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# Comparative review and interpretation of the conventional and new methods in blast vibration analyses

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**Abstract.** The customary approach used in the blast vibration analysis is to derive empirical relations between the peak particle velocities of blast-induced waves and the scaled distance, and to develop patterns limiting the amounts of explosives. During the periods when excavations involving blasting were performed at sites far from residential areas and infrastructure works, this method based on empirical correlations could be effective in reducing vibrations. However, blasting procedures applied by the fast-moving mining and construction industries today can be very close to, in particular cities, residential areas, pipelines, geothermal sites, etc., and this reveals the need to minimize blast vibrations not only by limiting the use of explosives, but also employing new scientific and technological methods. The conventional methodology in minimizing blast vibrations involves the steps of i) measuring by seismograph peak particle velocity induced by blasting, ii) defining ground transmission constants between the blasting area and the target station, iii) finding out the empirical relation involving the propagation of seismic waves, and iv) employing this relation to identify highest amount of explosive that may safely be fired at a time for blasting. This paper addresses practical difficulties during the implementation of this conventional method, particularly the defects and errors in data evaluation and analysis; illustrates the disadvantages of the method; emphasizes essential considerations in case the method is implemented; and finally discusses methods that would fit better to the conditions and demands of the present time compared to the conventional method that intrinsically hosts the abovementioned disadvantages.

**Keywords:** blasting; vibration; peak particle velocity; signature blast; scaled distance; non-linear behavior

## 1. Introduction

Common approach in efforts for predicting, analyzing and minimizing blast vibrations is to estimate the highest particle velocity relative to the scaled distance. In the literature, there are numerous accepted empirical formulae for estimating highest particle velocity (Davies *et al.* 1964, Ambraseys and Hendron 1968, Nicholls *et al.* 1971, Langefors and Kihlström 1967, Indian Standart Ins. 1973, Ghosh and Daemon 1983, Gupta *et al.* 1987, Roy 1991). Here are the steps followed in the method known as the conventional approach where these formulae were developed:

a) recording by seismograph the blast-induced seismic waves, and identifying peak particle velocities,

b) determining the ground transmission constant between the blasting site and the "target" site where blast vibrations are sought to be minimized,

c) developing the empirical relation involving the rule of propagation for vibration waves,

d) employing this relation to define highest amount of explosives that may safely be fired at a time for blasting,

e) employing this empirical formula developed on the basis of site-specific directional 'particle velocity-scaled distance relationship' to predict blast-induced particle velocities where no vibration measurement is conducted.

Efforts since early 1960s for minimizing blast-induced vibrations on the basis of the so-called PPV-SD (Peak Particle Velocity-Scaled Distance) relationship have found a wide practical use both in the international community (Duval and Fogelson 1962, Ambraseys and Hendron 1968, Siskind *et al.* 1980, Anderson *et al.*1982, Dowding, 1985, Siskind *et al.* 1989, Anderson, 1993, Persson *et al.* 1994, Muller, 1997, Muller and Hohlfeld,1997, Hoshino *et al.* 2000, Siskind 2000, Chen and Huang, 2001, Tripathy and Gupta 2002, Adhikari *et al.* 2004, Singh and Roy 2010, Lee *et al.,* 2016, Kumar *et al.* 2016, Mokfi *et al*. 2018, Hasaniponah *et al.* 2017) and the local community (Bilgin *et al.* 2000, Kahriman 2004, Cihangir *et al.* 2005, Ozer 2008, Kesimal *et al.* 2008, Hüdaverdi 2012, Tosun and Konak 2015). Despite very successful results yielded by properly structured studies, each step of the method involves certain disadvantages and defects as described above, and this may lead to poor results where near-field vibration control is required or where structural geology does not allow otherwise, in other words where non-linear natural conditions prevail.

As a matter of fact, Blair (2004) appeared as one of the first researchers to emphasize the need to deviate from conventional approaches in favor of developing new methods due to the non-linear behavior of blasts, arguing that the PPV-SD approach hosts numerous disadvantages. In 2008, Aldas and Ecevitoglu (2008), as inspired by Blair's

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(2004) studies, figured out the disadvantages and failures in the PPV-SD approach towards a desired vibration control, and developed a methodology to control seismic signals through a delayed firing system, as a basis for efforts to minimize vibrations. Also protected by an international patent (Aldas and Ecevitoglu 2011), this methodology has been and is being revised across myriad of geological-geophysical problems confronted in controlling blast vibrations as well as many natural events where non-linear behaviors are exhibited. Meanwhile, in his studies, Blair (2010) stressed that P and S waves are effective particularly in the transmission of seismic waves in the near-field (in other words, where non-linear plastic behaviors are exhibited), and that these waves are associated with the detonation velocity of the explosive, and further attempted to build a correlation between seismic waves and the detonation energy of explosive, arguing that not only the particle velocity but also the whole waveform should be controlled. Further, in 2014, Blair argued that the concept of reducing the amount of explosives, which have the most critical role in the PPV-SD approach, would lead to very unfavorable consequences in vibration control, and stated that such a reduction slows down the operations of the mine and does not have any function in reducing the impacts of vibration waves in non-linear conditions. Blair even argued that, amount of explosives in underground blasts have no effect in vibration amplitudes. Besides, there are many valuable contributions to blast vibration minimization issue on last decade (Ozacar 2018, Uyar and Babayigit 2016, Song *et al.* 2018, Abdollahzadeh and Faghihmaleki 2017, Li *et al.* 2018, Shivakumara *et al.* 2018, Mckee *et al.* 2018). Especially; pattern recognition approach of Li *et al.* (2016) is highly contribute to this subject.

