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ORIGINAL ARTICLE

Artificial screen for reducing seismic vibration generated by blasting

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Abstract The purpose of blasting operations is rock fragmentation. Blasting is a key component in the overall rock fragmentation system - the first element of the ore extraction process. It provides appropriate rock material granulation or size that is suitable for loading and transportation. However, in spite of many advantages explosives have, their usage may cause environmental problem such as seismic vibration. One of the solutions to this particular problem may be application of an artificial screen as a barrier to the seismic wave path. The results of experimental research on the artificial screen concept, its characteristics and role in attenuation of seismic effects generated by blasting are presented. The experiment is based on two physical phenomena: (1) the size and degree of discontinuity and (2) the reflection and refraction of seismic waves. More than 1,500 laboratory measurements were conducted with different combinations of screen sizes, positions of the screen to blasting source, and intensities of blasting impulses. The results of the study show reduction of generated vibrations up to 58% by employment of artificial screens.

Keywords Rock blasting · Environment · Seismic vibration · Artificial screens · Physical model

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Introduction

According to Siskind (2000), the United States mining, quarrying and construction industries use over two billion kilograms of explosives annually. The blasting process and usage of explosives, however, remain a potential source of numerous human and environmental hazards. Singh and Singh (2005) indicates that fragmentation accounts for only 20–30% of the total amount of explosive energy used. The remainder of the energy is wasted away in the form of ground vibrations, air-over pressure, and flyrock. The specific problem associated with ground vibrations represents the human response to them. A recent study completed by Raina et al. (2004) indicates the degree of human response to blast vibrations and air-overpressure.

Ground vibrations are acoustic waves that propagate through the rocks (Siskind 2000). The term ‘‘seismic wave’’ is a common synonym because the propagation characteristics are similar to the ground motions generated from earthquakes. Usually, parameters such as velocity, displacement and acceleration of particles are recorded during the vibration measurement (Rustan 1998). According to the same author, vibration velocity represents wave induced velocity of a particle in the media.

A number of researchers including Rossmanith et al. (2005), Bhandari (1997) and Valdivia et al. (2003) indicated the significance of several variables whose modifications can influence vibration reduction and improvement of blasting operations. Specifically, Bhandari (1997) classified the factors with influence on vibrations as controllable and uncontrollable. Those controllable influences include blast geometry, type of explosive used, steaming, priming and initiation, while uncontrollable factors are geological conditions and initiation timing errors.

In order to avoid the negative effects of ground vibrations, the US and many other countries around the world have defined standards to determine the maximum allowable level of these vibrations. However, as more and more construction and quarrying operations approach close proximity to the urban areas, new methods/technologies need to be developed in order to eliminate the negative aspects of ground vibrations. The potential solution for this problem may be application of an artificial screen as a barrier to the seismic wave path, i.e., ground vibrations.

An artificial screen, a man made object, represents discontinuity with significantly different properties compared to the surrounding rock mass. The objective is to reduce potentially damaging seismic vibrations in the rock mass beyond the screen. The effectiveness of the screen in reducing/eliminating seismic waves depends primarily upon parameters such as width w, depth d and length l of the screen, distance between blastholes and screen D and rock properties. The joints, fractures and the existence of faults in a surrounding zone are additional elements that should be considered. Figure 1 shows a schematic representation of an artificial screen, its position to blastholes and mining benches, and a zone that will be protected by implementing the screen.

Generally, there are two types of the screens that can be built: (1) discontinuous, represented by a row of holes with specific spacing between them and (2) continuous, the result of explosions of blastholes on the specific spacings and using accurate time delays. Fragmented rock mass can either remain in a newly created screen or be removed from it.

In order to efficiently apply screens in practical situations understanding the physics and mechanisms of seismic waves and their propagation through rock mass is essential. This scientifically based consideration spreads across several disciplines including: physics of explosions, mechanism of continuum media, gas theory, and theory of elasticity and blasting operations.

In an attempt to compensate for the problems of complex mathematical calculations and also to capitalize on results from previously performed experimental models, this research presents an original approach to development of an artificial screen model. The text that follows provides a literature review, theoretical background and explains the methodology used in this research. Experimental results and analyses along with appropriate conclusions appear in subsequent sections.

