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MEASURING OF BLAST-INDUCED GROUND VIBRATIONS; COMPARISON BETWEEN TWO DIFFERENT METHODS

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In quarry activities, the blasting operation is still considered to be one of the most effective methods in order to fragment the rock. The ground vibrations generated due to the explosions are an undesirable effect which is harmful for the nearby habitants and for the dwellings and should be prevented. In order to characterize this phenomenon, accurate measurements of the seismic waves are required and one of the most critical aspects of the field tests is represented by the coupling method between the transducer and the soil. In this paper, an attempt was done for the purpose of measure the blast-induced ground vibrations, comparing two different ground transducer coupling methods. The data were obtained through a measurement campaign realized in an opencast limestone quarry in the centre of Italy. The first coupling method was realized by attaching seismic accelerometers on an iron spike fixed in the soil, firstly in direct contact and then through a base of cement. The shape and dimension of this support were chosen in order to research the optimum configuration, also taking into account parameters such as frequency to be detected, soil density, mass and material characteristics. Simultaneously the signal was recorded with second coupling method; the transducer was fixed to the ground through a rock sack positioned on the tops of device for the purpose of maintain the proper adherence. Finally, the data obtained in terms of acceleration [m/s^2] were compared and discussed.

Key words: [quarry activities, blasting operations, ground vibrations, coupling methods]

1. Introduction

Explosives are the primary source of energy for breaking rocks in the mining and quarry activities [1]. Blasting operation transforms rock into a distribution of fragments and it generates different types of energy that can be divided into two principal groups. The first group consists of shock effects of gases formed during explosion, while the second one produces energy forms of heat, noise [2] and ground vibrations. These last consume explosive energy that could be utilized in order to fracture the rock [3]. High ground vibrations levels not only create problems to the nearby population, but can also affect adversely the integrity of the structures near the quarry area. Accurate measurements of ground motion are the key to prevent troubles among quarry workers and to respect national standards for blasting operations. The assessment of ground levels vibrations is very complex because of many natural factors that influence seismic-wave propagation into the ground (natural structure of ground, voids, splits, abrupt structural changes of the ground). Furthermore the wave propagation is influenced by other parameters, linked to the blasting operations (number of mines, parameters geometric of holes, type and quantity of explosive) [4] [5]. There is a general agreement about the importance of the coupling of the sensors to the ground to ensure good transmissibility of the signal since the vibration energy measured is strongly influenced by the contact conditions between the device and the ground. The modality of vibration signal transmission by each method is basically unknown and there is still some controversy used is basically unknown and there is still some controversy about the suitability of some suggested methods and about field guidelines. An efficient coupling method is needed in order to prevent that the sensor loses contact with the ground in the vertical or glides along the horizontal direction [6]. The first relevant aspect is that presence itself of the measurement device disturbs the incoming wave-field. Because of that, when a seismic wave hits an instrument on the ground, two physical mechanisms occur. The first one is an induced vibration in the mount system of the instrument as a response to the wave and it can be considered as a secondary source that radiates energy back into the ground. The second mechanism is the elastic scattering of the wave by the mount system and is generated by the contrast in acoustic impedances between the mount material and the surrounding soil. In fact the ground transducer coupling consists in a resonant phenomenon, where the transducer and system of ground coupling form a resonant system. The coupling phenomena have been studied by many researchers, analysing the parameter characteristics of the coupling resonant frequency, also through the use of numerical models combined with field experiments. Some researchers claim that the frequency resonance is insensitive to change in the mass or diameter of the transducer and that the coupling method influences the amplitude and phase of the vibration signal. Furthermore, transducer placement and the soil type, along his surface conditions, can drastically affect the measurements. Other authors, on the contrary, point out that the most important effects of ground-transducer coupling are attributed to the base area and to weight of the transducer [7]. The problematics described above can be explained because the research based on theoretical models and results from laboratory experiments, can only describe limited cases. The real field characteristics, such as surface soil properties, density gradients, non-linearity, quality of mounting system, moisture content of the soil, compaction of the ground around the measurement point, carry out an important role on the ground coupling phenomena but they are very complex to replicate. Therefore, although some of these parameters can be analysed through theoretical models and laboratory experimentation, the relationship between laboratory and field tests remains very complicated. The literature cites several types of ground-coupling methods, often selected as functions of the expected acceleration and the ground type at the monitoring point. Firstly a procedure is suggested of burying transducer completely for high frequency recordings or where there is loose soil, and in any case when the maximum acceleration falls between 0.2 and 1.0 g [8]. Secondly, where the measurement surface is made of rock, rigid cement or asphalt, the transducer should be fastened to the measurement surface with a bolt or with epoxy or other quick-setting material. Another technique which is used to fix the transducer to the ground is by placing a sandbag on top of the device. Some authors indicate this method as correct when the expected acceleration levels are below 1.0 g. Other experts affirm instead that this coupling technique may alter significantly the amplitude of the measured waveforms because it damps vibrations at low and mid frequencies, and amplifies them at high frequencies [9]. Finally the last coupling method is the employment of mounting spikes. The literature shows that it is a controversial issue since they can be an effective coupling system for ground acceleration below 1.0 g [10] [11], but they may also affect the characteristics of the ground motion recorded. Furthermore some scientific works claim that this technique overestimates the true ground vibration by 46.5% and that the coupling resonance frequency can be augmented proportionally with the length of mounting spikes [12]. Conversely this point of view is not shared by who developed a model showing that by increasing the spike radius and length, the frequency of resonance decreases [13]. The present paper compares two coupling methods through many different field tests

