# Application of the passive seismic Horizontal-to-Vertical Spectral Ratio (HVSR) technique for embankment integrity monitoring

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## SUMMARY

Embankments are common features in mine sites necessary for tailings storage, surface water management or general infrastructure such as dewatering ponds. Differing construction methodologies, from loosely placed waste material to engineered embankments with individually compacted lifts, will achieve varying density, strength and permeability. Conventional construction quality assurance is however not always possible without causing significant interruptions to the construction program. Estimating levees' bulk shear wave velocities via passive seismic HVSR surveying as a proxy for stiffness is a practical, continuous and non-invasive method that can be carried out with limited construction interruption over all types of structures. This also provides a continuous dataset throughout the embankment as opposed to discrete observations using conventional geotechnical methods.

Field data acquired over the length of several embankment types demonstrate the very good correlation between estimated shear wave velocities and the levees' degree of compaction. As a result, alternative construction methodologies can be quantitatively benchmarked against a bulk density spectrum with fully engineered embankments and loose waste dumps as end-members. Collection of repeated measurements over time also discriminates stable embankments from altering ones, and constitutes a cost-effective way to identify possible zones of weakness before hazardous failure.

**Key words:** Passive seismic, HVSR, Vs, embankments.

## INTRODUCTION

Embankments are common features in mine sites necessary for tailings storage, surface water management or general infrastructure such as dewatering ponds (Figure 1). Differing construction methodologies, from loosely placed waste material to engineered embankments with individually compacted lifts, will achieve varying density, strength and permeability. Conventional construction quality assurance is however not always possible without causing significant interruptions to the construction program.

The HVSR technique is a passive seismic method introduced by Nakamura (1989) that measures ambient seismic noise. The ambient seismic noise, or micro tremors, are produced primarily by wind and ocean waves culminating in what is proposed to be shear waves near the surface (Yamanaka *et al*, 1994). Anthropogenic sources can also add to wave propagation, typically at higher frequencies than natural sources. The HVSR method empirically defines that the constructive interference of waves within a layer will produce amplified horizontal oscillations relative to vertical oscillations and that the ratio of the horizontal and vertical components will produce a peak frequency related to the resonant frequency of the layer (Ali, 2013, Moro, 2015). In an ideal two-layer Earth model, this peak fundamental frequency can be used to estimate the shear wave velocity (Vs, in m/s) of the top layer if both layers display a high enough impedance contrast (Mucciarelli, 2001, Di Stefano *et al*, 2014).

Embankments, being man-made elongated trapezoidal slabs of compacted selected gravel material laid over bedrock, and whose geometry is recorded precisely by surveyors using differential GPS, are an ideal case scenario for HVSR surveying (Figure 2). Contrarily to explorers using the method to estimate crystalline basement topography from assumed laterally consistent overburden Vs (for example Owers *et al*, 2016), we propose to estimate embankments Vs from precise elevation measurements. Estimating levees' bulk Vs via passive seismic HVSR surveying as a proxy for construction stiffness is a practical, continuous and non-invasive method that can be carried out in-house with limited construction interruption. Furthermore, the affordability and small size of the required field equipment make HVSR surveying within active mining scenarios an economical and efficient alternative to more conventional ground geophysical surveys.


