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Geotechnical Characterisation of Compacted Ground: Interpretation of the HVSR Curve

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ABSTRACT

As part of the remediation works for a quarry in the final phase of its operational life, dynamic and roller compaction have been applied over large fill areas up to a total depth of 14 m. Assessing the quality of compaction in these areas by traditional techniques (CPT, DMT and Density tests) has been effective but also costly and time-consuming. Against this background, the quarry was used as a test-bed to investigate using the fast and low cost Horizontal-to-Vertical Spectral Ratio (HVSR) technique to characterise the compacted ground. The HVSR technique requires only a battery operated, lightweight and compact sensor to record the microtremors in the ground for the purpose of assessing and monitoring compaction. Moreover, as a passive method, the HVSR technique depends only on the ambient microtremors caused by natural events (tides, large-scale meteorological conditions) and cultural activities (industrial machinery, traffic) for its excitation sources. An approach by means of interpreting the measured HVSR curves was employed to make an initial assessment of the compaction achieved at the fill areas. This paper presents the results of this approach. A second approach based on the forward modelling of measured HVSR curve to estimate the V_s profile of the compacted ground will be discussed in a companion paper.

Keywords: Compaction, HVSR, Microtremors, Surface Waves

1 INTRODUCTION

Compaction is an effective method of ground improvement commonly applied in civil engineering construction. The quality of ground compaction is often assessed using dry density tests (e.g. nuclear gauge, sand cone replacement, etc). However, if the depth of compaction is very deep, as it typically occurs with dynamic compaction, *in situ* mechanical tests such as the Cone Penetration Test (CPT), Standard Penetration Test (SPT), Flat Plate Dilatometer (DMT) will be required. *In situ* tests are localised and only a small fraction of the site is actually being assessed. Thus results from the localised tests need to be extrapolated to cover the whole site. Alternatively, non-invasive, array-based surface wave methods such as the Spectral Analysis of Surface Waves (SASW), Multi-channel Analysis of Surface Waves (MASW) and Refraction Microtremor (ReMi) are more effective in characterising an extensive site. However, these methods require calibration against mechanical measurements to ensure reliable data interpretation.

A study has been initiated to investigate using a unique surface wave method, the Horizontal-to-Vertical Spectral Ratio (HVSR) technique, to geotechnically characterise compacted ground. This technique, advocated by Nakamura (1989), relies on passive ambient noise generated by natural events (tides, strong meteorological conditions) and cultural activities (cars, trains and heavy machinery) as the excitation sources. The setting-up and testing time for the HVSR technique is short. Unlike other surface wave techniques, it does not require the setting up of an array of interconnecting geophones nor external cabling in the field. Instead, it only utilises a standalone battery operated, lightweight (about 1kg) sensor for carrying out field measurements. Consequently, the potential advantages of the HVSR technique are speed, portability and low cost.

The dynamic- and roller-compacted fill areas within a quarry located in Western Sydney were investigated for this study. The compacted fill areas were assessed using the HVSR technique in two distinct yet complimentary ways: (1) directly interpreting the measured HVSR curve to provide a preliminary qualitative assessment of the compaction quality, and (2) forward modelling to estimate the shear wave velocity (V_s) profile reflecting the state of compaction of the ground. This paper will discuss the first method 'interpretation of the measured HVSR curve', while the latter will be discussed in a companion paper. Mechanical test data (CPT and DMT) were used to "calibrate" the HVSR curves to test the reliability of the HVSR results. A few CPT and DMT data were also held in reserve to verify the HVSR results so as to demonstrate the applicability of this technique to characterise a compacted ground.

