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# The Influence of Vibration Transducer Mounting on the Practical Measurement of Railway Vibration

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**Abstract**

When assessing ground-borne vibration related to railways, careful consideration needs to be given to the mounting and coupling of the transducers. This paper presents the results of research investigating some of these fundamental issues. Different couplant materials and four of the most commonly used transducer-to-ground coupling techniques (spikes, buried, slabs, and the transducer directly plastered to the ground), were compared and analysed within the frequency range 5 Hz to 500 Hz.

The data demonstrate that transducer vertical alignment has limited influence at small angles. "Blu-tack" showed to be an adequate couplant. Above 50 Hz coupling systems can influence the reading by up to 20 dB. Using the train as a source of vibration yields a high degree of non-linearity on the coupling systems performance.

**Keywords:** Ground-borne Vibration; Railway transducer coupling.

## 1 Introduction

Placement and ground coupling of the vibration sensor (transducer) are the two most critical factors to ensure accurate ground vibration assessment from railways. An effective coupling between the transducer and the ground is often difficult to achieve, especially when the transducer mounting is restricted to limited options that the ground structure offers. There isn't a unique transducer mounting method that can satisfy all types of ground structure; ground surfaces can be covered with cement, asphalt, embedded slabs or just soil, where conditions differ from site to site. Good coupling means the transducer maintains proper contact with the ground, and is essential for good measurements. This paper compares different ground coupling methods (spikes, buried slabs, and the transducer directly plastered to the ground) and assesses the reading with different transducer angular misalignment within the frequency range 5 Hz to 500 Hz at a number of sites

The paper reviews the issues associated with ground coupling for railway vibration measurements and then presents collected data upon which conclusions are drawn as to the influence of the coupling mechanism on the suitability of the readings.


## 2   Literature Review

Poor coupling can cause friction and slippage of the transducer, resulting in distortion, altering the amplitude and phase of the signal, often yielding higher measured vibration levels. It has been established [1] that ground coupling is a resonant phenomenon, where the transducer and the ground coupling form a resonant system.

Various researchers sought out to investigate the coupling phenomena, accrediting parameters to characteristics of the coupling resonant frequency. Through the use of numerical models combined with field experiments [2] attributed the primarily effect of ground coupling to the base area, weight of the transducer and conditions of the ground. [3] investigated how the coupling influences the amplitude and phase of the vibration signal and concluded that, along with transducer placement and spike length, the soil type and condition can drastically affect the measurements. [3] also raised the suspicion that the coupling resonance is insensitive to change in the mass or diameter of the transducer.

The above and other contradictions in this field can be explained. [5] claims that research based on theoretical models and results from laboratory experiments only describe coupling in practice to a limited extent. This is because characteristics difficult to replicate, such as near surface soil properties, density gradients, non-linearity, quality of mounting etc, play a bigger role on the ground coupling phenomena than some of the characteristics that can be analysed through theoretical models and laboratory experiments. [6] reveals that there isn't a simple relationship between laboratory and field tests.

However, most research and recommendations [7] [8] [9] [3] agree that for high frequency recordings or where there is loose soil the best coupling can be achieved by burying the transducer. Where the measurement surface consists of rock, concrete or asphalt the transducer should be fastened to the measurement surface with a bolt or with epoxy or other quick-setting, rigid cement. It is widely accepted [10] [11] [12] that when the maximum acceleration falls between 0.2 and 1.0 g, the transducer should be buried completely.

Literature reveals the use of mounting spikes to be a controversial issue. Although some authors [11] [12] claim that spikes can be an effective coupling system for ground acceleration below 1.0 g, [10] discourages the use of spikes claiming that they may affect the characteristics of the recorded motion. [13] claims that spike mounting over-estimates the true ground vibration by 46.5%. Conversely [3] concludes that burying the sensor or using long spikes are efficient ways of increasing the coupling resonance frequency. This view is not shared by [6] who developed a model showing that by increasing the spike radius and length, the frequency of resonance decreases. Another simple way of fixing a transducer to the ground is by placing a sandbag on top. [11] sees the good use of sandbags when the expected particle accelerations are below 1.0 g. Conversely, some authors [13] [14] discourage their use.

