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Investigating the effects of bench geometry and delay times on the blast induced vibrations in an open-pit quarry

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The paper analyzes the results of research aimed to monitor, predict and minimize the ground vibrations induced by blasting in an open pit limestone quarry in Italy. Data on 135 vibrations taken from 18 production blasts and 2 signature blasts were examined, including the effects of the bench orientations. Blast vibrations at the quarry were monitored for approximately three months. The blast vibration magnitudes and frequencies and their effects were analysed by both the conventional PPV concept and a software that is able to predict the vibration amplitudes of a production blast at the target sites by modelling signature blast data. The results have been rated and classified considering the peak particle velocities (PPV) measured in a number of critical areas near the quarry. A comparative analysis between the results predicted by the software and actual blast results was carried out. The benefits of the software were then highlighted, proving able to predict ground vibrations induced by blasting more reliably than the conventional site laws. Finally, based on the results, some arrangements were provided for two bench geometries employed at the quarry site.
Keywords: *explosive, vibrations, peak particle velocity, charge per delay, SeisBlast.*

Indagine sugli effetti della geometria di scavo e della temporizzazione sulle vibrazioni indotte in una cava a cielo aperto. *La nota analizza i risultati di una ricerca avente per oggetto il monitoraggio, la previsione e la minimizzazione delle vibrazioni indotte dallo scavo con esplosivo in una cava di calcare a cielo aperto in Italia. La campagna sperimentale è consistita nell'esame di 135 dati relativi alle vibrazioni rilevate da 18 volate di produzione e da 2 segnali pilota, considerando anche l'effetto dell'orientazione delle fronti di scavo. Il monitoraggio ha avuto durata di circa 3 mesi; l'intensità e la frequenza delle vibrazioni sono state analizzate sia secondo il classico approccio della PPV (velocità particellare di picco) sia mediante un software che, grazie alla modellazione dei dati ottenuti dal brillamento di un segnale pilota, è in grado di prevedere le ampiezze delle vibrazioni ottenute da volate di produzione in corrispondenza di obiettivi critici da salvaguardare. I risultati sono stati valutati e classificati considerando le PPV misurate in un certo numero di aree critiche in prossimità della cava. È quindi stata effettuata un'analisi comparativa fra i risultati predetti dal software e quelli effettivamente ottenuti dalle volate. Sono stati quindi evidenziati i vantaggi del software, dimostrandone la capacità di prevedere l'entità delle vibrazioni indotte da esplosivi in modo più affidabile rispetto alle convenzionali leggi di sito. Infine, sulla base dei risultati ottenuti, sono state proposte alcune modifiche da adottare in cava in funzione dell'orientazione delle fronti di scavo.*
Parole chiave: *esplosivo, vibrazioni, velocità particellare di picco, carica per ritardo, software SeisBlast.*

Investigation sur les effets de la géométrie du banc et des temps de retard sur les vibrations induites dans une carrière à ciel ouvert par l'abattage á l'explosif. *Le document analyse les résultats d'une recherche visant à contrôler, prévoir et minimiser les vibrations induites par excavation à l'explosif dans une carrière de calcaire à ciel ouvert en Italie. Les données sur 135 vibrations prises à partir de 18 abattages et deux signaux pilotes ont été examinés, y compris les effets des orientations du banc. Les contrôles des vibrations à la carrière ont été suivis pendant environ trois mois. Les grandeurs et les fréquences des vibrations et leurs effets ont été analysés à la fois par le concept de PPV classique et d'un logiciel qui, grâce à la modélisation des données obtenues par la génération d'un signal pilote, est capable de prédire les amplitudes des vibrations dues aux abattages à l'explosif par rapport aux objectifs essentiels qui doivent être sauvegardés. Les résultats ont été notés et classés compte tenu des PPV mesurées dans un certain nombre de domaines critiques près de la carrière. Une analyse comparative entre les résultats prédits par le logiciel et les résultats réels des abattages a été réalisée. Les avantages du logiciel ont ensuite été mises en évidence, ce qui prouve la capacité de prédire les vibrations du sol de manière plus fiable que les lois de site classiques. Enfin, sur la base des résultats, certains arrangements ont été fournis pour deux géométries du banc employés dans la carrière.*
Mots-clés: *explosif, vibrations, pic de vitesse des particules, charge par retard, software SeisBlast.*

1. Introduction

Although blasting is an economical and prevailing method for rock excavation in mining as well as in civil construction works, blast-induced vibrations cannot be completely avoided, though these certainly be minimized to an acceptable level, to avoid damage to the surrounding environment and to constructions to be safeguarded.

Blast-induced ground vibrations and their mitigation have been discussed for years. It is commonly assumed by many researchers (Duval and Fogelson, 1962; Ambraseys and Hendron, 1968; Indian Standard Institute, 1973; Langefors and Kihlström, 1967) that site laws are a reliable predictor for determining the PPV. They stated that peak blast vibration always increases with increasing charge. Based on this idea, many other works were conducted (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) as exhaustive empirical studies, taking into account frequencies, charge per delay (CPD), and distance effects of blast vibrations on structural response and damage. Blair (2004) however, stated that the traditional site laws used to predict the peak vibration levels from a blast are plagued with many prob-

Tab. I. General blast design of the quarry.
Dati salienti sul piano di tiro impiegato in cava.

Bench height [m]	5.0
Drill-hole length [m]	5.3
Drill-hole diameter [mm]	76
Bench inclination [°]	80
Burden [m]	2.5
Spacing [m]	2.5
Stemming [m]	2.0
Cartridge diameter [mm]	50.00
Cartridges/hole [-]	5.5
CPD [kg]	7.63
Holes/blast[-]	98
Total charge/blast [kg]	750.00
Delay between blast-holes of the same row [ms]	25/500
Delay between rows [ms]	42

lems. Aldas and Ecevitoglu (2008) have also developed a methodology, different from conventional charge weight scaling law, based on the suppression of surface waves by using proper delay intervals. In their methodology, contrary to the common assumption, vibration amplitudes can be reduced by applying suitable delays between blast-holes, without making any reduction in charge weights. Blair (2010) predicted that, in the near-field, the blast-induced seismic transmission is completely dominated by P-Mach and S-Mach wave propagation, which depends on detonation velocity (VoD).

Blair (2014) stated that Mach waves introduce a high near-field correlation of vibration within a uniform viscoelastic medium: this means that the diameter of a blast-hole being known, both near-field and far-field are included within a volume where the PPV is independent of the charge weight, on condition that the charge length is approximately 0.25 times greater than the blast-hole diameter. Large sets of vibration data from both underground and surface blasts were analysed by Blair (2014). He found that

the PPV measured underground due to underground blasting is not significantly dependent on the charge weight, and this is consistent with the predictive models about an indefinitely extended viscoelastic medium. However, the PPV measured at the surface and due to surface blasting was found to be strongly dependent upon the charge weight due to geological influences such as near-surface layering. This concept may disprove the classical perception of blast vibration analysis.

