



Performance of some coupling methods for blast vibration monitoring



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ABSTRACT

Field guidelines and recommendations for blasting vibration monitoring on a hard surface, suggest that the geophone mount should be coupled to the ground in a way that depends on the anticipated vibration level. However, the quantitative performance of the coupling method is basically unknown. In order to investigate this, the ground-to-mount coupling transmissibility (i.e. ratio of the response of the geophones mount to the rock motion, as a function of frequency) was measured between 16 and 200 Hz in 43 tests using a vibration exciter. The geophone mounts were freely placed, hold with a sandbag and anchored on granite. Free placed mounts applied outside the suggested range of vibrations (i.e. frequencies above 50–70 Hz at 5 mm/s) lead to the largest expected errors (up to 7.5 dB). Distortion is still significant (1.02 dB), though to a minor degree, at lower levels where this method is recommended. Sandbagging limits the maximum expected error to 1.6 dB, but it is ranked as the worst method irrespective of the vibration level and the sandbag planting at frequencies below 40 Hz. Anchoring appears as the only analyzed method that achieves a stiff rock-to-mount coupling, ensuring consistent measurements for the frequencies commonly found in blasting independently of the vibration level and the mount characteristics.

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1. Introduction

Ground vibrations are among the main environmental affection of rock blasting activities. Measurement of ground motion from blasting is necessary to prevent damage to buildings and structures in the surroundings of the blasting area (AENOR, 1993; BSI, 1993; DIN, 1999; Siskind et al., 1980). Vibrations are typically measured with digital seismographs formed by three orthogonally oriented geophones housed in a metallic mount and connected to a recording–sampling unit. The mount is usually placed outside the structure of interest and coupled to the ground in a way that depends on the anticipated vibration level and the characteristics of the ground; some of the suggested coupling methods for measurements on rock are shown in Table 1.

The quality of a vibration measurement can be expressed as a function of frequency f , as the ratio of the seismograph output velocity $V(f)$ to the velocity of the ground motion $V_{gr}(f)$, called motion transmissibility $T(f)$ (de Silva, 2007). Transmissibility is a measure of the error, and values of $T(f)$ around one show accurate measurements of the ground motion in the frequencies of interest. Let $V_m(f)$ be the velocity of the sensors mount, the transmissibility of vibrations can be broken down in two terms: ground-to-mount, or coupling, transmissibility

$T_c(f)$, and mount-to-geophone transmissibility $T_{geo}(f)$ that comprises the mechanical and electrical error components:

$$T(f) = \frac{V(f)}{V_{gr}(f)} = \frac{V_m(f)}{V_{gr}(f)} \frac{V(f)}{V_m(f)} = T_c(f) \cdot T_{geo}(f). \quad (1)$$

The mount-to-geophone transmissibility is obtained testing the seismograph with the sensor mount firmly attached to the plate of the exciter (Birch et al., 2014; Farnfield, 1996; Stagg and Engler, 1980) and it is usually provided by the manufacturer. Variability between different monitoring devices, and also between different calibration procedures, is accounted by design standards for blasting seismographs (DIN, 1995; ISEE, 2011) that define tolerance bounds of the transmissibility of the apparatus as a function of frequency.

Though there is a general agreement about the importance of the coupling of the sensors to the ground, the transmissibility for the different methods used is basically unknown and there is still some controversy about the suitability of some of the suggested methods and field guidelines (most of them stemming from an already classic work by the US Bureau of Mines — Nichols et al., 1971). Suggested methods generally assume that the sensor mount follows the ground motion whenever the expected vibrations are lower than a certain limit, see Table 1. But the coupling transmissibility is needed in order to assess the reliability of the measurements and also to compare observations among themselves or with a reference value (AENOR, 2005; JCGM, 2008; Taylor and Kuyatt, 1994).

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Table 1
Coupling methods for measurements on rock.

Coupling	Expected vibration level		Source
	Qualitative	Quantitative ^a	
Free placed Sandbagged	Low	$a < 0.2 \text{ g}$	ISEE (2009); ISRM (1992) InstanTel (2008) Konya and Walter (1991), ISEE (2009) InstanTel (2008); ISEE (2009); ISRM (1992)
	Very low	Non-defined	
	Low, medium	$a < 1.0 \text{ g}$	
Anchored	Any	Any	

^a a : acceleration.

Different researchers have shown that ground-to-mount coupling affects the seismograph response at certain frequencies (Blair, 1987; Drijkoningen et al., 2006; Hoover and O'Brien, 1980; Krohn, 1984; Washburn and Wiley, 1941). In this line, field measurements with mounts placed close each other and coupled to the ground using several methods show differences between observations from the same blast (Adhikari et al., 2005; Armstrong and Sen, 1999; Blair, 1995a; Hutchison et al., 2005; Wheeler, 2004; Williams and Treleaven, 2003; Yang et al., 2014). In particular, Wheeler (2004) evidences differences in peak particle velocity of 75 to 140% between measurements in soil made according to field guidelines by Stagg and Engler (1980). Blair (1995a) noted similar differences. Yang et al. (2014) have recently pointed out that the sensor mount coupling may also have a bearing on the usually wide prediction bands of vibration attenuation laws. Changes in the measured peak particle velocity and spectral amplitudes, and thus in the transmissibility, have been also observed between measurements made in the same way with side by side sensor mounts (Armstrong, 2001; Segarra et al., 2010, 2012a, 2012b); variations in the measuring conditions (i.e. contact conditions, such as fraction of the base area of the mount in contact with the ground, and sensor transmissibility) seem to be the source of such result.

