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The application of Seismic Surface Wave testing on stiff low-height embankments for the Construction of High-Speed Railway's Earthworks: A case study in the UK

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Abstract

The speed of seismic surface waves generated by the passage of high-speed trains is an important consideration in the design of railway earthworks. To ensure track stability and good earthwork performance, it should significantly exceed the train speed. Traditionally this requirement has been satisfied by specifying a minimum stiffness of earthwork, empirically shown to give acceptable performance. With train speeds increasing, it has been preferable to predict and then check (during construction) that minimum specified Rayleigh and shear wave velocities are achieved. This requires suitable geophysical tests and an understanding of their reproducibility and repeatability in defining wave velocities for compliance assessment. This paper presents the results of comparative tests to evaluate differences in estimated shear wave velocities, using Multichannel Analysis of Surface Waves (MASW) and Continuous Surface Waves (CSW) on a trial railway embankment. The results show that both methods estimated shear wave velocities to similar depths, but CSW produced more consistent shear wave velocity profiles when a stiff embankment overlies natural ground. The variation observed in the MASW testing was attributed to the additional complexity resulting from this unusual stiffness profile. This needs to be considered when specifying appropriate tests for shear wave compliance in earthwork design.

Keywords: Geophysics, Seismic Engineering, Geomaterial Characterization, Testing & Evaluation, Railway Track.

1. Introduction

In major infrastructure projects, earthwork material performance and condition play a significant role in overall system performance. For example, the High Speed Two (HS2) project in the UK that is currently under construction, requires earthworks that have specific engineering properties designed to meet the project's aims in terms of safety, maintenance and cost over its 120-year design life.

One aspect of the HS2 earthworks specification is the requirement to achieve minimum Rayleigh wave velocities in the ground to manage so-called critical velocity effects (Gao et al., 2017), namely the dynamic amplification of ground waves under the passage of a high-speed trains resulting in a rapid deterioration in track condition. These are caused when the train speed approaches the Rayleigh wave velocity (V_R) of the track-ground system. They have been observed at Ledsgaard, Sweden (Takemiya, 2003) and have been modelled numerically by several researchers (Krylov et al., 2000). Traditionally this requirement has been satisfied by specifying a minimum stiffness of earthwork (stiffness correlates with wave speed) which has been empirically shown to give acceptable performance. With train speeds increasing it is preferable to predict and then check in the field during construction that minimum specified Rayleigh wave and shear wave velocities are achieved, and these are increasingly being specified during construction. This requires suitable in-situ geophysical tests and an understanding of their suitability, reproducibility, and repeatability in measuring Rayleigh wave velocities for compliance assessment.

Rayleigh waves propagate at the surface of solids up to the depth of one wavelength and show geometrically dispersive behavior (Foti et al., 2014). Because wavelength is inversely proportional to frequency, lower frequency Rayleigh waves have a greater depth of penetration than shear waves (Foti et al., 2018).

In isotropic homogeneous elastic solids, Rayleigh wave (V_R) and shear wave velocity (V_S) are linked by Poisson's ratio (ν), but the errors resulting from anisotropy and heterogeneity in soils are relatively modest, and their relationship is commonly described by Equation 1 (Heymann, 2007):

$$\frac{V_R}{Vs} \cong \frac{(0.874+1.117\nu)}{(1+\nu)} \qquad (1)$$

Based on the above, as both V_s and V_R can be used to understand the performance of earthworks in respect of critical velocity effects, and seismic methods that can analyze either wave types are useful as control/compliance tests during construction. Therefore, seismic surface wave methods are potentially useful for this application, as they are non-invasive, significantly less expensive than invasive borehole geophysics and faster to apply. The methods most frequently used are MASW and CSW. These two have differences in the source used and the analysis process to evaluate the signals collected.

