Coupling of blasting seismographs to rock and its effectiveness for horizontal ground motion

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A B S T R A C T

In order to clarify the requirements for satisfactory coupling on rock, six methods to monitor vibrations with blasting seismographs are investigated in the longitudinal component of the vibratory motion. The methods studied consisted on placing the geophone mount on a granite surface freely (loosely), held with a sandbag, and attached with an anchor (the center of the geophone's mount was fixed with a plastic anchor, a bolt and a nut), thermal adhesive (glue), gypsum plaster (used as an adhesive) and double-sided tape. For each measuring condition, transmissibility in two mounts was assessed on a vibration shaker from 2 to 190 Hz at one or two vibration levels (5, 20 mm/s). The main findings of this work are: (1) Transmissibility varies with coupling method. It is flat at low frequencies and has a maximum at higher frequencies; in some trials mainly with anchored, glued and plastered such peak occurs outside the frequency range studied. (2) The frequency of the first maximum of transmissibility shifts towards smaller frequencies as the peak velocity increases when the bonding conditions are weak, as for free and sandbagged mounts. However, if the bonding is stiff enough, as for anchored or plastered mounts, transmissibility values at 5 and 20 mm/s are very similar. (3) The frequency of the first peak in the measured transmissibility provides a preliminary estimate of the performance of each method, so that its conditions of use should be defined upon frequency and velocity of the imposed motion, rather than using the anticipated peak acceleration, as it is currently made. These have been defined for the methods under study. (4) Anchoring and plastering provide the best performance, the later with smaller errors at high frequencies (> 128 Hz). (5) The seismograph itself (not the coupling) is another source of error that should not be neglected specially for measurements in the low frequency range; large errors, exceeding by one order of magnitude those from coupling are obtained in the 2–4 Hz band.

1. Introduction

The assessment and control of vibrations from blasting is an important environmental concern for blasting operations. Threshold limits for damage prevention in buildings and structures are defined by peak particle velocity-frequency charts.[1–4] In order to assess compliance with these regulations, the particle velocity history is measured directly with seismographs at the location of interest. These monitoring devices consist of a metallic mount with three orthogonally oriented geophones and an external digital recording-sampling unit. They usually meet the specifications of the International Society of Explosives Engineers– ISEE[5] for blasting seismographs, or the requirements of the DIN standard 45669-1,[6] the latter valid for vibration meters that are used to assess all type of vibrations (not only from blasting) affecting buildings and/or people in buildings. Among others provisions, these standards require that seismographs be calibrated on a periodical basis and have a frequency response within the tolerance range defined in the standard.

The use of sensors to measure vibrations from a large variety of sources, including blasting, is tackled in different ways by additional standards and recommendations. They basically address the location of the sensors and their coupling to the medium. Table 1 summarizes the suggested methods for measurements on a hard surface. Discrepancies and contradictions between suggested methods and the criteria to use them are apparent. The British standard[7] recommends firm attachments with mechanical fixings, like expansion bolts, as the preferred method. It is built on another standard, ISO 5348,[9] that describes attachment methods of accelerometers based on the amplitude responses of these transducers with the method in question; the responses are, as a rule, flat and around one (i.e. the measured signal is very similar to the motion of the accelerometer) at low frequencies with a resonance peak due to coupling at higher frequencies. Generally

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Table 1
Conditions of use of coupling methods to a hard horizontal surface (a acceleration, f frequency of the expected vibrations, f_r resonance frequency, Q_r resonance magnification factor, K stiffness of the coupling system, m mass of the mount).

Coupling method	Standards for vibrations from a large variety of sources, included blasting			Recommendations for blasting	
	BSI 7385–1[a7]	ISO 5348[b9]	DIN 45669–2[11]	ISEE[12]	ISRM[13]
None– mount weight					
Free (loosely) placed	–	–	$a < 0.3\,g$ and $f < 40$ Hz	$a < 0.2\,g$	$a < 0.2\,g$
Mechanical systems					
Anchor/stud	Any	High f_r, Q_r, K, m	$a > 0.3\,g$ or $f > 40$ Hz	$a > 1.0\,g$	$a > 1.0\,g$
Sandbag over the mount	–	–	–	$a < 1.0\,g$	–
Adhesives					
Beeswax	–	Med. f_r, Q_r, K, m	Not specified	–	–
Doubled-sided tape	$a < 1.0\,g$	Low f_r, Q_r, K, m[c]	–	–	$a < 1.0\,g$
Glue (soft)	Special conds.	Low–Med. f_r, Q_r	–	–	–
High modulus (epoxy) resin	Any	–	–	–	$a < 1.0\,g$
Methyl cyanoacrylate	–	High f_r, Q_r, K, m	–	–	–
Not specified	–	–	$a > 0.3\,g$ or $f > 40$ Hz	$a > 1.0\,g$	–
Mixtures					
Cement	–	–	$a > 0.3\,g$ or $f > 40$ Hz	–	$a > 1.0\,g$[d]

[a] Identical to ISO 4866[8].
[b] The Portuguese rule[10] refers to this standard to describe the attachment of geophones or accelerometers.
[c] Thick double sided tape shifts resonance to lower frequency compared with thin tapes.
[d] Cement could be a hydrocal or other gypsum-based cement set within 15–30 min.

good measurements are obtained when operating at frequencies not greater than 20% of the resonance frequency of the coupling system when the resonance magnification factor is high (i.e. undamped accelerometers); both the resonance frequency and amplification factor are qualitatively described for some methods in Table 1.

The DIN criterion[11] includes the direction of measurement. Methods in Table 1 correspond to measurements in the horizontal direction, where the threshold frequency to decide whether the sensor should be firmly fixed to the surface is 2.5 times smaller than for measurements in the vertical direction. In addition to the frequency content of vibrations, the DIN standard considers the anticipated peak acceleration at the monitoring point. It suggests that good measurements are obtained with free placed mounts at low accelerations and low frequencies, whereas the stiffness of the attachment should be increased as the anticipated vibration levels or frequencies do. Similar criteria are proposed by ISEE[12] and ISRM[13] for blasting seismographs; however, they only contemplate the expected peak acceleration at the monitoring station to decide the coupling method.

Several works caution about the quality of vibration measurements made according to the recommendations in Table 1, mainly when the mounts are free placed or held with a sandbag,[14–20] but no further amendments have been made to guidelines[12,13] and standards[11] typically used to monitor vibrations from blasting. Other researchers show that the sensor to ground coupling is a complex resonant system,[21–27] whose amplitude response (or transmissibility) determines the conditions of use of the method in question. At present these data are only provided for accelerometers by ISO 5348,[9] whereas they remain little investigated for the seismographs that are commonly used to monitor vibrations from blasting. These have a narrower frequency range (i.e. 1–315 Hz) than accelerometers and the operating conditions of coupling methods are different.