2. Materials and methods

In this study two different methods of coupling transducer-ground are compared; the first method involves the fastening of transducers on an iron spike inserted firmly in the ground and the second one fixing them through a sack filled with rocks. Within this experimental study, 10 different vibration levels originated by blasting operations were measured, carrying out two different measurement campaigns realized in a limestone quarry in the centre of Italy, 100 km far away from Rome. The various measurement points were chosen with arbitrary distances; in fact, since the rock fragments may be propelled to a long distance, it was chosen a safety zone where there were no damage risks for the measurement instruments. For this reason, unfortunately, it was not possible to characterize the source signal. Furthermore, in each blasting operations, the measurement point was identic but the distance between this last and the bench of rock blasting was variable each time, from a minimum distance of 80 meters to a max of 180 meters. The equipment utilized was capable of simultaneous readings of the vibration signal and data were always obtained simultaneously, using three accelerometers (one tri axial and two mono axial accelerometers). Before each measurement, a hammer test (quickly impulse on the ground near measurement point) was done. The aim was to determine if internal flaws had been introduced or significant ground differences could be appreciated on the effectiveness of the ground transducer coupling. In order to reduce thermal errors, all field tests were carried out under the same weather conditions.

2.1 Sampling Devices

In the measurement campaigns a tri axial accelerometer and two mono axial accelerometers were employed. The signal was recorded through four channels connected to a measurement device SoundBook and acquired through SAMURAI software. Then, the ground vibration data recorded for each rock blasting operation, were analyzed with Noise Vibration Work program. The setup of each device, was characterized by a sampling frequency of 1250 Hz and a gain of 3.15 V in order to avoid overload. The analysis filter frequency range was a compromise between the memory capacity of the recording units of the acquisition device, and the predominant frequencies of ground during blasting operations. The following table shows the characteristics and parameters of measurement.

Table 1: characteristics of instruments

Transducer	Sensitivity [mV/(m/s^2)]	Sampling Frequency [Hz]	Gain [V]	Frequency Range [Hz]
Accelerometer PCB 393A03 (mono axial)	10.55	1250	3.15	2 -1000
Accelerometer PCB 393A03 (tri axial)	10.55	1250	3.15	2 -1000

It is recognized that the tilt of transducer is to be kept to a minimum to avoid introducing another variable and then the sensor must be in a nearly level position. Cross-axis sensitivity (transverse sensitivity) can influence the measure on the signal acquired by a transducer, if it measures at right-angle respect to its working axis. The literature reveals that below 60 Hz amplitude distortion is more influenced by the vertical alignment of the transducer than it is to the coupling mechanism. In order to obtain a correct transducer position, before each field test, the vertical and horizontal correct alignment with respect to the ground was verified through a bubble level placed on the transducer (see Fig. 2).After each measurement, the devices were removed from the ground, except the iron spike (covered with a plastic protection), and the whole fixing procedure was repeated in each test.

