SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World
9-10 July 2015, Cambridge UK

A REVIEW OF THE DEVELOPMENT OF V_{S30} GROUND PROFILES FOR UK STRONG GROUND MOTION INSTRUMENT SITES

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Abstract: Site effects have caused significant damage to structures even in small magnitude earthquakes. However, in countries such as the UK where the seismic risk is perceived to be low, little site-specific seismic characterisation has been carried out, potentially reducing the resilience of infrastructure design. Research is being undertaken to develop a cost-effective method that produces detailed shear wave velocity profiles and hazard classification for previously uncharacterised sites. This paper reviews the application of this method as it is carried out on three strong ground motion stations in the UK. For each, a geological profile is determined through desk study, previous *in situ* measurements and walkover surveys. This profile is correlated with a database of worldwide shear wave recordings, using similarity of lithofacies and geological deposition. A shear wave velocity range is developed for each site, which is classified according to Eurocode 8 criteria. Microtremor testing was subsequently carried out, validating the theoretical results.

Introduction

The amplification of seismic shaking by near-surface soil deposits has had devastating consequences worldwide. Significantly, these site effects can appear unpredictable as they occur at large epicentral distances, notably the **M**8.1 1985 Mexico City Earthquake (e.g. Booth *et al.* 1986) and can be experienced in combination with more complex effects such as topographical amplification in **M**6.8 1988 Spitak Earthquake, Armenia (e.g. Yegian *et al.* 1994). Moreover, site effects have been implicated in significant damage in small magnitude earthquakes, as in **M**4.0 2007 Folkestone Earthquake (Ottemöller *et al*. 2009), highlighting the need for resilience of infrastructure design even in perceived low seismicity countries.

The Folkestone earthquake was recorded by the strong ground motion station network of the UK (Figure 1). The results of these recordings are used to predict likely ground motions in the design of sensitive infrastructure such as nuclear power stations. Yet, very little is known about the detailed characteristics of the ground beneath these strong ground motion stations. This lack of information has hindered the assessment of the parameters for the Folkestone earthquake principally in determining the likely shear wave (V_s) velocity for the site of the recording station nearest the epicentre (Ottemöller *et al.* 2009).

The time averaged shear wave velocity of the top 30m of ground (V_{s30}) is the most popular method of accounting for site effects in industry (Wills *et al.* 2000), despite its shortcomings (e.g. Castellaro *et al.* 2008). V_{s30} values are most clearly determined through site-specific, invasive measurement. However, this is expensive (Wald & Allen 2007) and would be economically unfeasible to complete the testing required at each of the 26 strong ground motion stations in the UK.

Consequently, research is ongoing into developing and preliminarily testing a cost-effective method to produce detailed V_{s30} velocity profiles and a hazard classification for sites with little or no previous characterisation. The aim of this paper is to review the application of this method to three UK strong ground motion stations and the results of their *in situ* site investigation.

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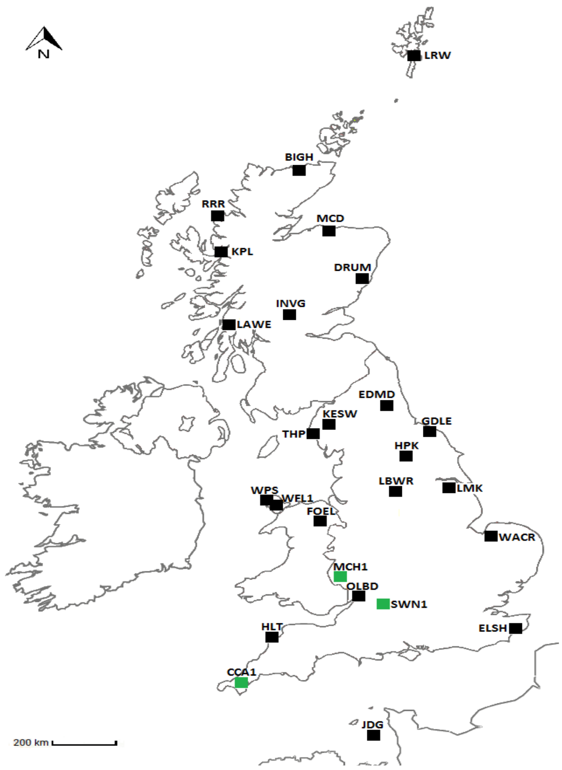

Figure 1. Locations of the strong ground motion stations in the UK (Tallett-Williams *et al.* 2015). The three reviewed in this paper are highlighted in green.

