Proceedings of the 7th World Congress on Civil, Structural, and Environmental Engineering (CSEE'22)
~~Lisbon, Portugal~~ Virtual Conference – April 10 – 12, 2022
Paper No. ICGRE 184
DOI: 10.11159/icgre22.184

Seismic Surface Waves Methods for High-Speed Rail Earthworks Compliance: A Review of Measurement Practice

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Abstract - In high-speed railways if the soil surface wave velocity approaches the train speed this can cause dynamic issues with the track. For the new high-speed railway (HS2) in the UK, Rayleigh and shear wave velocities are determined as part of construction compliance testing using seismic surface waves methods (typically Multichannel Analysis of Surface Waves (MASW) and Continuous Surface Waves (CSW)). However, as these methods are not standardised, there is the potential for differences in how contractors design, collect and process test data which could lead to differences in assessment for any given site. As part of a wider project investigating such tests, a qualitative interview study was undertaken of contractors testing HS2 earthworks to understand how they design and undertake such investigations. The interviews focus on data capture, data processing and interpretation. The interviews show there is variation in testing and analysis protocols for similar sites and that experience is important in undertaking such work. Contractors use experience from other projects and review their processes on site to check the data is suitable. They use both commercial and in-house software for data analysis and the final velocity profiles produced strongly depend on the assumptions made around soil conditions. While there are many similarities in approach used, the differences lead to variability in results. The paper concludes by proposing elements of the surveys that could (with further work) be included in best practice guidance around data collection and processing.

***Keywords*:** seismic surface waves, MASW, CSW, high-speed trains, inversion, dispersion

1. Introduction

In High-Speed Railway construction it is important to manage the earthwork stiffness and surface wave velocity response relative to train speed. Studies have shown that Rayleigh wave velocity (V_R) is an important parameter for the railway's track stability, as if Rayleigh wave speed reach the train's speed, dynamic resonant deflections may occur [1,2]. For this reason, V_R is now examined in the pre-construction phase of high-speed railways and critical values or minimum soil target velocity values (and/or stiffnesses) to a specific depth range are included in the construction specification. These parameters must be shown as being achieved during construction of the system. Such an approach is being used in the earthwork's construction for HS2, the new high-speed railway line in the UK (for HS2 V_{Rmin}= 160 m/sec).

However, the measurement of wave speed presents a challenge, as there are several methods by which the ground's seismic surface wave speed can be assessed, and these are not standardized. Various researchers have revealed that there is a difference in the way seismic data are analyzed and interpreted, based on the design of the tests and the experience of the staff processing the data or the basic method which the data was collected [3]. Therefore, where target seismic velocities are included in railway earthwork specifications, there is a need to understand how different approaches to the collection and analysis of seismic data may influence the absolute wave values presented.

The purpose of this study was therefore to gain an understanding of the ways seismic surface wave data are acquired, analysed, and interpreted in the UK by geophysics companies. This was performed through a structured interview process to feed into wider work linked to a subsequent comparative field trial to help inform routine testing for railway earthworks compliance. The study aims to understand how geophysics contractors potentially working on HS2 apply and evaluate some of the most well-known non-invasive seismic surface waves methods for assessing Rayleigh (V_R) and shear wave velocity (Vs) in such earthwork projects. By understanding the way data is collected and processed, this helps understand the issues when applying these methods in the field as well, aiding the understanding of the design of such surveys, to evaluate if there is scope for standardization of the processes. The paper initially presents a brief introduction of the appropriate methods. It then presents the interview process, summarizes the results and concludes on the approaches used, the differences found and the advantages and disadvantages of each approach, and the implications for methodological standardization or best practice.

1.1. Introduction To Geophysical Methods Of Surface And Shear Wave's Determination

The geophysical methods to measure ground's geotechnical properties for earthworks compliance generally assess seismic surface waves. In most cases surface measurements are made as part of site investigation coupled with borehole data and sometimes replace the use of classic, invasive seismic methods, such as cross-hole and downhole geophysics. The main benefits of surface methods are that they are quicker to implement, less expensive and more environmentally friendly. Seismic surface waves methods generally use a string of geophones mounted on the ground and a source to generate a seismic trigger and are usually directly measuring Rayleigh wave velocity (V_R). Raw data are processed to give, V_R for different frequencies of input, and through inversion an estimate of Vs (with depth) can then be made [4]. For earthwork compliance these values can then be compared to a specification target.