2.2 First measurement campaign

In the first measurement campaign, 5 measurements of blasting operations were taken in a point near the quarry border. Two coupling techniques were compared: the first consists on fastening the transducer on an iron spike and the second on fixing a transducer to the ground by placing a rock bag on its top (see Fig. 1). The weight of the sack was 10 Kg, with a size of 40 X 10 X 15 cm while the iron spike had an L orthogonal shape and its geometric parameters are reported in the following Table 2

Table 2: iron spike parameters

Weight [Kg]	Length [m]	Width [m]	Density[Kg/m^3]
1.9	0.5	0.05	7.96

Before each test, the correct position between rock bag and the device and between the iron spike and the ground was checked in order to ensure a good contact and maintain the correct alignment (see Fig. 2). Both devices have been positioned, respect to the bench of rock blasting, according to the same standard reference system; x-axis = perpendicular to the explosion point (longitudinal), y-axis = orthogonal to x-axis (transversal), z-axis = perpendicular to the ground (vertical). The tri axial accelerometer has acquired, through three channels, the vibration signal along all directions (X, Y and Z). The remaining channel was connected to a mono axial accelerometer, in order to measure the signal along only a direction, different in each different blasting operations.

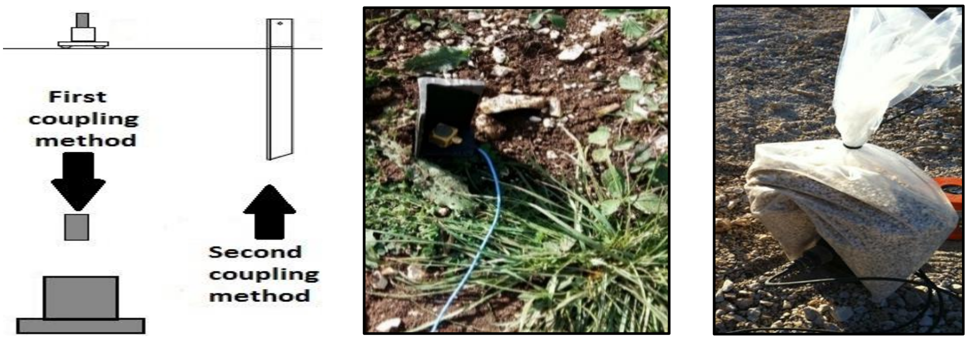

Fig. 1 : drawing of the coupling methods (left figure), positioning of transducer on the iron spike (central figure) and use of a rock sack (right figure)

2.3 Second measurement campaign

In the successive measurement campaign, others 5 measurements of blasting operations were obtained in the same point of the precedent test. The aim was compare the same coupling methods, but fixing, through a cement base, the iron spike in the ground. The first step was to realize a hole in the rock ground, employing a puncher machine; the depth of the hole was 0.55 m, with the 0.1 m diameter. Later the iron spike was inserted inside and the empty space was filled gradually with cement, in order to ensure the correct position of the iron spike. Before connecting the instrument, it was necessary to spend a day so the material was dried off (see Fig. 2)

Fig. 2 : correct alignment control (left figure), puncher machine (central figure) and the iron spike immobilized with the cement (right figure)

The device was positioned according to the same standard reference system of the previous campaign. After a first analysis, the data of the first measurement campaign showed that maximal strain axis was Y or X, never Z. For this reason in this measurement campaign the level vibration were obtained only along X and Y axis (see Table 3).

Table 3: connections of device channels

	Channel 1	Channel 2	Channel 3	Channel 4
Axis	x	y	x	y
Coupling Method	Iron spike	Rock sack	Iron spike	Rock sack

3. Results

The whole analysis is based on the data obtained from blasting operations during two measurement campaigns; they have been collated and reported in the following graphs and tables. As previously described, the results were taken employing three different mounting methods. In the first field test the transducers was fixed through a rock sack and iron spike fixed directly in the ground. In the second measurement campaign the method of iron spike was modified and the support was fastened in the ground through a cement base.

