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The Value of Alternative Geophysical Methods in Determining Shear Wave Profiles for Critical Infrastructure

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ABSTRACT

The impact of earthquakes worldwide on critical infrastructure has shown the importance of accounting for site effects in safe design. Including comprehensive shear wave (V_s) profiles in ground motion prediction equations has become an increasingly popular method. Yet, borehole measurement of V_s velocities in the near surface remains expensive. For locations with a perceived low seismic risk and little previous V_s investigation, this cost becomes a barrier to further development. This study examines three alternative geophysical methods and their value to determining site response. The methods are carried out at a previously uncharacterised strong ground motion station in the UK. The results of the testing were consistent within 10% of each other, producing a V_{s30} of 570ms ± 30ms for the site. Moreover the methods give indications of the variability of the site, a lower limit of the resonant frequency and clear validation of the geological profile. Thus, if correctly applied, these methods can provide a viable and cost-effective alternative to purely invasive techniques.

Introduction

The near-surface response of a site to seismic waves can have a dramatic effect on the shaking experienced by a structure. Significant amplifications have been known at large epicentral distances notably **M**8.1 1985 Mexico City Earthquake (e.g. Booth *et al*. 1986) and implicated in small magnitude earthquakes such as **M**4.0 2007 Folkestone Earthquake (e.g. Ottemöller *et al.* 2009). Thus, increasing importance is being placed on correctly accounting for seismic site effects in industry. The time-averaged shear wave velocity over the top 30m of ground (V_{s30}) is currently the most popular method of accounting for site effects in Ground Motion Prediction Equations (GMPEs) (Wald & Allen 2007). Despite its shortcomings (e.g. Castellaro *et al.* 2008), the development of the V_{s30} has led to discussion of site effects improving understanding of this field with studies such as Park & Elrick (1998) and Wills *et al.* (2000).

However, borehole measurement of V_{s30} remains an expensive and tortuous process where large equipment and specialist assistance are needed. For regions with little previous site-specific testing, the vast quantity of testing needed in order to use current proxy methods (e.g. Wills *et al.* 2000) has created a barrier to development (Wald & Allen 2007). This is especially true for areas of perceived low seismicity including the UK as the cost of such studies seems unfeasible.

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This paper reviews three *in situ* methods carried out at one of the UK strong ground motion stations: multi-channel analysis of shear waves (MASW), seismic cone penetration testing (SCPT) and ambient noise measurements (microtremor). The UK station network is currently being evaluated to determine detailed V_{s30} profiles for each station, using alternative, but affordable methods (Tallett-Williams *et al.* 2015). The three methods are compared in terms of what value they add to the shear wave profile for a site with no previous *in situ* testing.

Site Overview

Station ELSH is in the South East of England, near Folkestone. Little previous site-specific work has been carried out on the station. Moreover the location is remote to reduce man-made noise. However, a geological profile of the site (Table 1) is developed through desk-study, investigating previous invasive records from the surrounding region and a walk-over survey. The main area of concern that this identified is the extent and depth of weathering of the chalk. During the installation of the station the soil appeared to resemble white clay (Laughlin 2014), while far-field invasive logs recorded boreholes with layers of putty chalk (BGS 2013). The latter are mainly well bores, so contain little geological information. This lack of information combined with the distance between the records means there is not a good correlation. Therefore, the extent of this weathering is unclear both in degree and depth. This could have large consequences for the V_{s30} profile and thus made it a suitable station for further investigation.

Table 1. Geological profile developed for Station ELSH. This has an uncertainty Class 4 according to the system of Tallett-Williams *et al.* (2015).

Stratum	Depth (m b.g.l.)	Description
Middle Chalk (New Pit Chalk)	15-25m	At the surface stony, structureless chalk (almost like topsoil), progressing to mainly blocky strong chalk with few, but thick marl seams (100-200 mm). Several soft layers likely to include putty chalk. Rare flint and nodular chalk seams may be present, but more likely to be a residual chalk profile with dissolution features.
Middle Chalk (Holywell Nodular Chalk)	30m (End of Profile)	Generally hard nodular chalk with only thin marl bands and significant portions of shell debris. At the base hard to very hard, blocky chalk of the Melbourn rock.

Discussion of methods

The primary testing carried out at this site is MASW. This is a non-invasive method that was developed by Park *et al* (1999). It consists of a linear array of receivers (usually geophones) that record an active source deployed at points along the line. Increasing the number of geophones from the two receiver approach (SASW) increases the robustness of this method as well as making it less subjective (Foti *et al.* 2014). The recordings can be processed using a transform based approach producing a model of the site. For the station ELSH, the value of this method is that a large quantity of data can be collected over a short period of time, the testing taking one day for a 200m traverse. As a result, the variability of the site can be accounted for with a good quality of detail in the near surface. This is ideal for looking at the extent of weathering in the top 30m. Although the method requires specialized equipment, it is quick, reasonably affordable for smaller projects and the equipment is relatively portable.

