Methods for reducing unwanted noise (and increasing signal) in passive seismic surveys

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SUMMARY

Passive seismic surveys are becoming of increasing interest for characterising the near surface, in particular the depth of cover. For passive seismic acquisition ambient noise is both signal and noise. The 'signal' component is generally considered to be energy resulting from distant sources (earthquakes, storms, tides, etc.) while the 'noise' component is a result of near sources (vehicles, vegetation movement, etc.). To record low-amplitude passive seismic signals a combination of a low natural-frequency highly sensitive geophone with a low noise-floor acquisition system is essential to record low-amplitude passive seismic signals. To avoid wind noise the sensor should be well coupled to the surface and ideally buried. We found that placing wind-shields over the sensor made no difference to the noise level but increased noise if the sensor was poorly coupled. Our results show that good coupling is crucial for recording good quality data. If the geophone is not coupled adequately then the sensor rocks, resulting in the coupling-related resonance peak occurring at frequencies well within the bandwidth of interest. If the HVSR method is being employed then anomalous peaks can occur. The best coupling is obtained by burying the sensor, failing that then long, tapered spikes should be used. If the surface is too hard to use spikes then sandbags should be placed underneath, and on top of, the sensor.

Key words: passive, seismic, acquisition.

INTRODUCTION

Passive seismic surveys are becoming of increasing interest for characterising the near surface, in particular the depth of cover. For passive seismic acquisition ambient noise is both signal and noise. The 'signal' component is generally considered to be energy resulting from distant sources (earthquakes, storms, tides, etc.) while the 'noise' component is a result of near sources (vehicles, vegetation movement, etc.). For surveys to be successful we clearly need to maximise the former while minimising the latter. We cannot directly increase the amount of source energy so instead we need to ensure that we enhance the recording of the signal while minimising unwanted noise. The paper is divided into three sections, in the first we look at instrumentation we then examine methods to reduce wind noise reduction before finishing with coupling.

INSTRUMENTATION

The most critical decision when recording passive seismic data is the choice of instrumentation, in particular the geophones used and the noise level of the recording instrument. Geophones are typically specified by their natural frequency, i.e. the frequency at which the mass inside the geophone naturally oscillates. To prevent excessive oscillation at the natural frequency the geophone is damped by soldering a resistor across its connectors (Figure 1a). Below the natural frequency the response of the geophone decreases relatively rapidly (Figure 1b).

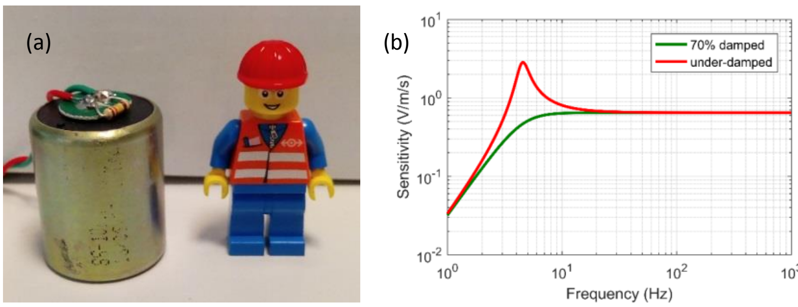

Figure 1. (a) Photo of a geophone showing the damping resistor (b) Comparison of the response of a 70% damped and under-damped 4.5 Hz geophone.

As well as their natural frequency geophones also differ in their sensitivities; for example Figure 2 shows the response of a 2 Hz, 4.5 Hz and 10 Hz geophones. The 4.5 Hz and 10 Hz geophones differ only in their natural frequencies whereas the 2 Hz geophone has a higher sensitivity level. To record low frequencies the choice of a low natural frequency geophones seems obvious, these geophones have drawbacks, however, they tend to be larger and heavier (the Sercel L-4A 2 Hz geophone, for example weighs 1,700 g vs. an SG-5 5 Hz geophone weights just 170 g), and considerably more expensive. Lower frequency sensors also require an external power source and therefore a warming up period before they can be operated (Guillier et al. 2008). They are also much more sensitive to tilt and require considerably more effort when being planted.

