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Inverted pendulum effect due to deep shear-wave velocity reversal identified using microtremor H/V

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ABSTRACT: The single station microtremor method, involves the calculation of the horizontal-to-vertical spectral ratio of ambient noise (H/V). Whilst the theoretical basis for the method remains controversial, empirical evidence, supported by the results of numerical simulations, have indicated that the H/V ratio provides a good estimate of the fundamental resonant frequency of SH waves, provided there is a sufficiently strong impedance contrast within the underlying ground (Bard, 1999).

This study focuses on the use of the single station microtremor approach to identify more complex site effects. H/V ratios from field measurements from a soft rock site in Somerset, UK are compared against 1D site response analysis numerical simulations using borehole geophysical data.

The results suggest that the H/V ratio can be used to identify the inverted pendulum effect resulting from the presence of a thin, less stiff buried layer which behaves as a natural seismic isolator, filtering out high frequency motions.

1 INTRODUCTION

The single-station microtremor method involves the calculation of the horizontal-to-vertical spectral ratio of ambient noise. For sites with strong impedance contrast the ellipticity of the Rayleigh waves coincides with the S-wave resonance of the site (Konno and Ochmachi, 1998; Lunedei and Alberello, 2010; Bonilla et al., 1997; Bard, 1999; Haghshenas et al., 2008). For horizontally layered sites, H/V has been shown to be a good predictor of the site's predominant frequency, f_0, irrespective of the relative proportion of different wave types in the noise wave field (Bonnefoy-Claudet at al., 2006).

Aside from the predominant frequency of the site, the H/V ratios are not always representative of the higher harmonics (Parolai et al., 2002). In addition, it is recognized that there is no simple direct correlation between the amplitude of the H/V peak and the actual site amplification (Lachet and Bard, 1994; Bonnefoy-Claudet at al., 2006; Haghshenas et al., 2008).

Recognising the potential benefits of the single-station microtremor method and because of its simplicity for deployment and relatively low cost, a series of microtremor measurements were made at the proposed Hinkley Point C nuclear power station site in Somerset, England in order to provide insights into any site effects, as part of a site-specific PSHA (Lessi-Cheimariou et al., 2018; Tromans et al., 2018; Aldama-Bustos et al., 2018). Inspection of the H/V results from across the site indicated a consistent peak at approximately 3.5 Hz from measurements made in the northern part of the site, which seemed rather low for a rock site with V_{s30} around 800 m/s. An explanation for the intermediate H/V peak was postulated based on the inverted pendulum effect in which the fundamental frequency is governed by the characteristics of a relatively thin, less stiff, buried layer. Such an effect has been observed elsewhere using borehole array data with sensors installed below, within and above a soft buried layer (Gueguen et al., 2011). This hypothesis was tested by undertaking a series of 1D site response analyses at locations for which data from borehole geophysical techniques were available and comparing the results with H/V spectra from the microtremor investigation and estimates of the fundamental frequency of an equivalent inverted pendulum based on a simplified lumped mass model.

2 INVERTED PENDULUM EFFECT

In many geological settings, the stiffness of the ground, as characterized by the shear-wave velocity, is observed to increase with depth, often a direct result of the process of consolidation of sediments over long periods of time. In certain depositional environments, however, a low velocity zone can be overlain by layers of higher velocity which can have a significant effect on earthquake ground motions at the surface. Gueguen et al. (2011) investigated this effect at an instrumented site in Guadeloupe, French Lesser Antilles, where a relatively soft mangrove layer was overlain by a stiff sandy deposit whilst Rahpeyma et al. (2016) considered site effects for stations on volcanic rock overlying softer sedimentary deposits in Iceland. Both studies suggested that the surface motion was governed by the properties of the low velocity zone rather than the stiffer layers above or below.