In the CSW energy is generated through a vibratory source at known frequency intervals. This is one of the main advantages of the method, as the frequency ranges of testing can be specified and therefore the maximum depth of testing can be controlled (Foti et al., 2018). Typically, 6 uni-axial geophones are used, and the vertical motion is captured. These are placed in a linear array at a distance from the source (Foti et al., 2018). During data acquisition, the parameters derived are the phase difference, and the frequency, from which wavelength (λ) and Rayleigh wave velocity (V_R) can be calculated as (Equation 3):

$$\lambda = 360/\ (\text{phase difference}), \qquad V_R = f\,\lambda \qquad (3)$$

MASW uses a hammer and a plate to generate seismic waves. A minimum of 24 geophones are commonly used, placed in a linear array, and at distance from the source (the offset) to be far enough to avoid near-field effects and close enough to limit high frequency attenuation of the signal (Foti et al., 2018). In this case, because the input signal is multi-frequency, a dispersion curve is plotted of V_R against frequency, from which a V_S profile against depth is estimated through an inversion process.

The accuracy, functionality and cost of surface wave methods have been discussed in various case studies, for both site characterization and railway track condition monitoring. A UK study on railway earthworks investigated both MASW and CSW tests to identify stiffness variations in the UK, showing that the best results were obtained by field equipment of wide frequency wave generation, as this helped in mapping the ground over various depths (Gunn et al., 2015). CSW was selected to spot the passage from fine to coarse grained material and MASW to locate voids; however, in combination the methods identified stiffness variations in complex and laterally varying materials. MASW was also applied in a railway embankment that settled in Ireland and was useful in mapping the steeply sloping bedrock (Donohue et al., 2011).

Neither MASW or CSW come with a standard method or practice of application, and their use strongly depend on the contractor's experience, soil material, source type and acquisition protocol (Kyrkou et al., 2022). Some limitations of MASW include the non-uniqueness of the inversion to Vs with depth from the measured V_R, their inability to identify the existence of lateral variations in the ground and the presence of higher modes of wave transfer that could be mistaken for the fundamental one (Foti et al., 2018).

To better understand these limitations on the usefulness of these techniques to verify earthworks construction, and because of the significance of Rayleigh waves in high-speed railways, in this study field tests of both methods were undertaken to compare the V_S -depth profiles and assess the level of difference in the results using similar test set ups on a stabilized trial embankment. The purpose of this paper is to present and discuss the results a series of tests undertaken at the same location, with geophones and seismic source placed at similar distances.

2. Case Study: Long Itchington Wood Tunnel

All geophysical tests were undertaken on a site near Southam, Warwickshire as part of the construction of HS2 on a lime-stabilised trial embankment. The underlying geology consisted of a weathered profile of clays and mudstones of the Sidmouth Mudstone Formation, part of the Mercia Mudstone Group; the stratigraphy of the area, taken from a nearby borehole, is shown on Table 1.

Strata Description	Depth (thickness)
TOPSOIL-soft reddish brown slightly sandy clay with occasional rootlets (< 3 mm x 5 mm)	0.3 m (0.3 m)
Soft brownish red sandy CLAY. Sand is fine to coarse. De-structured	0.3-1.5 m (1.2 m)
Stiff brownish red sandy clay with occasional pockets (< 10 mm x 10 mm) of greenish grey silt. Sand is fine to coarse. De-structured	1.5-2.3 m (0.8 m)
Firm brownish red silty clay with occasional pockets (< 40 mm x 70 mm) of greenish grey silt and with occasional lithorelicts (< 60 mm) of reddish-brown mudstone. Sand is fine to coarse. Destructed	2.3-3.5 m (1.2 m)
Extremely weak brownish red MUDSTONE. Distinctly weathered. Recovered as angular and subangular fragments (< 63 mm) of brownish red mudstone in a sandy matrix	3.5-3.68 m (0.18 m)

Table 1: The site stratigraphy.

The topsoil and softer superficial soils were removed to a depth of approximately 0.8 m, and the formation was proof rolled to give a stiff foundation prior to construction of the trial embankment. The fill material was treated with 1.5% lime and the embankment was constructed in 10 layers of 300 mm thickness on top of the natural ground to the height of 3 m.

The stiffness of most natural sites that are investigated using MASW or CSW increase with depth, creating a normally dispersive profile for surface seismic waves. The Long Itchington Wood Tunnel trial is interesting because it represents a situation more typical of the stiffness profiles expected for high-speed rail earthworks, with a high stiffness engineered embankment overlying a softer foundation whose stiffness then increases with depth. This stiffness profile may be expected to change the passage of the surface seismic waves in comparison to a normally dispersive profile which may add significant complexity to the interpretation of the MASW and CSW tests.