In addition, in the last 10 years many researchers have developed some artificial neural network (ANN) methods to predict PPV and shown their suitability over the widely used vibration predictors (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).

In the case under study, the compliance of PPV values with those suggested by the German standard DIN 4150-3 (1999) commonly adopted in Italy was evaluated, principally to avoid damage to surrounding structures due to blasts. The vibration data were analysed with both the conventional CPD method and a new technique that makes it possible to identify the most suitable delay times between groups of blast-holes: the methodology aims to employ the most suitable delay times among blast-hole groupings to render destructive interference of surface waves at the target location (where the blast-induced vibrations are to be minimized). In reflection seismology, surface waves are suppressed in the field using source/receiver patterns. The delay times necessary to destructively interfere with the surface waves are controlled by arranging the distances between individual sources within the source array, and between individual receivers within the receiver array. In rock blasting, however, the delay times necessary to conveniently fragment the rocks

and to mitigate the blast-induced vibrations are controlled by selecting appropriate delay elements.

Moreover, all the data obtained from the monitoring were analysed in order to identify the critical issues, such as the bench geometry, the blasting pattern and the delay times. Two site laws were found, one of them parallel to the "strike" direction of the rock's discontinuity beds ("Along the strike") and the other perpendicular ("Across the strike"). However, especially due to the presence of numerous discontinuities that characterize the rock mass under investigation, no meaningful correlations between the PPV and scaled distances were obtained.

Software specifically designed to evaluate the vibrations induced by explosives, called SeisBlast, was employed and accepted as a reliable predictor, considering a comparative analysis with results from actual blasts. Since two different bench geometries showed different responses to blasts, two different blasting schemes were proposed.

2. Data acquisition

A typical production blast is made by 98 blast-holes, arranged in three rows and blasted in two groups (50/48 or 30/68 blast-holes), with a total charge of 750 kg (cartridged emulsion explosives with a density of 1.2 kg/dm^3). A non-electrical system is employed to initiate the blast, using 500 ms delays at the bottom of each blast-hole, 25 ms surface shock tubes connections between the holes of the same row and 42 ms between the rows. Each blast-hole has a 7.5 kg CPD: this limit comes from the results of a previous monitoring campaign (Giraudi *et al.*, 2009), whose aim was the evaluation of the compliance with a 5 mm/s PPV (residential buildings). Hence an exploitation design based on limited bench heights (5 m) was developed,

in order to avoid difficult schemes of charging and timing along the same hole, whence issues could arise with the organization of the initiating system. As a consequence, to remove the same rock volume, a greater number of blast-holes and blasting caps are involved, with an increase of SD (specific drilling) and DC (detonator consumption).

The data pertaining to the blast design are provided in Table 1. During the experimental campaign, vibrations were measured by means of 10 instruments (n. 3 Instantel MinimatePlus and n. 7 Nomis MiniGraph 7000, all of them equipped with triaxial geophones) placed at different positions (the most significant are pointed out in fig. 1). The natural frequency adopted was 1 Hz, which means that geophones were able to record signals in the range 1-250Hz, including 15-50Hz, that are the natural frequencies of typical quarry blasts. All geophones were synchronized.

The following requirements were taken into account when choosing the location of the measurement stations: a) monitoring the seismic events in different directions, in order to detect the wave propagation phenomena; b) monitoring the seismic events at different distances, to obtain the relation between PPV and scaled distances; c) placing the instruments in continuity with the rock mass; d) choosing the locations near to the structures to be preserved, following the suggested standard DIN 4150-3.

Point 1 and 2 (fig. 1) are particularly important: point 1 is located in the vicinity of a residential building at a distance up to 195 m from the blasts. This point was found to be highly critical, as the results of monitoring produced very high PPV values, exceeding the limits suggested by the standard DIN 4150-3. Point 2 is a sensitive building (a furnace from the Roman period), being located 240 m from the quarry site.

Fig. 2 shows all the PPV values monitored according to the DIN

Fig. 1. Map showing the experimental positions adopted for vibration monitoring (point 3 and 7 are not represented, as they are located outside the area of quarry).
Planimetria con l'indicazione dei punti sperimentali adottati per il monitoraggio vibrometrico (i punti 3 e 7 non sono rappresentati, essendo localizzati in area distante dall'area di cava).
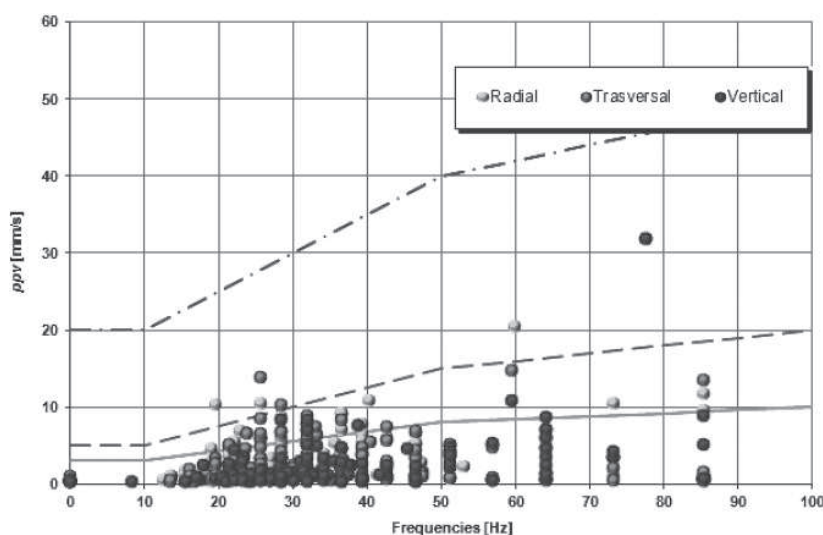

Fig. 2. Overall vibration data measured in their three components. Graphical representation of the reference values of PPV as function of frequency for the assessment of the effects on structures (DIN 4150-3).
Rappresentazione grafica, nel piano ppv-frequenza, di tutti i dati misurati nel corso della campagna vibrometrica. Il grafico adottato è quello utilizzato dalle norme tedesche (DIN 4150-3) per il controllo degli effetti delle vibrazioni sulle strutture.

4150-3 norms: it clearly indicates that only a few events exceeded the level for Class 2; as expected, those events belong to horizontal components (radial and transversal) of the vibrations. In order to reduce the vibration amplitudes, some adjustments were necessary, as explained in the following.