These studies show that, the conventional hypotheses suggested in the USBM RI 8507 (Siskind *et al.* 1983) criteria, namely “1) Particle velocity is still the best tool to identify and control ground vibration, and 2) Particle velocity is the most practical control tool capable of describing the destruction potential for a building with well-defined vibration responses” should be abandoned in favor of modern blast vibration analyses based on a modern scientific approach and technology considering the varying conditions of the present time.

In this paper, deficiencies during the implementation of the conventional PPV-SD method are illustrated separately for each step; defects and errors in data evaluation and analysis are addressed; essential considerations in case the method is implemented are emphasized; and finally the methods that would fit better to the conditions and demands of the present time compared to the conventional method that intrinsically hosts the abovementioned disadvantages are discussed.

## 2. Deficiencies of the practical stages of conventional method

In this section, each stage of the conventional method and respective deficiencies are discussed.

### *2.1 Stage 1: Recording the blast-induced seismic waves and identifying peak particle velocities*

As the method is based on developing the most

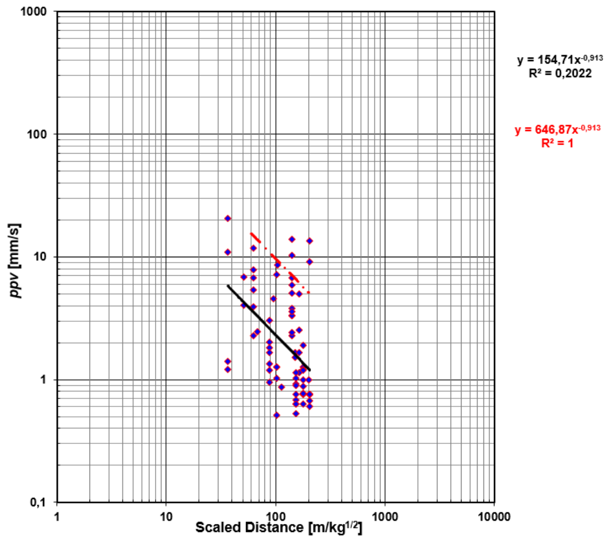


Fig. 1 Relation between peak particle velocity and scaled distance at the region reporting complaints for vibrations induced by blasts at the Holcim stone quarry in Italy

appropriate empirical formula for creating a correlation between peak particle velocity and scaled distance, minimum 30 vibration data should be recorded as per the literature (Konya 1991). This ends up with a quite long period of 30 days to collect data, assuming that the mine performs one blast every day and that there is one seismograph available, under the worst-case scenario.

Actual practices reveal that PPV-SD graphs are created based on a much less volume of data, and that empirical formula is also considered valid in cases of high regression coefficients. However, empirical formula relying upon merely 15-20 data items and offering high regression coefficients, also due to such limited data stock, do not prove demonstrate reliability. Besides, despite more than 30 data items are involved in some cases, no significant correlations can be built between PPV and SD due to a set of reasons including the i) changes in the blast location even the target site remains unchanged, leading to varied direction between the blast site and target site to some extent, ii) distinct geological environment where seismic waves propagate, and iii) structural differences. Fig. 1 shows a PPV-SD graph of seismic signals at a site reporting complaints for vibrations induced by blasts at the Holcim stone quarry in Italy (Cardu *et al.* 2015). Here, low regression coefficient suggests the lack of a significant relation for that target direction despite involving almost 50 particle velocity values. In such a case, employing the 95% reliability curve (red line) would be an insignificant attempt with no function but unnecessarily reducing the actual explosive demand of the mine.

Cihangir *et al.* (2005) experienced a similar situation during the efforts for minimizing blast vibrations for a limestone quarry and derived the following conclusion as a requirement of the scientific ethics since no reliable relation could be built between PPV and SD despite 49 data items: “With this functional equation developed for a total of 49 shots, it is not reliable for now to estimate, without specific measuring equipment, possible vibration values for similar shots at a certain reliability and for a certain time".

Unfortunately, some colleagues and researchers failing to respect such scientific ethics, or without adequate level of knowledge, may present "prescriptions" to the mine based on such unreliable formulae even in case of low correlation coefficients.