Literature review

Fourney et al. (1997) studied the effect of the open gaps on the particle velocity. They used two methods to evaluate results. The first method was based on the WONDY – a one-dimensional finite-difference wave-propagation code. The WONDY was developed by the Sandia National Labaratory and ‘‘solves the finite difference analogs to the Lagrangian equations of motion in one spatial dimension’’ (Kipp and Lawrence 1982). The second method was based on the experiments performed on a small laboratory model. The authors indicated that the experimental results were not in total agreement with the results obtained by WONDY. Thus, the experimental results are deemed more reliable than mathematical model, since the phenomenon of reflected waves from free surfaces was not included in the WONDY calculations.

The Russian scientist Hanukaev studied finite velocity propagation which causes rock mass disturbance (Voloh 1989). This scientist indicated importance of acoustic impedance ρv which is a result of the specific density ρ and the speed of sound in the rock v. The first group of rock was characterized by

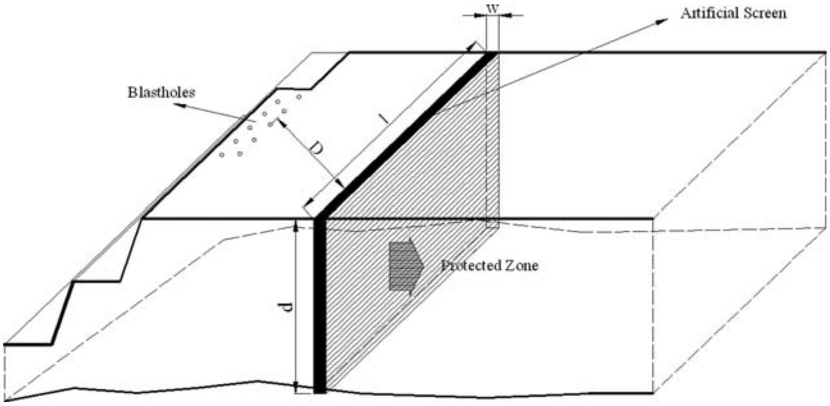


Fig. 1 A schematic representation of an artificial screen

ρv = (1.0–2.5) × 10^6 g/(cm^{2}s). Those rocks are fragmented under the influence of both primary compressive and tensile waves reflected from the free surface. The second group included rocks defined by ρv = (0.5–1.0) × 10^6 g/(cm^{2}s). Appearance of fractures and cracks commence from the moment of generation of stress waves and energy from detonation products. Finally, Hanukaev indicates a third group of rock based on acoustic impedance within ρv = (0.02–0.5) × 10^6 g/(cm^{2}s). As a result of experiments, Hanukaev states that up to 50% of the total amount of explosive energy is the energy of shock waves.

Voloh (1989) adduced the research work of Pokorovski who indicated that characteristics of the rock breakage depend on proportional distribution of velocity components: $v_x = u_x(x, y, z)$; $v_y = u_y(x, y, z)$, and $v_z = u_z(x, y, z)$, where v_x, v_y, v_z are velocity vector components, and u_x, u_y, u_z are components of the particle velocity vector. Pokorovski established the relationship between velocity components and overall velocity of detonation in randomly selected periods of time. This scientist indicates that the critical velocity of rock breakage can be defined by:

$$u^* = \frac{\sigma_p}{\rho v}\ (\mathrm{ms}), \tag{1}$$

where σ_p is tensile strength (Pa).

Further, Pokorovski listed the principal factors which have an influence on energy distribution including (1) energy of explosion (directly proportional due to weight of explosive charge), (2) volume of blasted rock mass (proportional due to explosive energy), (3) acoustic impedance (the massif composed of rock with different acoustic impedances causes attenuation and absorption of stress waves in the field environment), and (4) wave frequency filtration and rock anisotropy (the decrement of wave energy generated after an explosion depends upon rock anisotropy and wave frequency filtration).