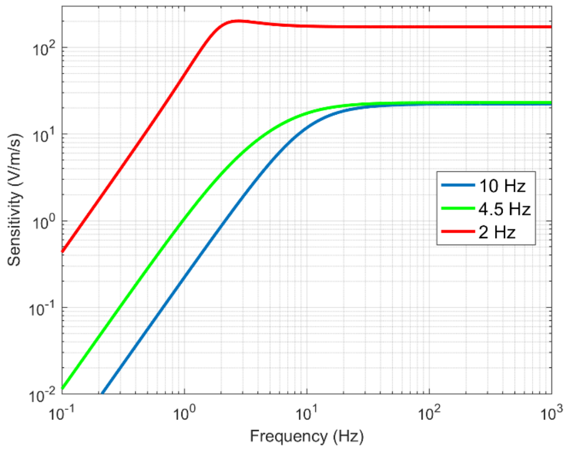

Figure 2. Geophone response curves for 2 Hz, 4.5 Hz, and 10 Hz geophones.

The characteristics of individual geophones also vary, in particular their resistance, natural frequency, damping and sensitivity. Thus before comparing spectra it may be necessary to correct for these differences. These parameters can be measured using instrument tests (Hagedoorn et al. 1988) or by conducting calibrations (Kann and Winterflood 2005).

The frequency limit of a recording system is a combination of three factors:

- Geophone response,
- Instrument noise level,
- Signal strength.

If the signal, after the application of the effect of the geophone response, drops below the instrument noise level then no useful data will be recorded. This is illustrated in Figure 3, the red lines are the high and low new low noise levels, i.e. the limits of the minimum level of noise likely to be observed when there is no other cultural or seismic activity (Peterson 1993). The blue, green and black lines are the measured noise spectrum of an instrument adjusted for three different noise levels, 0.3, 0.6, and 1.2 µV respectively. In this example we can see that we should be able to measure signals with strength corresponding to the HNLM for all three noise levels but that even at 0.3 µV we would not be able to measure signals with strength corresponding to the LNLM. Figure 4 shows a similar result but for a different geophone, one with a higher natural frequency (10 Hz vs. 5 Hz) and lower sensitivity (28.8 vs. 80 V/m/s). By comparing the two results we can see that the use of a different geophone has significantly reduced our ability to record low frequency data.

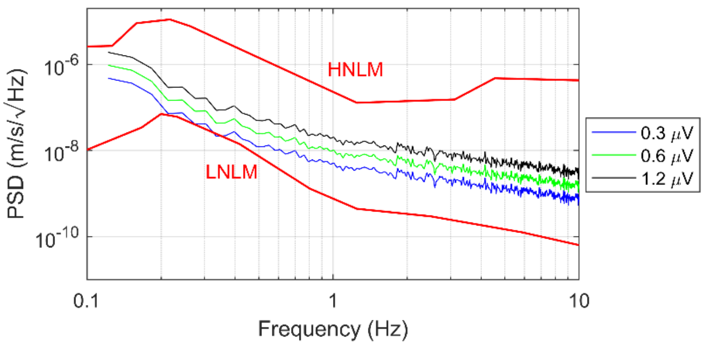

Figure 3. Noise levels of the combination of an SG-5 geophone (natural frequency = 5 Hz, sensitivity = 80 V/m/s) and a measured, but scaled, instrument noise level. The red lines are the high and low new low noise levels (Peterson 1993).

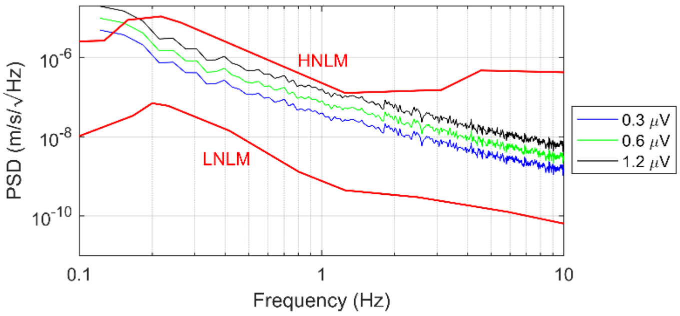

Figure 4. Noise levels of the combination of an SM-24 geophone (natural frequency = 10 Hz, sensitivity = 28.8 V/m/s) and a measured, but scaled, instrument noise level. The red lines are the high and low new low noise levels (Peterson 1993).