### *2.2 Stage 2: Determining the ground transmission constant between the blasting site and the "target" site where blast vibrations are sought to be minimized*

As mentioned in the introduction part, there is a wide array of empirical formulae given in Eq. (1), aimed at identifying the PPV-SD relation. With reference to the USBM RI 8507 formula here (Siskind *et al.* 1983)

$$PPV=Kx(SD)^{-\beta} \quad (1)$$

PPV: Peak Particle Velocity, K: Ground Transmission Constant, SD: Scaled Distance $[(R/(Q)^{1/2}]$, β: slope of the PPV-SD graph, R: distance between the blast site and target site, Q: amount of explosives per delay

The ground transmission constant here is the core parameter of the empirical formula. Because, as suggested by Olofsson (2002), this constant varies by the homogeneity of the rock and the structural geology. Assuming a residential area in a region reporting complaints for blast vibrations. Drawing on the conventional approach, if a researcher has a highly reliable empirical formula based on minimum 30 data items, he/she can use this formula to calculate the highest amounts of explosives per delay that would ensure remaining below destructive particle velocities, and present it to the mine professionals. This prescription would be valid in case the blast site is unchanged. However, during the course of mining operations with variable blast locations, the route of waves to the target site reporting complaints would differ from the path in the previous study. Whenever the rock structure and structural geology varies, as mostly expected indeed, the prescription presented to the mine would be invalid resulting in the relapse of the complaints. The essential action here would be to take the readings of minimum 30 blast vibrations, revise the empirical formula for the new route, and identify the new "maximum permissible explosive amount" per delay. Bringing a secondary cost to the mine, this action is usually neglected, and the prescription for a particular route is implemented for quite a long time.

### *2.3 Stage 3: Developing the empirical relation involving the rule of propagation for vibration waves*

The empirical correlation developed in this phase requires a high volume of data to develop the PPV-SD graph, yet still a significant relation may not be found due to the non-linear behaviors of the nature. Therefore, prediction of blast vibrations through the empirical approach can only be possible where nature exhibits uniform behaviors and where the blast site, and therefore the distance between the blast site and the target station remains unchanged. In addition to this major disadvantage, there are also two critical factors for the vibration analysis that are not covered by the empirical approach. One is frequency, and the other is the action time of blast vibrations. Formula (1) appears to lack these two major parameters, and seems to relate peak particle velocity only to the parameters of distance, ground transmission constant and explosive amount per delay.

Aldas (2010) equalized this formula, most commonly used in mining, with the attenuation factor in geophysics to develop a new formula also involving the frequency and explosive relationship. Rewriting the Eq. (1), she equalized the Eq. (2), predicting the particle velocity as follows to the common attenuation factor, and obtained Eq. (3).

$$PPV = k\frac{M^{\beta/2}}{R^{\beta}} \quad (2)$$

$$k\frac{M^{\beta/2}}{R^{\beta}} = \frac{e^{-\frac{\pi}{QV}fR}}{R^{1/2}} \quad (3)$$

M: Mass (kg) (explosive amount), Q: Seismic quality factor, V: Seismic Velocity (m/s), a: Attenuation factor (s/m), f: PPV-frequency (Hz)

Counting on frequency in Formula 3, a new definition called "PPV-frequency" related to peak particle velocity has been introduced in addition to the concepts of dominant frequency and zero-cross frequency in the literature (Aldas 2010).

$$f = \frac{QV}{\pi R}\ln\left(\frac{R^{\beta-1/2}}{kM^{\beta/2}}\right) \quad (4)$$

Incorporating the attenuation factor referred as "a" in the formula, Formula (4) and (5) are obtained.

$$\frac{1}{a} = \frac{QV}{\pi} \quad f = \frac{1}{aR}\ln\left(\frac{R^{\beta-1/2}}{kM^{\beta/2}}\right) \quad (5)$$

With this new definition, the frequency parameter not involved in the conventional formula can be found with the PPV, ground constants, attenuation factor and the explosive amount.

Another major parameter not covered by the conventional formula and thus neglected is the action time of blast vibrations. Since the conventional approach merely considers the peak particle velocity, it may fail to identify, because of its design blast parameters, the destructive effect due to long action time of vibrations despite low actual peak particle velocities.

An exemplary case was observed during the blasts at the Opencast Coal Mine of Orhaneli, Bursa, Turkey (Uyar *et al.* 2015):

As a result of the project to minimize the impact of vibrations induced by blasts, a blast pattern was developed and submitted to the officials of the mine. Fig. 2 shows vibration waves measured at a house reporting complaint for these vibrations. As shown, vibration amplitude is below 2 mm/s for each of the three components (1.65, 1.40 and 0.635 mm/s), and vibration period is less than 1 second.