Development of Geological Profiles

Park & Elrick (1998) established a link between geology of a site and V_s. This led to the formation of several proxy methods dependant on the near surface geology, most notably Wills *et al.* (2000). Despite being predictions of a predictor (Yong 2015), these methods have been marginally more successful on a confined scale than regional methods using slope angle (e.g. Wald & Allen 2007) or terrain (e.g. Yong *et al.* 2012), especially if based on a large number of measured V_{s30} results. In the UK, reference V_{s30} values are not commonly available. Instead, we have proposed the use of a geological profile which is then linked with a profile of sufficiently similar lithofacies and depositional environment in a database of worldwide V_s results (Tallett-Williams *et al.* 2015).

This new method is used at 3 sites (Figure 1): MCH1, situated at the foot of the Black Mountains in the Welsh Borderlands; CCA1, on the Carnmenellis Granite pluton, in Cornwall; SWN1, on the northern slopes of the Marlborough Downs, West Midlands. These stations are recorded as being located on Old Red Sandstone, granite saprolite and chalk, respectively. However, little more was known about the detailed geology of the site. Consequently, a geological profile is developed for each station using a desk study, a walkover survey and records of previous invasive investigations (Table 1). The confidence class classification system developed by Tallett-Williams *et al.* (2015) is used to provide a measure of the uncertainty associated with each profile. This system contains four classes, the first class being the most certain and class 4 having the greatest uncertainty (Tallett-Williams *et al.* 2015).

Station MCH1 (Figure 1) is determined to be a relatively simple rock site (Table 1). The desk study establishes the main areas of uncertainty to be the potential presence of Quaternary deposits and the condition of the bedrock. The geological map of the region (BGS 2004) shows the Quaternary deposits at the station to be dissimilar to the rest of the district which

Table 1. Geological Profiles Developed for Stations MCH1, CAA1 and SWN1. The profile for SWN1 was extended to 35m to account for the bunker depth.

MCH1- Class 2

Stratum	Depth (m b.g.l.)	Description
Concrete	~2	Isolated concrete plinth situated on bed rock.
Old Red Sandstone (St. Maughans Formation)	>30m (To end of profile)	Red marls, sand, mud and siltstones which form a cyclic progression. May contain calcerous layers. Expected to be weathered and fractured to end of profile, particularly the mudstone/shale deposits.

CAA1- Class 3

Stratum	Depth (m b.g.l.)	Description
Concrete	~2	Isolated concrete plinth situated on bed rock.
Saprolite (Weathered Granite)	10-20	Extensively weathered granite or 'soft' granite that may have been frost shattered. Possibly in the form of sandy clay, containing granite gravel, cobbles and boulders.
Carnmenellis Granite	>30m (To end of profile)	Medium to coarse grained, biotite granite. Likely to be extremely hard at depth, but possibly a weathered surface profile.

SWN1- Class 2

Stratum	Depth (m b.g.l.)	Description
Bunker/Disturbed Ground	5	Bunker and bunker foundations, suspected to be concrete.
Lower Chalk (Top of Zig Zag Chalk)	10-20	Hard grey chalk No flint, but likely to be weathered at the surface.
Lower Chalk (Zig Zag & West Melbury Marly Chalk)	23-30	Chalk marls and limestone layers.
Upper Greensand	>35m (To end of profile)	Inter-bedded sand and sandstones, frequently containing glauconitic nodules.

has thick glacial accumulations in the valleys. However, the walkover survey confirms that only a thin topsoil is present; bedrock being visible in a river bank close to the station. This survey also concurs with the invasive results (BGS 2013), which record a moderately to extensively weathered bedrock. Thus, the station is a Class 2 site as though, only far-field borehole recordings are available, the geology of the site is reasonably predictable.