Thankfully, the noise floor of most modern instruments low, a review of more than 20 available instruments yielded figures of between 0.09 and 1.2, the higher values tend to be instrumentation developed for large active seismic surveys where the noise floor is not such an issue. Several of the instruments designed for passive seismic surveys, however, had surprisingly high noise floors and the reader is advised to check specifications carefully.

WIND NOISE REDUCTION

Wind noise can extend to frequencies as low as 1 Hz (Bonnefoy-Claudet et al. 2006) and is thus well within the desired bandwidth of passive seismic data. Wind noise is related both to the impact of the wind on the geophone case and to waves resulting from the movement of vegetation. (Dean et al. 2015) with the latter considered to be the most significant. To reduce the impact of wind noise on the geophone casing a bucket is often placed over the instrument to shield it from the direct effects of the wind. To evaluate the effectiveness of this approach we conducted a series of experiments using a large fan as a source of wind (Figure 5a). As the 'wind' was highly localised we could examine the effects of casing-generated noise rather than noise coming from the movements of vegetation. Although the fan generated mechanical noise, despite it being placed on insulating foam mats, such noise was concentrated at frequencies above 70 Hz, considerably higher than the usual bandwidth of interest. The tests were conducted using 3-component 4.5 Hz geophones. Tests involved geophones that were poorly coupled, i.e. with their spikes resting on the ground, and well coupled, i.e. with their spikes fully inserted (Figure 5b).

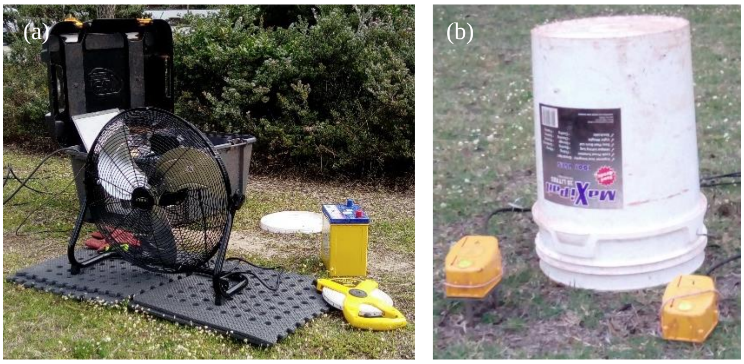

Figure 5. (a) the fan used for wind noise testing. (b) the geophone on the left is poorly coupled while that on the right is well coupled.

Figure 6 shows the PSD for the three components of a well coupled geophone at difference wind-speeds when covered by a large bucket. The increase in noise above 70 Hz is a result of increased mechanical noise from the fan, other than that there is no significant difference in the noise levels measured. When the geophone was poorly coupled, however, the bucket actually increased the noise level (Figure 7) far beyond the levels observed when the geophone was uncovered (Figure 8). This result brings us neatly to our next topic which is coupling.

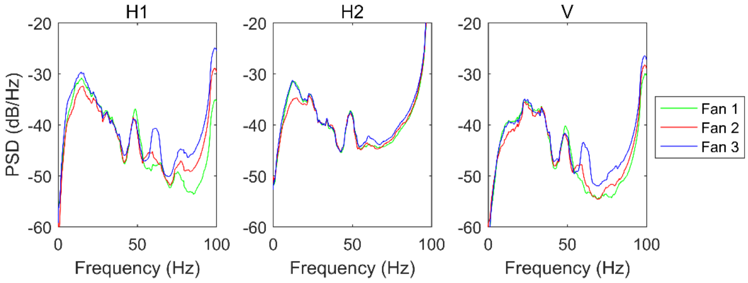

Figure 6. Average PSD for the three components of a well-coupled geophone for three different fan speeds. In this case the geophone was covered by the large bucket shown in Figure 5b.