3.1 First measurement campaign

The data are referred to 5 blasting operations, are expressed in terms of m/s^2 and are plotted in the following tables. In Table 4 data the first coupling method are reported in the left and central columns. These show acceleration values and respective dominant frequency for the longitudinal, transversal and vertical components of ground motion. The columns on the right evidence the results of the second coupling method (acceleration values and respective dominant frequency), the axis comparing and the difference in terms of acceleration [m/s^2] between the two techniques.

Table 4: results of first measurement campaign

First Measurement Campaign										
	Iron spike						Rock sack			
	a [m/s^2]			f [Hz]			Axis	a [m/s^2]	f [Hz]	Δa [m/s^2]
	X	Y	Z	X	Y	Z				
1	0.647	0.471	0.463	40-630	25	40	x	0.650	40	0.184
2	0.451	0.364	0.513	31.5-800	25-1000	40	z	0.583	40	0.07
3	0.059	0.083	0.041	25-63	25-1000	31.5	z	0.053	50	0.012
4	0.654	0.48	0.553	12.5-315	40-400	40	y	0.637	40	0.104
5	0.488	0.712	0.326	31.5-800	40-315	40	y	0.286	31.5-160	0.04

The data are referred to the same blasting operation. In Fig. 3, the time history graphs, expressed in terms of m/s^2, are shown for the X axis. The blue line refers to the first method (iron spike) while the red line describes the other method (rock sack).In Fig. 4 the corresponding frequency spectra are reported.

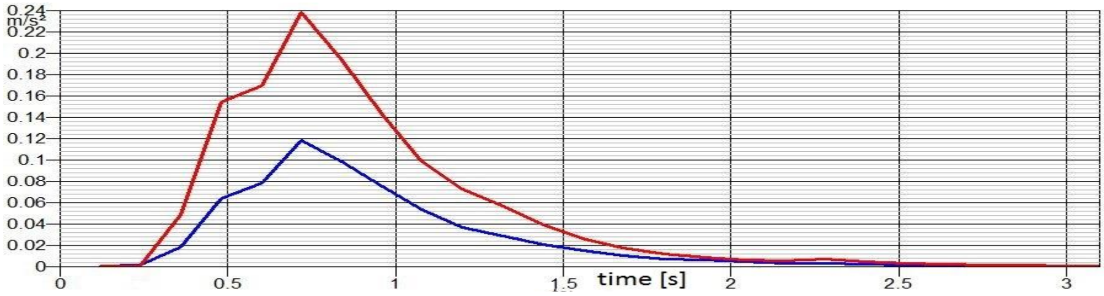

Fig. 3 : time history resulting from iron spike (blue line) and rock sack (red sack) along Y axis

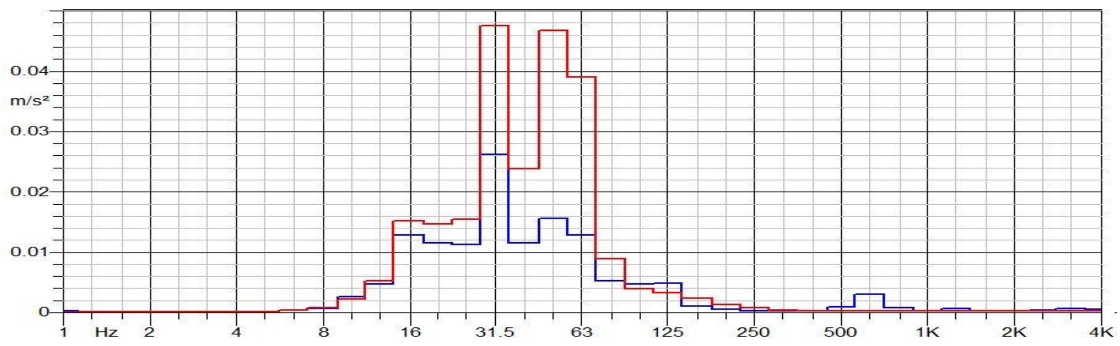

Fig. 4 : frequency spectrum resulting from iron spike (blue line) and rock sack (red line) along Y axis

3.2 Second measurement campaign

Results from the second measurement campaign are shown in the following graphs. All data are expressed in terms of m/s^2. In the following table for each blasting operation the values measured along X and Y axis are compared in terms of a [m/s^2]. In the last column the difference of measure is reported.