The above literature reveals inconsistency in what is the best way of coupling the sensor to the ground. Nevertheless, it is incumbent on the operator to evaluate field conditions and to obtain good coupling between monitoring instruments and the surface to be monitored. National and International standards [7] [8] along with professional body guidance [9] [12] state what are seen to be accepted mounting techniques, what should be avoided, and give alternatives, where the requirements can't be met. Still, analysts need to understand to what extent different mounting techniques influence the outcome and the impact on vibration measurement.

# 3   Methodology and Results

To investigate some of the issues mentioned above, the adopted methodology has to consider the fact that the actual input signal (train induced vibration impinging on the mounting system) is unknown.

For every set of tests, coupling effectiveness was assessed. This was done by feeding an impulse, excited by a sledgehammer blow on the ground, into the mounted transducers and then examining how the transducers correlate between each other through the usage of "Coherence analysis". This is an effective way of investigating if there are internal flaws or relevant differences in the structure (e.g. resonances) where the transducers are placed, certifying that all transducers see the same signal.

As demonstrated [3], the coupling phenomenon is non-linear and the resonance frequency can decrease almost by 100 Hz as the force applied increases. For this reason different classes of passing trains (43, 158, Freight 66, 153, 170 and 222) were used as the excitation mechanism. All vibration levels at the sensors were below 0.1 g.

As observed by [3], the ground structure can drastically affect the coupling mechanism. Therefore, two sites with different ground characteristics were selected to attempt to overcome this. The first site, 10 m from the train track, is a residential back garden. The ground consists of firm lawn, where the soil characteristics facilitate the use of all selected mounting mechanisms, also, well-bedded paving slab were available. At the second site, there is a path 3 m away from the train track. At this location, the ground is a compacted hard soil, where the soil composition and texture can compromise the quality of mounting, making it difficult to bury a transducer effectively.

Each event (passing train or force impact) was simultaneously recorded, on four channels using four different mounting mechanisms. For each mechanism, the spectral amplitude is derived using the power density spectrum (PSD) function. Relative comparisons between mechanisms are presented using "spectral amplitude difference curve" (SADC), within the frequency range of 5 Hz to 500 Hz (which is the difference between the two PSDs). A "representative spectral difference curve" (RSDC) consisting of an arithmetic average of six SADCs, each corresponding to a different passing train, will characterise a coupling mechanism within the selected frequency range.

For each figure presented, a single value ($\sigma$) that facilitates an overall comparison between coupling systems throughout the selected frequency range, is computed in a similar way as standard deviation, where the mean is effectively the SADC of the reference coupling systems. It is presented in dBw referenced to $10^{-6}$. This test will not give an absolute response for any mounting technique since the input vibration characteristics remains unknown. However, the intention here is to analyse and quantify the relation between mechanisms. Below the tests undertaken are described with details of the results for the couplants angularity of the transducers and the sensor planting mechanism.

## 3.1   Couplants

Prior to investigating the different mounting methods, an experiment to evaluate three couplant materials was undertaken. These couplants were used to connect a mounting stud, (to which the transducer is attached), to the slab. The selected couplants were: Dental plaster, (a solid and long lasting equivalent to cement); Beeswax, (one of the most commonly used and reliable couplants) and "Blu-tack", (reusablele putty-like pressure-sensitive adhesive), which was selected for its practicality of usage. Two different thickness of "Blu-tack" were tested, 1mm and 5 mm. The accelerometers employed for the test were placed at the same time on the same slab equidistant from the source.