2. Background-research context

The quality of vibrations measurements can be described from the amplitude response or transmissibility of the transducer to a known vibratory motion. Considering velocity as the measured magnitude, transmissibility is given as a function of frequency by:

$$T(f) = V(f)/V_{gr}(f) \tag{1}$$

where V is the seismograph output velocity, and V_{gr} is the velocity of the ground.

Transmissibility is a measurement of the error and values around one in a given frequency range show accurate measurements in it. Considering the measuring device as a geophone fixed to a case or mount, which in turn is coupled to the ground, transmissibility can be expressed as the product of the mount-to-geophone transmissibility (or seismograph amplitude response), T_{geo} and the rock-to-mount, or coupling, transmissibility, T_c:

$$T(f) = T_c(f) \cdot T_{geo}(f) \tag{2}$$

Segarra et al. [28,29] carried out a first campaign of measurements on a vibration shaker controlled by a single-point laser Doppler vibrometer (LDV). Table 2 shows the main characteristics of these tests. Two seismographs with different sensor mounts were used; they were coded Sm and Sv to avoid reference to commercial names. Table 3 gives their basic characteristics; it also includes the acronym used for the sensor mount. The seismographs were tested under a unidirectional, horizontal, sine type motion of constant peak velocity and frequency shift at a rate of 0.02 octave/s. The mounts were freely placed, held with a sandbag and anchored to a granite base; details of these layouts are shown in Fig. 1. The base was firmly attached to the plate of the shaker and its motion controlled with the LDV pointer of the control system. Each measuring condition was replicated four times with each seismo-

Table 2
Summary of tests series made in the first campaign (2013).

Test[a]	Layout		Seismographs tested	Motion		No. trials
	Coupling	Base		Peak vel. mm/s	Bandwitdh Hz	trilTrials
AM10	Anchor	Metal	Sm, Sv	10	16 – 202	3
FG5	Free	Granite	Sm, Sv	5	16 – 202	8
SG5	Sandbag	Granite	Sm, Sv	5	16 – 202	8
SG20[b]	Sandbag	Granite	Sm, Sv	20	16 – 202	8
AG5	Anchor	Granite	Sm, Sv	5	16 – 202	8
AG20	Anchor	Granite	Sm, Sv	20	16 – 202	8

[a] The acronym for the test is formed as follows: the first letter is the coupling method (A: anchored; F: free; S: sandbagged), the second one is the base (G: granite, M: metal plate), and the number is the peak velocity (5, 10 or 20 mm/s).
[b] In these tests the bag was looser, flatter and its paper wrinkly providing a wider contact surface with the slab than in SG5 series.

Table 3
Characteristics of the seismographs.

Characteristics	Sm	Sm+[b]	Sv, Sv1 and Sv2
Mount			
Acronym	Mm	Mm	Mv
Shape	Cylindrical	Cylindrical	Prismatic
Base size/height, mm	50 (radius) / 50	50 (radius) / 50	71×61 /44
Density, kg/m^3	2130	2130	2690
Mass, kg	0.905	0.905	0.508
Recording unit			
Memory capacity, Mb	0.96	64	200
Analog to digital converter, bits	12	16	16
Range, mm/s	± 254[a] ± 31.7[a]	± 254	± 200
Resolution, mm/s	0.127 0.0159	0.00788	0.006

[a] Seismograph Sm allows two measuring ranges, each with a different resolution.
[b] Seismograph Sm+ was identified as Sm-model 2 in Ref. 30.

graph. For each trial, rock-to-mount, or coupling, transmissibility was calculated according to Eq. (2), dividing motion transmissibility by the geophone transmissibility. The latter was obtained from testing the geophones mounts directly anchored to the metallic plate of the shaker.[31–33] In these conditions, coupling is assumed to be perfect, so that $T_c(f)\approx1$ and hence $T_{geo}(f)=T(f)$, see Eq. (2).

It was found that rock motion value can be modified by a factor from 0.16 to 1.25 depending on measuring conditions, e.g. frequency and peak velocity of the imposed motion, coupling, and mount. Anchoring is the unique method that ensured accurate measurements for frequencies below 100 Hz, irrespective of the mount and the input velocity. Free placed mounts amplify, in general, ground motion (transmissibility up to 1.25) for frequencies below 50 Hz; the acceleration at which this occur (roughly estimated as $2\pi f v_{gr}$), about 0.16 g, is similar to the most conservative threshold acceleration suggested for this technique in Table 1. For higher frequencies, free placed mounts damp strongly granite motion (transmissibility down to 0.16). Sandbagging was ranked as the worst method independently of the vibration level of the imposed motion (transmissibility down to 0.7) at medium frequencies (17–40 Hz).

Two more campaigns were made on the same vibration shaker following the testing procedure carried out in the first campaign. A total of 57 new trials were conducted with the same seismographs, though model Sm was replaced by an upgraded one (Sm+) with the same mount characteristics but different recording unit as Table 3 shows. Free laid, sandbagged, and anchored geophones mounts were tested at low-mid frequencies to extend transmissibility measurements from the first campaign down to 2 Hz, and assess their performance at typical frequencies of structures.[4] Three additional coupling means, namely: thermal adhesive (glue), a combination of duct tape and gypsum plaster, and double-sided tape, were studied across the complete bandwidth of interest (1.6–200 Hz); details on these tests are shown in Fig. 1 and discussed in the next section. Segarra et al.[30,34] considered 18 of the trials made in the second campaign, where taped mounts had not been studied yet, to advance preliminary results. According to these, free and sandbagged mounts only lead to accurate measurements below 15 Hz at the vibration levels studied (5, 20 mm/s). Glued and plastered mounts show similar transmissibility to anchored mounts at frequencies below 100 Hz. For higher frequencies, glued mounts show a slightly worse performance than anchored and plastered mounts, but they still do better than free and sandbagged.

