 RESULTS

The results of the analysis are plots of SIF over time displayed in figures 4 and 5.

It can be seen from the figures that in both cases SIF has a linear trend of growth over time but that SIF under dynamic loading (blasting ground vibrations) builds up more rapidly and has much higher values than under static loading (environmental factors).

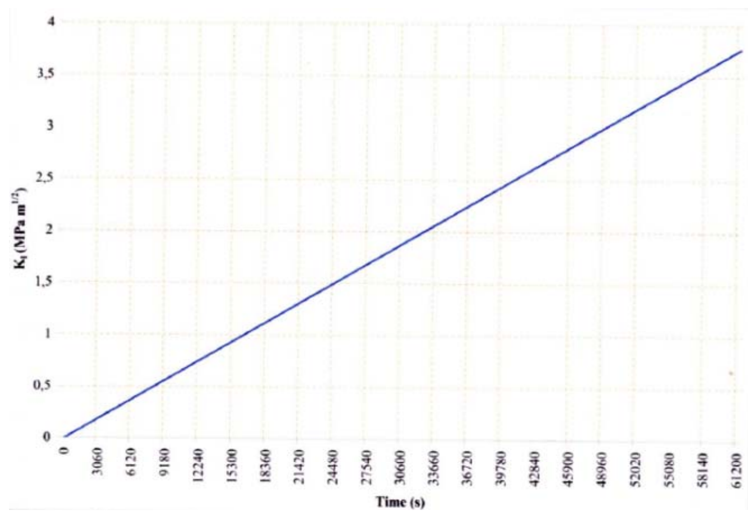

Fig. 4. Stress intensity factor over crack response, environmental factors influence.

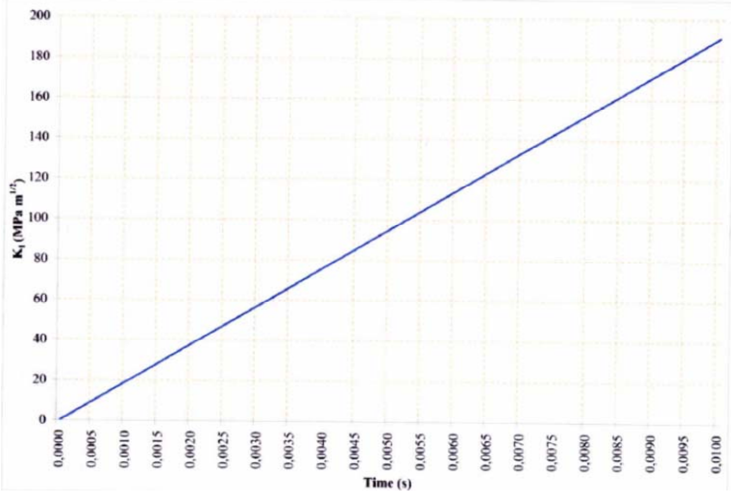

Fig. 5. Stress intensity factor over time, ground vibrations influence.

Another set of plots was created, SIF versus crack response, in order to determine equivalent crack responses in the terms of stresses under environmental influence and ground vibration influence.

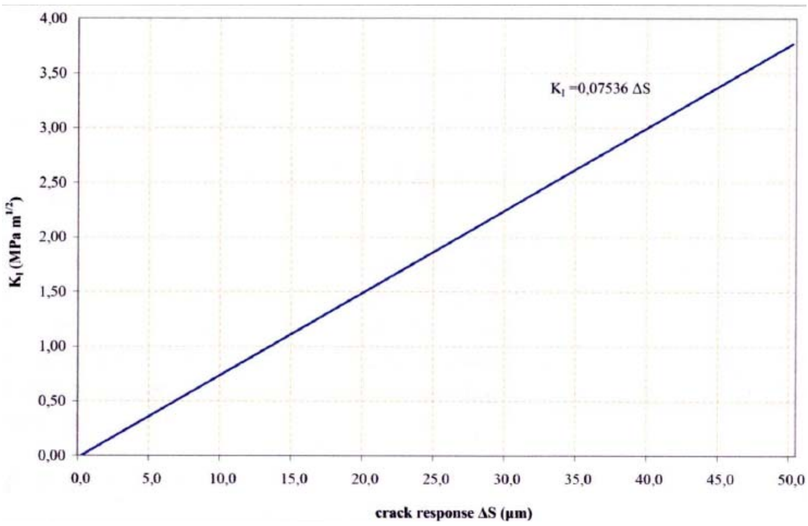

Fig. 6. Stress intensity factor over time, environmental factors influence.