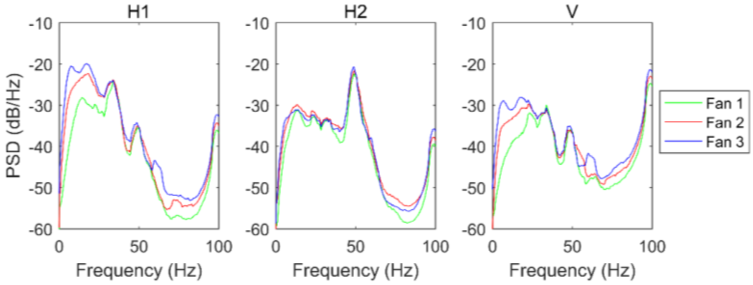

Figure 7. Average PSD for the three components of a poorly-coupled geophone for three different fan speeds. In this case the geophone was covered by the large bucket shown in Figure 5b.

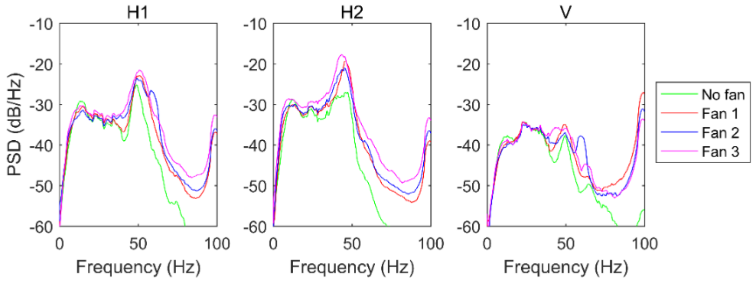

Figure 8. Average PSD for the three components of a poorly-coupled geophone for three different fan speeds. In this case the geophone was not covered.

COUPLING

The term coupling describes how well a geophone is attached to the ground and therefore how faithfully measurements made using it reflect ground motion. Krohn (1984) created a geophone/coupling model consisting of two damped springs, one being the response of the geophone and the other being the response of the coupling. The coupling response results in a second resonance peak at frequencies higher than the resonance peak of the geophone. If this coupling resonance frequency appears inside the bandwidth of interest then an anomalous amplitude peak will occur. This is demonstrated using a simple modelled result in Figure 9; the blue line in Figure 9a shows the response of a well coupled vertical geophone whilst the red line is a poorly coupled horizontal geophone. As shown in Figure 9b, this would result in an anomalous H/V peak at the coupling resonance frequency. Krohn (1984) found that having a horizontal geophone just 1 cm off the ground resulted in rocking of the geophone and a resulting resonance of 30 Hz or lower (vs. 130 Hz when in contact with the ground) so such a result is highly likely if the geophone is poorly coupled and this is, in fact, demonstrated in the next field data result.

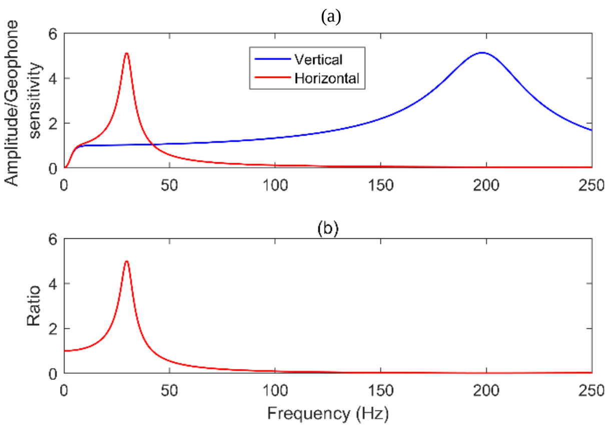

Figure 9. Modelled coupling results (a) shows the results for a well coupled vertical geophone with a couplng resonance frequency of 200 Hz and a poorly coupled horizontal geophone with a resonance frequency of 30 Hz. This results in an anomalous ratio peak (b) at 30 Hz.

Figure 10 is a photo of a test done to determine the optimum way to couple geophones to hard surfaces. Data was recorded using geophones firmly coupled in sand (top row), placed on a concrete slab (bottom left), planted in a bag of sand (bottom middle), and planted in a bag of sand with another bag placed on top (bottom right). The H/V ratio for the geophone planted in the sand show a consistent peak at around 7 Hz (Figure 11a), the one placed on the paver (Figure 11b), however, shows a second, larger peak at 50 Hz, when the geophone is planted in a bag of sand the amplitude of this peak is reduced (Figure 11c) and when covered by an additional bag of sand the peak disappears (Figure 11d).