In the current study, it is proposed to model a surface layer with velocity V_{S1} and thickness h_1 overlying a lower velocity, thinner layer (velocity V_{S2} and thickness h_2) using a simple lumped mass representation of the system. For situations where the $V_{s2} \ll V_{s1}$ and $h_2 \ll h_1$, the fundamental frequency, f_{0sl} of the system can be estimated with Equation 1:

$$f_{0sl} = \frac{1}{2\pi}\sqrt{\frac{k_2}{m_1}} \tag{1}$$

In which k_2 represents the shear stiffness of the softer layer and m_1 is equal to the mass of the overlying stiffer layer. For a soil column with a horizontal cross section area A, the shear stiffness of the soft layer can be written in terms of its shear modulus G_2 and its thickness h_2: $k_2 = G_2A_2/h_2$. Introducing the density ρ_2 of the softer layer, and using the expression $G_2 = \rho_2 V_{S2}^2$ and considering a unit area vertical column for which A=1 and $m_1 = \rho_1 h_1$, Equation 1 can be rewritten as:

$$f_{0sl} = \frac{V_{s2}}{4h_2}\frac{2}{\pi}\left(\frac{\rho_2 h_2}{\rho_1 h_1}\right)^{0.5} \tag{2}$$

This simple formula essentially models an inverted pendulum. When $h_2 \ll h_1$, the "moving mass" effect results in a strain localisation in the soft layer and shifts the soft layer "natural" frequency $f_{02} = V_{S2}/4h_2$ to a significantly lower value than if the soft layer was at the surface.

The closed-form solution in Equation 2, along with other formulae presented by Dobry et al. (1976) can provide a crude association between the resonances at a site and specific features of the idealized shear-wave velocity profile.

3 STUDY AREA

The examined site, Hinkley Point C, is bounded by the Bristol Channel to the North, Hinkley Point A and B to the east and agricultural land to the south and west. The solid geology underlying the site comprises a sequence of interbedded mudstones and siltstones: the Lower Lias of the Lias Group (Lower Jurassic) and the Triassic Penarth and Mercia Mudstone Groups. A typical north-south geological section at Hinkley Point C can be seen in Figure 1.

The strata at Hinkley Point C, are dipping gently 8°–10° towards the north. Up-faulted strata of the Mercia Mudstone Group outcrop in the southern part of the site onshore. The Penarth group outcrops north of this, on an east–west ridge of high ground which forms a

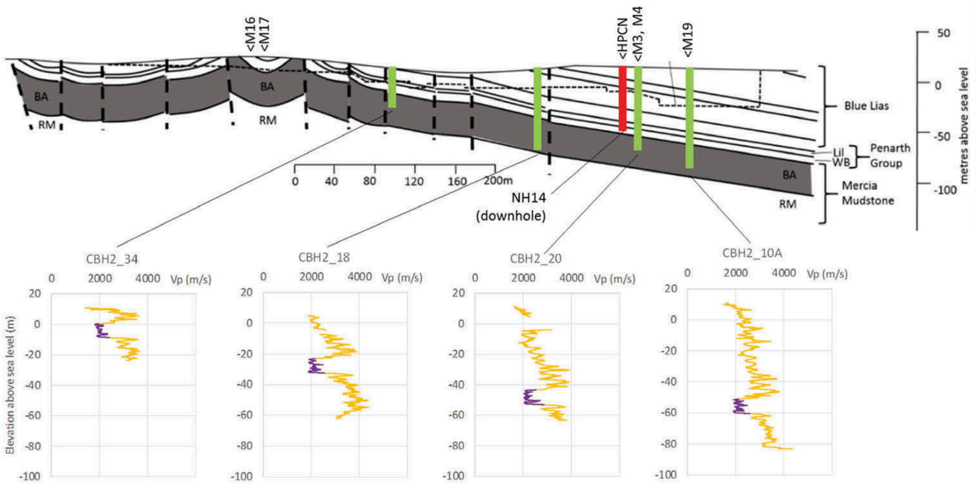

Figure 1. Typical north–south geological section at Hinkley Point C. Penarth Group comprises the Lilstock Formation (Lil) and Westbury Formation (WB); the Blue Anchor (BA) Formation and Red Marls (RM) are part of the Mercia Mudstone sequence. BA (shaded) was selected as the reference velocity horizon for the hazard calculations, from Lessi-Cheimariou et al. (2018). Sonic logs from four boreholes (CBH2_34, CBH2_18, CBH2_20 and CBH2_10A) indicate that WB (shaded purple in each profile) represents a velocity reversal. The positions of downhole measurement HPCN and various microtremor measurements M16, M17, M3, M4 and M19 are highlighted. North is to the right.

steeper rock scarp outcrop succeeded northwards by the Blue Lias Formation of the Lias Group which forms the geology up to the coastline. A total of eleven single-station microtremor measurements were made during two phases of investigation, the locations selected to cover the range of geological conditions present on site and in most cases corresponding with the locations of boreholes with geophysical measurements, including crosshole, surface-to-downhole or full-wave sonic logging. Locations of 6 no. microtremor measurements relative to a typical north-south geological section are shown in Figure 1.