Station CCA1 is recorded to be on granite saprolite, so an *in situ* weathered profile is expected. Moreover, the desk study indicates the region underwent high weathering during the last Ice Age (Leveridge *et al.* 1990). Yet no prospective depth of the bedrock could be discovered nor did the walkover survey find any rock exposures. Large granite boulders are found at the site, but these are randomly distributed and are not expected to be connected to bedrock. The previous invasive recordings are conflicting. Some such as at Boskin Porkellis show deep kaolin deposits (BGS 2013), while others record a strong, but weathered granite in the near surface (New 1985). These are plotted to establish regional trends, which suggest the saprolite to be of 10-20m depth (Table 1). However, this profile is of increased uncertainty compared to MCH1, as it is dependent on interpretation and so is of confidence Class 3.

The most geologically complex profile is station SWN1 which contains several different strata (Table 2). Though often incomplete, the previous *in situ* testing records concur sufficiently well, that they confirm the regional trends from the desk study and correspond to exposures in the walkover survey. The walkover survey highlights the two main causes of uncertainty as the Quaternary deposits and the large amount of human disturbance in the site. The topsoil is found to be much deeper than expected from the desk study and it is unclear how deep the clayey topsoil will extend. Looking at the likely weathering horizon and, as chalk nodules were not visible, the superficial strata is expected to be at least 5m thick. The station is unusual in the network as it is located in a bunker where as MCH1 and CCA1 are free field stations. However, the Science Museum provided the bunker's dimensions (Hopkins 2014) allowing this to be taken into account in the profile. This station is a Class 2 site. Although the depth of the Quaternary deposits are not fully determined, the underlying strata are well characterised both by invasive results and literature.

V_{s30} Correlation

Each of these geological profiles is compared with *in situ* V_s records in a database based on the work of Campbell (2014). These V_s velocities have been compiled from published literature, industry reports and other published databases worldwide. The database is used to estimate a likely V_s profile for each of the sites by correlating only sufficiently similar lithofacies and geological deposition. The distance from the site is not considered.

For MCH1, a relatively simple profile has been determined, the main concern being how extensively weathered the rock is and the effect of this on the V_{s30} profile. The database contains several V_s laboratory tests from the Old Red Sandstone of the Grampian Highlands. These have a mean V_s velocity of 4720m/s. Testing was carried out on small samples, thus they are considered to be representative of the velocities of intact rock. To account for the macro structure of the rock, twice the standard deviation is removed from the mean determining a best case scenario of 2800m/s. Though not thought to be completely weathered, 2800m/s for a Lower Devonian rock in the UK climate is considered to be optimistic. Consequently, the upper bound is reduced further by comparison to *in situ* measurements of strong, unweathered sandstones of different formations in the UK. For the worst case scenario, the sandstone is compared to weathered sandstones in Turkey and the USA. Several V_{s30} models are produced for the site which are simplistically weighted giving a range of 800-1200m/s, equivalent to ground type A for Eurocode 8 (EN 1998).

Comparatively, the state of station CCA1 is thought to be considerably less intact, forming a weathered profile (Table 1). The 10-20m of weathered material is compared to at worst UK clay deposits and at best a weak-moderate mudstone. The granite is compared both to laboratory and *in situ* results, similarly to MCH1. Using this series of models, a V_{s30} velocity range of 700-1300m/s is determined, classifying the station as ground type B/A for Eurocode 8 (EN 1998). This is a larger range than that of the MCH1 due to the uncertainty in the geological profile.

SWN1 is also considered to be weathered, with chalk of lower V_s velocities used as reference sites from the database. This is a more complex profile than the previous stations, having more layers and possible different thicknesses of each. Consequently, numerous models of varying thicknesses and condition of each strata are developed. This results in a range of 450 to 850m/s which is large as more factors were under consideration. This determined the station to be a ground type B for Eurocode 8 (EN 1998).