2.1. Effects of bench geometry on vibrations

One of the variables influencing the PPV values is the bench geometry. Fig. 3 shows the PPV values obtained parallely to the strike line of beds (in the following called "Along the strike" blast geometry). As evidence, this configuration led to at least two events exceeding the limit provided for Class 2 structures, referred to the monitoring station 1. Changes were then made to the blasting scheme and to the delays sequence, as elucidated later. Fig. 4 shows the PPV values obtained perpendicurarly to the strike line of beds (in the following called "Across the strike" blast geometry). This arrangement never led to higher values than those suggested by DIN 4150-3 for the monitoring points located outside the boundary of the quarry: in Point 1, which is a highly critical location, considerably lower PPV values in the "Across the strike" direction were monitored. Even though in Point 9 high values were recorded, this is due to the very short distance from the blasting area (about 35 m); for this reason, point 9 was not included in figg. 3 and 4.

Fig. 5 shows the PPV values-distance relation considering the two above-mentioned geometries. A decreasing PPV trend can be noticed. The same PPV values were analysed for each monitoring station, as shown in fig. 6.

As it can be seen, the "Along the strike" geometry gave rise to higher amplitudes than those obtained when adopting the "Across
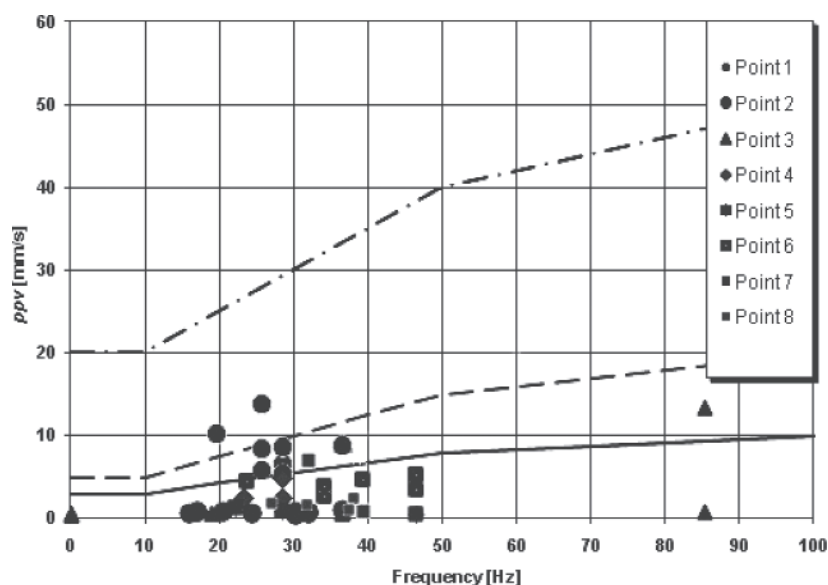

Fig. 3. "Along the strike" geometry: blasting-induced vibration data recorded in all components. Legend: point 1: civil building (North); point 2: Roman furnace; point 3: soccer pitch; point 4: civil building (West); point 5: S-E settlements; point 6: internal track; point 7: gate to access the quarry; point 8: quarry buildings.

Vibrazioni (nelle tre componenti) registrate a seguito delle volate effettuate in direzione parallela ai piani di discontinuità principali. Legenda: punto 1: edifici (Nord); punto 2: fornace romana; punto 3: campo di calcio; punto 5: stabilimenti a S-E; punto 6: pista interna; punto 7: cancello di ingresso alla cava; punto 8: edifici interni alla cava.
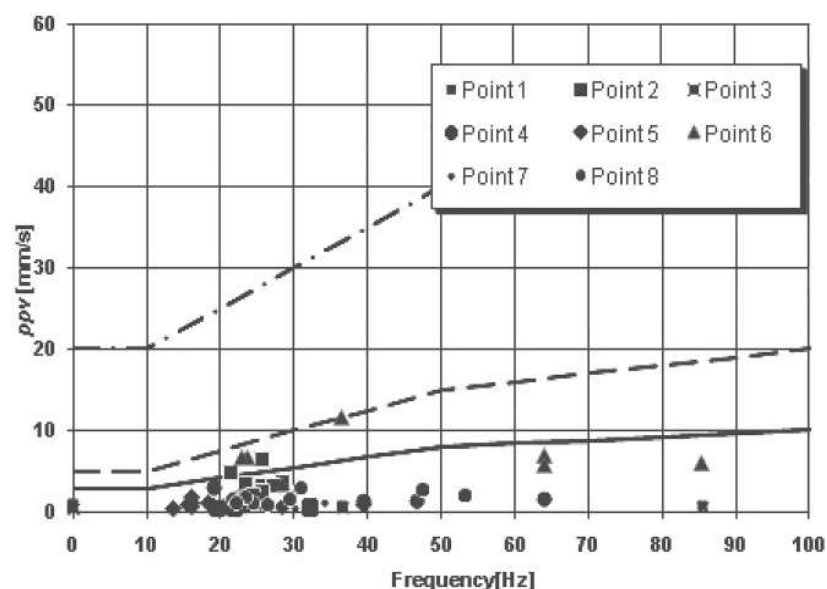

Fig. 4. "Across the strike" geometry: blasting-induced vibration data recorded in all components. Legend: Point 1: civil building (North); point 2: Roman furnace; point 3: soccer pitch; point 4: civil building (West); point 5: S-E settlements; point 6: internal track; point 7: gate to access the quarry; point 8: quarry buildings.

Vibrazioni (nelle tre componenti) registrate a seguito delle volate effettuate in direzione perpendicolare ai piani di giacitura delle discontinuità principali. Legenda: punto 1: edifici (Nord); punto 2: fornace romana; punto 3: campo di calcio; punto 5: stabilimenti a S-E; punto 6: pista interna; punto 7: cancello di ingresso alla cava; punto 8: edifici interni alla cava.
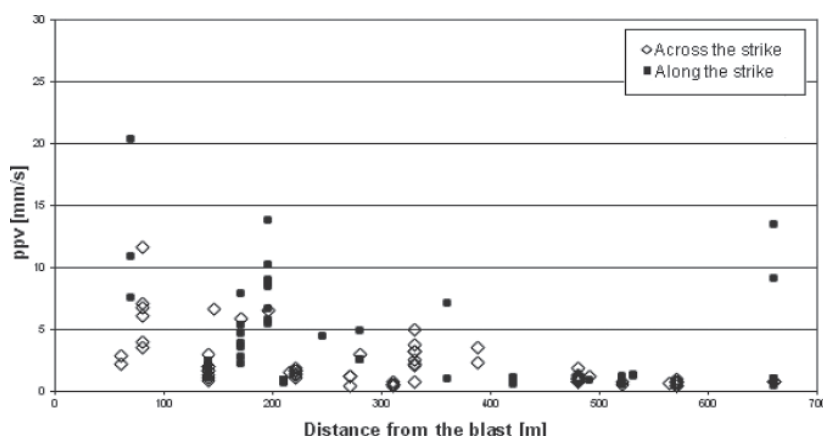
Fig. 5. PPV values of the blasts conducted at the benches with two different geometries.
Valori di PPV ottenuti dalle volate effettuate con le due differenti geometrie (parallelamente e perpendicolarmente ai piani di discontinuità principali).
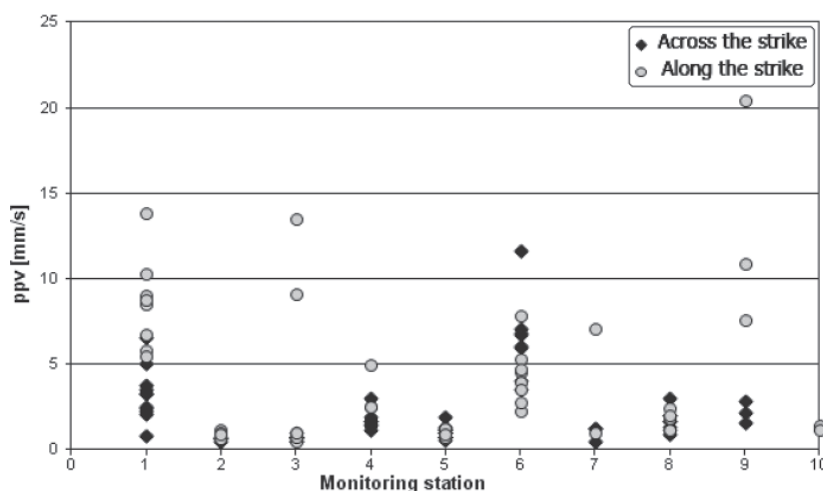