The present work describes and analyses transmissibility from the second and third campaigns and builds on the knowledge acquired in previous works published.[28–30,34] The whole body of data available is

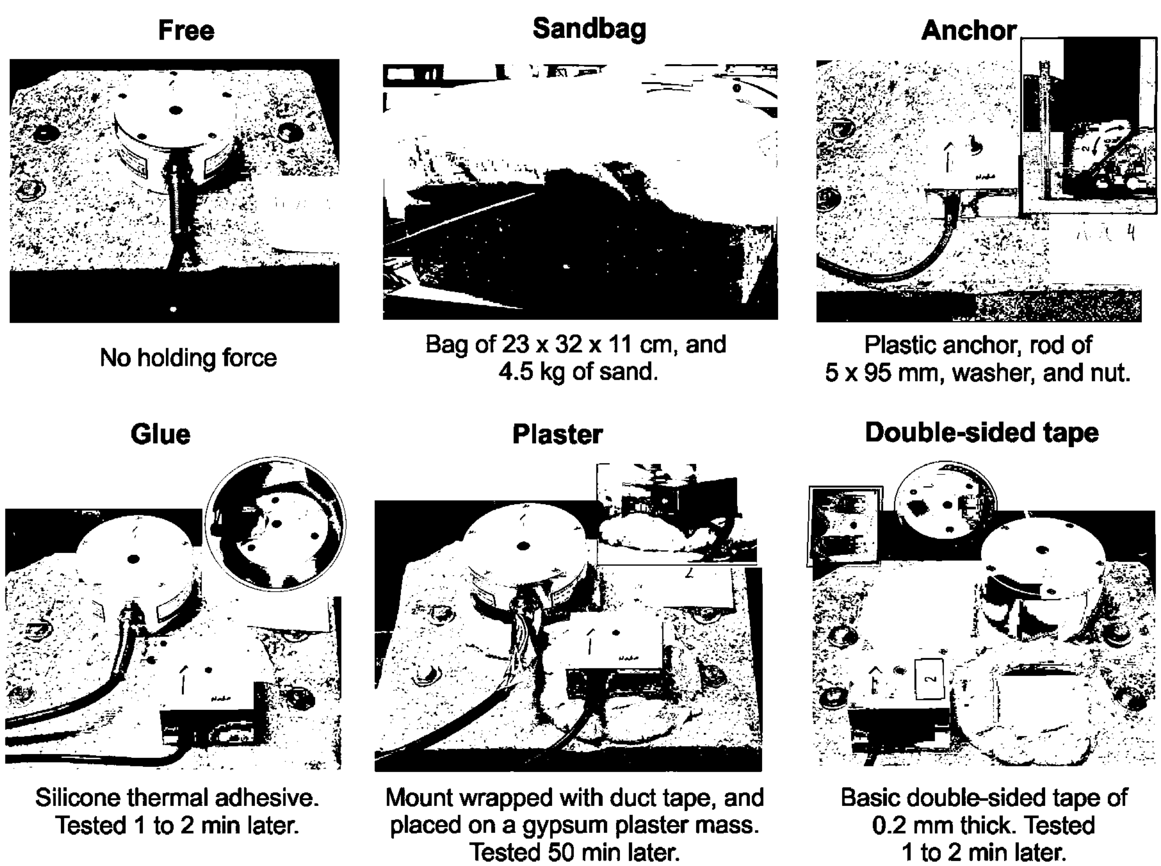

Fig. 1. Layout for coupling methods investigated.

Table 4
Summary of test series made in the second and third campaigns.

Test[a]	Campaign	Layout		Motion		Seismographs tested	No. trials
		Coupling	Base	Peak vel. mm/s	Bandwitdh Hz		
AM5	2	Anchor	Metal	5	1.6–200	Sm+, Sv1	2
AM5	3	Anchor	Metal	5	1.6–200	Sm+, Sv2	2
AM20	2	Anchor	Metal	20	1.6–200	Sm+, Sv1	2
FG5	2	Free	Granite	5	1.6–40	Sm+, Sv1	8
FG20	2	Free	Granite	20	1.6–40	Sm+, Sv1	7[b]
SG5	2	Sandbag	Granite	5	1.6–40	Sm+, Sv1	8
SG20	2	Sandbag	Granite	20	1.6–40	Sm+, Sv1	8
AG20	2	Anchor[c]	Granite	20	1.6–40	Sm+, Sv1	8
GG5	2	Glue	Granite	5	1.6–200	Sm+, Sv1	1
GG5	3	Glue	Granite	5	1.6–200	Sm+, Sv2	3
GG20	2	Glue	Granite	20	1.6–200	Sm+, Sv1	4
PG5	2	Plaster	Granite	5	1.6–200	Sm+, Sv1	1
PG20	2	Plaster	Granite	20	1.6–200	Sm+, Sv1	1
TG5	3	Double-sided tape[d]	Granite	5	1.6–200	Sm+, Sv2	2

[a] The acronym is formed similarly as in the first campaign, see footnote in Table 2.
[b] The file recorded with seismograph Sm+ in the second trial was corrupted and could not be used.
[c] Only tested at the most unfavourable, high, vibration level because of the good performance observed in the first campaign.
[d] Only tested at the low, favourable, vibration level as this method is recommended only at low accelerations, see Table 1.

used to quantitatively assess the vibration measurement errors with six suggested coupling methods over a broad band of ground frequencies, 2–190 Hz. The sound understanding of the quality of vibration measurement on a hard surface could be used as a starting point to review field guidelines for measuring vibrations from blasting in order to ensure more consistent measurements.

3. Overview of new tests

Table 4 shows the main characteristics of the tests series conducted in the second and third campaigns; the frequency bands investigated encompass displacements of the granite base (values calculated as $(2\pi f)^{-1}v_{gr}$) ranged from 0.497 to 0.004 mm for tests at 5 mm/s and from 1.989 to 0.016 mm in tests at the high velocity level. The same unit of seismograph Sm+ was used in both campaigns, and two units of the same model as seismograph Sv were used in each campaign; these are identified as Sv1 and Sv2 (see their characteristics in Table 3). The mount-to-geophone transmissibility of the seismographs was measured with the mounts anchored to the plate (series AM5 and AM20 in Table 4). In the rest of the tests, the geophone mounts were coupled to the granite slab with the six methods shown in Fig. 1. It also shows some additional features of the tests, like the LDV pointer (red dot in the top photos), and the direction of the vibratory motion. This is shown by an arrow in the top of the mount that indicates the orientation of the longitudinal geophone.

In the free, sandbagged and anchored mounts series (FG5, FG20, SG5, SG20 and AG20 in Table 4) each seismograph was tested separately four times, so that after each trial the mount was removed from the granite surface and the whole attaching procedure repeated; the same anchor-rod mounting was kept for all trials in series with anchored mounts (AG20). In the tests where standard thermal adhesive (GG5 and GG20), gypsum plaster (PG5 and PG20) and double-sided tape (TG5) were used, both mounts were coupled simultaneously (see Fig. 1), testing both at the same time. Due to the difficulties related with the use of gypsum plaster, the same plaster–attachment was tested once at each vibration level (PG5 and PG20 series in Table 4). Series with thermal adhesive and tape were tested at least two times (series GG5, GG20, PG5 in Table 4) at each vibration level; the geophone mounts in these three series were detached from the granite surface after each trial, and the whole procedure repeated again.