Testing

In order to validate these results, *in situ* site testing was carried out at each of the stations. As the aim of this study is to produce a cost-effective method, an alternative to invasive testing is used. Microtremor testing is a non-invasive, passive, geophysical method. The trace is formed from measurements of surface waves in the ground, which are elliptical and frequency dependant. Using Nakamura's H/V method (1989), the horizontal trace component is divided by the vertical. This ratio forms a significant peak close to the fundamental frequency of the strata if sufficient impedance contrast is present (Bard 1999). If the depth of the first layer can then be constrained in thickness, the remaining V_s values can be calculated using Equation 1: (Micromed 2013a)

$$f_0 = V_s/(4H) \tag{1}$$

Where f_0 is frequency, V_s is shear velocity and H is the thickness.

The main advantage of this method is that it is extremely cheap compared to invasive testing; the total cost of the equipment is approximately equivalent to drilling one shallow borehole. However, some debate concerning the theory of H/V testing remains. The exact analytical solution is unclear (Bard 1999). Empirical testing of this method has shown notable correlation between the fundamental frequency and the H/V curve. Thus, for the purposes of this investigation it is a good preliminary test. If the testing returns unanticipated results, then it would be possible to conduct further investigation with invasive testing.

Microtremor testing was carried out at each of the three sites using a Tromino instrument (Micromed 2013b) following the SESAME guidelines (2004). Both MCH1 and SWN1 are located in quite confined areas and so single stations measurements were carried out every 10m over 50m long traverses in perpendicular directions, crossing at the station. The same was completed at CCA1, but, as it is in more open land, the measurements were taken every 20m for 100m. The data from testing were processed using Mircomed Grilla Software (Micromed 2013a).

Results

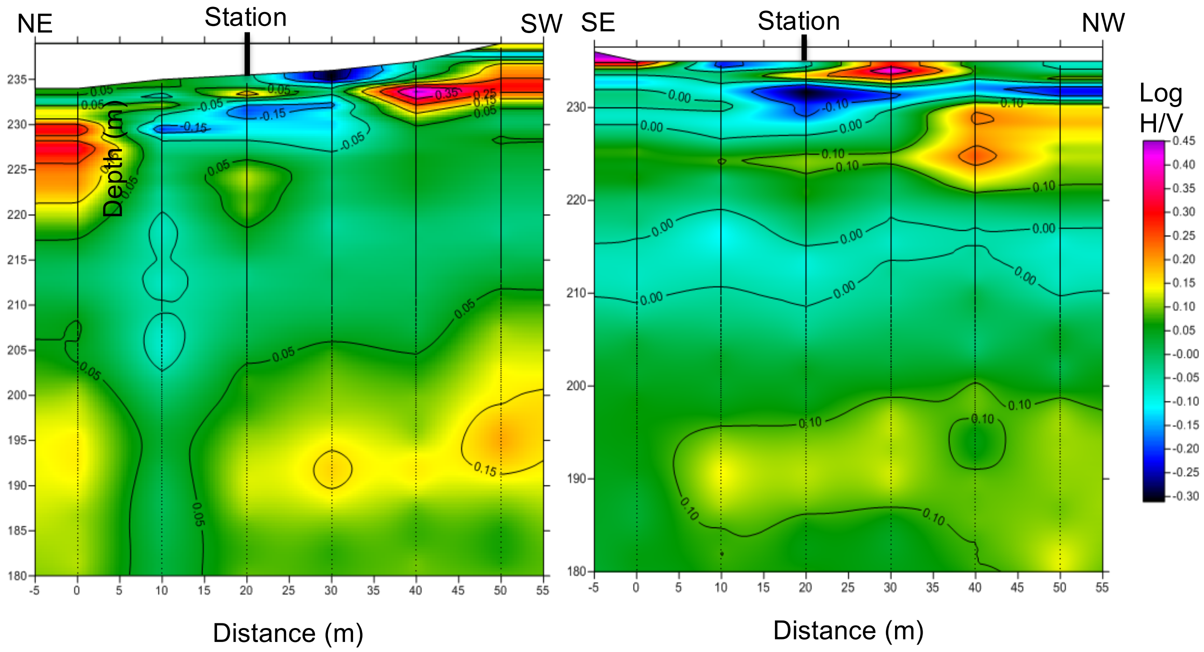

Figure 2. Microtremor cross-section of MCH1, north-east /south-west (left) and south-east/ north-west (right) with the station located at 20m in both. The sections were processed at 750m/s with an exponent of 0.25.