Fig. 2 reveals that, if the blast pattern proposed to the mine is implemented, vibration amplitudes that are well below the house destruction limits could be achieved, and most significantly, exposure time of houses to vibration

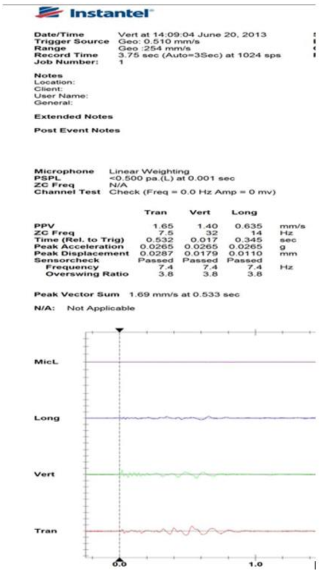


Fig. 2 Vibration recorded at a village house *reporting complaint for the blasts (400 m distance to the blast site)*

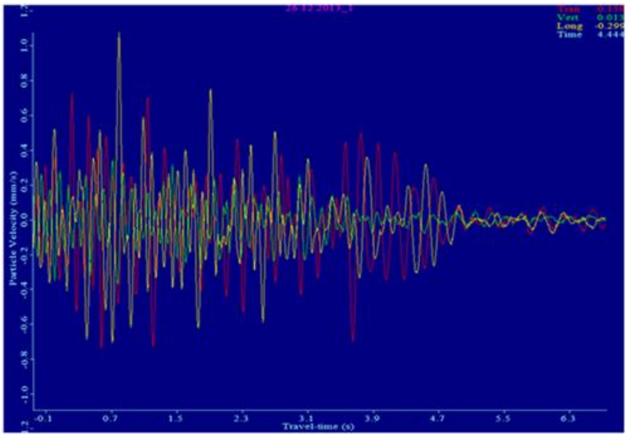


Fig. 3 36-hole group blast signal on 3 components. Yellow: longitudinal component, Red: transversal component, and Green: vertical component

would drop below 1 second. However, a new visit was made to the site since the complaints still prevailed, and a blast vibration reading was taken at the house, reporting the complaint, without notice to the blast contractor (Fig. 3).

Fig. 3 clearly reveals that, signals last more than 6.3 seconds during each of the three blast components. Since the device was configured to record a maximum time of 7 seconds, longer signals could not be recorded. Again as the figure illustrates, highest vibration amplitude occurs at the longitudinal component (yellow) (1.10 mm/s). Such long action-time of this vibration amplitude, despite low in value, caused deepening in the cracks already effecting the houses. Because, one of the most critical destructive parameters for the houses is the duration of exposure to the vibration amplitude. However, the investigation reveals that, the mine deviated from the blast pattern delivered, and extended delay time between drill hole shots. And this prolonged the exposure time of houses to vibration, despite in an amplitude range of 1-1.5 mm/s, and caused ongoing complaints.

This example clearly shows that, even if the vibration amplitude is well below the destructive limits, longer exposure to vibration raises the destruction potential in buildings, and explicitly underlines the significant need to consider the time factor in the conventional method.

While the criticality of frequency is stressed in this part, another consideration is the natural frequencies of geophones. In other words, the seismic wave detection ranges of geophones are very critical. Geophones largely found in the market due to their low price have a detection frequency of 4 Hz. And this means that, only the seismic waves at a frequency of 4 Hz or above can be detected, excluding lower frequencies. For a sound vibration analysis, use of 1-Hz geophones is crucial in view of a broader capability of signal detection. Otherwise, it would be lost the data within the 1-4 Hz range where the most destructive surface waves for buildings reside.

### *2.4 Stage 4: Employing this relation to define highest amount of explosives that may safely be fired at a time for blasting*

The method of reducing the explosive amount as a means of minimizing blast vibrations has widely been in use since 1960s following the introduction of the PPV-SD approach. However, as many researches primarily including Blair (2014) have recognized, this method fails in vibration waves propagating through complex geological structures or rocky structures with unexpected physical events (to be discussed later), and has no function but only slowing down the mining process. Uyar *et al.* (2015) observed a similar situation during blast operations at the Orhaneli coal mine. The blast contractor at the Orhaneli-Gumuspinar site defined the amount of explosives per delay in an aim to ensure that influx of vibrations to the village from the blast site is below destructive thresholds, and limited its blasting coverage to 3-5 holes. Fig. 4 shows three component (Tran, Long, Vert) signals of a 4-hole blast performed by the mine. Blast vibration waves were modelled by Uyar *et al*. (2015) with the SeisBlast software (Aldas and Ecevitoglu 2008) during the study at the site. 4 blast holes are shown on top left while vibration amplitudes in three components are shown on top right. Three signals in the middle of the image shows waveforms in the transverse, vertical and longitudinal component (from left to right). Two amplitudes in these waveforms were jointly drawn. High amplitudes in pale color show the total amplitude if all of these holes are shot at one time (7.10 units in the Long. component) while small amplitudes in bright color show the amplitudes after a delay of 100 ms between hole shots (1.52 units in the Long. component). In a 4-hole group blasting, explosive amounts were limited and vibration amplitudes were reduced to 1.5 mm/s. However, as it was very hard for the mine to maintain such a mining operation, the plant found a new solution where it divided 30-35 holes into 4-5 groups and shot individually every group.