SCPT was also carried out at the site. This is the most expensive of the three tests particularly considering the area covered. However with the growing popularity of cone penetration testing (CPT) in engineering design, if a suite of CPT testing is planned at a site, this method is a viable addition. The test consists of pushing a series of small diameter rods into the ground (e.g. BSI 2005). The rods contain dual seismic receivers at known positions. These record the shear wave pulse produced by a seismic source at the surface, but, due to the difference in depth of the receivers, a time delay occurs in the arrival time of the pulse. This is used to calculate the V_s velocities of the strata (In Situ Site Investigation 2014).

SCPT is an invasive test and most similar to other engineering tests. The benefit of this technique to the ELSH site is that it provides clear verification of a ground model. Though the method needs larger equipment than the MASW, it is not as aggressive or expensive as boring. It is also quick with it being possible to conduct several SCPT tests in one day. In addition, the procedure for processing the results is the simplest of the three methods.

Ambient noise measurement of microtremors is a non-invasive, passive geophysical technique. With the advancement of technology, this can be carried out using a single, portable, digital seismometer. These typically contain three orthogonal accelerometers and velocimeters which measure surface waves (Micromed 2013b.). Using the Nakamura (1989) H/V technique, the horizontal to vertical ratio of these elliptical waves can be determined. This ratio forms a peak at the lower limit of the fundamental frequency of the site (Bard 1999). If the depth of the first stratum is known, the following equation can be constrained to find the V_{s30} of the site, providing a detailed view of the near surface: (Micromed 2013a.)

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

where f_0 is frequency, V_s is shear velocity and H is the thickness of the stratum.

Though the theoretical and analytical basis for this method is not fully understood (Bard 1999), the empirical evidence is compelling and guidelines have been approved for the method (SESAME 2004). The main attraction of the technique for the ELSH site, apart from the determination of a lower limit of the fundamental frequency of the site, is the low cost of the test.

Testing

A MASW traverse was carried out at the site on a bearing of 220° with the station located at 11.5-13.7m. The traverse was 190m long formed of 96 10Hz vertical geophones. A hammer and plate source was used to shoot every 8m, each shot comprising a stack of 4 measurements to improve signal-to-noise both for MASW and later refraction analyses. The results were processed using the RadExPro MASW module software which has constraints on layering (Deco Geophysical 2014).

The SCPT was carried out 2.5m south-east of the station using an all-terrain CPT rig. The rods were paused every 0.5m and a seismic test was taken using a hammer and plate. The results were processed using In-Situ Site Investigation software (2014).

The microtremor measurements were carried out in two perpendicular traverses with recordings every 10m. The first was on the same 220° bearing as the MASW. This was carried out in accordance with the SESAME guidelines (2004) using a Tromino Zero instrument (Micromed 2013b.). This was processed using Grilla software (Micromed 2013a.).