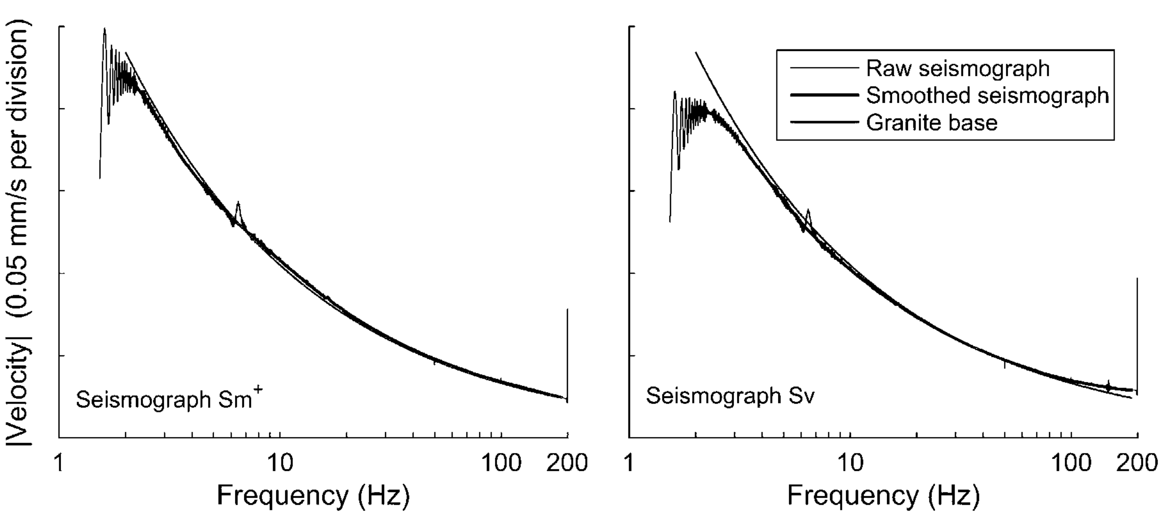

Fig. 2. Amplitude spectra of both seimographs for trial No. 2 in test series GG20.

3.1. Data processing

The velocities $V(f)$ and $V_{gr}(f)$ required to assess motion transmissibility according to Eq. (1), are calculated following the methodology in previous work .[28] This consists briefly in smoothing the amplitude of the discrete Fast Fourier transform of the vibrations recorded in the direction of the excitation (longitudinal geophone) to get the output seismograph response $V(f)$. Raw amplitudes at the extremes of the frequency sweep are affected by Gibbs oscillations, and are discarded for the analysis. Fig. 2 shows them (blue lines) for one trial with glued mounts at 20 mm/s (GG20). The noise in the smoothed seismograph responses (red lines) has been reduced to less than 1% of the initial content in the bandwidths considered; these are 2–38 Hz in trials with free, sandbagged and anchored mounts and 2–190 Hz for the others.

The velocity spectrum of the base motion $V_{gr}(f)$ is calculated as function of the waveform duration (t_w), the sweep rate (S), and the nominal peak velocity of the base (v_{gr}) with a modified formula for a swept-sine excitation based on Ref. 35:

$$V_{gr}(f) = kv_{gr}f^{-1/2} = \frac{1}{t_w}\sqrt{\frac{1}{S\,\log(2)}}\,v_{gr}f^{-1/2} \qquad (3)$$

The base response is also plotted in Fig. 2 (green lines). Note that the actual smoothed response (red lines) is a good match to the theoretical spectrum function, Eq. (3), green line. The latter is considered a good estimate of the actual motion of the base, as the experimental set-up used had a negligible error in frequency and below 2% in peak velocity.

4. Transmissibility

Measurements for the dataset currently available that comprises the results from the first (see Table 2), second and third campaigns (see Table 4) are all considered to study the transmissibility.

4.1. Mount-to-geophone transmissibility

Fig. 3 shows the amplitude response $T_{geo}(f)$ of the five seismographs (longitudinal geophones and recording unit combinations) tested. It was directly measured in series AM10 (see Table 2), AM5 and AM20 (see Table 4) with the mounts anchored to the plate of the shaker. This involves a systematic error in the calculation of the rock-to mount (or coupling) transmissibility. Such attachment is used in seismograph calibration, and the error in it (±2.6% or 0.22 dB expressed as gain) provides an estimate of the uncertainty of the measurement. Such error is smaller than the values shown later for sensors anchored to rock as the stiffness of the coupling to the plate is higher (the plate of the shaker has several threaded holes, so the geophone's mount was screwed to one of these holes and tightened with a torque wrench). Note that as seismograph Sm allowed two measuring ranges (and thus two resolutions, see Table 3), transmissibility of this device was measured in series AM10 at each resolution.

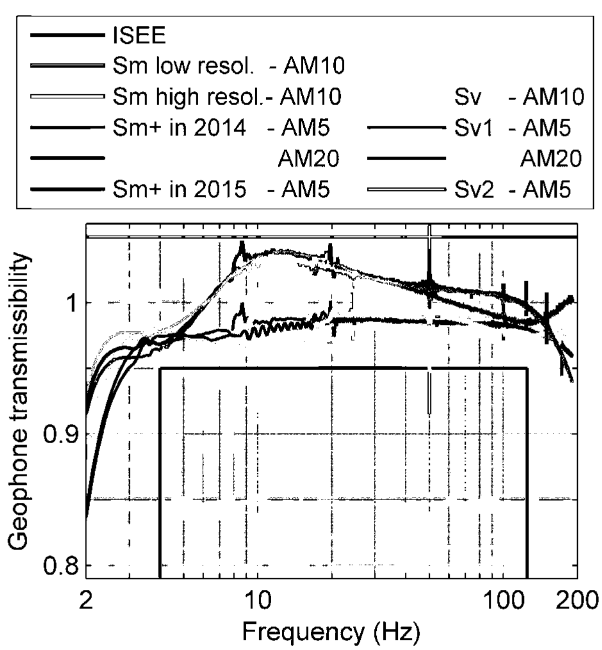

Fig. 3. Mount-to-geophone transmissibility of the seismographs tested; AM10 was made in the first campaign, and tests in 2014 and 2015 correspond to the second and third campaign, respectively.