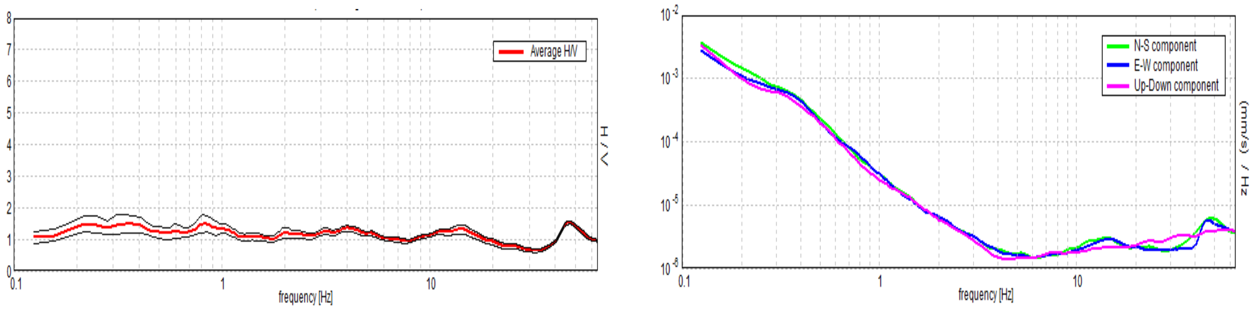

Figure 3: (Left) H/V trace from MCH1 at 20m, closest to the station, showing no clear peak. (Right) Single component amplitude spectra of trace

The cross-section for MCH1 (Figure 2) plots the logarithmic H/V showing the intensity of impedance contrast between the geological layers. For MCH1, there is some disturbance in the first five metres below ground level. This is likely to be caused by several permanent pieces of geophysical equipment in the field. For example, equipment at 40m in the north-east/south west appears to be causing a dipole in the section. The cross-sections confirm that there is no notable topsoil at the site. In addition, they show extremely little change in impedance in the deeper sub-surface. Though some layering is seen at around 210m AOD, the change in the impedance is small compared to other locations.

The record H/V trace at the station (Figure 3) confirms that there is little change in impedance. In fact, this trace appears flat at a H/V ratio of one. There are some small peaks, but these were not recorded in the remainder of the site traces. Thus, they are not considered representative. As it possible to assign any V_s velocity to a trace with a H/V ratio 1, the processing was not carried out. However, this does show that the rock is of a similar impedance to a significant depth, so it is unlikely this is a weathered profile at the near surface.

Unlike station MCH1, the site of CCA1 is exposed and windy. This caused a considerable amount of noise in the records. Two recordings had to be excluded from the results in the north south cross-section at 0m and 40m (Figure 4) as noise affected the traces. Though the overall section remains robust, it may mean it loses detail and so should be treated with caution.

However, it is clear, that there is a significant amount of saprolite/weathered deposits (Figure 4). The depth to unweathered bedrock appears just over 20m. The section shows the rockhead in the east-west section as a typical weathered granite profile, though this is not confirmed in the north-south profile. This is possibly due to the excluded traces.