The data collection methods are divided into active and passive. For active methods energy is generated by a seismic source (often a sledgehammer on a plate, a weight-drop, or a vibrating source) and for passive methods the soil's seismic response is captured from ambient noise [5]. The active methods most used are Multichannel Analysis of Surface Waves (MASW), a survey done in the field in the same way as seismic reflection/refraction using an impulsive source, and Continuous Surface Waves (CSW) where energy is generated through a vibratory source. The passive method used is Refraction Microtremor (ReMi), most usually done with the same receivers as MASW at the end of the survey. Only MASW and CSW are considered further herein. As multi-phase processes there are lots of areas where approaches to survey design, data collection and analysis may vary. A summary of the steps, factors and parameters taken into consideration for the survey design identifying where differences and similarities in data collection and assessment may occur are summarized in Figure 1 (please note space precludes further detailed explanation of the methods here but the reader is directed to [3].

While published work on the application of geophysics to railway earthworks compliance is limited, several studies which are relevant have compared results and analysis of various surface wave methods to borehole geophysics. MASW and ReMi were compared with SCPT and cross-hole seismic in terms of accuracy, functionality and cost at test sites in Missouri. This showed that MASW is considered the most accurate in deriving Vs after cross-hole and the most functional regarding data acquisition and analysis, as different processors were picking the same dispersion curve [6].

A study showed the difference in Vs from MASW and direct borehole measurements on unconsolidated river sediments was 8% to 15% [7]. MASW was also tested by using a land streamer, showing good agreement with CPT [8]. The same method, together with passive surface waves analysis, was compared to in-hole methods in the InterPACIFIC Project to estimate Vs at three test sites consisting of different materials. The results of the study were analyzed by a couple of expert's teams, to compare between the assessed Vs profiles. The comparisons showed there was a relatively good match of the derived Vs, with a variability of invasive and surface methods up to 0.20 COV (i.e., Coefficient of Variation) for most depths. The study also showed that for seismic surface waves methods, the COV was augmented with depth due to the difficulty of these methods to precisely give the bedrock's velocity [9].

Seismic surface waves methods have also been used in various case studies of a railway environment. They were applied in a high-speed railway in France, and the Vs to depth results were confirmed by Bender Element technique [10]. MASW was also applied in a railway embankment in Ireland where it successfully mapped the steeply sloping bedrock [11]. More specifically for UK railways, combined MASW and CSW methods were assessed to map stiffness variations in earthworks constructed of complex and laterally varying materials [12].

However, little has been published comparing geophysical methods for earthworks compliance as part of major infrastructure projects. The relevant work also shows that the data presented after a survey can vary according to the nature of the investigation, the expected conditions and data processing and ultimately the use of the findings. It is clear there is little standardization of approach as the surveys typically form part of specialist local investigations, and that companies do not follow specific common rules when acquiring, processing and interpreting seismic data, but apply methods more based on experience. If seismic data are to be used as part of routine earthwork compliance testing, then a wider understanding of the data collection process and its interpretation is required, and a level of standardization if possible.