Fig. 6. PPV values of the blasts conducted at the benches of different configuration with respect to the monitoring station.
Valori di PPV registrati nelle diverse stazioni di monitoraggio per le volate con le due configurazioni (parallelamente e perpendicolarmente ai piani di giacitura delle discontinuità).
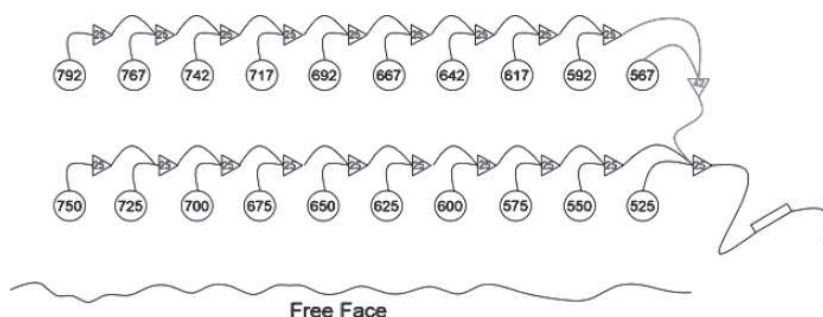

Fig. 7. Example of a serial-parallel configuration of the blast-holes. Delay interval is 25 ms between the holes and 42 ms between the rows. For simplicity sake, only 20 blast-holes are represented.
Esempio di configurazione del circuito di tiro in serie-parallelo. Gli intervalli di ritardo sono 25 ms fra le mine della stessa fila e 42 ms fra le file. Per semplicità di rappresentazione, sono indicate solo 20 mine.

the strike" configuration. A possible explanation is that the "Across the strike" blasts induce seismic waves to travel through a path involving many rock weakness planes, each of them implying a reduction of the amplitudes of the seismic waves: the general trend substantially confirms that the results obtained with this geometry were considerably lower. The most striking case is point 1: by varying the geometry of the bench, the PPV values are significantly reduced.

2.2. Initiating system timing

Due to the high PPV values found in some cases, the influence of timing was considered by checking the best delay time to be applied between blast-holes. It can be seen (fig. 7) that, even though the holes of the same row are blasted with a 25 ms delay, the 42 ms delays of the surface shock tubes connections between the rows imply that a delay of only 8 ms is found between blast-holes pertaining to different rows: this is a very low value, possibly responsible for the superposition of waveform amplitudes. It was therefore decided to change the initating sequence, using a series circuit path resulting in a 25 ms delay between the blast-holes. Fig. 8 shows the new delay sequence adopted. The analysis performed after the new sequence was established showed a non-negligible reduction of the PPV values, as can be seen in fig. 9.

3. New methodology for the evaluation of blast-induced vibrations

Two groups of monitoring locations have been identified in order to obtain two different site laws, referring to the two above-mentioned geometries. Obtaining a high data correlation would be useful to pre-determine the values of blast-in-
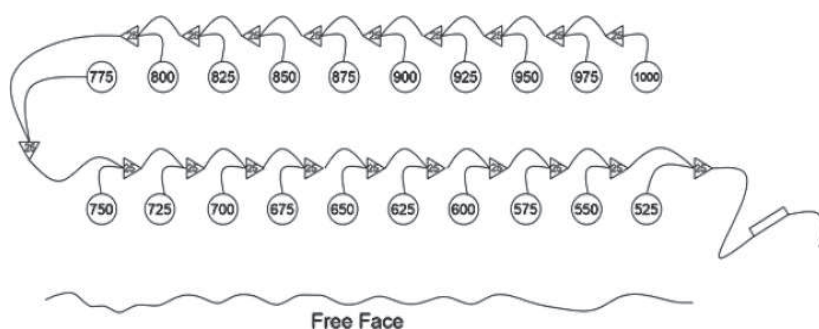
Fig. 8. Example of a serial configuration of the blast-holes. Delay interval is 25 ms between all the holes. For simplicity sake, only 20 blast-holes are represented.
Esempio di configurazione del circuito di tiro in serie. L'intervallo di ritardo fra le mine è di 25 ms. Per semplicità di rappresentazione, sono indicate solo 20 mine.
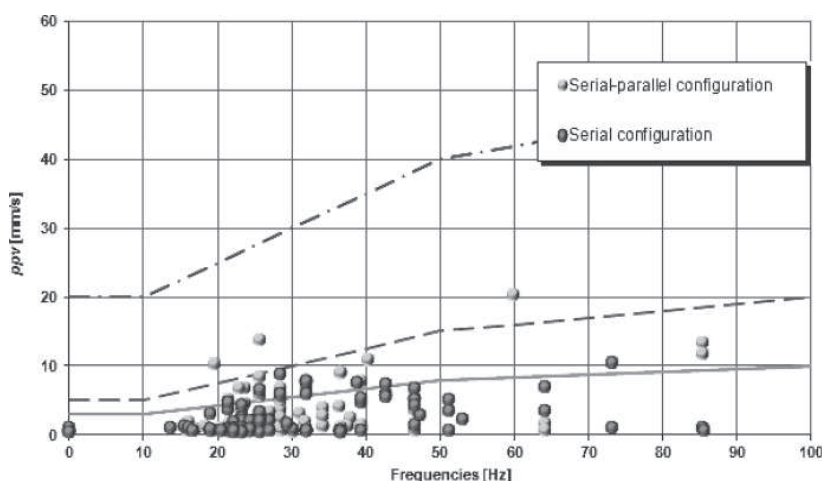

Fig. 9. Comparison of the PPV-frequency data considering the delay timing of "serial" and "serial-parallel".
Confronto, sul diagramma PPV-frequenze, dei risultati ottenuti mediante la configurazione delle volate in serie e quella in serie-parallelo.