Table 5: results of second measurement campaign

Second Measurement Campaign										
	Iron spike				Rock sack				Δa [m/s^2]	
	a [m/s^2]		f [Hz]		a [m/s^2]		f [Hz]			
	X	Y	X	Y	X	Y	X	Y	X	Y
1	0.133	0,128	12.5	12.5	0.171	0,195	31.5	25	0.038	0,067
2	0.181	0,11	25-1250	12.5-1250	0.203	0,139	25-80	12.5-40	0.022	0,029
3	0.111	0,119	31.5-630	31.5-630	0.181	0,259	31.5-50	31.5-50	0.07	0,14
4	0.596	0,349	25-1250	25	0.889	0,655	20-1250	40	0.293	0,306
5	0.404	0,312	40-315	50-315	0.510	0,359	40	40	0.106	0,047

In Fig. 5 and 6 time history and frequency spectra are shown for both methods (rock sack and iron spike immobilized through cement)

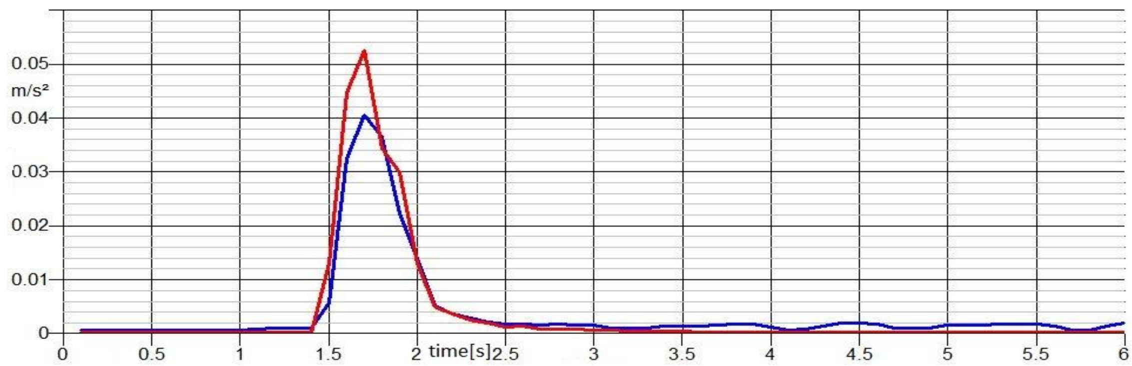

Fig. 5 : time history of accelerometer fixed with the iron spike in the cement (blue line) and rock sack (red line) along Y axis

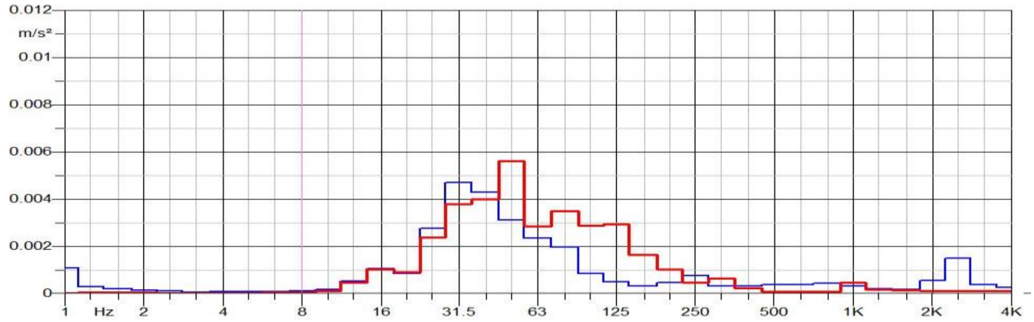

Fig. 6 : frequency spectrum of accelerometer fixed with the iron spike in the cement (blue line) and rock sack (red line) along Y axis