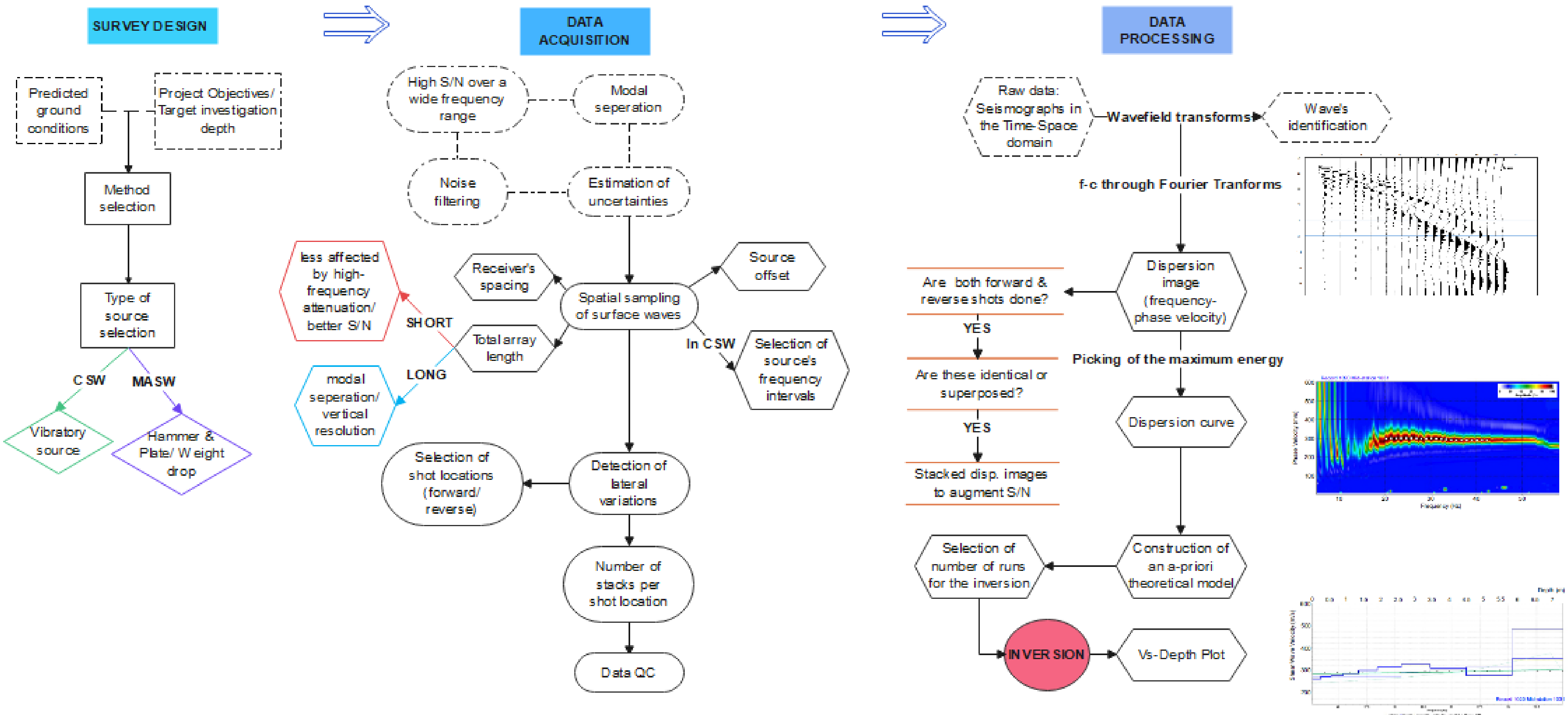

Fig. 1: Flowchart of the different considerations and steps in seismic surface wave speed acquisition and evaluation.

2. Methodology and Study Design

The purpose of this study was therefore to establish how companies in the UK approach seismic surface waves survey design for earthworks compliance via a semi-structured interview approach and by anonymously comparing their answers.

The semi-structured interviews included open-ended questions divided into themes and participants were free to elaborate as much as possible, to provide enough information about their experience with the methods. The questions used were designed from an understanding of the test process (Figure 1) and their application in railway earthworks, informed from the limited literature available: The survey was designed following standard survey methodology to minimize biases and leading questions from the interviewer [13].

The question themes were:

a) seismic survey design;
b) field equipment and data acquisition approaches;
c) data processing and interpretation;
d) benefits and limitations of seismic surface wave methods;
e) time needed for data acquisition, the number of field staff and the training they undertake;
f) possible correlations between the different methods (not covered further herein).

To reduce interviewer bias, questions were asked following the same order where possible. Four out of five main contractors currently working in the UK agreed to participate. The interview data were collected via transcript and then summarized under themes and attributes [13]. The attributes were common for all test methods (i.e., test design, data acquisition, processing and interpretation).

3. Results and Discussion

The four companies were interviewed about both invasive and non-invasive methods to derive shear wave velocity, but this paper concentrates on MASW and CSW. These two have typically been used to-date on earthwork compliance and are hence considered the main approaches. Space precludes reporting of other methods they employ, such as ReMi (Refraction Microtremor) and down hole, but they were included in the base survey.

The results are presented in themes. The general benefits and limitations of the methods identified in the surveys are outlined in Table 1, based on common grouped and tabulated responses from the interviews. Table 2 presents information on the acquisition time, number of staff participating in the field tests and the required training.

Based on the responses, MASW and CSW are the main methods, all undertaken by qualified staff (usually holding a degree in geophysics) who have significant training from within the companies. The surface methods are quicker and cheaper than invasive ones. MASW is seen as better for identification of fundamental mode (M0) than CSW, but the latter gets better frequency and depth control from the source and requires less space. In terms of time, both methods are equivalent, so overall they present their own benefits, and a choice should be made based on the needs of each project.