A coherence function was used to investigate if there are internal flaws or difference in slab's concrete structure, where the transducers were placed. It is worth noting that when plastering a surface small gaps can be left at the junction between structures which may compromise the coupling.
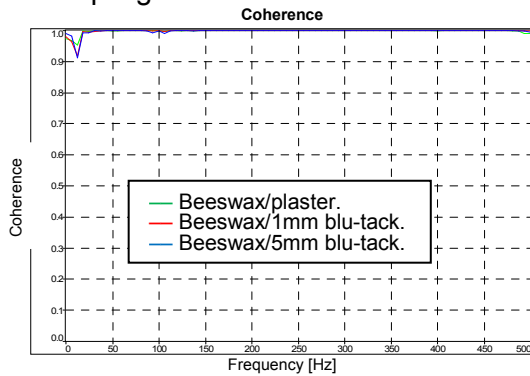


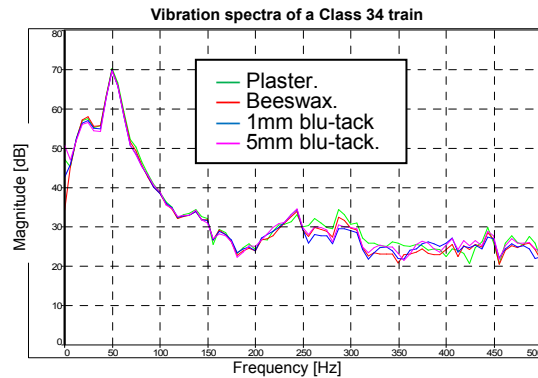Figure 1 – Coherence between the signal at the four transducers



Figure 2 – Representation of the three resulting spectra.

Figure 1 shows there are no compromising flaws in the structure adjacent to each transducer and that all the transducers share the same input signal. Figure 2 shows the four resulting PSD. Figure 3 reveals that all couplants perform similar up to 250 Hz. In this region divergence amongst them is kept to less than 1 dB. A 2.5 dB divergence around 375 Hz reveals that plaster couplant over predicts in comparison to the others. It is important to note, that "Blu-tack", which is not referred in standards performs very similarly to beeswax, which is said to be a reliable couplant. The 5mm "Blu-tack" σ throughout the entire frequency range is 0.38 dB (all σ are presented on the plot's label).
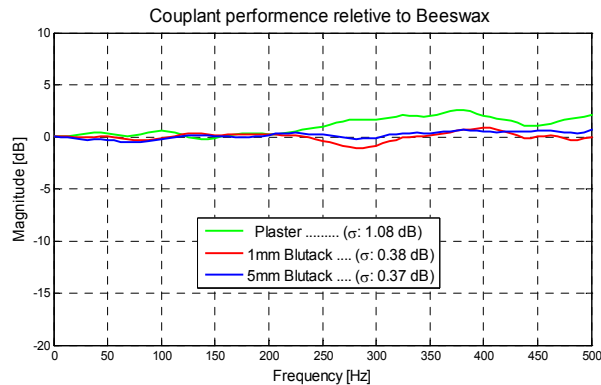


Figure 3 – Comparison of couplants using "RSDC"

## 3.2   Vertical alignment offset

Cross-axis sensitivity (transverse sensitivity) is the measure of error on the signal produced by a transducer if it is vibrated at the right-angle to its working axis. The specification of the transducers used for the tests shows the transverse sensitivity error to be less than 5 %.
It is often quoted that transducer tilt is to be kept to a minimum to avoid introducing another variable. [12] claims that *"The sensor must be nearly level",* but failing to specify the degree of nearly. [3] states that below 60 Hz amplitude distortion is more influenced by the vertical alignment of the transducer than it is to the coupling mechanism. To investigate the effect on the sensitivity misalignment, three transducers, each vertically aligned at a different angle, 0° 10° and 20°, were placed on the same slab equidistant from the source.
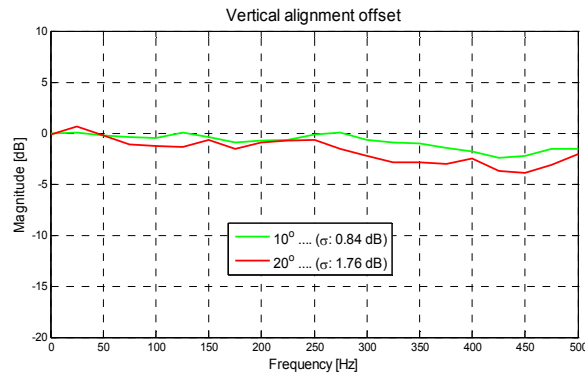
Figure 4 – "RSDC" relating the spectrum differences of 10° and 20° to 0°

Figure 4 shows up to 200 Hz the vibration spectra for all different tilting angles behave very similar < 3 dB. Above 200 Hz the transducer placed at 20° is not reliable. The transducer at 10° behaves within an acceptable deviation.