Results

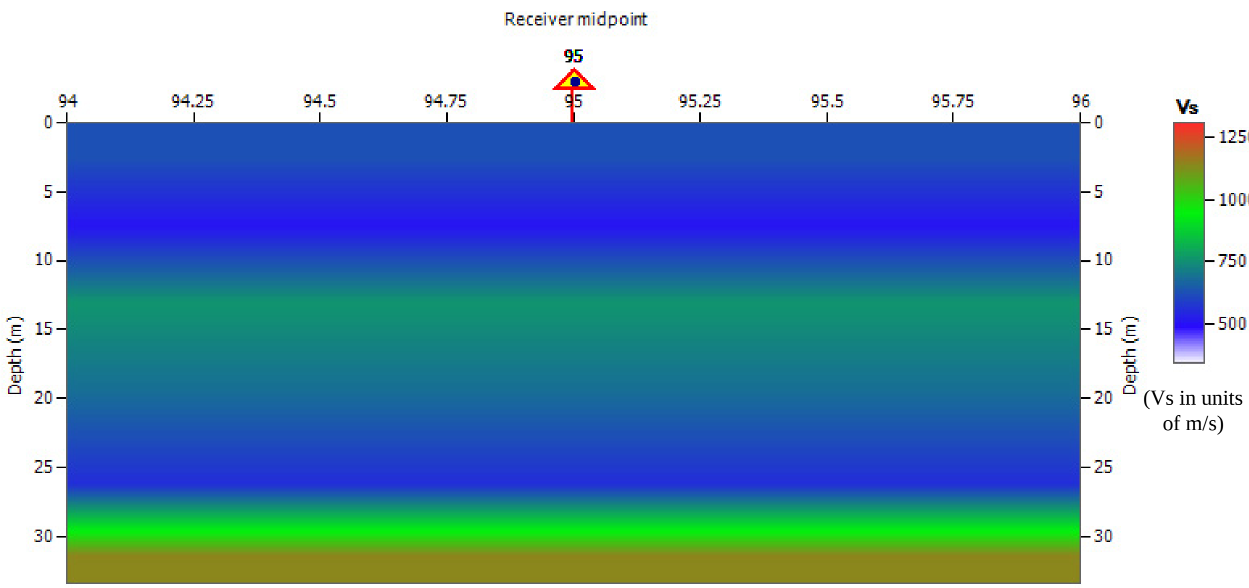

Figure 1: MASW model of the Station ELSH shown at the central section of the traverse.

The results of the MASW inversion (Figure 1) do not show a typical rock structure with increasing V_s velocity with depth. There is a higher velocity surface layer which decreases to more soil-like velocities at about 7m below ground ground level (b.g.l.). This is underlain by a stratum of around 850 m/s at 14m bgl. However, this appears not to be the competent rock as the speed decreases again below, with higher velocity layers appearing at around 30m. The velocity inversions present in the profile indicate that it is non-uniformly weathered.

The dispersion curves are well-defined, but show clear lateral differences. The theoretical fit for each shot forms a very different V_{s30} profile in terms of velocities of the layers and the depth at which they occur. Most profiles include layers of around 300m/s which suggest the presence of highly weathered putty chalk. However, these could not be correlated indicating that the model (Figure 1) shows only the main velocity distribution of the site, but not the detailed weathering profile. However, an average V_{s30} of 590 m/s is determined for the site.

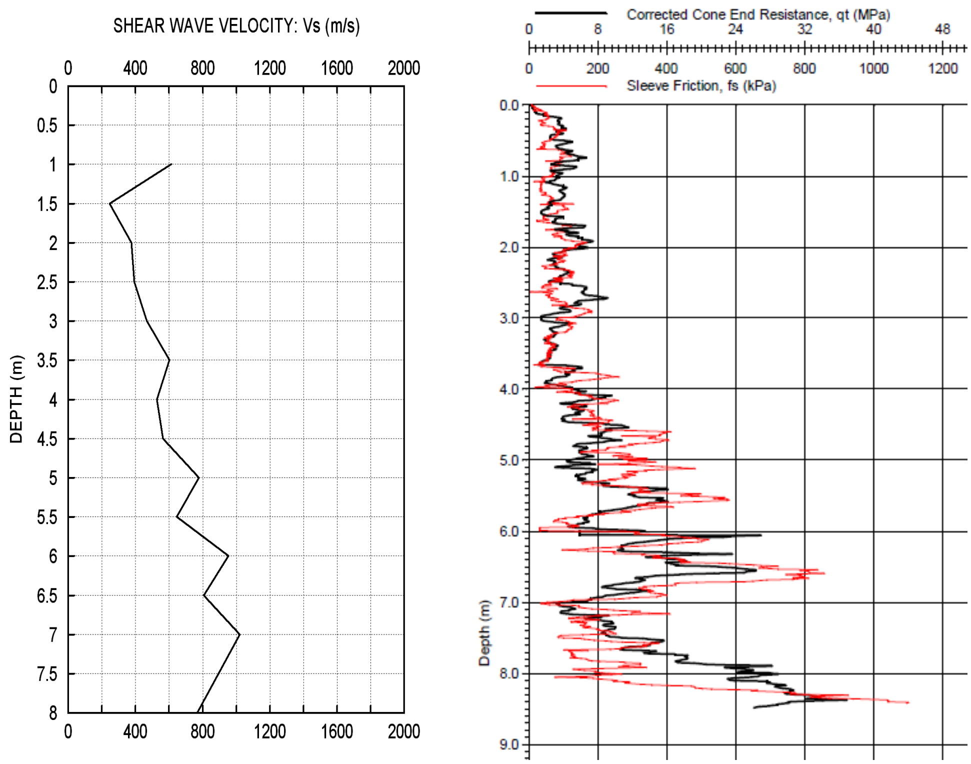

Figure 2- SCPT test results (left) and the results from an adjacent CPT (right).