duced vibrations corresponding to the neighboring area of the North-West and South-East villages. Analysing the data, a 48% correlation for the "Across the strike" bench orientation (see fig. 10) and 26% for the "Along the strike" bench orientation (see fig. 11) were found: these values are not satisfactory (transposition of the curves that provides a confidence level of 95% were also drawn in figg. 10-11). Thus, a new method developed by Aldas and Ecevitoglu (2008) was employed to predict and minimize blast-induced ground vibrations at the target sensitive structures nearby the quarry site. This methodology is quite different from the conventional approach, which does not take into account the me-

chanics of seismic waves: it does not consider any blast parameters such as explosive types and amounts, blast geometry, blast-hole design, hole depth/diameter, etc., except delay times (Moser, 2008). The aim of the methodology is to employ the most suitable delay times among blast-hole groups, to attain a destructive interference of surface wave amplitudes. The crucial point of the method is the use of a signature-blast signal which takes account of the seismic properties of all the complex geology between the blast and the target locations. Therefore, it does not require any geological model or assumption. In other words, the methodology needs a signature-blast signal, obtained by recording a sin-

gle event (one blast-hole) ignited in the vicinity of the production blast. The signature-blast signal embraces the geological seismic properties between the production blast and sensitive structures. Seismic waves that originate from the signature and production blasts should travel through the same geological structures, such as lithology and stratigraphy.

Since the signature-blast carries all the information related to the above stated factors, only two seismic records are necessary, related to: (1) the signature blast, and (2) the production blast. The seismic records obtained from the signature and production blasts share the same blast-design properties.

The production-blast signal is artificially created by summing several signature-blast signals up, as though each production hole would generate the same waveform as the signature blast-hole, adding the surface delay applied under field conditions.

This technique is based on Linear System Theory (Oppenheim and Schafer, 1975), and on its result: the superposition principle. Although the blasting event is non-linear in nature, linear behaviour may still be acceptable for practical reasons: explosion phenomena are not completely non-linear all the time. If, say, a whole explosion event takes 50 ms, at least the first half of the time, prior to the rock fragmentation, creates elastic waveforms mostly due to the linear behaviour of the explosion. If the rocks are plastically deformed from the very early stage of the blasting, there would be no seismic wave generation: rocks are stretched before fracturing. With this stretching event, seismic wave propagation starts; in other words, at this stage, most of the elastic waves are generated where the above expressed assumptions are supported. The first elastic waves are not affected by the fracturing process occurring later and, therefore, the linear assumption is valid.
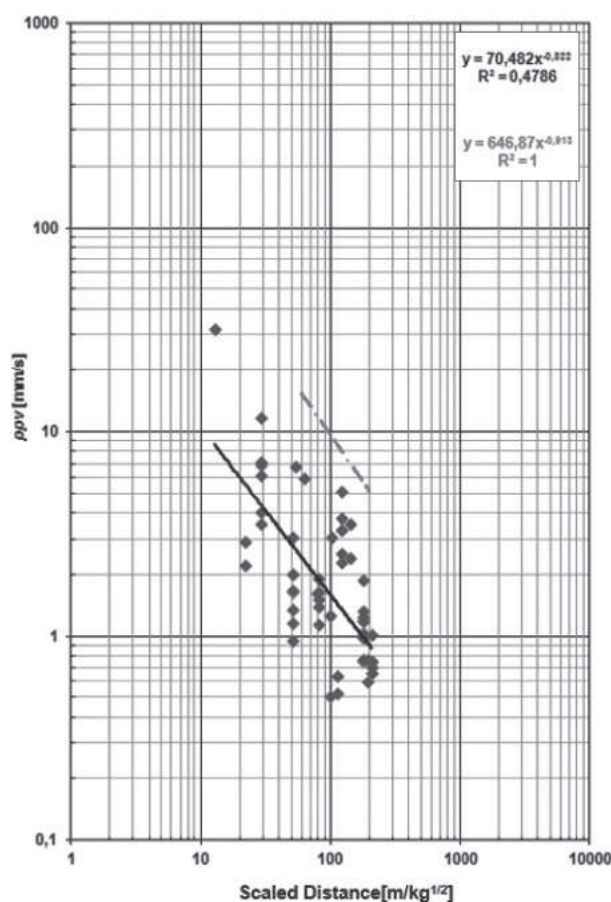
The advantages of this method-

Fig. 10. Site law pertaining to the blast records when the "Across the strike" bench orientation was employed. The regression analysis provides a not satisfactory result. The dashed line represents the transposition of the curve that provides a confidence level of 95%.

Legge di sito ottenuta dall'analisi dei risultati delle volate con configurazione di bancata perpendicolare ai piani di giacitura delle discontinuità. L'analisi di regressione fornisce valori non soddisfacenti. La linea tratteggiata rappresenta la trasposizione della curva che offre un livello di confidenza del 95%.
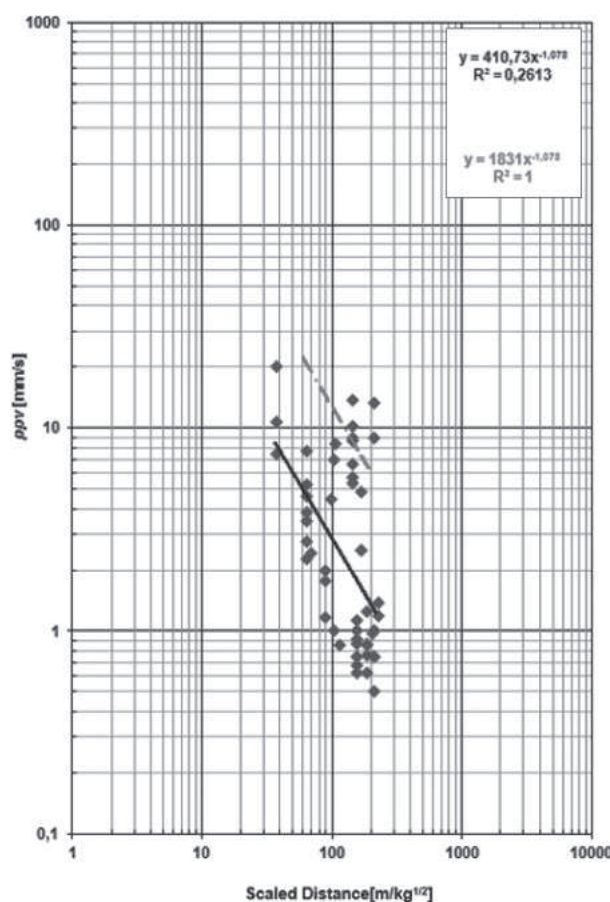
Fig. 11. Site law pertaining to the blast records when the "Along the strike" bench orientation was employed. The regression analysis provides a very low correlation. The dashed line represents the transposition of the curve that provides a confidence level of 95%.