4 METHODOLOGY

The single-station microtremor survey was carried out using a three-component Lennartz LE-3D 5s seismometer. All data acquisition and processing followed the industry best-practice SESAME guidelines (SESAME, 2004; Electronic supplement of Bard, 2008). The fieldwork and initial data processing was undertaken by BRGM-France (BRGM, 2014 and 2015), with further processing undertaken by Jacobs (formerly CH2M) as part of the development of the site characterization for the site response analysis.

Each measurement was undertaken for a duration of 45-60 minutes and sampling rate of 100 Hz was found to give stable results in all locations for the Hinkley site. To minimize the effect of wind perturbations the instrument was covered by a plastic container.

The data were processed using the software Geopsy (http://www.geopsy.org/) using the following principal steps:

- Each three-component ambient noise time history was subdivided into equal-length time windows, typically 50 s long. Spurious transients were removed using an anti-trigger algorithm.
- Fourier spectra were computed for every time window and each component and smoothed using the Konno-Ohmachi logarithmic filter (Konno and Ohmachi, 1998). The bandwidth parameter was fixed at a value of 40.

- The two horizontal Fourier spectra for each time window were combined based on the quadratic mean.
- The horizontal-to-vertical (H/V) Fourier amplitude spectral ratios were calculated for every window and the geometric mean and standard deviation computed over all windows.
- Any observed predominant H/V peaks were assessed against the six reliability criteria from SESAME (2004).

The H/V ratios from microtremor were compared against the results from numerical simulations for measured and inferred shear-wave velocity profiles at a number of different locations across the site. The numerical simulations involved 1D linear site response analysis using Strata (Kottke et al., 2013). A constant damping of 2% was employed and the unit weights for the elastic half space (EHS), the reference velocity horizon in the seismic hazard calculations, and the overlying deposits were set equal to 19 kN/m^3 and 25 kN/m^3 respectively. For each microtremor location, the H/V spectra from ambient noise were compared against the transfer function from the site response analysis computed as the ratio of the Fourier amplitude spectrum of the surface motion to that of the outcropping motion at reference velocity horizon. Whilst this comparison was done for numerous locations across the site, only relevant cases are discussed hereafter.

5 ANALYSIS AND RESULTS

Microtremor locations HPCN and M3 (see Figure 1) were positioned to coincide with borehole NH14, for which a 70 m-deep shear-wave velocity profile was available from the surface-to-downhole technique. This measured profile is denoted "NH14 – option 1" in Figure 2a and extends from the surface through the Blue Lias and Lilstock and approximately 10 m into the Westbury Formation. As indicated in Figure 2a, the Westbury Formation represents a low velocity zone, having Vs of around 600 m/s, compared to approximately 1000 m/s in the overlying geological unit. A modified shear-wave velocity profile, denoted "NH14 – option 2" in Figure 2a is identical to option 1 but extended by around 5 m to penetrate fully the Westbury Formation and a few metres into the stiffer underlying Blue Anchor Formation, which represents the elastic half space for the purposes of the site response analyses. The depth of the Blue Anchor Formation and typical values of shear-wave velocity within this unit are based on data from nearby, deeper boreholes. This extended profile emphasizes the shear-wave velocity reversal between approximately 60 m and 70 m depth which coincides with the Westbury Formation.

The transfer functions between EHS and surface for both of these profiles using 1D linear site response analysis are plotted in Figures 2b and 2c respectively, overlain onto H/V spectra from the nearby microtremor locations HPCN and M3. The two sets of results are plotted on common axes to assist the comparison.