In his textbook Voloh (1989) states that the theoretical research dedicated to explosive effects in the rock has two directions of approach. The first is based on the redistribution of velocity fields and managing pressure in the explosive charge utilizing different drillhole diameters, delay times, charge heights, initiation systems, points of initiation, and appropriate explosives with suitable velocity of detonation (VOD). The second approach presents calculation of the explosive energy and its transmission into surrounding rock characterized by different physical-mechanical characteristics. The investigation into energy transmission was performed using standardized experimental conditions and elementary wave propagation laws. According to the author, this approach was successfully applied only in ideal working conditions, utilizing uniform material. The investigation indicated the importance of using short delay blasting, i.e., millisecond delay blasting. Short delay blasting is “a method of blasting where charges are detonated in a short time sequence, usually 25–500 ms between the charges” (Rustan 1998). These short delays have the purpose to improve fragmentation and reduce vibration. The effect of short delay intervals is discussed in detail by Worsey (1986). Characteristics of rock fragmentation processes principally depends upon well calculated initiation intervals and single or batch initiation of explosive charges. For instance, increase of delay time from 20 to 50 ms results in reduction of both seismic effect and boulder frequency appearance. Further increase of delay time to 70 ms results in better fragmentation (bolder reduction), but the level of generated vibrations increase.

Additional significant progress in research and modeling of seismic waves-discontinuity interaction is the work of Rossmanith et al. (2005). In the research conducted on small laboratory models, Rossmanith et al. (2005) explained the importance of boundary effects on wave propagation, fracture development and fragmentation. They emphasized the relevance of generated pulse and model characteristics.

Fourney et al. (1997) presented the importance of gaps on ground motions that result from the detonation of an explosive source. Utilizing electromagnetic velocity gages, they recorded particle velocities at several locations on both sides of an open gap. The study was restricted to the transmission of the particle velocities normal to the gap. In their conclusion, they emphasized the importance of the gap size in particle velocity changes and reduction of transmitted stress waves through the gap.

Daehnke and Rossmanith (1997) studied interactions of longitudinal-P and transverse-S waves with a variety of interfaces types. They stated that upon interaction between stress wave and joints, incident energy reflects and refracts. In the study they compiled stress, energy, displacement and velocity amplitudes of stress waves, which reflect and refract by a variety of interfaces. The principal findings and conclusions from their research indicate that characteristics of reflected and transmitted waves, formed during the interactions of stress waves with rock mass discontinuities, are governed by a large number of parameters such as free boundary, condition of interface and presence of joints.

A company called Skanska (Olofsson 1997) developed another method of reducing ground vibrations from blasting close to existing buildings. It is completely mechanical method based on the intensive drilling operations. Measurements have shown that the slot, which separates the building from blasting site, acts as effective damper of seismic waves. A disadvantage of this method is a cost of development.

Methodology

The influence of a screen on the level of ground vibrations is defined by the displacement of particles or their velocities, and the reflection, refraction and diffraction of seismic waves. Figure 2 shows a graphic interpretation of wave-screen interaction.

As seen in Fig. 2, interaction between inner and outer medium was explained by divergent *F* and convergent *B* waves (Simha 1996). Diverging waves propagating radially outward generate converging waves upon reflecting at the screen. The explosive charge *a* is placed in the center of the spherical model. This charge is surrounded by inner medium and separated from the outer medium by the screen of width δ. The inner and outer mediums are composed of the same material. The waves generated by the explosion cause displacement of the core at the radius *b*. The mathematical interpretation is given by:

$$a_b = -(F + B)/b^2 - (F' - B'))/bv_1, \qquad (2)$$

where a_b is displacement of the core; *b* is radius of the inner medium; v_1 is wave velocity in the inner medium, and primes *F*' and *B*' denote differentiation.

Waves and energy can be transmitted across the discontinuity only when the magnitude of displacement a_b is larger than the width of discontinuity δ, i.e., $a_b > \delta$. Otherwise, waves will be reflected and oscillation will be localized only in the inner medium (Simha 1996).

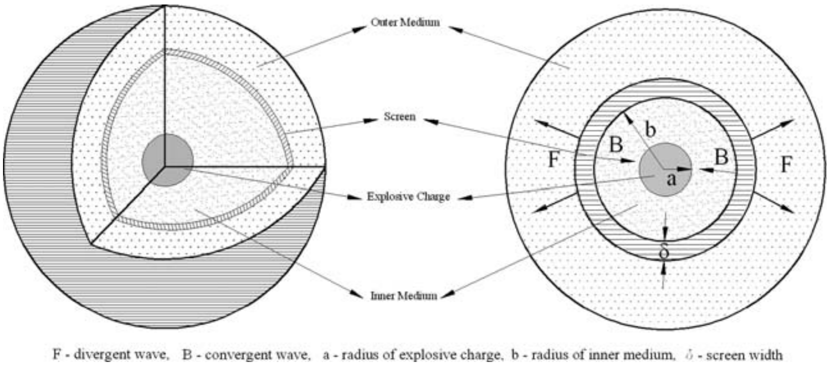
After wave-screen interaction, a part of the energy remains in the rock environment prior to encountering the screen. The balance of the energy refracts into the rock environment beyond the screen with an abrupt change in wave bearing propagation (Voloh 1989). According to the same author, many laws of reflection and refraction are based on Huygens' principle. For instance, Snell's law establishes the relationship between angles of incidence and refraction for a wave impinging on an interface between two media with different indices of refraction. Since a detailed description of Huygens' principle and Snell's law are common knowledge and appear in many science-related textbooks, this paper does not cover their fundamentals.