## 3.3   Sensor planting Mechanism

To investigate the ground-to-transducer planting mechanism, four techniques were selected. The buried transducer method, which is considered by a vast number of experts as the method that minimises ground coupling distortion. This method consists of boring a cavity with suitable dimensions, allowing the sensor to fit leaving the top of the vertical axis at ground level. In order to minimise the risk of disturbance and also ensure good coupling with the ground, the pit should be refilled with the excavation soil and then hand-tapped around the sensor.

The spike method, which is the most common used method for ground vibration surveys, consists of a small transducer mounting disc welded to a steel spike. The spike is to be driven fully into the ground vertically. There are different recommendations for the shape and size of the spike. For this study two different spikes were produced: a 250 mm long round stainless steel spike (O-Spike) with a 30 mm diameter following the recommendations of [7] and [9]; and a 500 mm cross spike (X-Spike) following the recommendation of [8]. [3] found that the damping and resonance frequency was directly proportional to the length of the spike. This was attributed to an increasing surface area in contact with the ground. For a spike of 120 mm, [3] found the resonance frequency to be around 650 Hz. If this is the case then both commissioned spikes are fit for purpose.

Fixed slabs and portable small slabs were also tested. Although not recommended by some, it is common practice to use small slabs as a base for small light transducers, changing their mass ameliorating ground coupling. In some situations, such as where the site is floored with fixed slabs, these become unavoidable. On this experiment different types of slabs were used to quantify the impact it has on the coupling system. Plaster direct on the soil was also tested. The loose soil and vegetation was removed prior to the pouring of dental plaster.

### 3.3.1  Site 1

Plots below were selected for their clarity but are representative of the results obtained throughout the tests. Figure 5 shows the four resulting spectra from each of the chosen ground-to-transducer coupling mechanisms, where the input signal is the resulting ground-borne vibration induced by a passing train, in this case a Class 153. The buried transducer and the O-Spikes yield similar spectra. In comparison to other coupling systems the X-Spike under predicts the vibration level. With the exception on Site 2, where the X-Spike did not under predict within frequencies around 250 Hz (see Figure 13 dark and light blue), this trend

was consistent for all the 46 different passing trains measured at both sites tested. This could be seen as the adequate mounting system. However, buried transducer response will be chosen as the reference, since it is agreed by the majority of experts as the method that yields the best results. Figure 6 shows the relative effect of different ground coupling systems, where each system is directly compared with the others. The resulting spectra of plastered and buried transducers diverge (light blue) by up to 10 dB between 350 Hz to 500 Hz. O-Spike and buried transducer performance (black) converge up to 400 Hz. If not for the divergence around 150 Hz to 200 Hz the X-Spike would yield an adequate spectrum in comparison to the buried system.
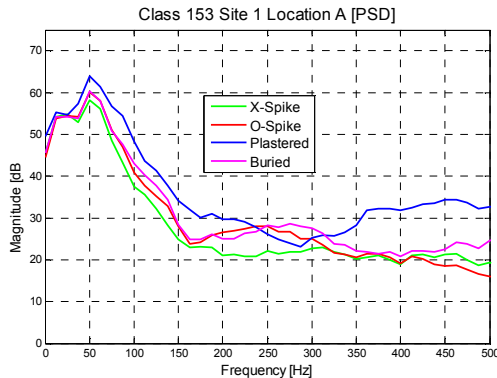
Figure 5 – Class 153 train different resulting spectra (coupling technique dependent).
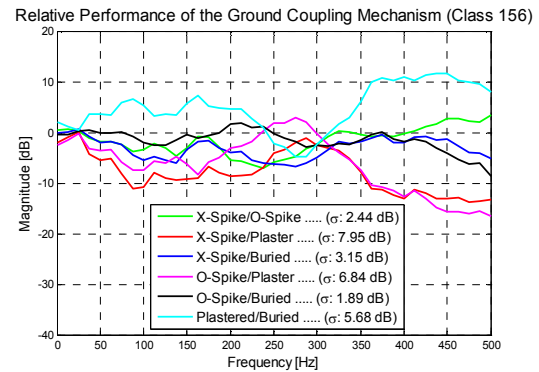
Figure 6 – SADC relating the 4 different spectra on Figure 5.