Both H/V spectra indicate a distinct peak at 3 to 3.5 Hz. This peak is also consistently present in all the other microtremor H/V results from measurements made in the northern part of the site, further typical examples of which (microtremor measurement locations M4 and M19) are shown in Figure 3. The transfer function from 1D linear site response analysis for NH14 - option 1, which is the measured profile, lacks a distinct peak at 3 to 3.5 Hz and appears to be almost flat at low frequencies due to the absence of an impedance contrast at 70 m depth. The transfer function from 1D site response analysis for NH14 - option 2, the extended profile, shows a fundamental frequency, f_0 coinciding with the f_0 observed in the H/V spectra, although the amplitude of the peak from the transfer function is lower. This agreement between the transfer function from 1D linear site response analysis and microtremor H/V spectra regarding the location of the fundamental frequency but not necessarily the amplitude of the peak is well-established e.g. Lachet and Bard (1994) and Lunedei and Albarello (2010).

This comparison between the numerical and the experimental results supports the extrapolation of the measured profile at NH14 to include an impedance contrast at 70 m, to coincide with the top of the Blue Anchor Formation. The peak at 3 to 3.5 Hz in the H/V ratios can be

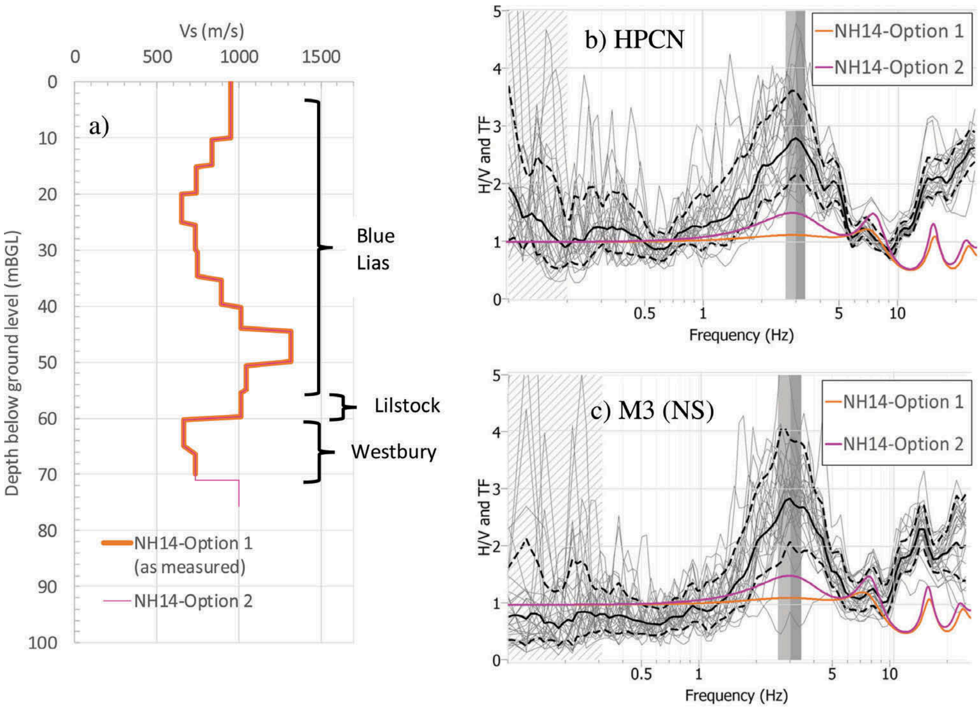

Figure 2. Microtremor H/V results compared against transfer functions from 1D linear site response analyses on the same axes for two locations HPCN (b) and M3 (b) in the northern part of the site. In each case, transfer functions are plotted for two different versions of the Vs profile at borehole NH14: (a) Option 1 and Option 2.