Segarra et al. (2014) have assessed ground-to-mount transmissibility $T_c(f)$ of vibrations based on tests on a vibration exciter, in which two seismographs were freely placed, sandbagged, and anchored to rock. It was found that the coupling technique may alter significantly the amplitude of the measured waveforms with transmissibility values from 0.2 to 1.2. Free laid mounts amplify ground motion gradually up to around 60 Hz, where transmissibility is up to 1.13. Above that frequency, ground motion is strongly damped. Sandbagging damps vibrations at low and mid frequencies, and amplifies them at high frequencies, with transmissibility from 0.78 to 1.2. Anchoring showed an excellent accuracy (i.e. $T_c \approx 1$) for frequencies below 100 Hz. The present work builds up on that study with many more tests, thereby improving the quantitative significance of the results, and somewhat correcting its preliminary conclusions.

2. Test set-up and description

Two seismographs were tested in a computer-controlled vibration exciter designed for seismograph calibration. The seismographs are identified as Sm and Sv and they both meet the International Society

Table 2
Characteristics of the seismographs.

Characteristics	Sm ^a	Sv
Mount shape	Cylindrical	Prismatic
Mount base size/height, cm	5 (radius)/5	7.1 × 6.1/4.4
Mount density, kg/m ³	2130	2690
Mount mass, kg	0.905	0.508
Analog to digital converter, bits	12	16
Resolution, mm/s	0.127	0.0159
Range, mm/s	± 254	± 31.7
		± 200

^a Two measuring ranges, each with a different resolution, are available.

of Explosives Engineers – ISEE (2011) specifications for blasting monitoring devices. Table 2 summarizes their main characteristics.

The exciter table was capable of a force of 144 kN, controlled by a single-point laser Doppler vibrometer (LDV). The vibration was a horizontal sine type motion of constant peak velocity. The frequency was shifted from 16 to 200 Hz at a rate 0.02 oct/s. The memory capacity of one of the seismographs and the fact that the vibration exciter spends more time vibrating at low than at high frequencies prevented to cover a wider frequency range (including, e.g. low frequencies, 4–16 Hz, typical of urban dwellings, Siskind et al., 1980) without sacrificing the upper frequency bound to values below 50 Hz; this would have left out the predominant frequencies of vibrations from blasting. Further testing is expected to be undertaken in the near future on low frequencies.

A total of six test series were implemented. Their main characteristics are shown in Fig. 1 and Table 3. A first series of three trials (AM10) was performed anchoring the sensor mounts directly to the table and inducing a vibratory motion of 10 mm/s. Seismograph Sv was tested once and seismograph Sm was tested twice setting a different measuring range (and thus a different resolution) in each trial, so that its performance with each available set-up (see Table 2) is investigated.

In order to simulate the attachment of the geophone mount to rock, a gray granite slab of size 24.5 × 30 × 8 cm was fixed to the plate of the exciter with four hex lag bolts; the granite had a density of 2650 kg/m³, and measured propagation velocity of p waves of 4258 ± 38 m/s (mean and standard deviation). Among the limitations of tests on a vibration exciter as compared with field tests, Blair (1995b) notes that it prevents to study the scattering response of the wave produced by the geophone mount since there are no traveling waves. This, however, is not a problem for our study that focuses on the quality, or stiffness, of the coupling means. Three coupling methods suggested by the different field guidelines for measurements on rock (InstanTel, 2008; ISEE, 2009; ISRM, 1992; Konya and Walter, 1991), namely: free, sandbagged, and anchored, were assessed at one or two vibration levels, so that each method was tested within its suggested range of accelerations; details on the tests are given in Table 3. All trials on rock were done four times with each seismograph, making up a total of 40 trials; after each trial the sensor mount was removed from the granite surface, and the whole attaching procedure was repeated, in order to incorporate the experimental variability to the test result.

In all the tests, the longitudinal geophone was aligned with the motion axis of the exciter. The response of the geophone was recorded and sampled at a rate of 2048 Hz. Seismograph Sm was set to a similar resolution than seismograph Sv in tests at 5 mm/s (AG5, FG5 and SG5), whereas the resolution was lowered in tests at 20 mm/s (AG20 and SG20), in order to increase the measuring span, preventing measurements out of range.

3. Results and analysis

The waveform recorded by the seismograph in the longitudinal component was processed through a discrete fast Fourier transform. The noise (estimated from peak-to-peak variations) in the resulting amplitude response $V(f)$, see Eq. (1), is reduced in the range from 16 to 200 Hz to less than 1% of the initial content using locally weighted linear regression with linear polynomials (Cleveland, 1979).

The spectral amplitude $V_{gr}(f)$ of the velocity of the base, see Eq. (1), is calculated fitting the raw spectrum of the applied swept-sine excitation with a modified power-type formula based on Gloth and Sinapius (2004):

$$V_{gr}(f) = k v_{gr} f^{-1/2} \quad (2)$$

where k is a fitting constant which, for our data, is equal to 0.03320 s^{-1/2}, and v_{gr} is the peak velocity of the vibratory motion of the base. The

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