In Figure 7 the spectra are directly compared. Each curve describes the relationship that each ground coupling system has with the buried ground coupling system's resulting spectrum. Vibration induced by different sets of passing trains (to allow for non linearity) is used to derive the RSDC. Figure 7 reveals a similarity between the O-Spike and the buried transducer's performance, with a maximum deviation of 3 dB between 5 Hz and 450 Hz. The legend values show the average amplitude deviation in dB.
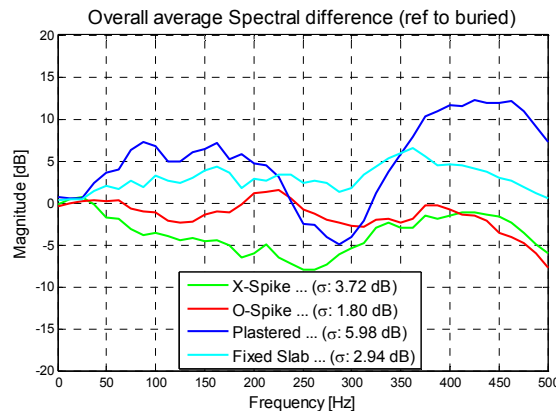
Figure 7 – Four "RSDC" showing the relative effect of different ground coupling systems for site 1 location A.

### 3.3.2  Site 2

On site 2, the good correlation between the buried and O-Spike spectra no longer holds. As seen in Figure 8 (dark blue), there is more affinity between the two spike's performances, producing almost the same spectrum up to 300 Hz, where deviation is kept within 3 dB. The

buried and O-Spike performance, which proved to be similar in the previous site, yields an average deviation greater then 12 dB. The reason for this may be that the stiff dense granular soil showed to be adverse for a proper burying of the transducer. There is the likelihood that the transducer failed to sit perfectly on the cavity's base and that the type of soil compromised the refilling of the cavity, allowing the transducer to sway. However, the figure shows (black line) that the coupling system can compromise the vibration measurement up to 20 dB in a 100 Hz wide band centred on 180 Hz.
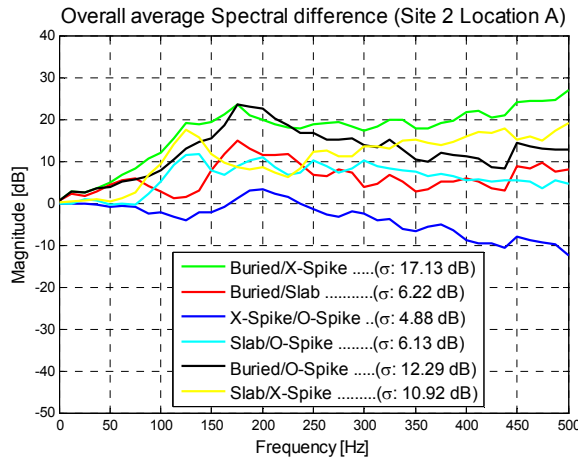


Figure 8 – "RSDC" relating the different ground mounting systems for site 2 location A