Figure 10. Photo of the test setup.

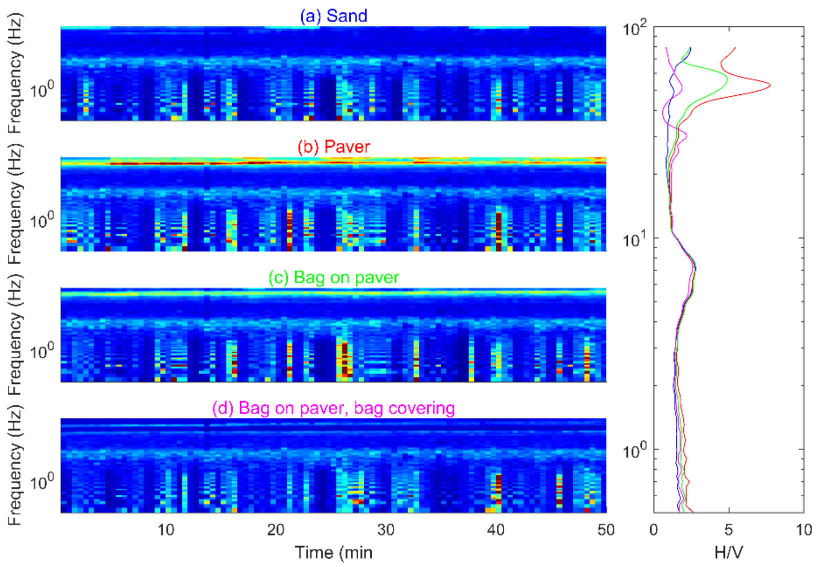

Figure 11. (a) to (d) H/V ratios calculated in 30 s windows for the four different geophone coupling conditions shown in Figure 10 and the average H/V results for all the windows. The colours of the lines on the latter plot correspond to the colours of the headings.

Figure 12 shows average PSD spectra obtained when recording noise with five different geophone coupling conditions (the soil was mostly well compacted sand). To compare the different datasets we need to examine their respective PSDs for the coupling resonant frequency, which as shown in Figure 9 will appear as a peak. Looking at the H2 component (Figure 12b) the best coupled geophone (buried) has a resonance peak at a frequency greater than 150 Hz (the magenta arrow) as the quality of the coupling decreases the resonance frequency also decreases, dropping as low as 28 Hz for the poorly coupled geophone (the blue arrow). Comparing the results for the vertical component (Figure 12c), the resonant frequencies are considerably higher (the poorly coupled resonance peak is above 120 Hz) and highly consistent, apart from the geophone with no legs.

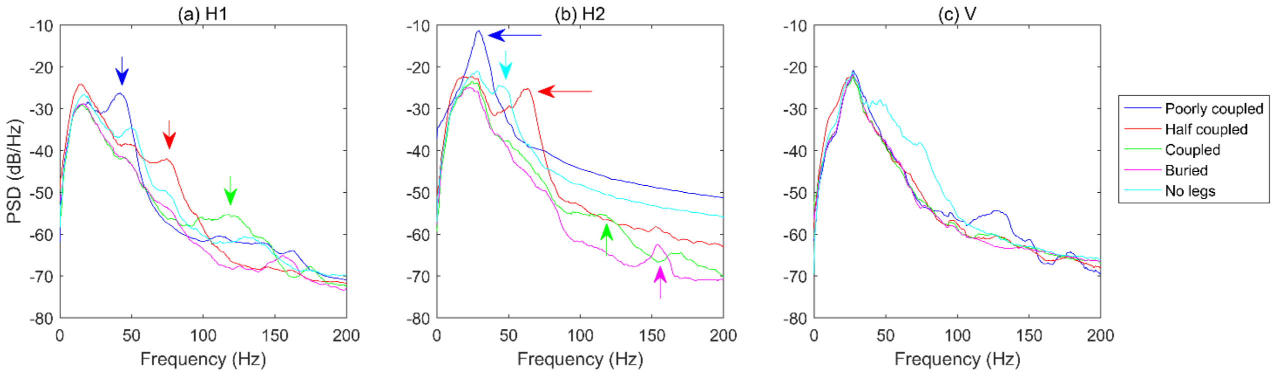

Figure 12. Normalised average PSD spectra obtained using a sledgehammer source at an offset of 20 m. Poorly coupled is with the geophone sitting on its spikes, half coupled is with the geophone pushed half-way in, coupled is with the spikes fully inserted, buried is with the geophone buried beneath the surface and no legs is with the spikes removed and the geophone sitting on the surface.