The results from the SCPT (Figure 2) show a general increase in velocity with depth with fluctuations in V_s velocity towards the base. This is echoed by the CPT (Figure 2) carried out adjacent to the SCPT test which shows increasing resistance with depth. Both tests had to be terminated at 8m depth as a resistant ground layer prevented further rod penetration. These results concur with the MASW testing with the slightly stiffer surface layer, but the SCPT results show a local hard layer which may not be visible in the MASW model.

The SCPT V_s measurements range from a minimum of 244 m/s in the weathered layer to a maximum of 1021 m/s located in a blockier layer at 7.0 m depth (Figure 2). Though there is a local alternation in the hard and soft chalks possibly due to weathering or differing marl content, there is an overall increase of V_s velocity with depth. The V_s measurements provide a time averaged velocity of 583 m/s in the top 8 m of ground.

The profiles produced by the microtremor measurements (Figure 3) also show a complex structure, highly weathered in the near surface. The south-east/north-west traverse shows a layered profile that indicates the localized resistive stratum which prevented the SCPT penetration at 8 m b.g.l. at the station. However, like the MASW, this shows that it is not competent rock which appears to be a lower impedance layer located at 30m b.g.l. The north-east/south-west traverse appears as almost an end-on view of the layers which are revealed as more isolated circles. This too shows the lower impedance rock as well as the high impedance layer at approximately 25 m b.g.l. However one record had to be removed from the north-east/south-west traverse at 30m as it had a significant dipole near the surface, resulting in some loss of detail.

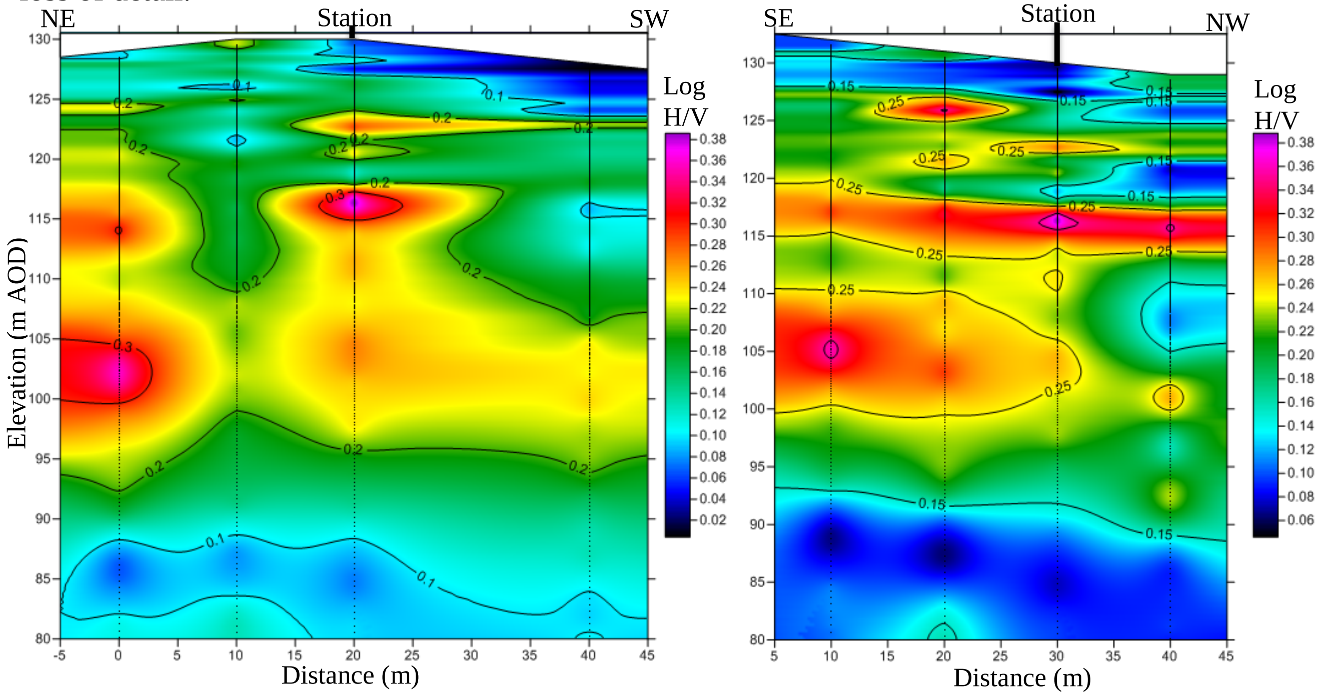

Figure 3. Microtremor cross-section of ELSH, north-east /south-west, station located at 20m (left) and south-east/ north-west (right) with the station located at 30m. The sections were processed at 550m/s with an exponent of 0.25.