To illustrate that such practice is dangerous and unnecessary, and further that vibration amplitudes may be reduced down to 1.5 mm/s by applying appropriate delays between holes without any explosive limitation, blasts were grouped as shown in Fig. 5. In this pattern, total of 26 holes

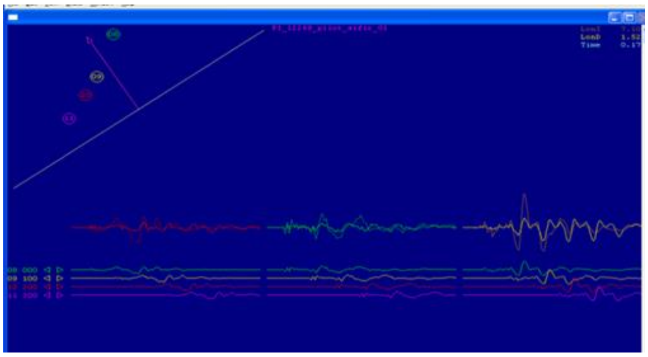

Fig. 4 Three-component waveforms for a 4-hole blast performed by the plant due to the limitation of explosives and holes

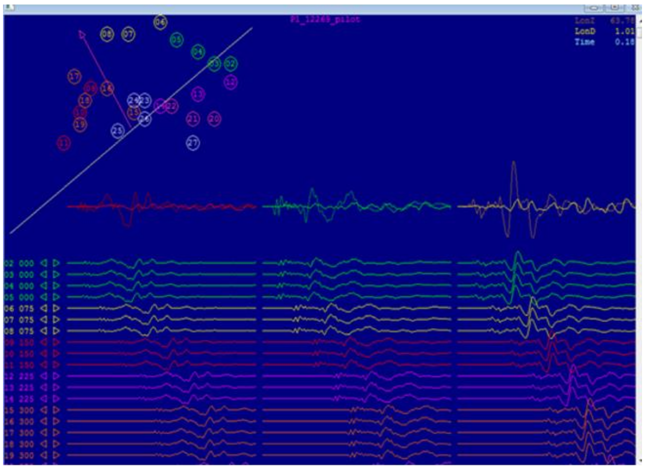

Fig. 5 Vibrations induced by blast groupings where 26 holes are shot under an appropriate delay pattern without any explosive and hole limitation

were grouped in sets of 3 and 4, a delay of 100 ms was applied between holes, and all were blasted in one single shot. As shown in top right corner, vibration amplitudes for the longitudinal component are 63.28 units for one-time shooting, and 1.01 units for delayed shooting.

Assessment of Fig. 4 and 5 reveals that, vibration amplitude in the blast pattern limited to 4 holes due to explosive and hole restrictions is 1.52 units while it is 1.01 units in group blasting where 26 holes are shot after appropriate delays. This demonstrates that, today seeing the operation of even electronic firing systems capable of assigning any desired delay to the process, limitation of explosives in an attempt to minimize vibrations would have no function but only impeding the mining operation.

### *2.5 Stage 5: Employing the empirical formula developed on the basis of site-specific directional 'particle velocity-scaled distance relationship' to predict blast-induced particle velocities where no vibration measurement is conducted*

Defects and disadvantages of the empirical formula are discussed in the first four stages of the process. These may be summarized as the burden of repeating the test structured on a specific PPV-SD relation for each varying geological environment, yet still the disadvantage of absent core parameters (frequency, duration), and impossibility of minimizing vibrations always by reducing the amount of explosives. In the following part, discussion will be why it is misleading to predict, in the cases of unexpected geological and physical events, the particle velocity through formulae based on the PPV-SD relationship.

## 3. Physical and geological events, not addressed by the conventional approach, effecting the propagation mechanisms of blast-induced waves

While propagating from the blast site to the environment, blast-induced vibration waves may, contrary to expectations, not display a trend declining with distance as a result of some unexpected physical and geological events, and may even increase with distance. While the conventional PPV-SD approach attempts to control blast vibrations, it can describe ongoing complaints in the far field, as this is not originally foreseen by the conventional method of such conditions, the most critical one is the "formation of channel waves", the other is "interaction of soil amplification with the bedrock in blast vibration analyses", and finally the "non-linear behaviors of blast vibrations" as the most recent one.

### *3.1 Formation of channel waves*

Blasts within the stripping material and the coal seam should be given utmost care particularly if the coal seam lies under the surrounding residential units. In such cases, besides the impacts of direct and surface waves conventionally studied, also the impacts of channel waves formed in the coal seam should be investigated. Because, coal layers having a low seismic velocity and density compared to the surrounding rocks act like a channel (Essen *et al.,* 2007). Seismic waves induced by blasts in coal or the overlying stripping material channelize in the coal seam after full reflection beyond the critical angle (where reflection angle is 90° incidence angle is called the critical angle) (Ravindra and Cerveny 1971).