All units are in compliance with ISEE specifications for blasting seismographs[5] (grey lines in Fig. 3); the peaks in transmissibility curves, such as those at 50 Hz for seismographs Sm+ and Sv2, are spurious and are not considered. Each unit has a different transmissibility at each frequency. This is a first source of variability in field measurements with side by side seismographs. The peak velocity of the imposed motion does not have an apparent effect in the geophone transmissibility, and the variability in the response of seismograph Sm+ in 2014 between tests at 5 and 20 mm/s (AM5 and AM20, respectively) is in line with the experimental error of the tests, 2.6%; a similar conclusion was obtained with the other seismograph, Sv1. Interestingly, although the calibration period of the seismographs is typically set at one year, the transmissibility of seismograph Sm+ at 5 mm/s (AM5) in summer of 2014 and 2015 are very similar. This unit was last calibrated in November 2013, so the low use of that seismograph during that period, less than 15 times, may be the reason of such result.

4.2. Rock-to-mount transmissibility

Rock-to-mount, or coupling, transmissibility calculated with Eq. (2) is shown in Fig. 4. The results from each test series are plotted in a different graph in Fig. 4 using a curve of different colour for each mount type. ISEE bounds for blasting seismographs[5] (grey lines) and the experimental error of the tests (yellow lines) are plotted as a reference in each graph.

All methods ensure a range of frequencies in which transmissibility is relatively flat and close to one. The width of this band depends upon the testing conditions, but it cannot be defined directly from Fig. 4 due to the scatter in some series. The frequency of the first peak in the transmissibility curves provides an estimate, in excess, of the upper limit of this bandwidth; the range of such frequency is shown at the bottom part of each graph in Fig. 4. Transmissibility for some coupling methods, like anchor (AG5 and AG20, third row graphs in Fig. 4) and plaster (PG5 and PG20, fourth row graphs in Fig. 4), do not have a maximum in the frequency range studied. For these methods, transmissibility increases monotonically from approximately 1 at about 100 Hz to less than 1.1 at the end of the band studied, and it is little affected by the mount type, i.e. differences in transmissibility are below the experimental error of the tests.

Transmissibility with glued mounts (GG5 and GG20, fourth row graphs in Fig. 4) look similar to those for anchored and plastered mounts in most of the trials, but transmissibility is higher, up to 1.3, and dispersion is large. Only in one trial made at 5 mm/s (see blue curve in GG5), there is a peak at 123 Hz, and transmissibility decays strongly down to 0.7 at higher frequencies. Variations in the procedure followed when gluing the mounts, such as uneven cleaning of the granite surface or glue distribution on the mount base, and/or changes in the granite surface, especially roughness, may be behind the large scatter. Taped mounts (TG5, bottom row graph in Fig. 4) exhibit a single peak in each trial, but its frequency and amplitude vary widely, 80–150 Hz and 1.05–1.5, respectively. This makes up a variable

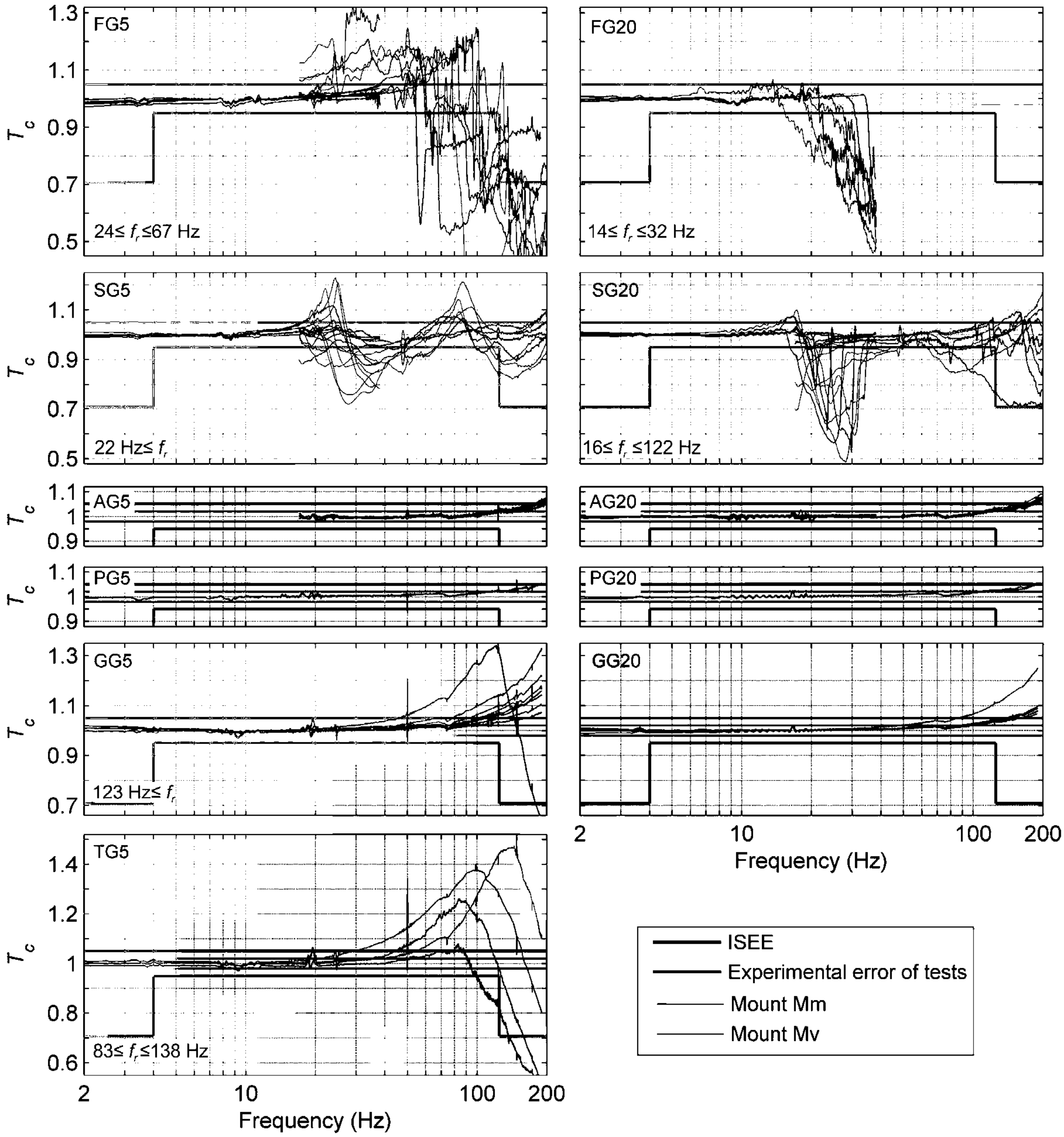

Fig. 4. Coupling transmissibility for free (FG5, FG20), sandbagged (SG5, SG20), anchored (AG5, AG20), plastered (PG5, PG20), glued (GG5, GG20), and taped (TG5) mounts on granite (the first letter of the test code is the coupling method – F: free; S: sandbagged; A: anchored; P: Plastered; G: Glued; T: Taped–, the second one is the base –G: granite–, and the number is the peak velocity); f_r is the frequency of the first peak or resonance frequency.

operating band beyond which the base motion may be amplified or damped.