**Figure 1: Aerial photography over a tailings storage facility.**

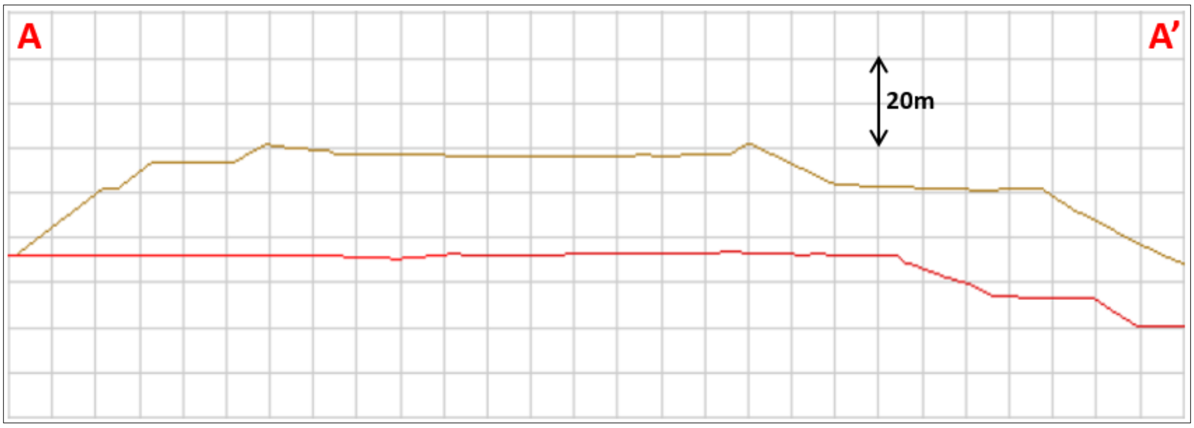


**Figure 2: Section across embankment along AA' in Figure 1.**

## METHOD AND RESULTS

HVSR surveying was undertaken over embankments built using various construction methodologies, from loosely tipped waste material to engineered embankments with individually compacted lifts, each achieving a different degree of stiffness. The highest level of robustness is attained using civil earthwork fleet and following engineering principles, where selected fill with a specific moisture content is placed in layers typically 200 mm to 300 mm thick, then individually compacted by rollers until the required compaction percentage is reached. Quality controls, which involve monitoring moisture content and lift density, are undertaken after the completion of each layer. As a cost-effective alternative, embankments can be constructed by tipping waste material in lifts between 1.5 m and 2 m high then flattened and compacted by mining fleet. The resulting lower density and higher permeability are usually offset by designing wider structures with more gentle batter slope. Both these methods nevertheless achieve better density, strength and lower permeability than end tipping of waste material at heights in excess of 10 m.

Ambient seismic tremor was recorded on top of embankments using a portable three-component seismometer. Traverses were collected wherever possible using a nominal station spacing of 50 m. At each station, data was recorded for a duration of eight to ten minutes once good ground coupling and levelling was achieved in an area free of debris or rubble. A cover was placed over the unit to protect from the wind, and a 50 m exclusion zone was maintained during recording to avoid interference from the operator's movements.

Data quality assurance and control, standard HVSR processing and peak resonance frequency ($f_0$, in Hz) selection was undertaken in a proprietary software (Figure 3) following a workflow similar to the one described in Owers *et al* (2016). Embankment Vs is then estimated following the empirical equation from Nakamura (2000); $\mathbf{Vs = 4 * h * f_0}$, where h is the known embankment thickness (in m) at the station location. A summary of average Vs results collected over 69 passive seismic stations across five sites (embankments and tailings) is presented in Table 1. It is worth noting that data quality was excellent despite being in an active mining area.