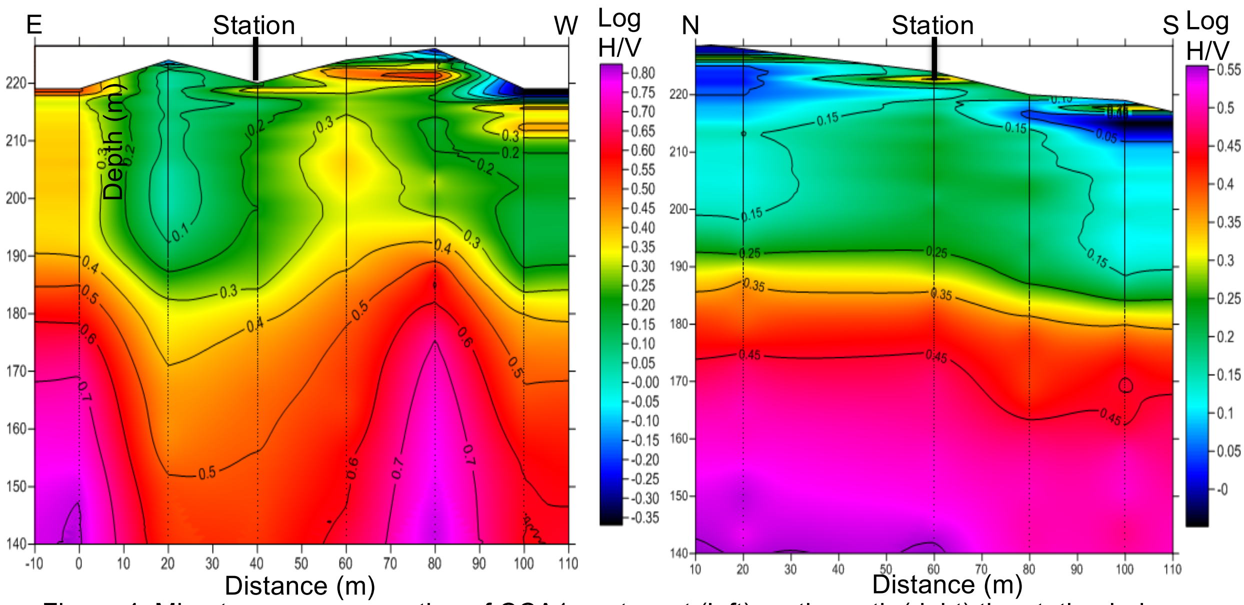

Figure 4. Microtremor cross-section of CCA1 east-west (left) north-south (right) the station being located at 40m and 60m respectively. The sections were processed at 700m/s with an exponent of 0.25.

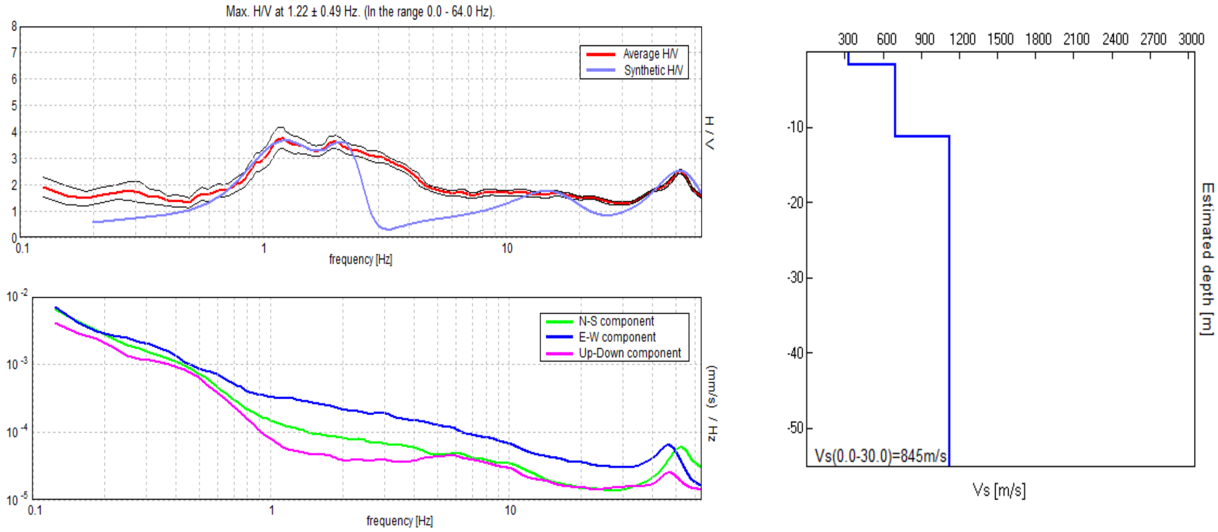

Figure 5: (Left Top) H/V trace from CCA1 at 40/60m recording, next to the station, showing fundamental peak at 1.22Hz +-0.49 Hz. (Left Bottom) Single component amplitude spectra of trace (Right) V_s model for the site until 50m depth.