Transmissibility with free mounts at 5 mm/s (FG5, first row, left column graph in Fig. 4) varies from 0.16 to 1.3 and shows an erratic and noisy pattern. The frequency of the main peak ranges from 24 to 67 Hz, with higher frequencies obtained with mount Mv. The lower frequency is smaller than the threshold frequency of 40 Hz established by DIN standard[11] (see Table 1) and the acceleration at that frequency is 0.13 g. This figure is also smaller than the accelerations of 0.2 g and 0.3 g suggested for this technique by ISEE[12] and DIN,[11] respectively (see Table 1). In the high velocity series (FG20, first row, right column graph in Fig. 4) free mounts were only tested up to 40 Hz, to prevent the mount from falling from the slab. Amplification, though limited (up to 1.05), started at lower frequencies and the maximum transmissibility occurred from 14 to 32 Hz. Damping also shifts toward smaller frequencies. The effect of the mount type is opposite to that observed in tests at the low velocity level; the smaller resonant frequencies were obtained with mount Mv.

The use of a sandbag to hold the mount (SG5 and SG20, second row graphs in Fig. 4) results in general in transmissibility away from one and shows multiple peaks. Exceptions are the results from two trials with mount Mm (blue lines) at 5 mm/s in which transmissibility is from 0.95 to 1.05 with no apparent maxima in the frequency range studied. In the rest of the trials at that vibration level, the first peak occurred around 22 Hz, and transmissibility varies from 0.7 to 1.2 depending on frequency, mount and sandbag planting. At the high vibration level (SG20), transmissibility changes; the first peak shifts towards smaller frequencies than in series at 5 mm/s, and transmissibility falls steeply at lower frequencies. In the 40–70 Hz range transmissibility is relatively close to one and it grows or decays again at higher frequencies.

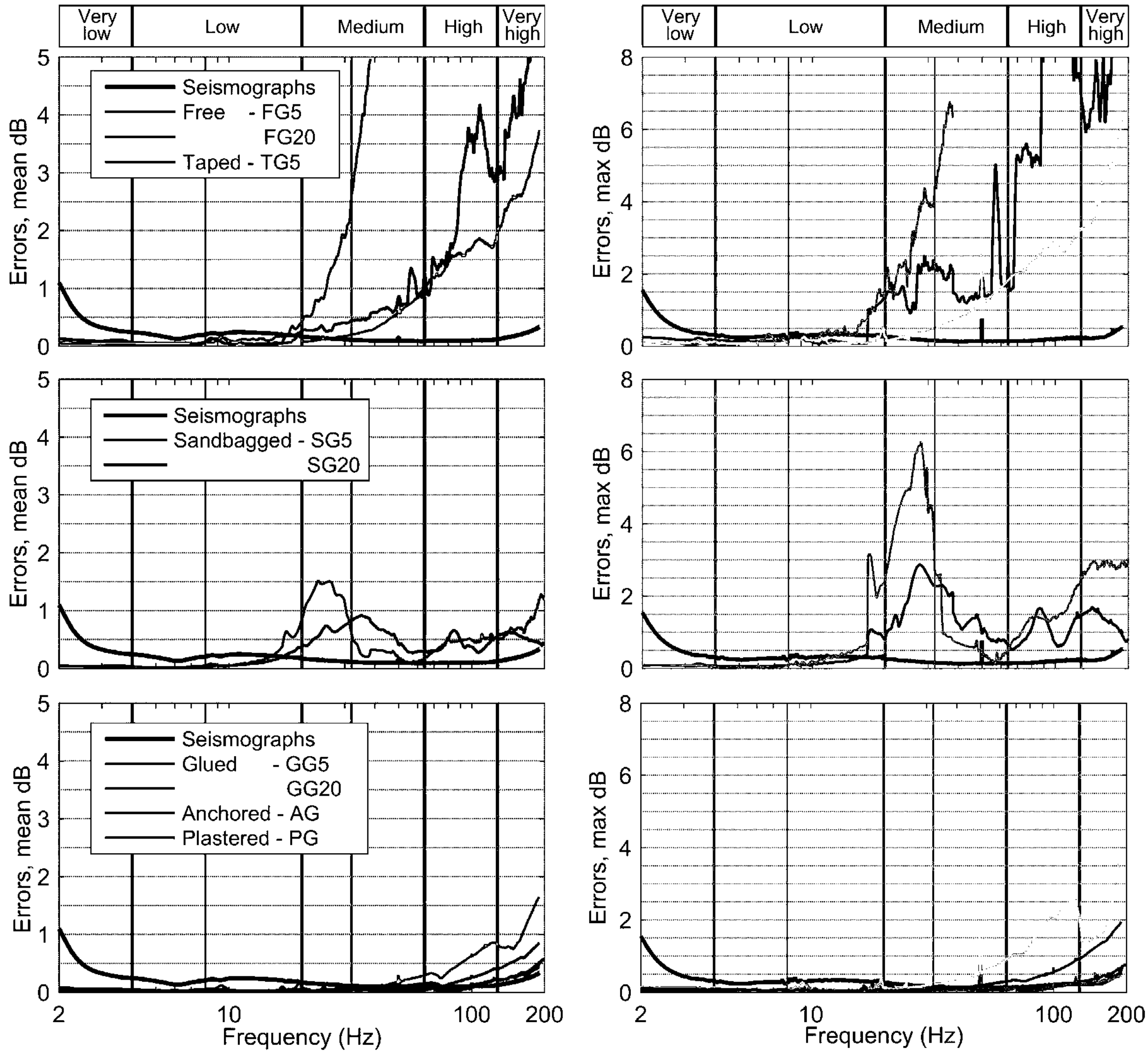

Fig. 5. Errors: expected (left graphs) and maximum (right graphs) for each test series (the first letter of the code is the coupling method – F: free; S: sandbagged; A: anchored; P: Plastered; G: Glued; T: Taped–, and the second one is the base –G: granite). Vertical scales are different for left and right graphs; vertical thick lines show the bounds of the frequency intervals considered, being from left to right 4, 8, 20, 32, 64 and 128 Hz.