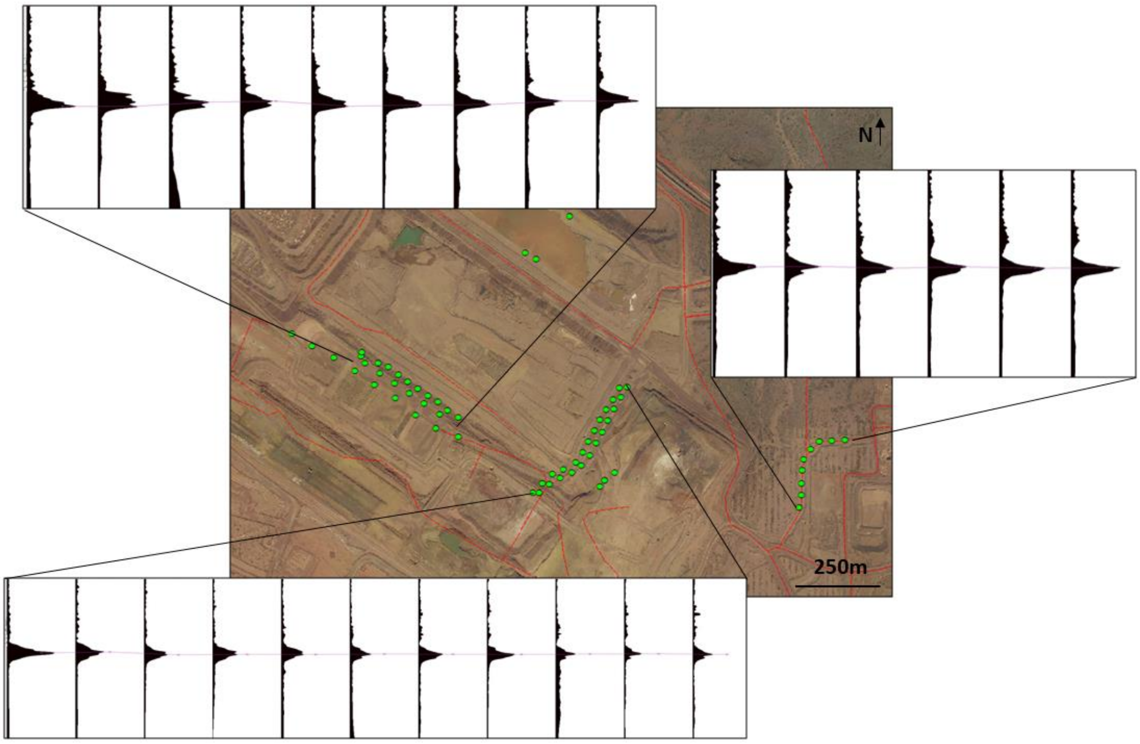


**Figure 3: Passive seismic stations (green) over aerial photography. HVSR results along selected traverses are displayed as vertical stacked spectrums with frequency on the ordinate decreasing down and station fiducial on the abscissa. The thin magenta line represents the automatically selected peak frequency $f_0$ across each station.**

| Site ID | Construction Description | Lift Height (m) | Material size (m) | Age and Usage | No of HVSR Readings | Vs (m/s) | SD (m/s) |
|---|---|---|---|---|---|---|---|
| **Site # 1** | Following engineering principles | 0.3 | < 0.2 | 2 years | 11 | 664 | 81 |
| **Site # 2** | Compacted using mining fleet | 1.5 | < 1 | New | 24 | 373 | 80 |
| **Site # 3 (middle)** | End tipped waste material | 20 | Up to ~1.5m blocks | > 4 years and used as haul road | 17 | 519 | 27 |
| **Site # 3 (edge)** | End tipped waste material | 20 | Up to ~1.5m blocks | > 4 years and used as haul road | 9 | 488 | 24 |
| **Site # 4** | End tipped waste material | 20 | Up to ~1.5m blocks | New | 4 | 304 | 23 |
| **Site # 5** | Deposited tailings | ~0.5 per month | Very fine | < 1 year after deposition | 4 | 189 | 22 |

**Table 1: Average Vs and associated standard deviation estimated from HVSR surveying over various structure types.**

An analysis of the HVSR results suggested that material type and degree of compaction may be the main controlling parameters on measured Vs. Deposited tailings from Site # 5 which are comprised of dry silt and clays, and received the least amount of compaction (deposited by pipe and solely allowed to settle over time), returned a Vs significantly lower than other compacted structures made of waste material containing mostly chert, shales and iron-bearing rocks. Site # 1, which is the site which experienced the most amount of compaction during construction, returned the highest Vs value. Similarly, even though Site # 3 and Site # 4 are made of the same material using consistent construction methodologies, the newer embankment has a significantly lower Vs than the older one which was subsequently used as a haul road, which in turn has a slightly higher Vs in the middle than along its edge, where vehicle traffic is less frequent.

In addition, a repeat acquisition in 2017 of HVSR data collected in 2015 (Figure 4) over an older embankment constructed with mining fleet (Site # 3) has returned remarkably similar average Vs values within 1.3% (516 m/s in 2015 and 523 m/s in 2017). This demonstrates the repeatability of the HVSR method, and the possibility to monitor embankments integrity over time.