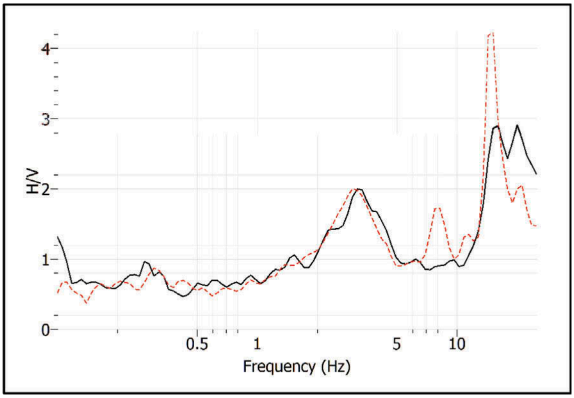

Figure 3. H/V spectral ratios for M4 (solid black line) and M19 (dotted red line) from the northern part of the site showing consistently a peak at 3.5 Hz.

best replicated in the numerical results where both an impedance contrast at approximately 70 m depth and a shear-wave reversal at the Westbury Formation at approximately 60 m depth are present.

Owing to the limited spatial and depth coverage of shear-wave velocity data from borehole geophysical techniques, other datasets were consulted in order to verify the presence of a velocity reversal corresponding with the Westbury Formation. The full-wave sonic logging was particularly useful in this regard. This method, which uses a fixed transmitter-receiver spacing of 1 m, gives a continuous log in the unlined section of the borehole over its full depth, highlighting local variations in seismic velocity. Profiles from this technique along a north-south section line through the site are presented in Figure 1. Data within the Westbury Formation are distinguished using purple shading. The data clearly show a distinct low-velocity zone (P-wave approximately 2000 m/s) corresponding with the 10 m thick Westbury Formation. The strata above and below have P-wave velocities closer to 3000 m/s.

The fundamental frequency of the profile characterized by NH14 – option 2, which includes the shear-wave reversal at the Westbury Formation, has been calculated using Equation 2, assuming the inverted pendulum model. Taking the properties of the less stiff layer as V_{s2} = 600 m/s, ρ_2 = 2.1 t/m^3 and h_2 = 10 m; and the properties of the overlying stiffer layer as ρ_1 = 2.5 t/m^3 and h_1 = 60 m, the fundamental frequency of the inverted pendulum system using Equation 2 is equal to 3.6 Hz. The same exercise was repeated using the quarter wavelength approximation, QWA (Boore and Joyner, 1997). As described by Poggi et al. (2011) the QWA can be implemented using an equivalent two-layer model with the bottom interface being equal to a depth associated with one-quarter of the wavelength. Therefore, the QWA can be used to provide an "impedance amplification" effect as a function of frequency or equivalent depth. Such an approach results in a fundamental frequency in the range between 3.0 to 3.6 Hz corresponding to the overall Westbury formation. Both closed formed solutions are merely approximations with resonances in the TF of any given profile getting contributions from multiple strata.

Based on the previous numerical results, the shear-wave velocity reversal at the Westbury Formation at NH14 contributes to the response at the fundamental frequency of the site and both the QWA and Equation 2 suggest that this shear-wave velocity reversal is responsible for the peak in the TF at around 3.5 Hz. This is supported by Figure 4 which shows the TFs for NH14 - option 2 between the outcrop motion at different target levels and the outcrop motion at the elastic halfspace (EHS). In agreement with the closed form solutions the TF suggests that a small amplification can be attributed to the shallower layers (between 0 and 58 m) whereas the shear-wave velocity reversal at approximately 58 m is the main contributor to the 3.5 Hz resonance.

The significance of the shear-wave velocity reversal to the intermediate frequency peak, as consistently observed in the H/V measurements from the northern part of the site, is further endorsed by the lack of any distinct features in the H/V spectra from the southern part of the site where the Westbury Formation is at a much shallower depth. As indicated in Figure 1, microtremor measurements M16 and M17 targeted an area where the Westbury Formation is almost outcropping. The depth to top of Westbury at M16 and M17 is around 6 m and 3 m respectively. H/V spectra from M16 and M17 are presented in Figure 5. Results are presented