A physical model developed in a laboratory environment can be used to simulate particular phenomenon. Using such a model allows observation of a majority of relevant parameters and their interdependences. Additional advantage of this approach is a cheaper and much faster way for data acquisition than in the field experiments. However, information obtained from laboratory experiments often serve only as a guideline for field practice. In many cases bridging the gap between laboratory and field results is difficult.

The basic principle of experiments conducted through this study is shown in Fig. 3. Generally, a physical model is composed of two blocks, a chassis with swing arm for pulse generation, and instruments for data acquisition. Block I receives a generated pulse from the swing arm and energy is transmitted to Block II which is protected by the screen of a width δ. Seismographs called Vibraloc (ABEM 2006) are used to measure peak particle velocity.

The beginning phase of experimentation involves calibration of the model. This is necessary in order to define an appropriate energy level for different stages of the experiment and response of the model

Fig. 2 Geometry of wave-screen interaction (Adapted from Simha 1996)



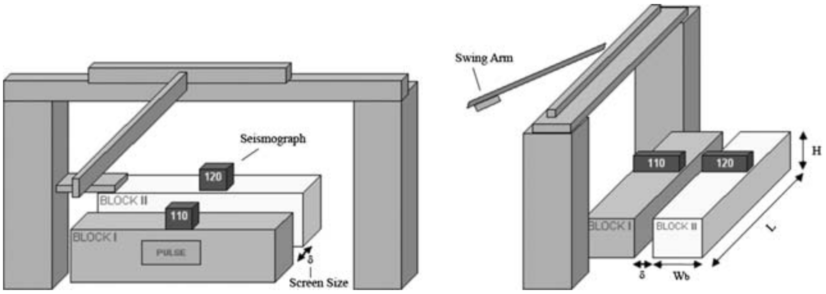


Fig. 3 Physical model used in lab experiments

to such an energy source. All laboratory tests are conducted utilizing blocks of artificial building material which have a basic composition of sand, limestone, cement and water. All the blocks had length $L = 60$ cm; width $W_b = 24$ cm and depth $H = 20$ cm.

Prior to the trial experiments the blocks underwent testing to obtain their physical properties. These properties were obtained by ultrasound dynamic method using OYO Sonic Viewer System. The Poisson's ratio and Young's module were obtained by mathematical formulae which incorporate the values of measured longitudinal and transverse velocities. The measurements were performed at the three different positions of the block. The arithmetic means obtained from six specimens are: velocity of longitudinal waves $v_p = 1{,}677$ m/s; velocity of transverse waves $v_s = 855$ m/s; Poisson's ratio $\mu = 0.32$; Young's module $E = 1.39$ GN/m^2, and specific weight $\gamma = 721.5$ kg/m^3.

In order to gather as much as of data as possible without physical damage or destruction of a block, a chassis with swing arm was developed. The purpose of the swing arm was to generate a pulse of constant energy. To obtain such a source of energy, the wooden plate with dimensions 17.5 × 8 cm was attached to the free end of the swing arm. The other end of the swing arm was fixed on the chassis over a ball bearing and axle. An appropriate geometry of ''blasting charges'', defined by dimensions of wooden plate was used. The scale used for this purpose was driven by a real blasting parameters defined by row of 5 holes, spacing between them 3.5 m and depth of 8 m.

During the experimentation phase, the energy pulse generated by the work of the swing arm, then width and depth of the screen, position of the screen, and the model volume were the controllable factors. For instance, to obtain a reasonable number of different combinations, in one of the experiments the width and depth of the screen had constant dimensions, while the generated pulse and position of the screen varied.