Legge di sito ottenuta dall'analisi dei risultati delle volate con configurazione di bancata parallela ai piani di giacitura delle discontinuità. L'analisi di regressione fornisce una correlazione molto bassa. La linea tratteggiata rappresenta la trasposizione della curva che offre un livello di confidenza del 95%.

ology with respect to conventional methods are: (1) Data evaluation is not solely based on PPV as it is for conventional methods. Seismic waveforms, their frequency content, and their time-duration are also taken into account; (2) The proposed methodology does not impose any restriction on the amount and type of explosives to be used, or on blast design; (3) The new methodology requires fewer seismic stations than conventional methods to analyse blast-induced vibrations.

Actually, one seismic station located at the target location is suf-ficient for data analysis, if the approximate surface wave velocity is known. Conversely, in the case of conventional methods based on empirical models, at least 30 seismic records are needed to make a reliable data analysis.

Two experiments based on this methodology were conducted in this quarry. The former was organized in the "Along the strike" bench, the latter in the "Across the strike" bench. Therefore, the effects of geometry and delay times on the vibration signals could be analysed by using this method.

3.1. Signature blast modelling

The SeisBlast software analysis consists of (1) Filter and (2) Delay modules. The Filter program applies a band-pass filter to the seismic data, removing high-frequency noise. The Delay program displays the geometry of each production blast-hole. It is possible to group up the blast-holes and assign appropriate delay times to each one, in order to apply a suitable sequence that will cause destructive interferences between major wave lengths.
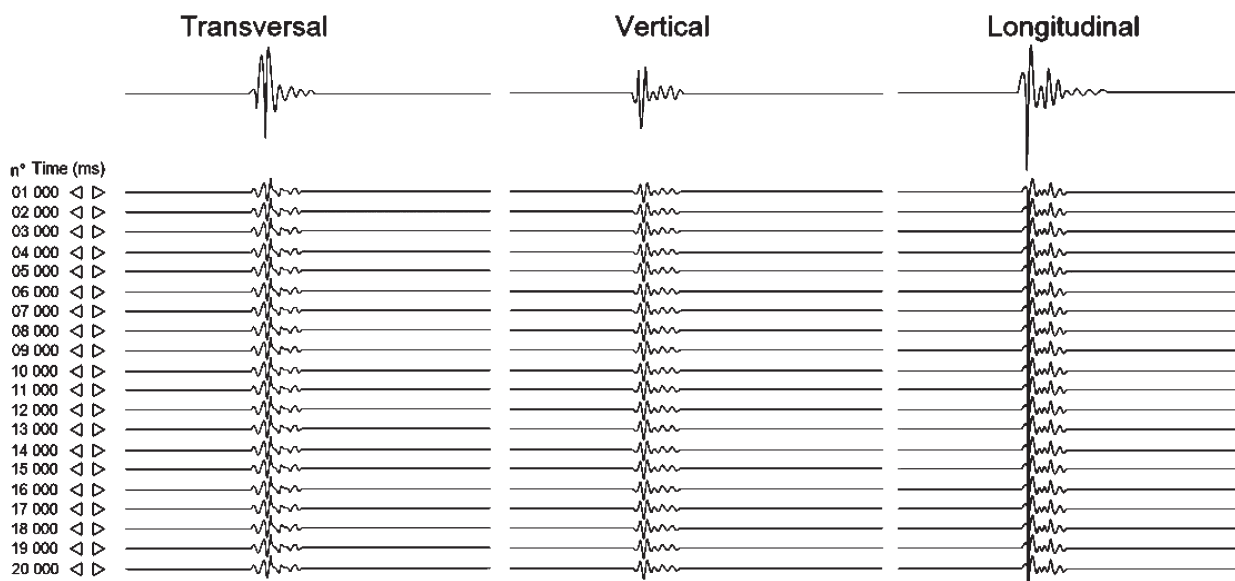
The theory under the Delay pro-

Fig. 12. Blast-holes are arranged so that they will blast simultaneously: at this stage, no delay is given between blast holes yet.
Ogni mina è chiaramente identificabile, e tutte detonano simultaneamente: in questa fase non è stato ancora inserito alcun ritardo fra le mine.

gram is based on the Linear Superposition Principle. After recording the signature-blast signal, the seismic signals of each blast-hole in the production-blast are simulated as if they were the same as the signature blast signal. The assumption made is that the linear superposition of each blast-hole signal, which is actually the signature blast signal, represents the group blast signal. Using the Delay program, it is possible to modify the delay times among blast-holes, applying suitable lags to produce destructive interferences between major wave lengths.

As is well known, the prime objective of mining is to properly fragment the rock. Therefore, when designing the blast with the aim of minimizing the vibration problem, it is also important to consider the rock's proper fragmentation to comply with the mining purposes. According to Aldas & Ecevitoglu (2008), most of the effects on constructions are caused by lateral compounds of vibration (transversal and longitudinal). Therefore the Delay program works on the lateral component, presenting higher amplitudes. Proper delay times are applied to this

selected component. Practice shows a substantial minimization of vibration occurring in the other components as well.

Fig. 12 shows the Delay program screen with no delay applied to the blast-holes. In the figure, the blast-holes are numbered from 1 to 20, each of them showing the three components of waveforms. The single waveforms are all the same. The

vibrogram on the top shows the signal produced by the blast obtained as linear sum of the events recorded by each blast-hole, which corresponds to the value obtained from the pilot signal. The automatic setting does not including the introduction of delays, the vibrogram refers to a simultaneous blast.

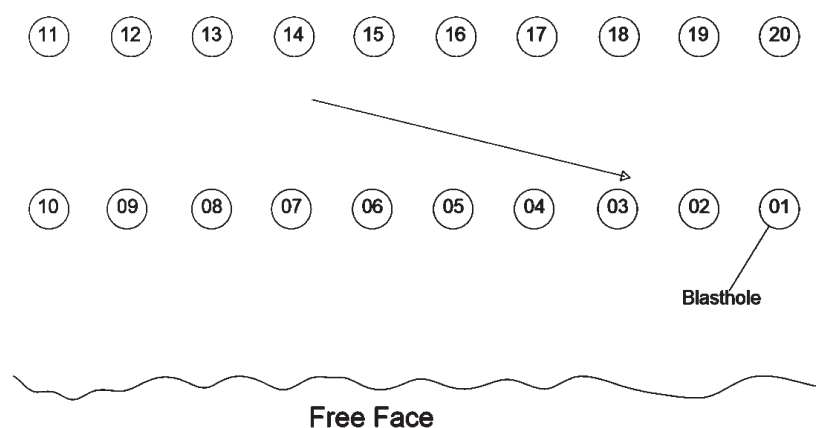The plan view of the blast is shown in fig. 13, where the arrow