Further context from the interviews in addition to these main summary tables is detailed below. This reports specific issues highlighted by companies and shows differences in their company practice based on their experience. This build on the findings in Tables 1 and 2.

3.1. General questions

When selecting the most appropriate technique to use, there was agreement that this depends on the objective, the nature of the survey and the target of interest. One company highlighted that the target's depth, size, characteristics and "detectability" (i.e., easiness to identify) matter, as well as the assumed underlying geology (i.e., physical properties and likely contrasts), the site conditions (i.e., external noise that may affect the data, an important consideration for construction sites), logistical limitations for deploying the equipment and the client's budget, all impact the survey design. One firm also talked about the client's time frame, while another mentioned parameters like the ground's weathering and fracturing, stiffness and/or water table level. One said, they base their initial design decisions on experience of similar sites with similar objectives. They also use rules of thumb for the parameters being measured (survey length and maximum depth) and quite often they would not use a single method but would deploy multiple methods to give them "*the best chance of answering the questions from the client*". This implies that experience of the survey designers and analysers is vital.

Table 1: The benefits and limitations of seismic surface waves methods

Seismic Surface Waves Methods					
Benefits			**Limitations**		
MASW	CSW	ReMi	MASW	CSW	ReMi
+ Fast to implement + Cost-effective + Repeatable source + Robust identification of Fundamental Mode (M0) + Data redundancy + Various processing options + Can be used together with refraction + Good identification of soft ground + Ability to test a moving profile + Ability to switch to passive mode (if needed) + Robust to local heterogeneities + More interpretation power (versus CSW)	+ Easy to bring on site + Time and cost-effective (versus invasive methods) + Potentially quicker than MASW (6 locations/day) + Source frequency control + More resolution at the shallow + Needs less space + Resilient to background noise	+ Cheap broad Vs estimate + Greater depths than MASW/CSW	– Limited depth range – Vs estimate-uncertainty – Not always good resolution – Ambiguity in dispersion picking – Potential issues to Quality Control data on site – Sensitive to background noise	– Uncertainty of Fundamental Mode (M0) – Uncertainty (assumptions needed)	– Very coarse – No fidelity of detailed info for the top 15-20m

Table 2: The training, time and staff participating in the tests.

	Methods	
	MASW	**CSW**
Data acquisition time*	*1- 2.5 hours (just data acquisition takes less than an hour)	2.5 hours
Distance covered with a Land Streamer	***maximum of 1.500m per day Could be 200m to 1km per day, depending on number of shots*	N/A
Number of field staff	***2-3 people	2 people
Training in place	Internal online training modules and CSCS for health and safety/on the job training (inhouse training scheme-both field and classroom based) and competency sign off for technical understanding- always a lead or senior geophysicist on site/ minimum of an annual review of staff's competency matrix	
** In the case of 24 geophones, from arriving to the field till departing. In this question, an example of using 1m geophone spacing, doing a forward and a reverse shot, plus three shots at regular spaces throughout the spread, with also checking data quality for each shot gather. Assuming there are no access restrictions and that the site team can drive their vehicle to the working location.* *** In case the site is accessible (i.e., open access and flat), with 10m shooting interval.* ****In the case of 100m MASW profiling across open ground.*		

3.2. Equipment details and data acquisition approaches (MASW and CSW)

The second set of questions aimed to explore the equipment companies use, and the steps followed in the field for data acquisition. For MASW, companies mostly use a hammer (6kg standard weight), and a plate as the seismic test source. One uses hammers between 6 and 9kg and another said hammer choice depends on the desired investigation depth (heavier for deeper). All mentioned the use of an accelerator weight drop system for depths more than 50m. The literature states, that the most common 6kg hammer has limited energy in low frequencies, turning it good for surveys which map the subsurface to 10-20m depth, as is typical of railway earthworks [5]. Most use a synthetic impact plate (i.e., polyethylene), as it helps generate low frequencies. One talked of metal plates, being good for generating higher frequencies. They explained that they tend to initially experiment in their field work with combinations of hammer and plate to give the desired frequency range and signal quality. All use a standard commercial seismograph, and controller acquisition software (typically 48 channel), but the capabilities of the recording equipment does vary. While there are many consistencies in approach, the dissimilarities lead to possible differences in collected data for any given site, particularly at the margins of the survey design (high or low frequency extent of data).