A second visit to the site allowed some corrections. The base of the cavity was plastered in the same way as the first; also two buried transducers were assessed simultaneously. Still, the results showed poor correlation between the buried transducer and the O-Spike. The direct comparison between buried transducers (Figure 9) revealed an inconsistency between them. It can be that the burying of a transducer in this type of ground is difficult to achieve.
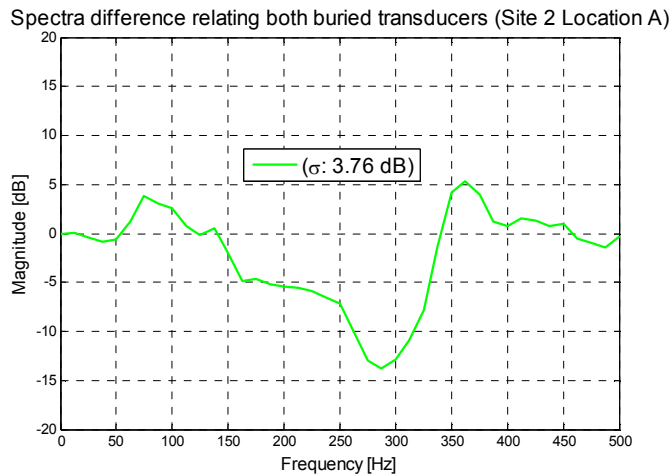


Figure 9 – 2 buried transducer (0.5 m apart) "RSDC".

### 3.3.3 Slabs

A comparison between 3 similar fixed concrete slabs was conducted using an O-spike (since the system is portable and easy to implement) as the reference mechanism. These slabs are 500 mm wide and 3 meters long. Figure 10 illustrates how different fixed slabs can perform when placed between the ground and transducer.
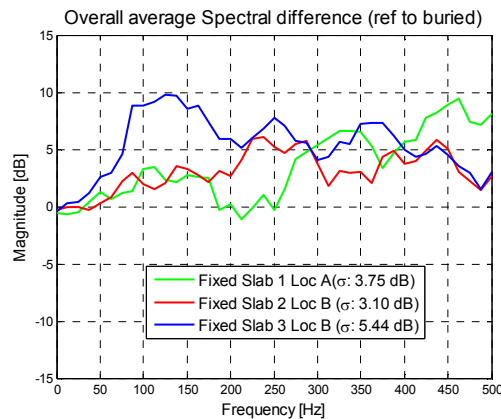
**Overall average Spectral difference (ref to buried)**

Figure 10 – Comparison of slabs performance through "RSDC" referenced to O-Spike.

The same method as above was used to compare 3 different portable slabs. These slabs are: "Big-Slabs" – 450 mm square 35 mm thick, weighing 20 kg; "Mid-slab" – 55 mm by 130 mm by 45 mm, weighing 8 kg; "Small-Slab" – 300 mm by 100 mm by 65 mm, weighing 2 kg; Figure 11 illustrates how different slabs perform when used as a transducer's base support. There were some difficulties in the mounting of the "Big-slab" due to its large base area; this might have compromised the quality of mounting. The likelihood that the slab's entire surface did not couple to the ground totally, and might explain the over prediction seen in Figure 11 (blue).
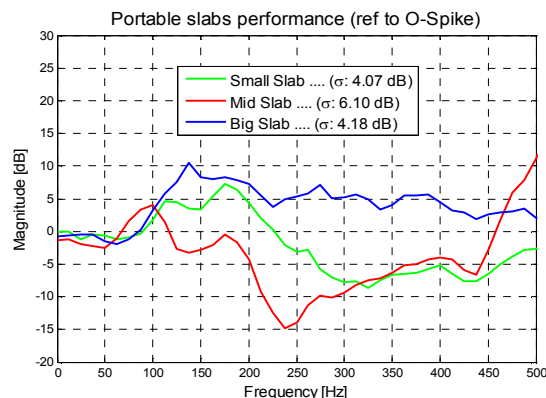
**Portable slabs performance (ref to O-Spike)**

Figure 11 – Comparison of slabs performance through "RSDC"

### 3.3.4 Linearity

Comparison on how coupling mechanisms relate their performance at different vibration levels was done using four different resulting vibration spectra to generate "RSDCs". The selected input signals were the resulting ground-borne vibration from: a freight train locomotive Class 66, producing an un-weighted overall level, within the frequency range of interest, of 111 $dB_w$ (ref $10^{-6}$); Class 222 (overall level of 97.6 $dB_w$); Class 156 (overall level of 94.7 $dB_w$) and force excitation using the sledgehammer blow (overall level of 91 $dB_w$).