2.1 Geophysical Survey Design: Methodology and Test Plan

The anonymised surveys presented in this paper are part of a larger geophysics trial using the arrangements shown in Figure 1. MASW tests were undertaken by four companies on the same site and the CSW method was applied by one. The selected surveys presented herein include an example of the MASW results, the CSW results as well as the comparison of both methods, . In the trial, all seismic lines were designed to have the same centre location and the same inter-geophone spacing and offset combinations were applied to both methods. Energy was generated at two shot locations, at both offset ends of the seismic line (i.e., forward and reverse shots). All geophones had 4.5 Hz resonant frequency. In the MASW surveys, energy was generated through a 14 lb hammer and a plastic plate, 24 vertical spiked geophones were used. Data were registered using a Geometrics Geode Ultra-Light Exploration Seismograph. In the CSW surveys, a 70 kg frequency-controlled vibrator was used as the source and 6 vertical spiked geophones used as receivers. The frequency range applied was 7.5 Hz to 100 Hz with 2.5 Hz increment and from 100-250 Hz the increment was augmented to 10 Hz.

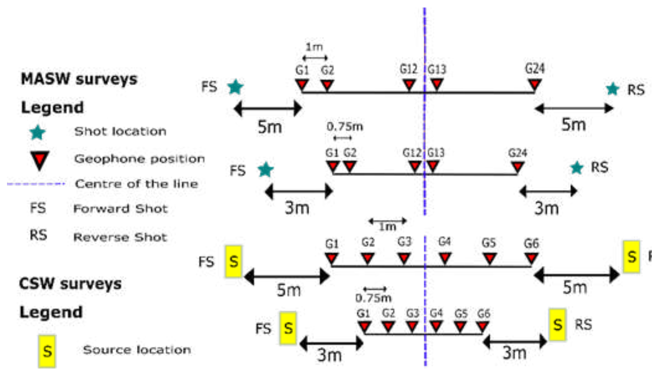

Figure 1: Field test protocols per method. All lines were centred between geophone G12 and geophone G13 for MASW and between G3 and G4 for CSW tests- the common mid-point represented by the blue dotted line.

Since it was important to evaluate the outcome from routine procedures used by the companies for commercial geophysical work, all data were acquired and processed by them, using their normal procedures, for example for establishing the most appropriate dispersion curves, data inversion to produce Vs-depth profiles and stacking datasets to maximise signal to noise ratios.

3. Results and Discussion

In this section, a selection of resulting V_S -depth profiles determined from both methods are compared. The interpretation of MASW results requires an assumption of an elastic half-space below which V_S is assumed to be constant, and only the layers above the half-space (i.e., depth to assumed bedrock) were taken into consideration and are included in the figures. In every case, the graphs correspond to the best fit models derived from the inversion of the dispersion curve by the companies.

3.1. Vs-depth profiles from MASW tests (example of 0.75 m spacing and 3 m offset)

Figure 2 presents the shear wave velocity profiles determined by each company when the geophones were spaced at 0.75m and the source had a 3m offset. This example is typical of the results received for all test protocols in that it shows significant variability in the results. Considering the stiffer stabilised fill on top of natural ground, only Company C found a progressively increased V_S in the top 3 m of stabilised materials, although Company A's data does show a drop in V_S below 3 m and Company B shows a high Vs layer at the surface overlying soils of lower V_S. It is probable that the inverted stiffness profile discussed above is particularly challenging to interpret resulting in significant variation in Vs with depth and differences between the results of the different companies. It is possible that the stiffness profile has caused higher order modes to have been excited creating artifacts in the final V_S profiles (i.e., V_S higher than 700m/sec in the top 1.5 m) from the inversion process (Foti et al., 2018).