2 SITE CONDITIONS AND TEST PROCEDURES

2.1 Test Site

The test sites are situated in a sand and gravel quarry on the Hawkesbury-Nepean River floodplain west of Sydney at the foot of the Blue Mountains. Once all quarrying material has become exhausted, this 1,935 ha area will be transformed into predominately water based recreational parkland with potential urban precincts. The bedrock substrate within the region generally consists of shale with some sandstone beds, all part of the Wianamatta Group (e.g. Bringelly shale, Minchinbury sandstone and Ashfield shale). Geological maps show the material located above the bedrock consists of quaternary alluvium, gravel, sand, silt and clay. The layer of sand and gravel is mined for use in the local construction industry. The remaining clayey, silty and sandy overburden material is used as fill material at other areas of the site. In the earlier days, the fills were compacted to only a parkland or recreational use standard. However, with subsequent plans for potential urban housing and associated infrastructure development, a more stringent rehabilitation approach is being applied. In areas identified for future infrastructure development but yet to be rehabilitated, the filled grounds are compacted by heavy rollers in a systematic fashion. In existing deep uncontrolled fill areas which do not contain adequate compaction records for infrastructure development, the ground has been dynamically compacted. The two test areas used to trial the HVSR technique are designated as follows:

1. Dynamic Compaction (DC) Area – an area of 6,000 m^2 of fill which has a depth of approximately 13 m to the level of the bedrock was compacted with dynamic compaction. There are a total of 24 single station HVSR measurements and 9 invasive mechanical tests within the test grid. This area has been compacted by dropping a 20 tonne weight attached to a purpose built crane from a height of about 23 m above the ground. High impact energy from the falling weight leads to rearrangement of the soil particles, closer particle packing and reduction in the air voids, that is densification of the soil. The impact reaches its limit of influence when the penetration of the compression waves effectively ceases. The degree of densification or compaction achieved from this form of compaction depends on the height of drop, falling weight, number of drops, drop spacing and soil type.
2. Roller Compaction (RC) Area – an area of 1,200 m^2 with the total depth of fill of approximately 13 – 14m, also to the level of the bedrock, was compacted using conventional earthworks techniques. There are a total of 20 single-station HVSR recordings in this area. This area has been compacted using a combination of heavy sheep-foot rollers and graders. Fill material was placed in either 400 mm or 450 mm lifts (depending on location) and compacted until the required surface level was reached. Compaction in this area was monitored with density tests conducted to assess the compaction achieved. The target density was set at either 95% or 98% (depending on depth) of the Standard Maximum Dry Density (SMDD) and a moisture content tolerance of ± 3 % of the Standard Optimum Moisture Content (SOMC).

2.2 Measurement of Microtremors

A three component (2 horizontal and 1 vertical) high-resolution electro-dynamic sensor (Tromino^{TM} from Micromed) was used to capture the ambient noise at the test station. All measurements were made following the guidelines recommended by the European study, SESAME (2004). The sensor was initially aligned along the North-South axis, using a set of spikes to securely couple it to ground followed by levelling of the instrument with a bulls-eye spirit level. Ambient noise was sampled at 512 Hz at each station. The average HVSR curve was obtained by dividing the 16 minute signal into 20-second windows (for the spectra above 1 Hz). Each window was detrended, tapered, padded, FF-transformed and smoothed with triangular windows of width equal to 10% of the central frequency.

The two horizontal components (H_{EW} and H_{NS}) were combined using a geometric average, and then divided by the vertical component (V) to compute the measured HVSR curve as shown in equation (1).

$$HVSR_m = \frac{\sqrt{H_{EW} \times H_{NS}}}{V} \qquad (1)$$

3 EXPERIMENTAL RESULTS

3.1 Impact of Compaction on the Measured HVSR Curve

In this study, the HVSR technique was investigated for its detection of impedance contrasts (i.e. detect changes in soil/material characteristics) within the surface layers. Impedance is defined in this context as the product of density and shear wave velocity, (ρV_s), and impedance contrasts are generally registered by the HVSR technique by peaks in the measured curve. Thus a large contrast between layers will result in a higher peak than a small contrast in layers. Also, the location of the peak in terms of frequency, is indicative of the depth of the impedance contrast (e.g. Ibs-von Seht & Wohlenberg 1999). Generally speaking, peaks of higher frequencies reflect the upper layers of the soil and the peaks of lower frequencies, the deeper layers.