Formation of channel waves in coal mines was first studied and modelled by Babayigit (2012). Additionally, Uyar and Babayigit (2013) worked on the TKI YLI Husamlar quarry to compare the results of the model with actual blast data. Fig. 6 and 7 show the presence of channel waves in agreement with the model results. In this study, 2 groups of blasts were shot at the Husamlar Quarry, owned by the Yenikoy Lignite Office of the Turkish Coal Enterprise, on the coal seam extending down into the Husamlar village, and the resulting vibrations were recorded with 4 three-component seismic recorders installed in the quarry and the village. Models employed in the study are structured according to the channel wave theory. The models do not rely upon empirical approaches based on ground surveys. Models so structured were tested by 2 ground data. Efforts were made to improve current methods in an attempt to demonstrate the impacts in blast vibrations of the channel waves, theoretically proven years ago. Next, after the first-group blast (Fig. 6), the impact of the channel wave was detected through increase in amplitude at the

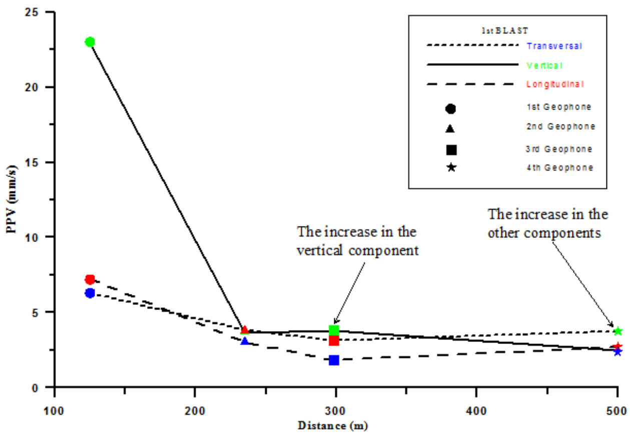


Fig. 6 1st blast at the Husamlar coal quarry

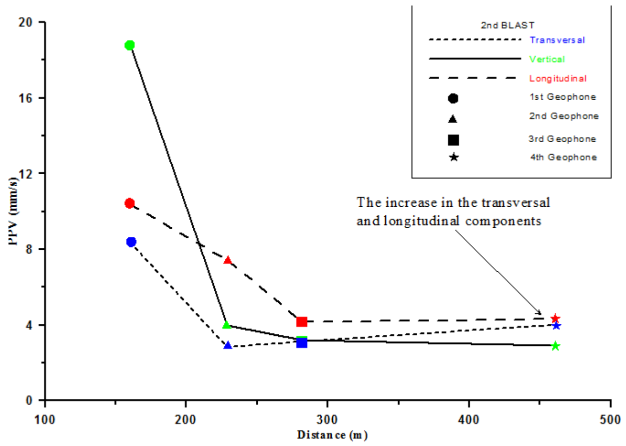


Fig. 7 2nd blast at the Husamlar coal quarry

vertical component of the signal recorded by the geophone installed 300 m far to the blast site. Again in the first-group blast, increase in transverse and longitudinal components of the signal recorded by the geophone installed 500 m far to the blast site is assessed as the impact of the channel wave. Furthermore, data obtained after the second-group blast (Fig. 7) revealed a channel wave impact at the longitudinal component of the signal recorded by the geophone 230 m far to the batch site, and further at the transverse component as recorded by the geophone 500 m far to the site. Agreement between the pattern and the ground data suggests that the pattern may be employed at least as a preliminary data source (showing trends of vibration amplitudes) in efforts for reducing blast vibrations. These results show that the seismic wave propagation in the coal seam has no uniform regression relationship with distance. It was found that amplitudes, supposed to exponentially decrease with distance, exhibit increasing trends at some points due to constructive interferences within the coal seam, and hence augment the impact of vibrations induced by blasts.

### *3.2 Interaction of soil amplification with the bedrock in the blast vibration analysis*

Surface geology, geotechnical characteristics of ground layers and the surface topography have major effects on