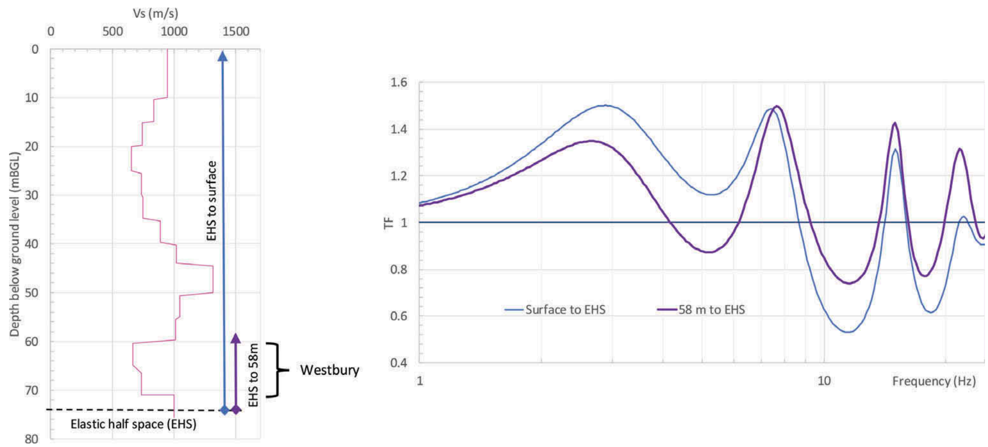

Figure 4. Transfer functions for profile NH14 - option 2 for different target levels.

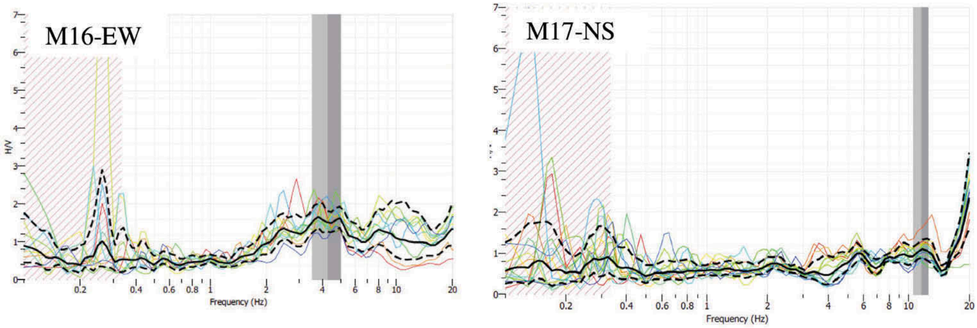

Figure 5. H/V measurements from the southern part of the Hinkley Point C site, close to the Westbury outcrop.

for a single horizontal component at each location, although similar results are observed for the perpendicular component in each case. It can be seen that there is no distinct peak at 3.5 Hz in the H/V spectra. In fact, there are no H/V peaks at any frequency which demonstrate a clear site effect according to the SESAME guidelines (Bard et al., 2008).

The stability in the location of the H/V peak at around 3.5 Hz for several microtremor measurements in the northern part of the site between HPCN and M19 (see Figure 1), which represents a range of values of depth to the softer layer, can be explained with reference to the inverted pendulum model described in Equation 2. Since $f_{0sl} \propto h_1^{-0.5}$, it is relatively insensitive to changes in h_1, certainly for the range of values (60 m to 75 m) covered by these measurements. For h_2 = 10 m, the corresponding range of f_{0sl} is 3.6 Hz to 3.2 Hz. It is acknowledged that, under some conditions, basin effects can also give rise to a stable resonance frequency which is insensitive to the depth to the high velocity layer. However, such an effect has been observed, till now, only in embanked valleys (i.e., with steep sides) filled with soft deposits. At Hinkley Point C, the strata dip to the north only very gently and the velocity contrast is not sufficient to give rise to a basin global resonance effect. The observed 3.5 Hz peak is not considered due to a 2D effect but due to the buried velocity contrast.

6 DISCUSSION OF RESULTS/CONCLUSIONS

A comparison between H/V spectra and the results from 1D site response analysis for locations at the Hinkley Point C soft rock site have suggested that a consistent H/V peak observed in a specific region of the site at the unexpected intermediate frequency of 3.5 Hz is the result of a shear-wave velocity reversal at depth. This is supported by considering a simplified inverted pendulum model of the site, which gives a consistent estimate of the fundamental site frequency.

The current results suggest that the single-station microtremor method may be useful for identifying similar effects at other sites, caused by a velocity reversal at depth.

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