One of the investigations carried out in this study was to assess how the HVSR curve of the ground will be impacted when a layer of 1.5 m thick uncompacted surface soil was being subjected to compaction. Two sets of measurements were conducted. The first set of 4 measurements was taken directly on top of the uncompacted surface soil. The second set also of 4 measurements was taken on recently compacted soil located immediately adjacent to the uncompacted soil. Figure 1 shows the 8 measured HVSR curves produced by both sets of measurements. The first set of curves is shown with the broken lines, while the second set of curves produced is shown with the solid lines. Three differences between the two sets of curves could be observed:

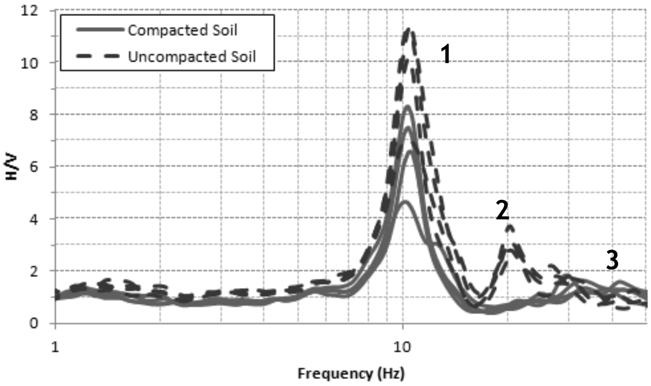

Figure 1. Measured HVSR curves 'before – uncompacted soil' (broken) and 'after – compacted soil' (solid) compaction

1. HVSR curves from the first set of measurements (the uncompacted soil) show higher amplitudes of the predominant resonance frequency (f_0) signifying a lower level of compaction of the surface layers. In this case f_0 is at approximately 10 Hz.
2. Secondary peak observed at approximately 20 Hz on all the HVSR curves from the first set of measurements.
3. A relatively flat line with no distinct secondary peaks at higher frequencies above f_0 is observed for the second set of HVSR curves (compacted soil).

In (1), the predominant peak at f_0 typically represents the impedance contrast between the bedrock and the overlying softer surface layers. A higher amplitude of the predominant peak at f_0 could be interpreted as representing a lower level of compaction of the near surface layers, as illustrated by the results shown in Figure 1. In (2), the secondary peak at approximately 20 Hz observed in the HVSR curves of the uncompacted soil (broken lines) could be interpreted as being due to the impedance contrast between the uncompacted soil and underlying soil. In (3), the higher frequency section (approximately 18 – 50 Hz, in this example) of the curve (after f_0), is indicative of the compaction quality. The compacted (solid) curves showing much flatter lines compared to the uncompacted (dashed) lines, represent better consistency in the compaction.

3.2 Dynamic Compaction

Figure 2a represents a typical measured HVSR curve from the DC area following dynamic compaction. Three distinct key characteristics could be identified:

1. Predominant peak frequency f_0 (approx. 4.5 Hz), indicating that there is a strong impedance contrast between the bedrock and surface layers above it.
2. Trough between 6.5 Hz and 10 Hz (where the H/V ratio dips below one).
3. Possible first higher mode of f_0 at approximately 12 Hz (corresponding to $3f_0$) and other discernible secondary resonance peaks above the predominant resonance frequency.

In (1), the relationship between predominant peak and fundamental resonance frequency of the surface layers has been pointed out in many previous studies (see, e.g. Bonnefoy-Claudet et al. 2006 and references therein). In (2), the trough at approximately $2f_0$ is often due to the Rayleigh wave ellipticity (Castellaro & Mulargia 2009). It is possible, however, in this instance that the Rayleigh wave ellipticity may have obscured a weak embedded layer lying just above bedrock (since the trough is located just above f_0), otherwise known as a 'velocity inversion' (Castellaro & Mulargia 2009). This is because the presence of the embedded softer/loose layer in this area is borne out by the CPT and DMT results shown in Figure 2b for BH 9.6, as well as other CPT and DMT results in the area showing a softer/loose layer above the bedrock between approximately 8 to 13 m. In (3), secondary peaks which are not due to higher modes of f_0 convey a valuable qualitative measure of the consistency or uniformity of the compaction in the surface layers. The presence of the impedance contrasts (and not higher modes of f_0) needs to be verified by constrained modelling of the HVSR curve in conjunction with mechanical test results.