The H/V for CCA1 (Figure 5) shows a much clearer peak than in the MCH1. This is a double peak consistently throughout the records, possibly signifying a layer in the granite. There is also a peak at 14Hz which corresponds to a topsoil layer of 1.6m at the surface. Between this surface peak and the fundamental peak there is a flattening of the trace which was difficult to model. It can be matched generally using small layers of increasing V_s values. Thus, this section of the trace is thought to represent the weathered deposits and the underlying, weathered rockhead. Potentially, this is most convincingly modelled by infinitesimal layers of soil with increasing V_s. However, the software used to process this trace uses the principle of Occam's Razor (Micromed 2013a), encouraging the use of as few layers as possible. Therefore, this section is simply modelled using one peak. A V_{s30} velocity of 845m/s was determined for this site (Figure 5).

Although SWN1 did not have the same challenges of noise, one recording was removed at 0m in the south-east/north-west section (Figure 6). This was taken too close to a road pavement and had problems with inversion in the trace. However, in the near surface the human disturbance is visible until about 5m b.g.l. Beneath this is a lower impedance section of chalk, though it is not clear where the boundary between the two formations lie. This is underlain by a larger impedance layer, thought to be the Upper Greensand.

The H/V trace for this section (Figure7) is unusual due to the clear double peak which is even visible in the component spectra. The first few metres of disturbed ground can be modelled fairly accurately. Similarly to CCA1, it was difficult to model the section between the surface deposits at 12Hz and the first fundamental peak at 4Hz. This is possibly due to weathering. The first fundamental peak also appears to have a double quality (Figure 7). This is thought to be caused by the Upper Greensand and a slightly thicker deposit with a similar fundamental frequency directly beneath it, though the nature of the deposit is unclear. A V_{s30} velocity was determined to be 503m/s for the site (Figure 7).

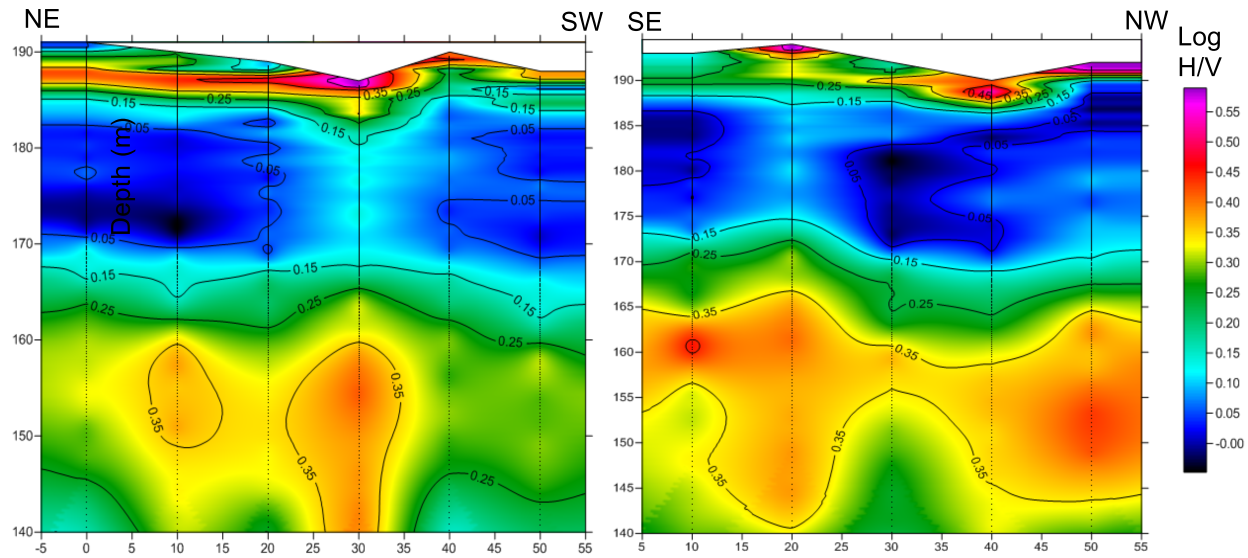

Figure 6. Microtremor cross-section of SWN1, north-east/south-west (left) and south-east/north-west (right). The sections were processed at 500m/s with an exponent of 0.25. The station location is not marked as it lies within the bunker.