Fig. 13. Example of a production blast carried out on rows of blast-holes. The geophone that detects the signal from the "signature blast" is located at short distance (<200 m) in the arrow direction.
Esempio di volata realizzata su 2 file di mine. Il geofono che capta le informazioni provenienti dal segnale pilota è localizzato a breve distanza (<200 m) nella direzione della freccia.
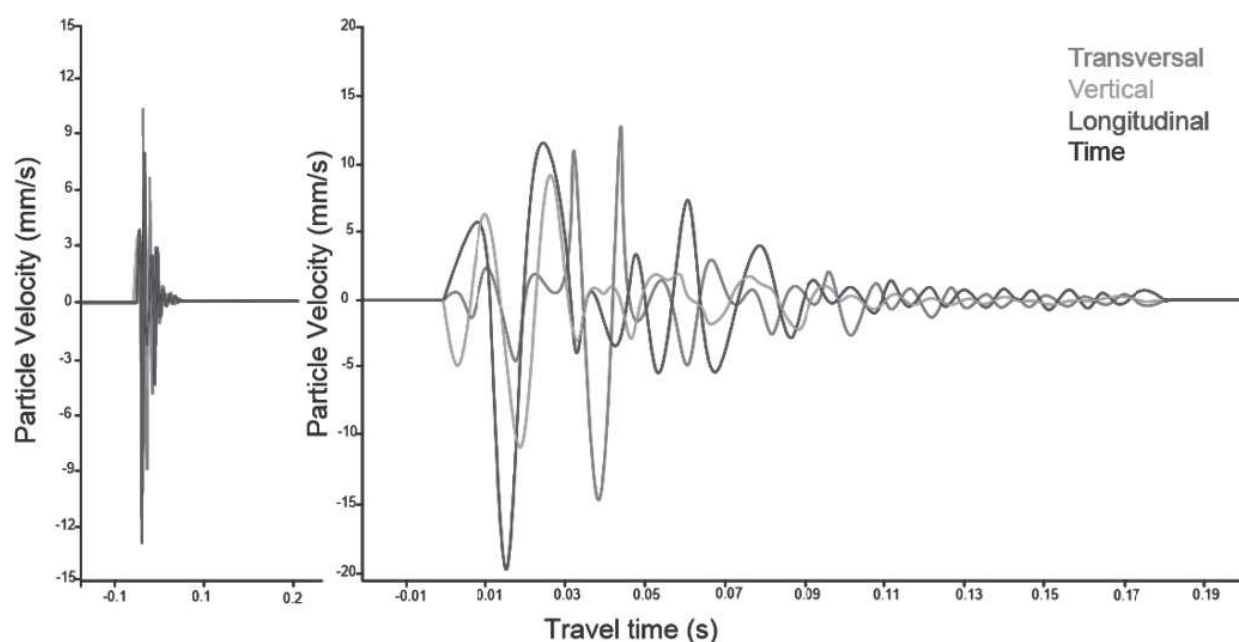
Fig. 14. Signature waveform recorded 70 m away from the single hole blast at the bench "Along the strike". A magnification of the waveform is provided on the right.
Segnale pilota registrato a 70 m dal brillamento di una singola mina con configurazione di bancata parallela ai piani di giacitura delle discontinuità. A destra si osserva una migliore definizione della forma d'onda, essendo stata ampliata la scala dei tempi.

shows the direction of the measurement location.

Fig. 14 illustrates the signal waveform recorded 35 m away from the signature blast. It is clearly noticeable that, especially in the longitudinal and transversal components, the vibrations recorded have reached 15 mm/s. A further point of interest is that the detonation of the individual hole (pilot signal) has resulted in a vibration event whose duration was only 0.19 s. Moreover, being the measuring point very close to the source, the frequency is high, around 50 Hz.

3.1.1. "Along the strike" geometry

The usual blast design of the quarry applies a 25 ms delay-time between holes of the same row and a 42 ms delay between different rows. The next step was then to insert those delays, in order to predict the results, which will be compared with the vibration records (triaxial geophones) obtained from the actual blast. Fig. 15 shows the delay times applied to the blast-holes and the resulting waveforms. The vibration reduction in the longitudinal components of the waveform is significant (from 42.20 mm/s to 11.10 mm/s). Looking at the PPV values from the actual production blast, it can be seen that the longitudinal component is 10.9 mm/s close to the SeisBlast predicted value, i.e. 11.10 mm/s.

3.1.2. "Across the strike" geometry

As previously explained, in order to reduce the blast vibration amplitudes (especially at Point 1), the blast design was modified. The initiating sequence was organized with 25 ms delay-times, serially. Thanks to the signature blast signal, the blast was modelled and the predicted results were compared with those obtained from the actual production blast in terms of induced vibrations. Fig. 16 shows the results obtained. The vibration reduction in the longitudinal components of the waveform is significant in this case too

(from 37.54 mm/s to 3.14 mm/s). Then, the predicted results were compared with those that were actually recorded by the geophones used for the monitoring of the blast. Considering the results of the actual blast data, the longitudinal component of PPV is 2.89 mm/s, while the model predicted 3.14 mm/s, confirming to operate correctly.

4. Discussion and conclusions

The proposed methodology is based on Linear System Theory, where the superposition principle holds. A minimum amount of interaction among the blast-holes was assumed. It is obvious that earlier blasts modify the conditions of the later blasts in a group-blast sequence. This fact causes some discrepancy in the model and real data comparisons, though it is not very substantial.

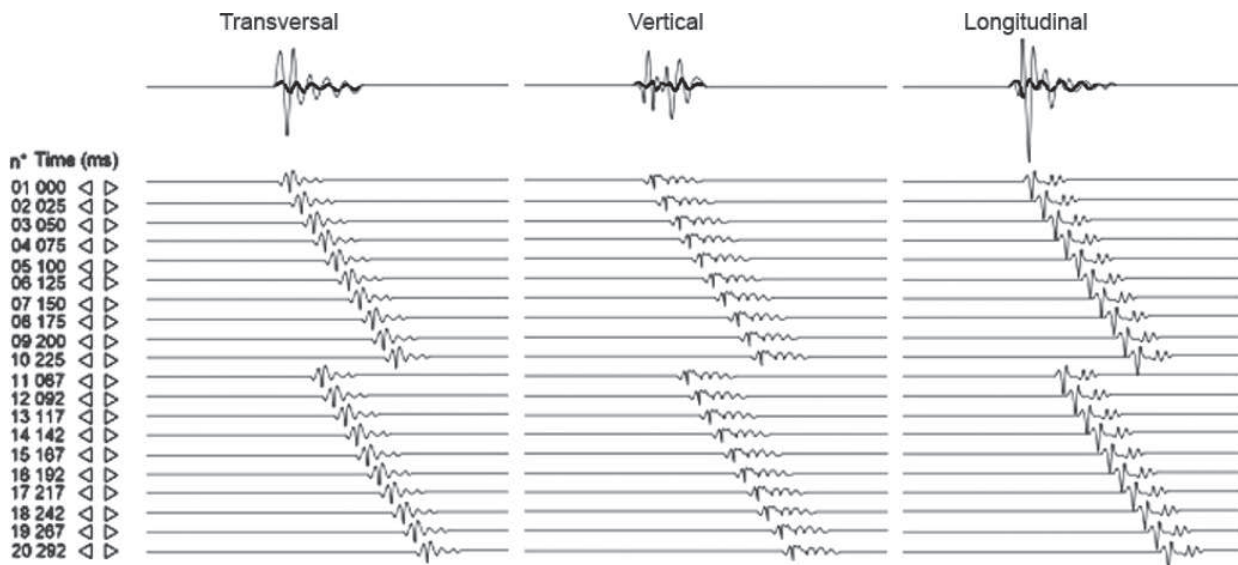Results obtained from the vibration monitoring show that the PPV