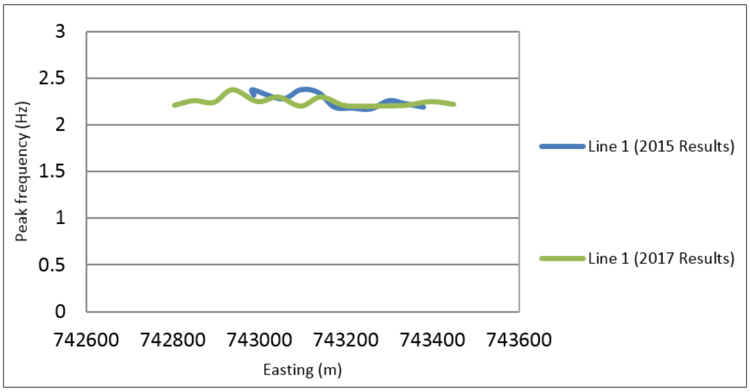


**Figure 4: HVSR automatically selected peak frequencies over an old embankment constructed with mining fleet acquired in 2015 and again in 2017.**

## DISCUSSION

The Vs values acquired from HVSR surveying have been compared against existing geotechnical information in order to assess whether the qualitative correlation with degree of compaction could be reconciled with laboratory and in-situ test results, and if estimated bulk Vs could be a reasonable quantitative proxy for embankment stiffness.

Typical waste material that was used in the construction of Site # 1 and Site # 2 were sampled for laboratory testing. Samples densities were measured at various moisture contents following a standard Proctor Compaction Test (PCT) with material passing a 19 mm sieve size. Vs was also measured for each cylinder of resulting compacted soil. Measured soil densities varied between 1.46 t/m$^3$ and 2.44 t/m$^3$ with an average of 2.08 t/m$^3$ and Vs values varied from 169 m/s to 366 m/s with an average of 248 m/s. A linear relationship between ln(Vs) and density could be determined with an acceptable fit ($R^2$ = 0.85) for this material (Figure 5).

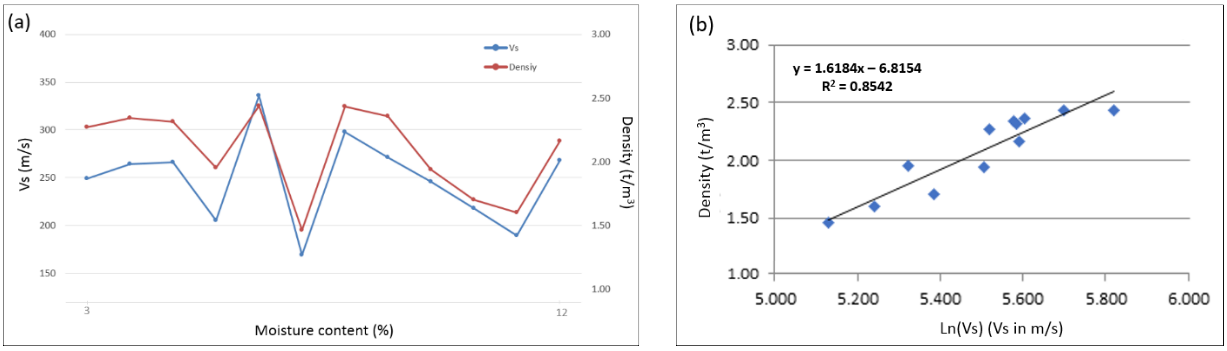


**Figure 5: Vs and density laboratory testing results (a) PCT results for various moisture content, (b) observed linear correlation between density and ln(Vs).**

Theoretical bulk densities were subsequently calculated for the higher Vs values estimated from HVSR surveying by extrapolating the aforementioned linear relationship. Results for each site ranging from 1.63 t/m$^3$ to 3.58 t/m$^3$ are presented in Table 2.