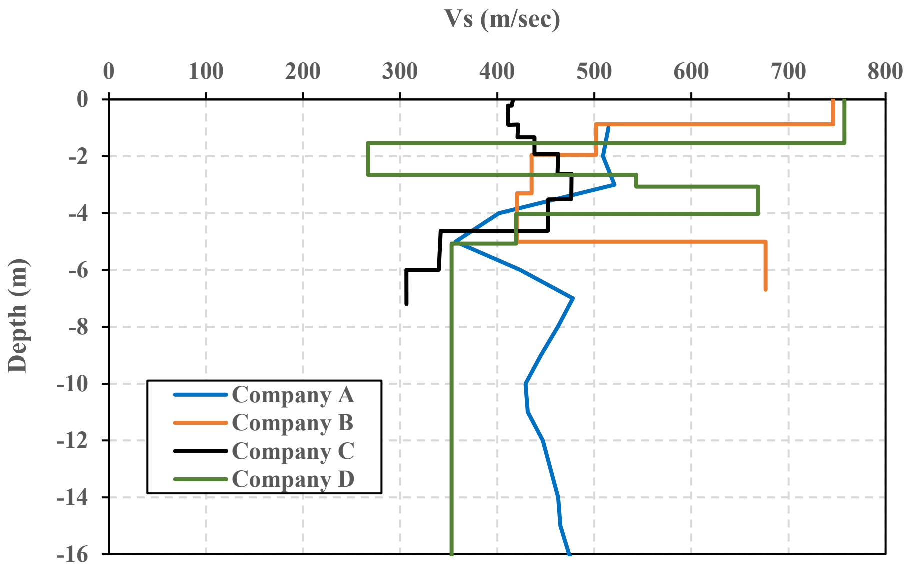

Figure 2: Example of the results of MASW for all companies - survey protocol of 0.75 m spacing/ 3 m offset.

3.2. V_s -depth profiles from CSW tests

Figure 3 presents the results of V_s -depth profiles for the forward shots (backward shots not included for clarity) of two CSW profiles; (3m offset with 0.75 m spacing, as above, and 5m offset with 1 m spacing). For the shorter CSW line, the subsurface was mapped to a shallower maximum depth (about 10 m) than the longer line (15 m). In the top 7 m, both profiles have high resolution, with data points at intervals <1 m. At greater depths the resolution of both plots reduces, significantly for the longer line data which goes to greatest depth. Within the top 7 m, both profiles are generally very consistent with each other, typically showing differences of up to 10%. Below 7 m, as the resolution of the surveys reduced, the difference between them increased.

In contrast to the MASW data of Figure 2, this CSW data shows the ground to have highest stiffness in the top 3 m and then lower, but consistent stiffness at greater depth. This is what would be expected for a profile which consisted of stabilised embankment fill overlying a natural profile of the Sidmouth Mudstone Formation.

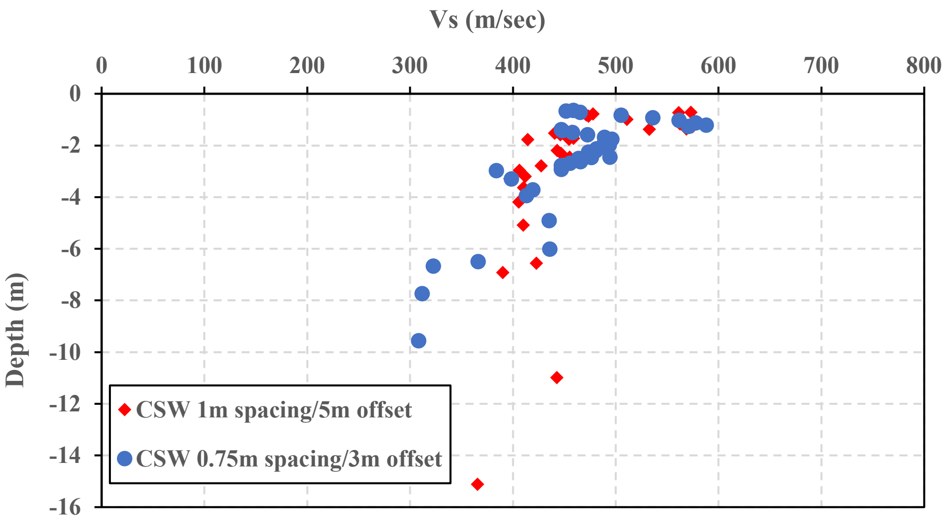

Figure 3: The results of CSW (forward shots only) for the two survey protocols.