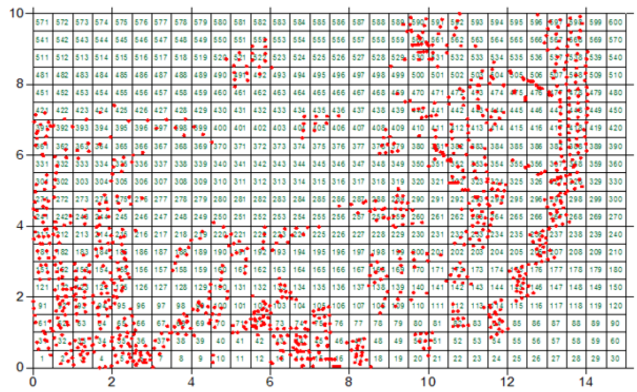


Fig. 8 2nd blast at the Husamlar coal quarry

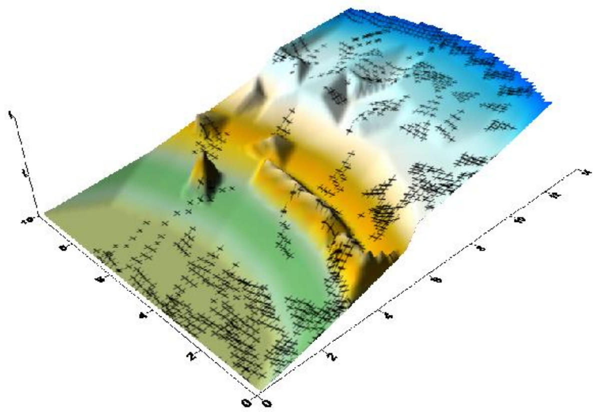

Fig. 9 2nd blast at the Husamlar coal quarry

blast vibrations. Increase in vibration amplitudes is controlled by source, seismic wave’s route, topography, absorption and dispersion effects. In general, characteristics of vibration waves (amplitude, frequency, and period) may vary due to the ground, ground’s geometry, surface topography, absorption and dispersion. Investigation of many regions reporting complaints for blast vibrations reveal that, sites mostly effected by blasts are sometimes very small zones. With a blast in the bedrock, differences between blast effects on the surface were investigated, however it has been quite difficult to prove whether such differences result from the region’s local geologic configuration or the propagation of seismic waves. Surface geology and geotechnical profile of ground layers are of great significance for blast vibrations. Characteristics of the wave zone (amplitude, frequency content and period) may vary by ground and surface topography. And variations in the characteristics of the wave zone may create increases or decreases in vibration amplitudes.

Surface waves formed by blasts for engineering and mining purposes tend to have augmented long-wave components as the low-frequency content progressively gains strength off the blast site. And therefore, surface waves induced by blasts maintain their impacts even at remote sites.

In addition, dispersion and absorption, and lower frequencies getting predominant due to absorption in the wave propagating off the source lead to resonation along the wave path. And this may cause great damage to residential areas. For this reason, propagation characteristics of surface waves should be understood well.

Can (2007) modelled the impacts of ground topography, absorption and dispersion on blast vibrations, and proved the model with actual blast data.

The model, application and the examples have shown that, when identifying soil augmentation through surface waves, it is strictly necessary to consider the impacts of absorption and dispersion on the wave structure, and the interaction of ground topography with the incident waves (dispersions, reflections, repeated reflections, etc.).

On blasts at the GELI Yatagan coal quarry previously owned by TKI, Can (2007) modelled how waves propagate towards the Yesilbagcilar city and how they react with the bedrock. Seismic fracture and reflection procedures were carried out to figure out the seismic velocity structure and the structural geology in an aim to explain soil amplifications and bedrock interactions along the route of blast-induced vibration waves. Can' thesis study (2007) is aimed at developing a model identifying the sites where blast-induced vibration waves undergo soil amplification after getting effected by the bowl-shaped marble bedrock along its route to Yesilbagcilar and repeatedly striking the same points. Because, despite previous studies based on the conventional method, there were unexplainable complaints in the village. Presence of far-site complaints and even damages contrary to the absence of any near-field complaint led to the awareness that the region is affected by different physical events not addressed by the conventional approach. Therefore, Can (2007) has mapped soil amplifications induced by the bowl formation caused by the marble contact in the region, recorded amplitude growth induced by actual blasts, and aligned them to the model. In the following figure extracted from the study detailed in the thesis (Fig. 8), sites to undergo soil augmentation, in other words, zones reflecting from the bowl formation and repeatedly being struck are shown. Fig. 9 shows the topology corresponding to sites of vibration amplitudes grown due to such repeated exposures. Localization of these sites has revealed that, for the zones that previously reported complaints, yet supposed to have no exposure to vibrations under the conventional approach to impact declining with distance, such zones were damaged due to soil amplification induced by repeated exposure to vibration indeed.

## 4. Methods alternative to the conventional method

Aldas and Ecevitoglu (2008, 2011) developed a new method alternative to the current one of "defining highest amounts of explosives per delay to ensure remaining below damage limits" in an aim to minimize blast vibrations. In this method, contrary to the conventional one, explosive amount loses its significance. This method introduces no limitation to blast-related parameters (number of holes, hole design, explosive amount, type, location of holes, etc.). The core principle of the new approach is to model seismic waves resulting from multiple blasts and apply appropriate delays for cross-attenuation of the waves by first obtaining a seismic wave after a pilot shot and using its signature. Delay parameters obtained from the data analysis are implemented during the actual grouped blasts.

Pilot blast is the foundation of this method. Seismic waves originating from the blast site and propagating to the target site encounter various factors during the route. Explosive amount, type, explosive-rock interaction, bench effect, complex geology (stratification, tectonic and lithological characteristics) primarily represent such factors. Seismic waves induced by pilot blasts reflect all these impacts in the form of different waveform formation and amplitude scaling. Here, the assumption is that, each hole within a grouped blast would create a wave equivalent to the one in the pilot blast. The basis of the data processing method employed is the superposition principle as a major feature of linear systems (Oppenheim and Schafer 1975).

The most striking aspect of the method is that, the signal from the pilot blast hosts all impacts (blast-related features, geological complexity, etc.). Therefore, there is no need to a specific assumption or a geological modelling.

Its superiority to existing methods can be listed as (i) assessments are not merely based on the peak particle velocity, but on waveform, frequency content and vibration time, (ii) no limitation is brought to explosive amount, and the current operational blast process remains intact, and (iii) capability of conducting an analysis based on recorded vibrations even from a single recording station (if seismic phase velocity will not be calculated).