The results presented here show the importance of good coupling, generally speaking geophones are coupled to the ground using spikes. A wide variety of spikes are available, two of which are shown in Figure 13, spike (a) has a constant diameter along its length apart from its tip whilst (b) has an increasing diameter. To test their ability to couple with the ground we measured the force required to insert and remove each spike from four different types of sand/soil. The results (Figure 14) show that spike (b) is far more effective at coupling than spike (a).

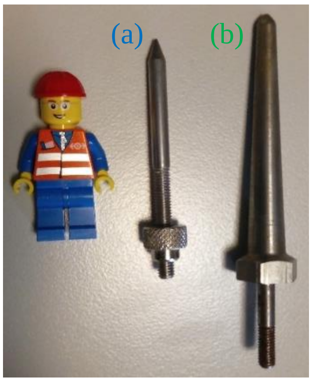

Figure 13. Geophone spikes used in the test.

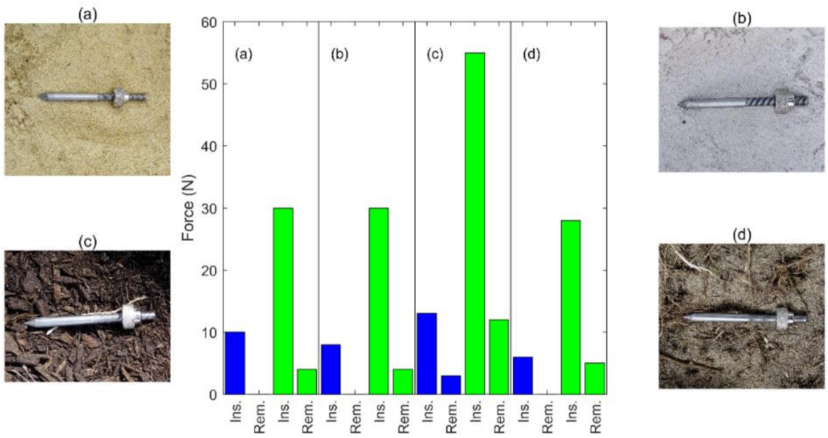

Figure 14. The force required to insert and remove two different spikes (green – spike a, blue – spike b) from four different types of soil. The minimum force meter value was 2 N so values less than this are not shown.

DISCUSSION AND CONCLUSIONS

In this paper we have examined ways in which we can record passive seismic data. Starting with instrumentation, we showed that a combination of a low natural-frequency highly sensitive geophone with a low noise-floor acquisition system is essential to record low-amplitude passive seismic signals (Figure 3 and Figure 4).

Moving on to wind noise, we found that consistent with other studies (Baraja-Olalde and Jeffreys 2014, Barajas-Olalde and Ramadan 2011) noise resulting from the direct impact of the wind on the geophone casing (rather than noise induced by the movement of vegetation etc. in the wind) increased with increasing wind speed. Efforts to reduce wind noise by shielding the sensor by placing a bucket over the top were counter-productive, noise actually increasing as the bucket acted as a 'noise antenna' (Figure 7). This result was restricted, however, to a poorly coupled geophone, well coupled geophones showed that the bucket had a negligible effect (Figure 6).

Finally, we looked at coupling. The importance of coupling to the faithful recording of passive data was born out by a series of experiments we conducted. If the geophone is not coupled adequately then the sensor rocks, resulting in the coupling-related resonance peak occurring at frequencies well within the bandwidth of interest. This effect is particularly strong on the horizontal components (Figure 12), thus if the HVSR method is being employed then anomalous peaks can occur (Figure 11). The best coupling is obtained by burying the sensor, failing that then long, tapered spikes (e.g. Figure 13) should be used. If the surface is too hard to use spikes then sandbags should be placed underneath, and on top of, the sensor (Figure 12).

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