3.3. V_S -depth profiles from MASW and CSW tests for 0.75 m geophone spacing and 3 m offset

For this offset and geophone spacing, both the forward and reverse shots of CSW were compared to the MASW test from Company C whose results seemed to better match with the known soil profile (Figure 4). For this comparison, and since MASW showed high variability (Figure 2), the MASW only from one company is presented, and the minimum and maximum V_S values data spread from the other firms is shown as red bars, up to 10 m depth at 2 m intervals to show the extent of variation while maintaining readability of the graph. In terms of the maximum investigation depth, the average of CSW shots was 14 m, while for MASW the deepest layer before the half space for the selected test was identified at only 7 m below ground level.

Comparing forward and reverse shots from the CSW surveys shows similar profiles, revealing that the ground does not present significant lateral variations as the data are similar in both directions and the ground corresponds similarly in the wave's propagation, as would perhaps be expected in a well-controlled constructed stabilised embankment. The most significant difference between these shots is in the top 1.5 m, which also showed the greatest difference to the selected profile from the MASW testing, indicating that the data in the very near surface is difficult to rely upon, possibly linked to the issue of higher order modes in analysis described above. From 1.5 to 7.5 m depth, the difference in average V_S between the two CSW shots is approximately 10%, and this depth range also shows the best match to the MASW data presented. Below 7.5 m the resolution from the CSW decreases and their differences tend to increase a little. This will obviously be critical to the ground model used in analysis.

Comparing MASW and CSW, over the entire depth profile the MASW data fluctuate significantly as described previously, whereas the CSW data seem to be more consistent.

3.4. V_S -depth profiles from MASW and CSW tests for 1 m geophone spacing and 5 m offset

The results for this offset and geophone spacing are shown in Figure 5. To map the difference of forward and reverse CSW shots, they were both compared to MASW, to show the relevance in the results of this frequency-controlled method. The variability of V_S -depth profile from all MASW tests from the other companies is also shown again with red bars similar to Figure 4. Based on Figure 5, CSW mapped the subsurface to approximately 60% deeper than MASW.

For the forward and reverse shots of CSW, there are significant differences in the top 1 m (up to 30% on the average V_S), but below this the two shots show a very good agreement, at least to 7 m before the resolution reduces significantly.

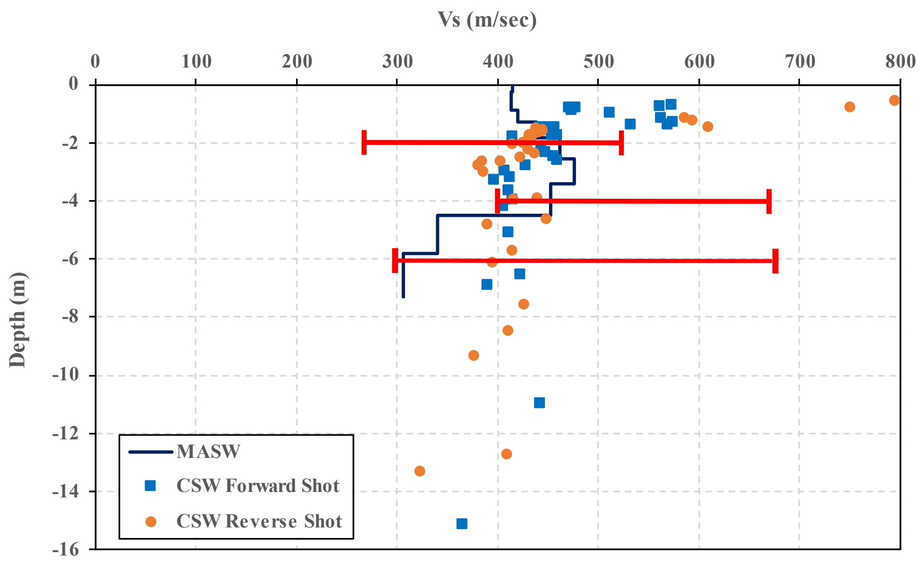

Figure 4: The V_S to depth profiles for both MASW and CSW surveys, for the same geophone spacing and offset location (0.75 m spacing, 3 m offset). The MASW plot is the one which best fits the CSW data.