Analysis and results

Screen size is one of the crucial parameters that determine the intensity of particle velocity. Based on experimental setup shown in Fig. 3, screen size was varied and particle velocity was measured for both Block I and Block II. Figure 4 shows the relationship between screen size and particle velocity.

The curve marked as ''Block I'' represents the change of particle velocity for the block which receives a generated pulse. The curve marked as ''Block II'' represents the change of particle velocity for the block behind the screen, i.e., the protected block. A difference between particle velocities for the Block I and Block II at the beginning of experiment (when screen size $\delta = 0$) is caused by imperfect contact between used blocks.

The segment of the curve ''Block I,'' from its beginning until reaching maximum value, shows nearly linear growth in particle velocity intensity. This occurs because of the effect of free surfaces and their influence on wave reflection. According to Rustan (1998), that free face is an unconstrained surface almost free from stress. This means that the free surface is a rock surface exposed to air, water or buffered rock which provides space for expansion upon fragmentation. Experimental work by Fourney et al. (1997) revealed that ''there is a critical gap width below which the velocity amplitude changed very little with gap width.''

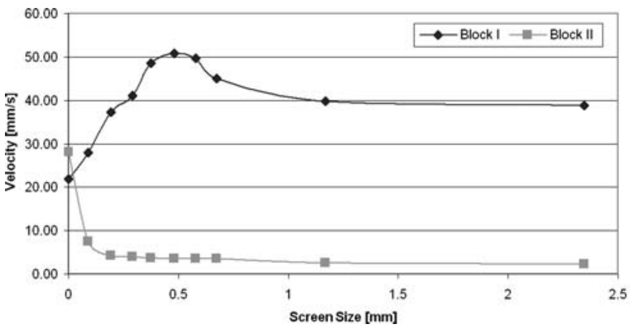


Fig. 4 Relationship between screen size and particle velocity

They felt that to be due to “fragments bombarding the far surface as the near free surface spalls and craters as the stress wave reflects from the free surface.”

As seen in Fig. 4, by increasing the screen size, a number of the particles capable of reaching the far surface of the screen will be reduced. For example, when the width of the screen δ is equal to the critical width of the screen δ_k , i.e., $\delta = \delta_k \approx 0.5$ mm, vibrations through the Block I have a maximal value. At the same time vibrations through the Block II have a minimal value. The increment of the particle velocity for the Block I indicates improvement of fragmentation. The intensity of particle velocities beyond the screen (Block II) is caused by the waves refracted from the ground. Because of confinement, such as lack of a sixth free surface, which has an influence on the experiment’s performance, the ground effect was impossible to isolate. It is assumed that in the ideal working conditions, with six free surfaces, the model will be confirmed and the transmission of the stress waves from a source into protected zone will be completely prevented.

During experimentation, different screen positions were considered. Figure 5 shows the case of a screen placed perpendicular to the direction of P waves. The particle velocity for the Block I was 23.03 mm/s. However, the particle velocity for the Block II was 17.92 mm/s, which represents a reduction of 22%. Figure 6 shows the case with screen placement parallel to the direction of P waves. The pulse generated through the Block II and the measured particle velocity were 14.01 and 12.39 mm/s for Block I and Block III, respectively. This represents a reduction of 39% for Block I and 46% for Block III. Slight differences are caused by imperfect contact between used blocks.