Fig. 15. Results for 25 ms delay between blast holes and 42 ms delay between rows. Vibration reduction by applying serial-parallel delay timing is noticeable. The dark black curve refers to the "destructive interference" of the waves, thanks to which a noticeable reduction of vibration can be obtained.

Risultati ottenuti con 25 ms di ritardo fra le mine della stessa fila e 42 ms di ritardo fra le file. Si osserva chiaramente una riduzione delle vibrazioni ricorrendo a temporizzazione in serie-parallelo. La curva più scura rappresenta l'effetto dell'interferenza distruttiva delle onde, grazie alla quale si rileva una notevole riduzione delle vibrazioni.
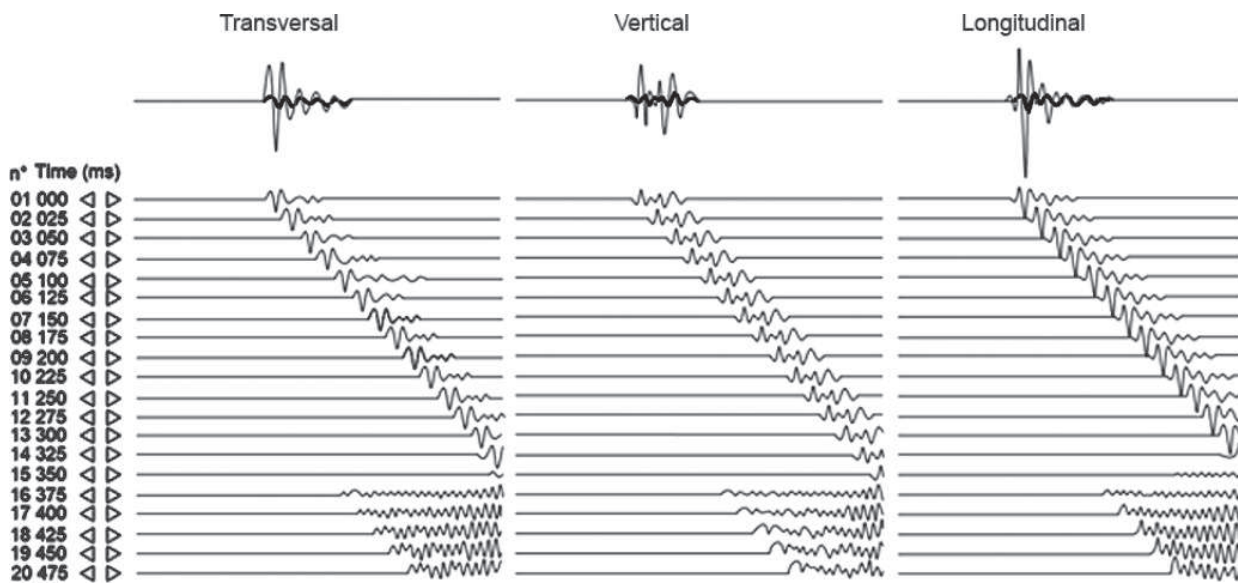

Fig. 16. By applying 25 ms delay between blast-holes, the model predicts that vibration amplitudes will reduce from 37.54 unit to 3.14 unit, in other words, 11.95 times reduction in longitudinal components. The dark black refers to the "destructive interference" of the waves, thanks to which a noticeable reduction of vibration can be obtained.

Applicando un ritardo di 25 ms fra le mine, il modello prevede che l'ampiezza delle vibrazioni si riduca da 37.54 a 3.14 mm/s, ossia di 11.95 volte nelle componenti longitudinali. La curva La curva più scura rappresenta l'effetto dell'interferenza distruttiva delle onde, grazie alla quale si rileva una notevole riduzione delle vibrazioni.

values are generally within the limits suggested by DIN 4150 norms for class 2 structures, except for two events: this may be due to both bench geometry and delay sequences. Blasts conducted with the "Along the strike" geometry showed generally higher values than those measured with the "Across the strike" scheme. A possible interpretation is that the blasts performed perpendicularly to the discontinuities induce seismic waves to cross a path involving many weak layers in the rock, resulting in a reduction of the ampli-

tudes of the seismic waves.

As for the analysis of the delay blasting sequence, all the surface shock tubes connections (25 ms delay caps) were organized in series instead of series-parallel. This led to a significant reduction of vibration amplitudes.

Approval of the delay sequence was also assessed by means of the SeisBlast software. Two signature blasts were performed. The first test refers to blasts organized with the "Along the strike" geometry. The model prediction (11.95 mm/s) and production-blast results (10.9 mm/s) matched properly. Other trial tests were performed grouping the blast-holes differently (i.e., grouping blast-holes in pairs) but no reduction of vibration was noticed.

The second test refers to blasts organized with the "Across the strike" geometry. In order to reduce the blast vibration amplitudes especially in critical areas, the blast delay sequence was changed. Blast-holes were delayed by 25 ms, serially. The longitudinal component of real PPV was 2.89 mm/s. Then, the 3.14 mm/s value predicted by the model is definitely comparable.

Another interesting conclusion was inferred by setting the simultaneous blasting of two blast-holes in the group: the software in this case predicted an extremely large reduction of vibrations: indeed, the longitudinal component of the PPV reduced from 30.29 to 0.91 mm/s (with a ratio of 33.28). This implies that, although increasing CPD, by adopting a value double than the usual, the PPV could be considerably reduced.

This approach certainly involves the need for further testing, to compare more reliably the results obtained from the numerical analysis with the real ones. In any case, it has to be pointed out that the CPD currently employed at the quarry is the result of a great number of previous tests for the evaluation of an appropriate site law. Therefore, the new CPD proposed by the results obtained should be tested in the quarry.

The method here presented, not based on extrapolations of data obtained from the PPV-Scaled Distance graphs but on concrete analysis of the waveform obtained from a signature blast signal representative of the medium, although requiring further investigation, represents an attractive alternative approach for the evaluation of induced PPVs.

If these assumptions were verified, it would be possible to adopt interesting changes to the blasts geometry, by increasing the CPD without impairments to sensitive constructions.

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