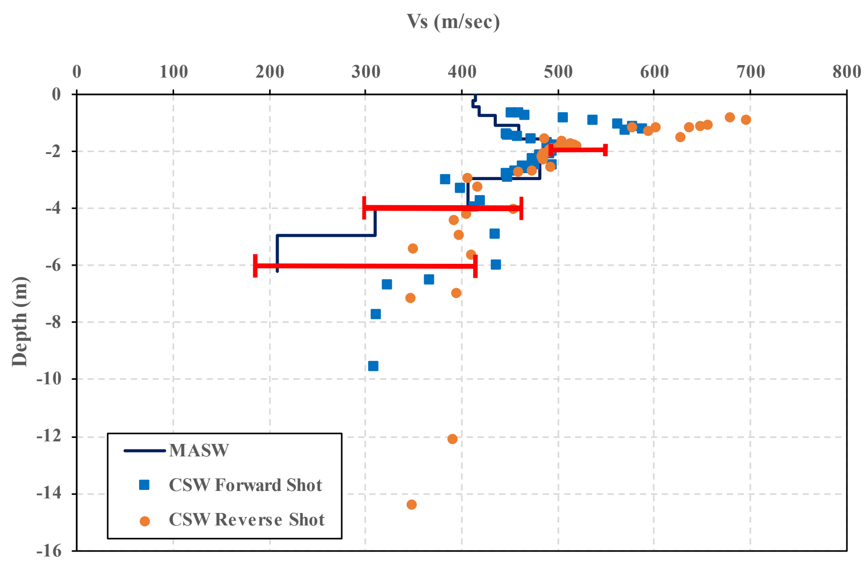

Figure 5: The V_S to depth profiles for both MASW and CSW surveys, for the same geophone spacing and offset location (1 m spacing, 5 m offset).

4. Conclusions

In this study, the methods applied were MASW and CSW and aimed to explore the level of agreement between them in respect of assessing the estimated shear wave velocity variations with depth of a stabilised embankment. For both methods, shear wave velocity profile is interpreted from measured Rayleigh waves and this interpretation requires several assumptions to be made. In CSW there is greater data resolution in the near surface due to the ability to generate specific source frequencies and intervals, compared to MASW where the frequencies generated depends on the energy of the impact shot with the triggering hammer. Specific conclusions are:

- CSW gives more detailed information for the near surface, compared to MASW, when all company data were compared.

- The overall investigation depth between the two methods, where resolution does not decrease, is relatively similar. In CSW method, the longer length survey reached a depth that was approximately 60% higher than for the case of shorter line.
- The CSW forward and reverse shots showed similar V_S -depth profiles for both survey design protocols.
- Conversely, the MASW results from all companies showed high variability between companies and in some cases significant variability of V_S within this soil profile. This could be attributed to this particular site having a high stiffness stabilised embankment overlying natural soil which adds significant complexity to the inversion process required to assess V_S, and corresponding artifacts in the V_S (for instance significantly high velocities, attributed to issues with higher order modes).

Regarding data resolution, this was better in the shorter line of CSW compared to the longer one. However, when comparing the two methods, it is not clear from these results that closing the geophone's spacing gives necessarily more accurate interpretation of the near surface. Accuracy is also dependent on the amount of supporting information available to the analyst and their skill.

Broadly, these data showed that CSW on this site provides more robust information in the near surface than MASW. Further research will be undertaken on a wider dataset into the way the fundamental mode is picked from MASW dispersion data, and the parameters that mostly affect the final Vs to depth profiles in the post processing inversion process. This will aim to get a better understanding of issues related to control and variability within MASW testing and data processing. This will further investigate if the variability in these data was due to the issues with a relatively thin stiff layer (the stabilised embankment) overlying natural ground and how this is accommodated in analysis. This is an important issue to understand for compliance testing of shear wave velocity on stabilised embankments.

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