5. Analysis and discussion

Logarithmic values of transmissibility, expressed as gain, are used to draw the quality figures of vibration measurements across frequency and to further assess the characteristics of each method. Absolute values of the gains are an estimate of the measurement errors either for the seismograph (e_{geo}) or for the coupling (e_c):

$$e_{geo} = |20\log_{10}(T_{geo})| \quad \text{or} \quad e_c = |20\log_{10}(T_c)| \tag{4}$$

The mean of the absolute value of the errors over a centred running window of 0.5 Hz width is used to describe the expected error at each frequency; in the limits of the band the window is non-centred and its width varies as function of the available data on each side. The maximum or highest absolute value of the error gains at each frequency has been also considered; the fact that the number of experiments is not large (i.e. eight gains-errors have been obtained, in general, at each frequency) makes it difficult to estimate any extreme percentile, e.g. 95%. In practice vibration measurements are made with a wide variety of seismographs, and thus with mounts of different characteristics, so errors from both mounts are considered together.

Fig. 5 shows errors due to coupling. For a quick interpretation, expected errors (left graph) and maximum errors (right graph) are split in three graphs: free (FG5 and F20) and taped (TG5) methods are displayed in the top graphs, sandbagging (SG5 and SG20) in the central ones and the others (glued, GG5 and GG20; anchored, AG; and plastered, PG) in the bottom graphs. For anchored and plastered mounts errors at both velocity levels have been pooled into a single data set denoted as AG and PG, respectively, as variations in transmissibility (and thus in coupling errors) between trials at 5 and 20 mm are in line with the experimental errors (see third and fourth row graphs in Fig. 4). Errors of the seismographs (the mount-to-geophone ones) are also plotted in Fig. 5 to indicate the unavoidable error in vibration measurements. They increase at the extremes of the band especially at low frequencies, while being constant at other frequencies. In contrast, coupling errors increase generally as the frequency does except for sandbagged mounts in which error peaks at medium frequencies (SG5 and SG20 in Fig. 5).

Absolute error gains from Fig. 5 are investigated in seven octave bands starting at 2 Hz. As in the first campaign transmissibility was measured from 17 Hz, the limit frequency between the third and fourth bands was extended from 16 to 20 Hz to account for these data in the low frequency interval. Table 5 shows both the highest expected error and the maximum error within each frequency band for the seismographs and also for the different measuring conditions studied.

The seismographs govern the quality of the measurements at very low frequencies (2–4 Hz) where they provide large errors compared

Table 5
Higher expected and maximum absolute gain error (in dB) at different frequency intervals. Colors and typing: Bold-green for negligible errors (*e*≤0.22 dB, this value is the measurement capability of the laboratory[36]); blue for small (0.22 < *e*≤0.45 dB; the last value is the maximum error between 4–125 Hz according to ISEE specifications of the seismograph); black for medium (0.45 < *e*≤0.9 dB); red for large errors (0.9 < *e*≤3 dB); and bold-red for very large (*e* > 3 dB).

Source	Method	Input veloc.	Frequency intervals, Hz						
			Very low	Low		Medium		High	Very high
			$2\leq f<4$	$4\leq f<8$	$8\leq f<20$	$20\leq f<32$	$32\leq f<64$	$64\leq f<128$	$128\leq f$
Geo.	-	5, 10, 20	1.10–1.55	0.24–0.34	0.24–0.40	**0.17**–0.30	**0.15–0.17**	**0.12**–0.25	0.34–0.55
Coup.	F-free	5	**0.11**–0.25	**0.07–0.15**	0.25–1.33	0.43–2.51	1.35–**5.03**	**4.17–16.03**	**6.60–9.85**
Coup.	F-free	20	**0.05–0.11**	**0.06**–0.35	0.40–1.61	2.41–**4.41**	**4.97–6.78**	-	-
Coup.	T-tape	5	**0.07–0.13**	**0.07–0.14**	0.24–0.55	**0.20**–0.49	1.01–2.56	1.94–**3.26**	**3.73–6.39**
Coup.	S-bag	5	**0.05–0.14**	**0.04–0.09**	0.36–1.08	0.81–2.87	0.91–2.30	0.66–1.67	0.63–1.69
Coup.	S-bag	20	**0.05–0.10**	**0.03–0.09**	0.77–**3.16**	1.51–**6.28**	0.61–2.70	0.59–2.42	1.28–**3.01**
Coup.	G-glue	5	**0.08–0.17**	**0.04–0.13**	**0.17**–0.41	**0.11**–0.36	0.29–0.92	0.86–2.60	1.64–**3.65**
Coup.	G-glue	20	**0.04–0.11**	**0.05–0.08**	**0.10–0.18**	**0.05–0.08**	**0.15**–0.31	0.41–0.96	0.85–1.94
Coup.	A-anchor	5, 20	**0.02–0.06**	**0.03–0.06**	**0.09**–0.23	**0.07–0.20**	**0.07–0.22**	0.23–0.39	0.57–0.78
Coup.	P-plaster	5, 20	**0.06–0.13**	**0.04–0.07**	**0.07–0.19**	**0.04–0.14**	**0.10–0.12**	0.26–0.44	0.44–0.57

with coupling; this explains the deviation in Fig. 2 between the seismograph response (red lines) and the base motion (green lines) in the low frequency range. All coupling methods provide accurate measurements between 2 and 8 Hz even at the higher velocity level tested. In the next band (up to 20 Hz), expected errors are still limited but free and sandbagged mounts may provide large errors at the high velocity level. At intermediate frequencies (20–32 Hz) free and sandbagged mounts lead to large expected errors at the high velocity level, with maximum errors exceptionally high, whereas they still provide reasonable expected errors at the low velocity level. It can be seen in Fig. 5 that the error curves of free and sandbagged mounts shift towards smaller frequencies as the velocity increases, reducing then the operating bandwidth of the method; such an effect of the velocity in the coupling errors is in line with other works.[21,26] In this frequency range, taped mounts qualify close to the glue, plaster and anchor attachments.

At higher frequencies (32–64 Hz) the three methods with worst performance are free, taped and sandbagged. Anchoring and plastering still qualify as the best methods, whereas glued mounts perform worse. In these, the largest errors are found at the low velocity level where the stresses applied on the mount are lower; such a result, observed also at higher frequencies, may indicate a weaker bonding in series at 5 mm/s than at 20 mm/s. The fact that most of the trials at the low velocity level were made in a different part of the granite surface than tests at the other vibration level may be the cause for such result.

At frequencies above 64 Hz, the attachment with double sided tape shows the largest expected errors only after the free placed mounts tested at the same velocity (5 mm/s); in fact the force required to remove them can be qualitatively described as low, probably due to the limited contact provided by the rough granite surface. Anchored and plastered mounts still ensure small errors in the high frequency band (64–128 Hz), and at higher frequencies they still perform acceptably well. Glued mounts qualified as the third best method, but errors may be significantly higher than those for anchored and plastered mounts; in the best case, tests at 20 mm/s, large errors may be obtained at high and very high frequencies.