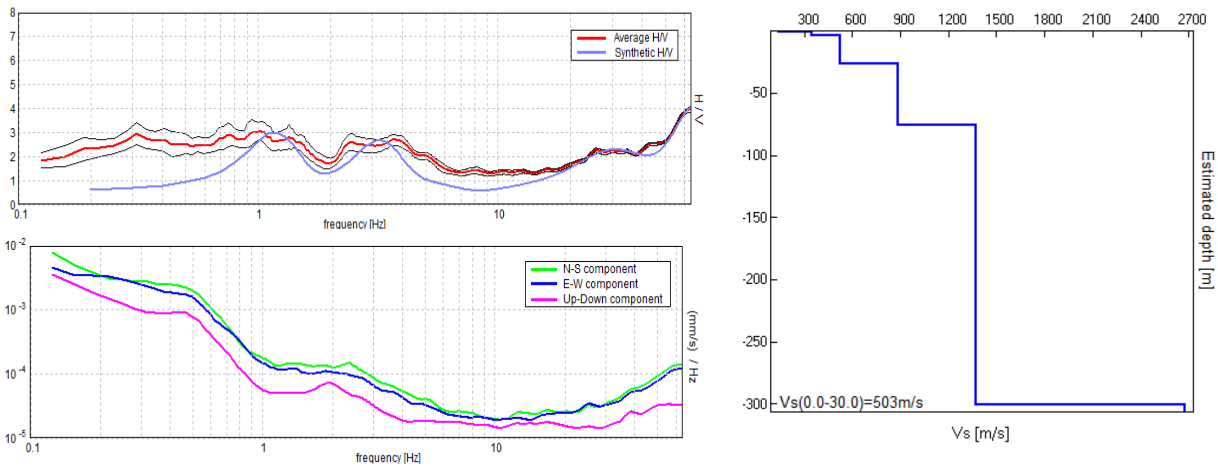

Figure 7: (Left Top) H/V trace from SWN1 at third recording, closest to the station. (Left Bottom) Single component amplitude spectra of trace (Right) V_s model for the site until 300m depth.

Discussion and Conclusion

Three UK strong ground motion stations of varied ground conditions have been assessed by developing a geological profile for the sites and correlating these to a global V_{s30} database, using similarity of lithofacies and geological deposition. The results from *in situ* testing for stations CCA1 and SWN1 produced V_{s30} velocities within these estimated ranges. Both are at the lower end of the predicted ranges. This is expected as both sites are found to be close to the worst case expected for the weathering of the strata.

The station MCH1 is indicated to be on homogenous rock by the *in situ* testing. This prevents a V_{s30} profile being developed using these results. However the site can be determined to be Class A ground type (EN 1998) as the weathering does not appear extensive and the rock is still intact. With such low impedance, the main concern for this station would be fundamental frequency of the site. If further information was needed, only invasive testing would yield a result as alternative geophysical methods to the H/V method also depend on the impedance contrast of the strata. Further invasive investigation could in addition add weight to the other station results, if it could be afforded.

Unlike the preliminary study of this method (Tallett-Williams *et al.* 2015), there were significantly more unknowns in the station profiles. These increased in complexity from MCH1 to SWN1, particularly in terms of weathering which is not often modelled in V_{s30} investigations. Yet, there was still a sufficiently good resource of *in situ* data. The next stage will be to consider regions with little information in the geological records or Class 4 sites (Tallett-Williams *et al.* 2015).

In more complex ground conditions, it appears effective to use a weighted series of simple geological profile models to account for different likely depths and conditions of strata. However, this could be vastly improved, perhaps through a logic tree scheme. The worldwide database of V_s too is still limited, but is continually growing. It is hoped that this database can be made open access and as contributions are made, the properties which control V_{s30} will become clearer.

ACKNOWLEDGEMENTS
The authors would like to thank Mike Raines for his generous advice and wise instruction, Brian Baptie, John Laughlin and the BGS, Matthew Free, ARUP, Micromed S.P.A. for their kind guidance and profitable discussion. Access to the sites was gratefully accepted from Mr & Mrs Spencer, Mr Phillips, Mr Hopkins and the Science Museum.

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