4. Discussion

The vibration results, obtained from 10 blasting operations, are analyzed. The two sets of values are exposed for the first and the second measurement campaign. In the first one, for each blasting operation, the acceleration values, expressed in terms of m/s^2, and the dominant frequencies are shown. The data, with the first ground coupling method, are obtained for the longitudinal, transversal and vertical components of ground motion while with the other mounting system only for a single axis, different in each measurement. The acceleration value is assessed from the wave-form recorded by the device as the maximum instantaneous value of the ground vibration component. In all cases, it is observed that the values obtained with rock sack coupling method are higher than the ones measured with iron spike fastened in the ground. The average difference between two coupling methods is 0.082 m/s^2, from a minimum value of 0.04 m/s^2 to a max of 0.184 m/s^2. It is possible to clarify this fact because the sack positioned on the top of device constitutes a coupling system that it may be influenced from the air blast and consequently the contact conditions can be modified. Furthermore, data point out that, in almost every measurement, X and Y axis are the direction of greater stress in almost all measurements. Only a case evidence that Z axis is more stressed, probably due to the detachment of the iron spike from the ground. Additionally the dominant frequency is evaluated; it is defined as the frequency at which the spectral amplitude, derived through fast Fourier Transform Analysis, is maximum. The main frequency is almost the same in all measures, in a range from 12.5 Hz to 63 Hz. The spike ground coupling method shows a relevant frequency harmonic component along X and Y axis, from 800 to 1250 Hz. On this aspect it may be observed that these harmonic frequency components are characteristics of mounting support and depend on the mass of the iron spike. Only a measurement shows a minimum frequency component with rock sack method. Moreover the results highlight a damping effect in the iron spike coupling method; its frequency spectrum respect to the rock sack, starting from the dominant frequency (12.5-30 Hz), decreases more quickly in comparison with the other coupling system. Subsequently the data acquired in the second measurement campaign are analyzed. The level vibrations have been acquired simultaneously along X and Y axis. The results show a similar trend of the previous campaign; the rock sack method points out higher acceleration values respect to the ones obtained with iron spike. Comparing acceleration values measured with both coupling methods, a higher difference is observed between values. In the first campaign, the average of differences has a value of 0.082 m/s^2 along each axis comparison, while in this case it reaches 0.105 m/s^2 along X axis and 0.117 m/s^2 along Y axis. It is possible to explain this aspect because when a seismic wave is incident upon a mounting system coupled to soil, complex scattering effects are generated. The acoustic impedances between the mount material (iron spike) and the surrounding soil generate a radiating energy back into the ground. This mechanism effectively reduces the input energy to the system mounting and it is amplified by the cement base present between the iron spike and the surrounding soil. Furthermore the frequency spectrum points out the similar frequency range to previous campaign (12.5 Hz- 80Hz). The most stressed direction is similar for both methods in the same range (12.5-80 Hz) and a harmonic component is present along both axes (800-1250Hz). Finally the graphs highlight the same damping effect of the iron spike coupling method.

5. Conclusion

This study has examined, through a comparative method, performance test of two different mounting techniques of the transducers under the particular conditions in a limestone quarry in Italy. The work has shown that the mounting system can cause a change in the level of vibration transmitted to the device. As it would be expected, when the devices, fixed through two different coupling methods and under similar boundary conditions, are hit from the same wave, they show different results of vibration levels. In particular, in spite of a limited number of available measurements, the accelerometers have read, except for one case, higher acceleration values obtained with the rock sack method respect to the ones with the iron spike. Besides in all cases of the recorded blasting events, the x-axis (the longitudinal one) and the y-axis have been the most stressed and only in one case the z direction (the orthogonal direction to the ground) was found to be the most relevant. From this study it has been shown that if a faithful representation of the vibration level is required, these methods illustrated must be employed carefully. The use of rock sack coupling method allows a quick and easy application but it is difficult to ensure contact conditions between the device and the soil because of air blast effect. The iron spike method maintains, instead, a good contact during a long time but requires a long and complex procedure in order to insert it in the rock ground. Furthermore the employment of a cement base presents the limit of generating a relevant damping effect.

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