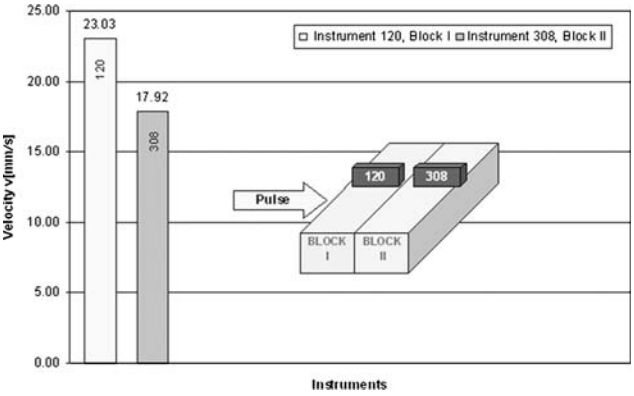


Fig. 5 Particle velocities with screen perpendicular to the direction of P waves

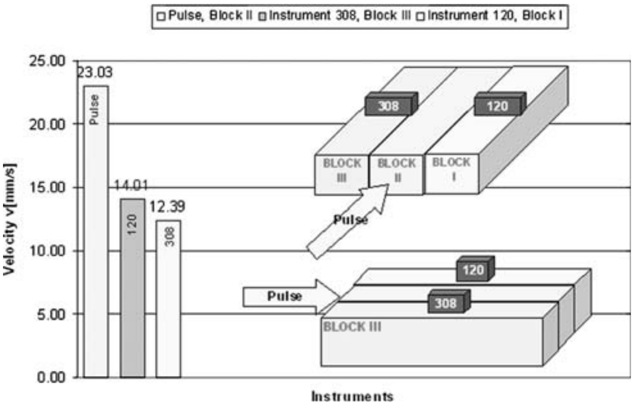


Fig. 6 Particle velocities with screen parallel to the direction of P waves

Further experimental trials were conducted by changing the input parameters such as the level of pulse, position of the screen to source of vibrations and the volume of the model. Different levels of energy for strong and weak pulse were determined by the height from which the swing arm started to fall. Strong pulses originate from a higher initial level of the swing arm, i.e., 50 cm while a weak pulse originates from lower initial level of the swing arm, i.e., 25 cm.

Figure 7 shows the position of the screen at 2/3 of block length. Using the weak pulse, the particle velocity dropped from 17.07 to 7.68 mm/s. This represents a reduction of 55%. At the same time, using the strong pulse, particle velocity dropped from 46.35 to 29.64 mm/s, representing a reduction of 36%. The highest reduction in the particle velocity, from 58.64 to 24.21 mm/s or by 58%, was achieved using the strong pulse and the screen which is placed closer to the vibration source, i.e., at 1/3 of the block length (Fig. 8). This setup shows the lowest reduction of particle velocity using a weak pulse. Particle velocity measured at instrument #110 was 12.19 mm/s while the velocity at instrument # 120 was 9.84 mm/s. Figure 9 shows a low reduction rate for a strong pulse while the screen is further from the vibration source (2/3 of block length). For the strong pulse, the particle velocity was reduced from 53.05 to 44.09 mm/s, or by just 16%. For the weak pulse, the particle velocity was reduced, from 17.01 to 8.74 mm/s, or by 55%.

These results imply that stronger pulses require screens closer to the vibration source, while weaker pulses require screens farther from the vibration source, either for volumetrically larger or smaller model configurations. These findings are very important for conducting real blasting operations, and anticipating problems due to vibrations. For such