A high divergence on the resulting spectra was found when comparing the slab to buried coupling mechanism (Figure 12 left), where a 20 dB impact can be seen, between 200 Hz and 350 Hz, due to different induced vibration characteristics. This shows the big impact that vibration characteristics have on the ground coupling mechanisms. The mechanism that showed to be less affected was the O-Spike. However, it still was found to be highly non-linear, as seen in Figure 12 right.
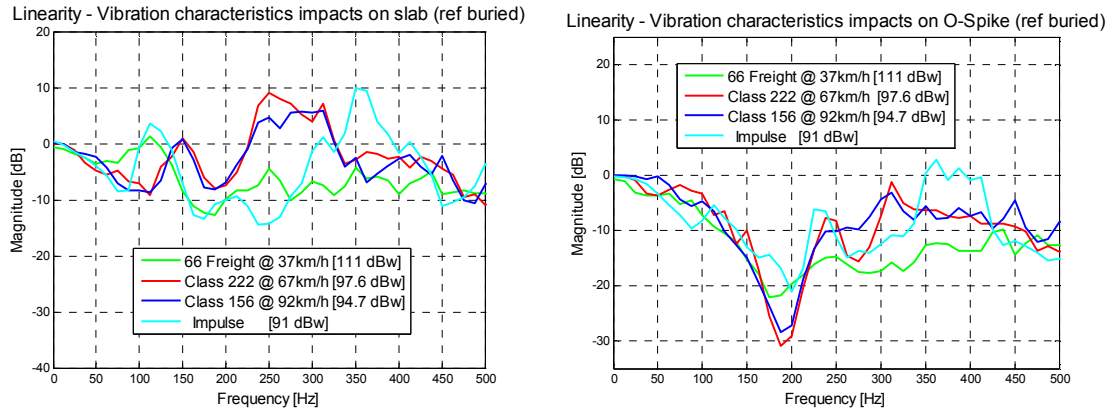
Figure 12 – SADC dependent on input vibration characteristics, left: relationship between slab and buried transducer, right: O-Spike and buried transducer.

### 3.3.5 Location

To assess the degree of impact that the mounting locations have on the ground-transducer coupling performance, each site was tested at two nearby locations, less then 5 m apart. At Site 1 there is less resulting spectral deviation than for Site 2, (almost 10 dB difference around 170 Hz and 400 Hz, difference between light and dark blue lines on Figure 13). Two reasons may be attributed to this; the soil characteristics vary to a greater degree at Site 2 than it does at Site 1, meaning that the ground structure is affecting the behaviour of the coupling mechanism. The second reason can be attributed to the nature of the wave front that impinges on the coupling device. Because the planting locations at site 2 were nearer to the track, more p-waves and s-waves (dispersive waves) are present in comparison to Rayleigh waves (non-dispersive wave) which decrease with distance at a lower rate. Thus a greater change in characteristics of the wave front can be produced at site 2 when the transducers are moved 4 m (from location A to B) than at site 1 where almost only Rayleigh waves are present.
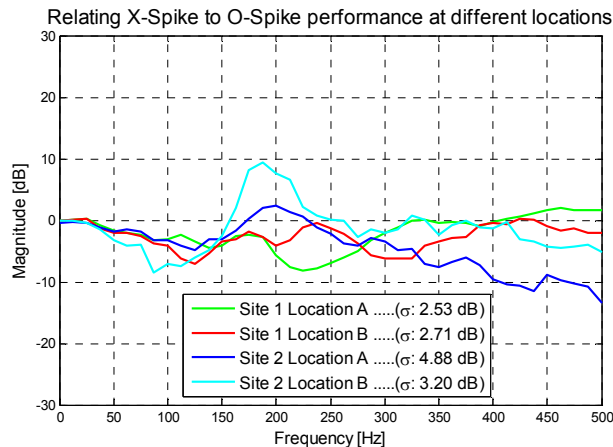


Figure 13  – "RSDC" comparing the behaviour between spikes at different locations.