For receivers, for standard MASW, all normally use 4.5Hz resonant frequency vertical spiked geophones but choose geophone's type, number (typically 24-48) and array lengths to use, based on the project (some may use 12Hz geophones as an alternative). One stated that if they required a geophone spacing of 2m and a spread length of 48 or 96 geophones, they would probably use all the geophones they have available and double the data density rather than just use 12 or 24 geophones, because "*it's better to have oversampling than risk of under sampling*". Another said that the number of receivers used might be impacted by the logistics of the available space on site for the test. Also, the spacing used could be adapted due to understanding the velocity of the near surface, so they might need to use a tighter spacing. They stated "*you really must understand why you are asked to do the survey. There is no one rule for every site, but you can have a general starting point*". They added that most typically the receiver interval would be between 1m and 2m spacing. A third company stated, "*it's the spread length that dictates the achieved survey depth and the receiver's spacing that is important to resolve soil stiffness*". All participants identified preliminary tests to see what frequency ranges they capture. More specifically, they try different spacings and impact point offsets prior to concluding on which combination is the best for a specific site or project's aims. It was noted that sometimes this can also depend on the client's available time, so assumptions are made in their tenders and therefore, there may not be time to really explore the best possible impact, offset and geophone spacing.

Two firms possess a land streamer (i.e., geophone's array, towed along the ground). They reported that these can be used to cover a large area or a long linear distance (up to 1500m per day in an accessible flat site, if using 10m shooting intervals) to profile the ground, but at the expense of precision in the measurement and the determination of representative stiffness values.

One firm reported they own several 24 or 48-channel land streamers, set for either 1m or 2m intervals, but can adjust them if needed. Both firms have found it difficult and time consuming to move the streamer on rough ground. Thus, the rapidness of the streamer versus the classic MASW can be advantageous, depending on the geophone interval, the number of shots, the evenness of the terrain and the productivity. This may offer advantages in rail earthworks compliance testing and needs further evaluation. It is clear therefore that there is some variability in the initial setup for data collection in terms of number and spacing of geophones and relative shot positions. Most adjust the survey based on initial tests and this would appear best practice.

For data acquisition parameters, all participants underlined that these depend on site-to-site assessment and that their field teams would assess the data and make sure that the ground wave signal is not reaching beyond the end of the recorded trace. It would therefore seem imperative to check that the full signal is collected in any data collection setup. One firm mostly uses 0.25msec sampling rate stating, *"that's usually sufficient to image first breaks from P-waves"* (depending on the velocities they pick on site), adding "*obviously, the faster the general materials, the greater the sample rate needed"*. However, they would usually aim to sample the dataset with enough sampling points to process for refraction if needed, even if it is not the survey's objective. The recording time length varies and would also be chosen in the field; it must be long enough to encompass the entire surface wave train. Another reported for a standard test, they mostly use a sample interval of 0.125msec and a record length of 1 sec. If they know they are in very slow material, they might extend the record length to 2sec, to guarantee they capture all the wave energy. Two firms stated that typically their sampling interval would be 0.5msec and the record length would be 2sec.

For ensuring good quality data, they focused on the acquisition protocol and the field techniques to augment the signal to noise ratio (S/N). Two companies said that they often shoot from both ends of the geophone spread, and depending on the objectives, they might get some mid-spread shots too. Another mentioned the shot interval through the spread will be double the geophone spacing, and at the processing stage they may also stack (overlay) the shot data if needed. Another said that they do forward and reverse shots, by undertaking a symmetric line (i.e., same shots at equal distances at both ends of the line, so data is collected on waves travelling in each direction). A further company shoots at both ends, if there is space available, but only shoots along the line where necessary to produce 2D profiles. It is therefore apparent that all companies have different systems and approaches to collect good wave speed data and that this if often adapted on site to make sure the data quality is suitable.