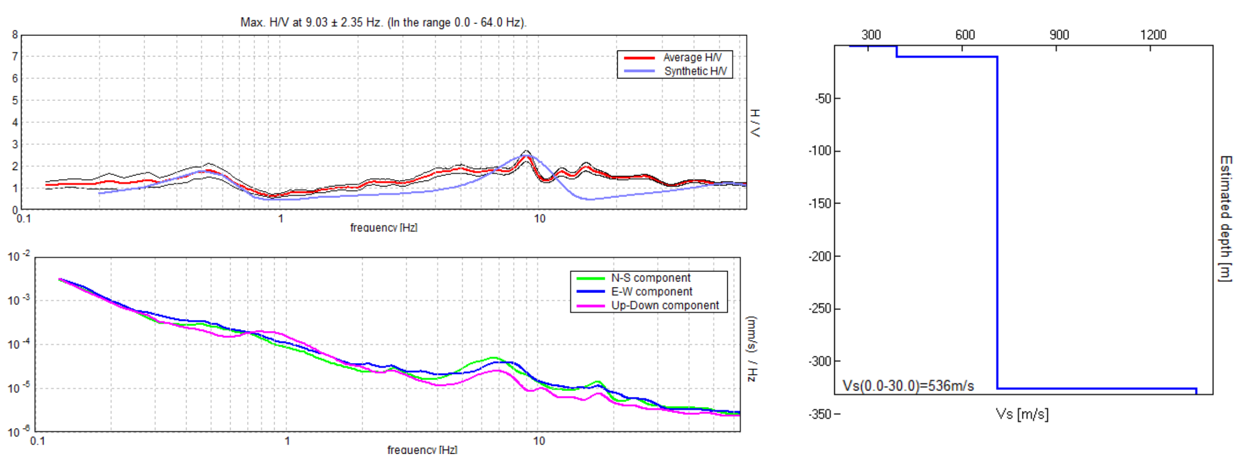

Figure 4: (Left Top) H/V trace from ELSH at 20/30m recording, next to the station, showing fundamental peak at 9.03Hz ±2.35 Hz. (Left Bottom) Single component amplitude spectra of trace (Right) V_s model for the site.

The H/V traces (Figure 4) are highly variable particularly in the upper frequencies which represent the near surface, again suggesting an irregular weathering profile. Thus, it is difficult to fit the synthetic curve representatively. However, in all the traces, there are peaks present at approximately 0.5 Hz and at 9 Hz. Therefore, only these are modelled to find the V_{s30} profile as the remainder of the trace is not representative and could be caused by higher modes. This is reflected in the frequency spectra (Figure 4) which has a significant overlap of the vertical component from 0.6 Hz to 2.5 Hz which suggests a velocity inversion. The V_{s30} profile for this site was determined from the H/V trace to be 536 m/s.

Discussion

All three methods produced similar V_s velocity estimates consistent within 10% of each other, resulting in a V_{s30} profile of 570 ± 30 m/s. Moreover, the derived geological profile results have good correlation: the SCPT and microtremor both indicate a localized resistive layer at 8 m b.g.l. near the station and MASW and microtremor both indicate more competent rock at ~30 m b.g.l.

However, there are further benefits to using these methods. The MASW covered a large traverse in a short amount of time. Though it did not pick up on the more localised layers, the raw data did give a good insight into the variability of the site. The SCPT test presented a clear validation of both the other results with little damage on site and for less cost than a borehole despite being an invasive test. The microtremor gives a lower limit estimate of the site resonant frequencies and provides a detailed view of the near surface, though we should be cautious not to over interpret these sections.

The most difficult part of all three of the methods is found to be the inversion of the testing results to find the V_{s30} profiles. This is overcome with improvements in software which are continuing to develop. Yet, although demanding, it is found that it is possible for an engineering 'amateur' to use this complex geophysical software.

Conclusion

Three alternative methods to an invasive borehole investigation have been carried out at the strong ground motion station ELSH on chalk near Folkestone. Despite the complex weathering of the site, the methods provide corroborating ground profiles. Thus, with improvement in technology they present viable alternatives to the engineering community which are cost-effective, but often overlooked. This is regardless of the further valuable information they can produce for a site.

However, their successful application significantly depends on the knowledge of the geology of the site. It is critical a good understanding of a site is formed through a desk study, walk-over survey and previous invasive records in the region. If this profile could be combined with geologically similar V_{s30} recordings through a worldwide database of results, such as we aim to develop, these methods would provide cost-effective validation techniques, and could remove the barrier for further development for perceived low seismicity countries.

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