Seismic data yielded by the pilot blast are transferred from seismic recorders to the computer through a commercial software, and then assessed under a specific software. After the assessment, how to group the holes of the same blast and how to assign delays to each group are defined. Grouped blasts are conducted based on these parameters. And the second dataset obtained from the grouped blast is used to figure out to what extent vibrations could be prevented.

In the second part of this article, the group blast modelling by this is shown in Fig. 5. On the top left corner, there are 26 group-blasting holes with entered coordinates, the location of the head (straight line) and the measuring direction (arrow). Group-blasting signals modelled from the pilot signal are also shown in the figure. Most appropriate delays that should be assigned to each group for the seismic waves to undergo destructive interference and cross-attenuation were defined and applied. On the top right corner in Fig. 5, the vibration amplitude of delay-free blast for the longitudinal component at time 0.18 sec is 63.76 units (LonZ) while it is 1.01 units for delayed blast (LonD). In order to test the model, delay intervals defined by the model were applied to the blast groups designed in the model, and vibration data from the far-site station was compared to the model result, confirming that the actual blast vibrations also dropped down to the levels proposed in the model (Uyar *et al.* 2015).

The most superior aspect of the method compared to the conventional one is as follows: In the conventional method, empirical approaches based on minimum 30 data items are employed to define ground constants between the blast site and the target site. Next, these are translated them into an empirical formula, and then particle velocity is estimated for this target site, and explosive amount per highest permissible delay to keep particle velocities under damage limits are defined. However, when the blast site changes, all these procedures become null, and it becomes necessary to gather minimum 30 data items again to develop a new formula for the new site. On the other hand, in the new method, whenever the route of vibration waves change, a new pilot blast is conducted to create a signature of the new route, and grouped blasts are modelled. In other words, data from only 1 pilot blast is sufficient rather than 30 data items.

This method has been successfully applied in many research published in valuable journals (Uyar 2016, Aksoy *et al.* 2016, Cardu *et al.* 2015, Kucuk and Aksoy 2017, Ozacar 2018) and used in many projects done in Turkish mining and industrial sectors (Uyar 2019, Ozcelik *et al.* 2018, Uyar 2018, Uyar 2017, Uyar and Gungor 2017, Uyar 2016).

As one of the first scientists to recognize the disadvantages of the PPV-SD approach, Blair (2010) has been researching since 2004 on modifying blast patterns and modelling P and S waves varying by the detonation velocities of explosives rather than limiting the explosive amounts, and has been taken into consideration not only the peak particle velocity but also the whole waveform to minimize vibrations.

Moreover, over the last 10 years, the ANN (artificial neural network) method has found a wide area of use in predicting PPV (Khandelwal and Singh 2007, Kamali and Ataei 2011, Mohammadnejad *et al.* 2012, Ataei and Kamali 2013, Ghasemi *et al.* 2013, Khandelwal 2012, Xue and Yang 2013).

## 5. Conclusions

The conventional approach defining the peak particle velocity-scaled distance relationship based on the limitation of the explosive amount has widely been used since 1960. Achieving successful results in minimizing vibrations in reliance to the current level of knowledge and technology in 1960s, this method fails to yield satisfactory results in near-field blasts and complex geological structures today. And this is confirmed through ongoing complaints for blast vibrations despite various actions. However, this approach has some disadvantages that may be resolved by modern knowledge and technology of the present time. In this paper, disadvantages of each of the five steps under the approach are separately discussed. To summarize;

(i) Assessments in the conventional method are exclusively based on peak particle velocity (PPV); neglecting the waveform, frequency content and vibration time.

(ii) A limitation is brought to the explosive amount, slowing down the mining operations of the plant.

(iii) When the route to which the empirical formula applies changes, blasts should be repeated to gather minimum 30 data items in order to define ground constants.

(iv)The conventional method fails to handle some physical and geological events that effect the propagation mechanisms of blast-induced waves. As one of these events, blast vibrations propagating through structures within layers with higher seismic velocity than the structure's itself, like coal seam, transform into channel waves within the coal seam, and may be transmitted to very remote sites. Another one is the relationship between soil amplification and bedrock interaction in the blast vibration analysis. Another disadvantage is that, the conventional method fails to protect near-field targets (located within the first 100-m distance to the blast site) as blast vibrations here display non-linear behaviors.

(v) Another issue found during the data collection stage is that natural frequencies of geophones are neglected. 4-Hz geophones commonly available in the market are only capable of detecting the frequencies at 4Hz and above, hence significant data within the 1-4Hz range are lost. It would be rational to employ 1-Hz geophones capable of recording these low-frequency surface waves inducing the biggest damage to buildings.

As an alternative to the conventional method having the abovementioned disadvantages, the paper further discusses the methods characterized by the principle of attenuating blast vibrations at the target site by assigning most appropriate delays, and further considering not only PPV but also frequency and time parameters.

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