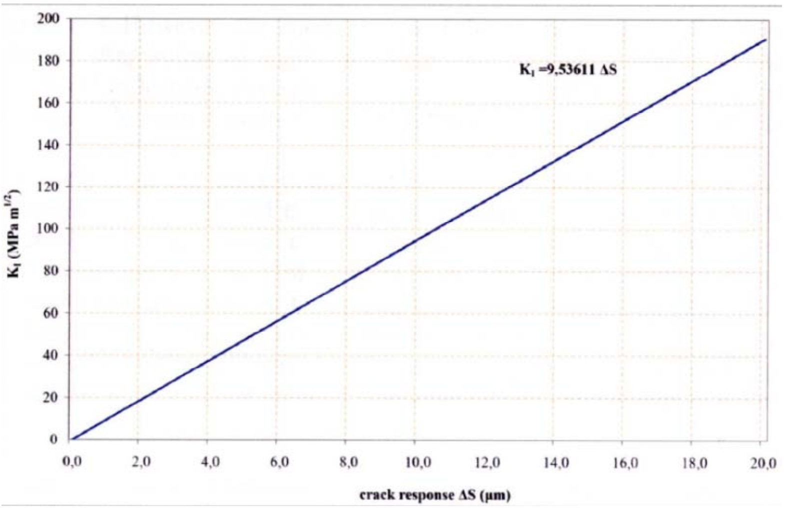

Fig. 7. Stress intensity factor over crack response, ground vibrations influence.

In this case too, SIF has a linear trend of growth with the increase of the crack response. The SIF is correlated to the crack response as

$$K_{Is} = 0.07536\ \Delta S_s\ , \tag{3}$$

for static load (environmental influences) and

$$K_{Id} = 9.53611\ \Delta S_d\ , \tag{4}$$

for dynamic load (blasting ground vibrations)

From the condition of equal stresses around the crack tip equivalent crack responses are determined as

$$0.07536\ \Delta S_s = 9.53611\ \Delta S_d$$

$$\Delta S_s = 126.54\ \Delta S_d$$

Or, from the condition of equal crack responses, stresses resulting from blasting ground vibrations and environmental influences are in relation as

$$\frac{K_{Id}}{9.53611} = \frac{K_{Is}}{0.07536}, \rightarrow K_{Id} = 126.5 K_{Is}$$

This means that, for equal stress state around the crack tip, crack response, in the form of crack opening, to blasting ground vibrations will be 126 times smaller in value than crack response to environmental factors, Also, for equal values of crack responses to blasting ground vibrations and environmental factors, stresses around the crack tip, resulting from ground vibrations influence, will have 123 times higher magnitude than stresses resulting from environmental factors.

4. Conclusion

Crack response monitoring approach gives direct and unquestionable answer to the question of existence of causal connection between blasting induced ground vibrations and damage to structures. However, the interpretation of the results suggested by various authors mast be criticized. Regardless of significant difference in crack responses to blasting and non-blasting related influences, even in those cases when blasting influence is considerably smaller than other influences it can not, and should not be neglected because the fact is that it exists.

FEM analysis of the crack model and comparison of stress intensity factors under static and dynamic loading showed that dynamic influences generate much higher stresses around the crack tip. Equivalent crack responses to blasting ground vibrations and environmental factors stand in relation of 1:126.54. This means that stress state around the crack tip for recorded crack response to blasting ground vibrations is equal to the stress state of 126 times larger crack response to environmental factors.

As a contribution to the crack response monitoring approach the following definition of causal connection between blast-induced ground vibrations and damage to structure can be made:

The casual connection between blasting operations exists and is proven only if the crack response in the form permanent crack opening is recorded. If the crack does not respond to blast induced ground vibrations causality can not be proven.

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