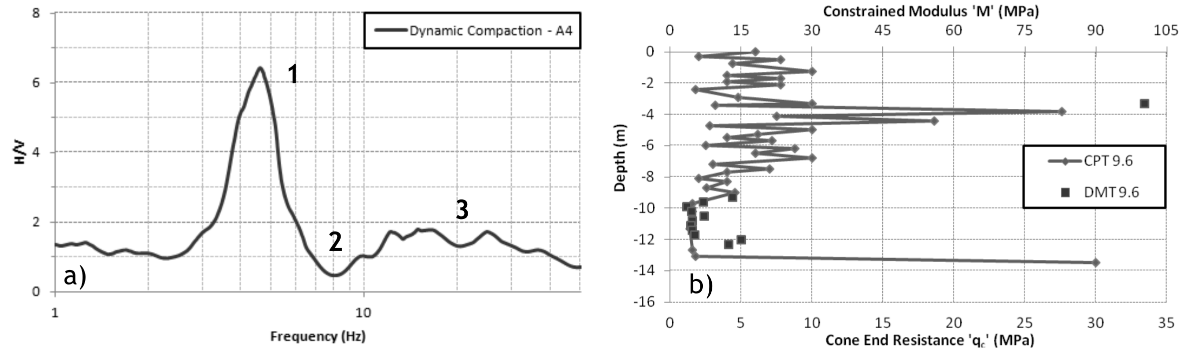

Figure 2. (a)Typical measured HVSR curve representing the DC area and (b) verification of interpreted measured HVSR curve by CPT 9.6 and DMT 9.6

3.3 Roller Compaction

Figure 3 represents a typical measured HVSR curve from the RC area. It also shows three distinct key characteristics:

1. Presence of a peak or predominant resonance frequency f_0 at approximately 5.1 Hz: this is generally indicative of the impedance contrast between the bedrock substrate and the softer soil layers situated above it.
2. Trough at approximately $2f_0$ due to Rayleigh wave ellipticity.
3. Aside from the possible first higher mode of f_0 occurring at approximately 16 Hz, a relatively smooth flat line with relatively small resonance peaks, in the frequency range 10-50 Hz where the H/V ratio is generally less than one.

The RC area was strictly monitored with a large amount of density testing for quality control. Thus a more uniform level of compaction has been achieved area- and depth-wise (from the surface to the firm substrate located at an approximate depth of 13 – 14 m). It may be inferred that the relative uniformity of the compaction with depth is borne out by the relatively smooth flat upper section of the HVSR curve (above predominant resonance frequency (f_0)) as discussed in (3) above. There are a few minute peaks at the higher frequencies, however, they are all located below an amplitude of 1. It is also noted that "velocity inversion" or the presence of a discernible softer/weaker layer lying just above the bedrock has been ruled out as being the cause for the through at $2f_0$ on the basis of the record of density tests in this area. Thus in (2), the trough has been unambiguously attributed to the Rayleigh wave ellipticity.