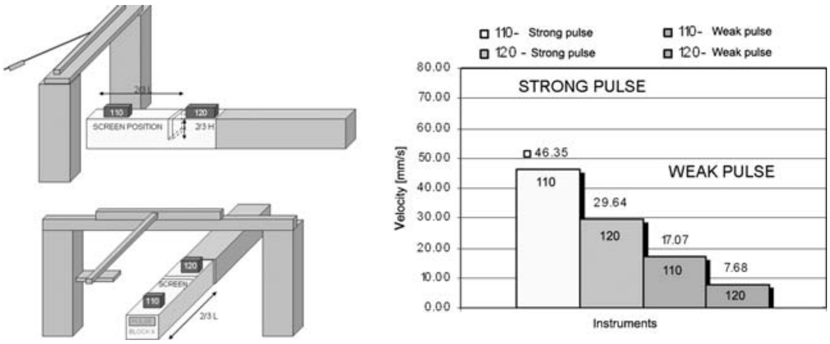


Fig. 7 Particle velocities with supporting block and screen positioned on 2/3L

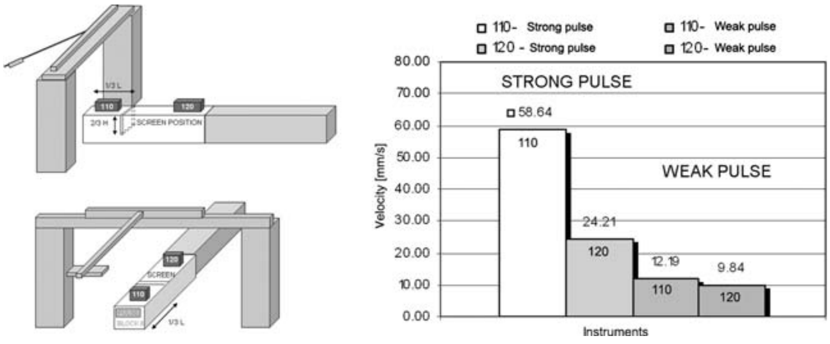


Fig. 8 Particle velocities with supporting block and screen positioned on 1/3L

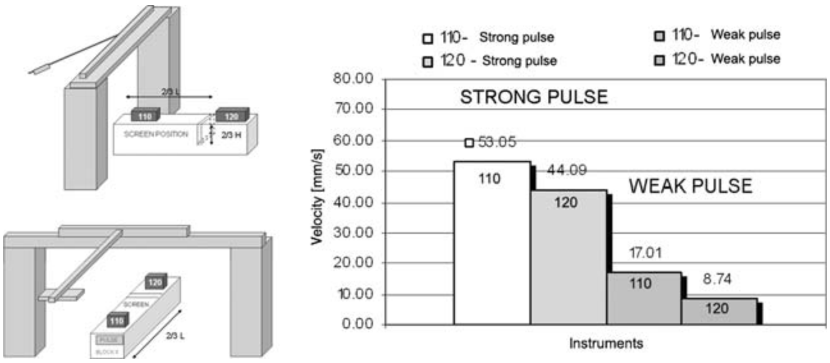


Fig. 9 Particle velocities without supporting block and screen positioned on 2/3L

occurrences, position of the artificial screen needs to be defined considering the amount and type of used explosive, blasting geometry, frequency of blasting operations and existence of adjacent objects.

The final set of experiments was performed taking into the account the size of the model and influence of the wall on the level of particle velocity. Figure 10 shows the model with supporting wall and screen placed at 2/3 of block length. Five instruments were used and blocks were connected by resins. The purpose of the wall was to absorb a large portion of the energy transmitted through the blocks. Again, the strong and the weak pulse were used and the results are presented in Fig. 11. It can be noticed a reduction in particle velocity from 10.22 to 5.03 mm/s or by 50% for weak pulses and from 34.27 to 22.11 mm/s or 36% for strong pulses.

Figure 12 shows a model without supporting wall and screen placed at 2/3 of block length. Again, the strong and the weak pulse were used and obtained results are presented in Fig. 13. It can be observed a reduction in particle velocity from 4.46 to 2.37 mm/s or by 47% if a weak pulse is used.

The best results in reduction of particle velocity are obtained from utilizing a weak pulse, when the screen is placed further from the vibration source, for both volumetrically larger and smaller model setups. However, according to Voloh (1989) the screens with inappropriate parameters such as pulse, distance between screen and source of vibration, geometry of the