| Site ID | Construction Description | Lift Height (m) | Material size (m) | Age and Usage | Vs (m/s) | Calculated density (t/m$^3$) |
|---|---|---|---|---|---|---|
| **Site # 1** | Following engineering principles | 0.3 | < 0.2 | 2 years | 664 | 3.58 |
| **Site # 2** | Compacted using mining fleet | 1.5 | < 1 | New | 373 | 2.73 |
| **Site # 3 (middle)** | End tipped waste material | 20 | Up to ~1.5m blocks | > 4 years and used as haul road | 519 | 3.30 |
| **Site # 3 (edge)** | End tipped waste material | 20 | Up to ~1.5m blocks | > 4 years and used as haul road | 488 | 3.20 |
| **Site # 4** | End tipped waste material | 20 | Up to ~1.5m blocks | New | 304 | 2.43 |
| **Site # 5** | Deposited tailings | ~0.5 per month | Very fine | < 1 year after deposition | 189 | 1.63 |

**Table 2: Average Vs estimated from HVSR surveying with associated calculated bulk densities following the equation presented in Figure 5.**

In-situ nuclear and laboratory density tests were undertaken during construction of Site # 1 in 2013 following the Australian Standard for soil testing AS1289. The average bulk density measured across the embankment was 2.91 t/m$^3$. Although this density is relatively high compared to common natural geological environments, it is significantly lower than the density calculated of 3.58 t/m$^3$ using the site-derived correlation and Vs determined from HVSR surveying. The main limitations with in-situ and laboratory tests are the limited depth of investigation within the embankment (namely 150 mm), and the fact that PCT can only be done on sieved material. Therefore, neither method accounts for the larger particles present in the fill. Using the results of a Particle Size Distribution (PSD) study for this material, it is possible to estimate the amount of material which has not been accounted for during geotechnical testing, and apply a correction established by the American Society for Testing and Materials (ASTM D4718) to cater for the contribution of larger particles. Such corrected maximum dry density would be 3.48 t/m$^3$ which is significantly closer to the calculated bulk density for Site #1 of 3.58 t/m$^3$. The need to account for possible larger particles when analysing laboratory test results is also demonstrated by the fact that the maximum achieved Vs for sieved material from Sites #1 and # 2 was 366 m/s, much lower than the bulk Vs estimated from HVSR surveying over Site # 1.

In 2011, prior to the HVSR surveying, Cone Penetration Test (CPT) data was collected as part of the decommissioning assessment of a tailings storage facility, from which Vs was estimated. This method consists of using a portable rig which pushes a metal cone into the surface at a constant speed while the cone sensor records the degrees of resistance. Resulting estimated average in-situ Vs values across the thickness of the tailings ranged between 160 m/s and 190 m/s which is in accordance with the recent HVSR Vs estimations of approximately 189 m/s. As part of the test, density laboratory testing has also been undertaken on dry tailings material samples which returned densities between 1.52 t/m$^3$ and 1.74 t/m$^3$ with an average of 1.64 t/m$^3$, which is also consistent with the calculated dry density for Site # 5 (1.5 t/m$^3$). Although this kind of investigation cannot be done in more compact medium, the existing CPT data support the HVSR approach for the softer deposited tailings.

Although it is not yet proven that the linear relationship illustrated in Figure 5 can readily be extrapolated across the range of Vs values measured with HVSR surveying, reconciliation with limited in-situ and laboratory geotechnical testing shows an encouraging accordance, and further corroborates the validity of estimating bulk Vs and even possibly density using HVSR surveying as a proxy for embankment stiffness.

## CONCLUSIONS

The passive seismic HVSR method has proven to be a rapid, non-invasive and cost-effective way of characterising shear wave velocities within mining embankments. Data acquired over the length of several embankment types demonstrate the very good correlation between estimated shear wave velocities and the levees' degree of compaction. Both calculated shear wave velocity and bulk density values are consistent with in-situ and laboratory measurements once limitations of material size have been taken in account. As a result, alternative construction methodologies can be quantitatively benchmarked against a bulk density spectrum with fully engineered embankments and loose waste dumps as end-members. Collection of repeated measurements over time could also discriminates stable embankments from altering ones, and constitutes a new tool to identify potential zones of weakness before hazardous failure. Further site-specific studies including in-situ and laboratory geotechnical testing for density, Vs, PSD and moisture content will nevertheless be required to ascertain the correlations observed during this pilot study.

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