## 4   Conclusions

Analysis carried out demonstrated that for long wavelength vibration where the motion of interest is the same as the predominant vibration such as ground-borne vibration where almost 70 % of the energy is transmitted through Rayleigh-waves, cross axis deviation up to

10 % does not compromise the measurement. "Blu-tack" was revealed to be a suitable couplant for outdoor vibration assessments where the weather, especially heat, can compromise the use of beeswax.

The second part of the study, which analysed the degree of sensitivity of the four most commonly used coupling mechanisms, demonstrates that the decision on the coupling system can influence measurements up to 20 dB within a 100 Hz bandwidth. The significance of the non-linearity on the coupling system's performance was shown; it was verified that coupling system's performance varies greatly with the input vibration characteristics and transducer mounting location.

This research revealed the degree of difficulty there is in identifying a trend that can characterise the use of any of the assessed coupling mechanisms, especially when different ground types are considered.

However, most environmental assessments only deal with frequencies up to 50 Hz, where the coupling system performances yield little impact.

## References

[1] Washburn, H.; Wiley, H., The effect of the placement of a seismometer on its response characteristics. *Geophysics*, Vol 6, 1941, pp 116-131. [From Krohn]

[2] Omata, S. Ground couplings and measurement frequency ranges of Vibration transducers. *Journal of the Acoustical Society of America*, Vol 73 (6),1983 pp.2187-2192

[3] Krohn, C. E., Geophone ground coupling. *Geophysics*, Vol 49 (6), 1984, pp 722-731.

[4] Hoover, G.M.; O'Brien, J.T., The influence of the planted geophone on seimic land data. Geophysics, Vol 45, 1984, pp 1239-1253.

[5] Faber, K.; Maxwell, P.W.; Edelmann, H.A.K. Recording Reliability in Seismic Exploration as Influenced by Geophone-Ground Coupling. 56th meeting of the EAEG, Vienna, 1994.

[6] Drijkoningen, G.G.; Rademakers, F.; Slob, E.C.; Fokkema J.T. A new elastic model for ground coupling of geophones with spikes. *Geophysics* Vol 71 (2), 2006, pp. Q9-Q17.

[7] BSI, British Standards Institution. BS 7385-1: *Evaluation and measurement for vibration in buildings, Part 1: Guide for measurement of vibrations and evaluation of their effects on buildings.* London. 1990

[8] DIN, Deutsches Institut fur Nurmung. DIN 45669-2:2005-6: *Measurement of vibration immission Part 2: Measuring method*, Berlin, 2005

[9] ANC, Association of Noise Control, *ANC Guidelines: measurement & assessment of groundborne noise & vibration*, Fresco, Uckfield (UK), 1st Edition, 2001

[10] Dowding, C.H., Suggested method for blast vibration monitoring. I*nternational Journal of Rock Mechanics and Mining Sciences & Geomechanics*, Vol 29 (2) 1992, pp 145-156

[11] Stagg, M. S.; Engler, A.J. Measurement of Blast-induced Ground Vibrations and Seismograph Calibration, *US Bureau of Mines* (RI 8506), 1980.

[12] ISEE, *Field Practice Guidelines for Blasting Seismographs*, USA, 2009, www.isee.org

[13] Blair, D.P., Blast vibration in soil and on large resonant structure. *Explo'95 Conference.* Brisbane, Australia, September 1995, pp 317-322.

[14] Robertson, D. A., The Neglected Step to Accurate Blast Monitoring: Proper Coupling. 9th Annual Symp. On Explosives and blasting research, ISEE, January -Feb., San Diego, pp.83-98