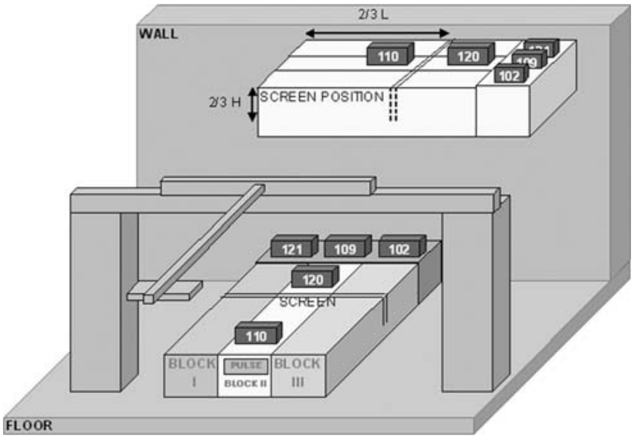


Fig. 10 Model with supporting wall

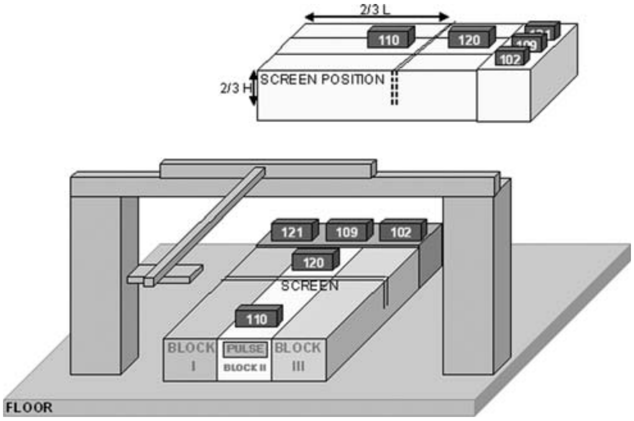


Fig. 12 Model without supporting wall

screen, etc. can produce a negative effect on vibration reduction, i.e., increased level of vibrations beyond a screen. Such a case is presented in Fig. 13. It can be noticed an increment of particle velocity from 16.52 to 19.51 mm/s, or by 15%. Also, slight increment of particle velocity is experienced at the instruments #109 (2.49 mm/s) and #121 (2.41 mm/s). That increment can be explained because the resin and blocks are composed from the different materials.

An important note is the significance of pulse, screen position, and the model size in the reduction of particle velocity. The best results were achieved using the experimental configuration presented in Fig. 8, which shows maximum reduction of particle velocity.

Conclusion

The authors developed a novel experimental setup that explicitly indicates not only the advantage of an artificial screen in seismic vibration reduction processes, but also an improvement in fragmentation. A physical model is composed of two blocks, a chassis with swing arm for pulse generation, and instruments for data acquisition. Applying various combinations of screen position and geometrical parameters, over 1,500 measurements were performed through this study. Based upon the results of these experiments, it can be concluded that vibrations can be reduced by 30–58%. The differences in results from this experiment are caused by imperfect experimental performance conditions. It can also be observed that a proper design of artificial screens primarily depends upon well defined elements which designate their spatial position (distance from the blasting site), and geometrical elements such as width, length and height.

Prior to practical testing and application in real field conditions, conducting geophysical observation of the particular area is important. This analysis will reveal layers with different wave velocity propagation properties. In terms of economic value, the depth of such a shallow layer (layer with significantly different velocity propagation properties) will define the depth of a screen. Such an example presents the best case scenario from a geophysical point of view.

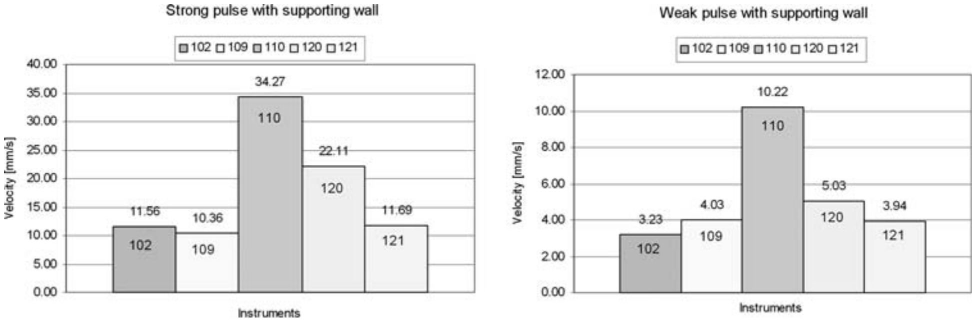


Fig. 11 Diagram of particle velocities with supporting wall and screen placed at 2/3L

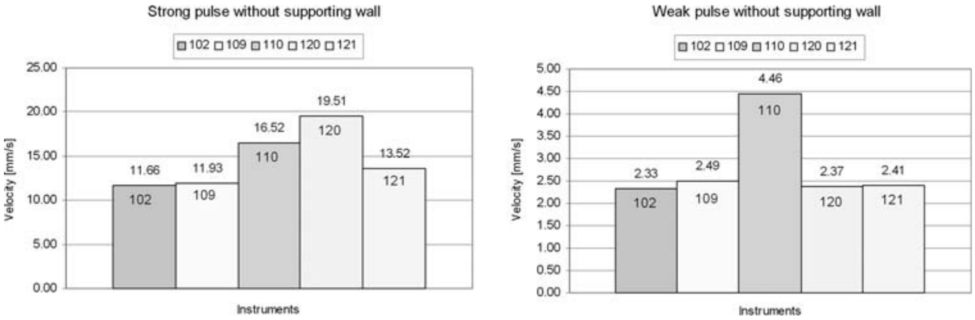


Fig. 13 Diagram of particle velocities without supporting wall and screen placed at 2/3L

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