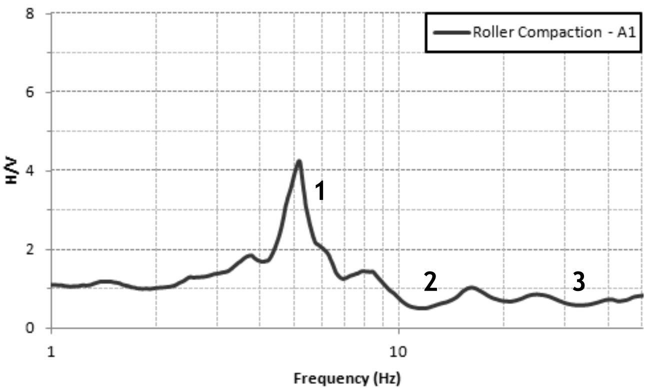

Figure 3. Typical measured HVSR curve representing the RC area

3.4 Comparison of Roller vs. Dynamic Compaction

Due to the completion of compaction at the RC and DC areas before commencement of this project, a pre- and post-compaction comparison of the HVSR curves in these two areas is not possible. However, since the fill material, the type and depth of the bedrock substrate, and the depth of fill are generally similar in the RC and DC areas, a comparison between the HVSR results in these 2 areas should reveal interesting stratigraphic differences mainly due to different compaction methods. Typical HVSR curves taken from a random observation point in each of the DC and RC areas are superposed and presented in Figure 4.

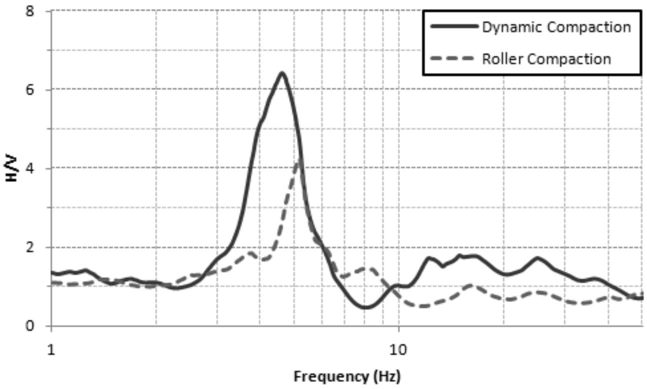

Figure 4. Comparison of typical Roller (station A1) and Dynamic (station A4) measured HVSR Curves

The comparative results suggest that the RC area is a better compacted ground than the DC area for the following two reasons:

1. The RC area is generally more evenly or uniformly compacted depth-wise, which is indicated by the relative flatness of curve to the right of its f_0 vis-à-vis the curve for the DC area. The correlation between the flatness of the section at the high frequency end (above f_0) of the HVSR curve and the depth-wise uniformity of the compacted layers was established earlier in the section "Impact of compaction on the measured HVSR curve". Here it was illustrated how the high frequency part of the HVSR curve lying to the right of f_0 flattens out to a H/V ratio of roughly one with corresponding diminution of the secondary resonance peak(s) as compaction was applied.
2. The RC area has the lowest peak amplitude at f_0 (2.5 to 5.0) while its f_0 value (5.1 Hz) is the highest. These compare with the peak amplitude of 3.2 to 10.8 and f_0 of approximately 4.5 Hz for the DC area. The first measure, the peak amplitude of the HVSR curve at f_0, is an indication of the strength of the impedance contrast between the bedrock and surface layers; that is, the higher the

amplitude, the stronger will be the impedance contrast between bedrock and surface layers. This implies that as surface layers become increasingly stiff relative to the bedrock, a corresponding reduction of the peak amplitude at f_0 is observed. The second measure, the value of f_0, may be applied as a first approximation related to compaction on the basis of equation (2):

$$f = \frac{V_s}{4h} \tag{2}$$

where h is the thickness of the surface layers above the bedrock. For the same thickness h (about 13 m for both areas), it follows that the shear wave velocity of the surface layers V_s is proportional to predominant frequency f_0. In consequence, according to (2) the average V_s for the RC area is the higher indicating the higher level of compaction between the two areas.

4 CONCLUSION

The results obtained so far bode well for the use of the HVSR technique as a fast and low cost method for the geotechnical characterisation of compacted ground, in combination with reduced mechanical tests. Interpretation of the measured HVSR curve provides preliminary insight of the compaction quality. Moreover, this technique allows for the determination of the fundamental resonance frequency of a site, an important parameter for assessing a site’s susceptibility to seismic activities.

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