Table 5 can be used to define the operating band of the coupling methods depending on the expected accuracy. If this is fixed in line with the most restrictive accuracy allowed for blasting seismographs, i.e. 0.45 dB, the frequency bands shadowed in Table 5 will approximately apply; note that the maximum errors exceed slightly this value for taped mounts at 8–20–32 Hz, and also for plastered mounts at very high frequencies. Anchored and plastered mounts ensure consistent measurements across the band commonly found in blasting at both vibration levels. Other methods may do if the frequencies of the vibration are sufficiently low.

The general performance of anchor/stud, cement, glue and double-sided tape shown in this work is consistent with that from ISO 5348.[9] Errors shown for glued mounts correspond to a standard thermal adhesive, the performance of which is similar to soft glues in Table 2. This adhesive type is suggested for non-permanent set-ups of accelerometers, and is less effective than strong-fast adhesives, such as Methyl cyanoacrylate.[37] Cyanoacrylates are the recommended adhesive when accelerometers, lighter than the geophone mounts tested here, are used.[9,37] Their use may shift resonance to higher frequencies, thus improving the accuracy of this method. Their drawback is that they will likely damage the surface in which they are used when the vibration mount is removed. Two-part epoxies are also recommended by some sensor manufacturers; this adhesive provides a better coupling than standard thermal adhesive,[38] and in some cases its performance is in line with cyanocrilates.[39] However ISO 5348[9] does not provide the frequency response for these epoxies. In general, adhesives have a smaller operating bandwidth than anchoring, and their performance improves with the surface smoothness and with the stiffness of the adhesive.[9,37,38]

Although the coupling transmissibility for the methods considered here has not been investigated in components of the vibratory motion other than the longitudinal, it follows from the results of this study that poor measurements are likely to be obtained with free, taped and sandbagged methods in any components of the vibratory motion. For the 'good' couplings – such as anchor and plaster gypsum– their rigidity in the vertical component may differ from that in the horizontal plane, as the motion transmission is done by shear in the horizontal movement (as in this work) and by tensile/compressive stress in the vertical. Nevertheless, given their excellent performance on shear it is likely that their behaviour be just as consistent in tension. Nonetheless, the assessment of coupling transmissibility under a vertical vibration remains a topic for future research.

6. Conclusions

The performance of some suggested methods to couple blasting seismographs to a hard rock surface for horizontal motion has been experimentally studied on a vibration shaker. The methods investigated were free (loosely) placed, sandbag over the mount, and attachments with an anchor, thermal adhesive (soft glue), gypsum plaster and double-sided tape. Two different mount types were used. Rock-to-ground, or coupling, transmissibility – that is the ratio of the velocity of the geophone mount to the velocity of the ground, as a function of frequency – has been considered to investigate the performance of each method. It was assessed from 2 to 190 Hz at one or two vibration levels (5, 20 mm/s) for 100 signals recorded under 14 measuring layouts, in which either peak velocity of the imposed motion, base and/or coupling changed. The results emphasize the effect of coupling on the quality of horizontal vibration measurements and provide guidelines to decide what coupling method can be used to measure vibrations on a hard surface depending on the expected accuracy.

For all tested conditions transmissibility is close to one at very low frequencies. As the frequency increases, so does transmissibility and it may be maximum within the bandwidth studied depending on the mount coupling. In these cases, transmissibility decays strongly at higher frequencies. Transmissibility for anchored and plastered mounts is relatively flat and close to one in most of the bandwidth independently of the mount type and peak velocity. Glued mounts show a poorer performance and transmissibility may be maximum near 120 Hz; results are affected by the quality of the bonding and distortion was larger in tests at the low velocity level than at the high velocity. Transmissibility for taped mounts peaks above 80 Hz and varies from 0.5 to 1.5. Distortion with free and sandbagged mounts started at lower frequencies, and transmissibility is maximum from 22 Hz at 5 mm/s and from 14 Hz at 20 mm/s. Transmissibility with these two methods depends on the mount type characteristics and it is not a linear function of frequency and velocity. This underscores certain limitations to use acceleration to decide the type of attachment, and suggests the use of both frequency and velocity; in order to illustrate this, free laid mounts show a different performance in tests at 5 mm/s and frequency of 60 Hz than in tests at 20 mm/s and frequency of 15 Hz, although the peak acceleration is the same, 0.19 g, in both cases. The following conditions of use are obtained assuming acceptable measurement errors to be lower than the smallest errors allowed for blasting seismographs, e.g. ± 5%:

1. Free mounts at 5 and 20 mm/s can only be used at frequencies below 8 Hz, with larger errors obtained at the high velocity level.
2. Holding the mount with a sandbag does not extend the operating bandwidth observed for free laid mounts, and may lead to larger errors than free mounts in certain frequency bands, like 8–20 Hz.
3. Taped mounts are suitable from 2 to 32 Hz at 5 mm/s.
4. Glued mounts can be used up to 32 Hz (result from tests at 5 mm/s). But the bandwidth can be stretched to 64 Hz (conclusions from tests at 20 mm/s), if the bonding is tight. Errors with glued mounts are smaller in this operating bandwidth than when double-sided tape is used, making it advisable to use glue instead of double-sided tape.
5. Anchored mounts show a good performance for frequencies below 128 Hz at both velocities levels.
6. Plastered mounts show a similar performance to anchored mounts, the former with lower errors at high frequencies (> 128 Hz).

All methods, except anchoring, lead to large and unpredictable errors when operating at higher frequencies than those suggested. This makes advisable to anchor or plaster the geophone mounts at the monitoring point whenever the characteristics of the expected vibrations are unknown. The performance of adhesives, such as glue and to a greater extent double-sided tape, depends mainly on the characteristics of the mounting surface, such as roughness and porosity, and on its preparation. Rock surfaces like the one in this study, do not favour a stiff enough bond when double-sided tape was used. Polished surfaces that allow a large contact area between the tape and the surface favour a significantly firm attachment in which the mount cannot be removed manually. In any case attachment techniques are susceptible of settlement errors, so a fixing procedure that includes a quality checking is suggested.

The effect of the seismograph (the mount-to-geophone transmission) should not be neglected for measurements in the low frequency range; this work has shown that errors in the 2–4 Hz band exceed in one order of magnitude those from coupling. Further work is ongoing to understand the effect of seismographs on the quality of vibrations signals in the low frequency range. As a consequence of this work, the coupling method followed to measure vibrations and the actual amplitude response of the seismographs should be reported in vibration studies to assess the reliability of the measurements.

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