For ensuring good signal to noise ratio (S/N), one company undertakes noise test to start with, to determine the baseline for background noise, so any noisy geophones can be adjusted. Then, during acquisition, they check the shot records in real time, and if there is visible noise in the time domain, that can be eliminated during processing to minimise noise. One firm might also dig small holes or scrapes, if needed to protect geophones from wind noise. However, all said their site control includes basic checks, like a shot timing to ensure that trigger time zero recognition is consistent and stacking shots (overlaying data from the same collection point) together to improve S/N for processing. In the raw data records, they look at the interaction between body waves and surface wave's energy and may "*adjust the shot offset to separate body from Rayleigh waves"*. Based on the literature, close to the source (i.e., distance less than a wavelength) direct waves are identified instead of plane Rayleigh waves, resulting in apparent lower phase velocities, called "*near-field effects*", so offsets that are too small should be avoided. This needs to be considered in the survey design [5]. Finally, some firms look to generate field dispersion curves to assess the phase velocity- frequency relationship on site. One firm would experiment with different offsets and their field staff would decide on stacking shots during the survey. Regarding the offset, they discussed a 10km route survey with a streamer and reported that the ideal process for obtaining the most useful dispersion curve and extracting fundamental mode (M0) will never be the same for each shot along that 10km section. They recommend to always have at least two or three offsets for every streamer position, alternatively they have occasionally used additional geophones. If they design a survey with 24 geophones, but they deploy a longer spread of 48, they only need one shot, but they can process it for different offsets from that same shot. Therefore, by default, to have many more options, if they use 48 receivers, they can then choose 24 traces (i.e., from No 1-24, 2-25, 3-26 etc.) at the processing stage.

For the CSW method, all use similar systems with shaker sources, controlled through an instrumented system. They can be run through a pre-set range of frequencies 5-500Hz. They also usually have a linear array of typically 6 stick geophones which can be spaced at 0.5-1m (i.e., total test length 3-6m), depending on the general stiffness of the ground. It provides the Rayleigh wave velocity and through assumptions of soil's density and Poisson's ratio, it also calculates Vs, the shear modulus, the Youngs modulus and other parameters. Another firm uses a system with potential frequencies 5-700 Hz, but generally, they cap the top frequency used at 400Hz for rail compliance work, stating *"at data above 200Hz the wavelengths are becoming smaller than our geophone intervals, so we're reaching a sampling problem"*. One firm said they are not limited to 6 geophones and often when they do CSW, they also do MASW at the same time, so they tend to use the same recording equipment. This means that they might have more than 6 geophones set out to record more data than they necessarily need for CSW. Then, they will just select the number of geophones they want to use for the processing step.

Regarding the chosen frequencies, they collect data at customised frequency intervals, so they have a configuration file that steps up typically between 5Hz and 500Hz. It samples the lower, mid-range and higher frequency ends at different intervals. On a stiff soil, they would use a different frequency range and they would focus more time and steps at one end or other of the ranges. On softer soil the system can be set up to sample at 100Hz max frequency but undertake more surveys between 50Hz and 100Hz. Also, they can change the geophone interval to focus on the stiffer or softer soil layers. Another said the interval can be as small as 0.1Hz, obviously depending on the target depth and the amount of required data. At lower frequencies they would generally choose between 2Hz and 5Hz increments and then step them up as they get to higher frequencies, to 25Hz or 50Hz increments, depending on the survey design. The total recording time for CSW depends on the level of detail and the number of frequency intervals chosen. Typically, 20-30 mins is required, but if more detail of the subsurface is needed, with a higher number of frequency intervals required, it could be more than 1h per test. **Good data quality is ensured by** just putting the source at one shot location and checking the coherence of phase velocity difference between the geophones. One firm said they typically do not do reverse shots for CSW and they can identify the existence of any other source whose frequency coincides to the vibrator's, by the graphs per geophone they see on screen.

3.3. Data processing and interpretation (MASW and CSW)

The next questions focused on the way participants process and interpret data in the office.

For processing of MASW data, participants use either (or both) commercial and in-house software (typically MATLAB-based codes written for specific applications). However, they would probably not mix and match the two types of software, but they would rather choose which to use based on the objectives (i.e., commercial is preferred for straightforward investigations and their in-house for bespoke deliverables and more freedom in data adjusting). One contractor uses both in-house and commercial packages for different processing steps and, explained, "*with the in-house package, we pick the dispersion step manually and then we use the commercial for the inversion*".

For the dispersion curve, one stated, it is better to pick manually, as they can make a critical judgement of the picked mode, rather than relying on automatic processes and their potential overlapping errors. This is because the recognition of the fundamental mode from secondary and tertiary modes is very important for not ending up with a completely incorrect Vs model. This is also supported in the literature, as joint inversion of the fundamental and higher modes gives more reliable outcomes. However, the strategy for accounting for higher modes is not yet standardised and are not put into practice in most commercial packages [5]. It should be noted all inspect the dispersion curves to see they fit, but it seems this may vary from site to site.

One firm uses CMP (Common Mid-Point) method, so they always look at the dispersion image from the centre of the spread first. Another stacks (overlaying) their data in the frequency domain and sometimes windowing (a process to focus with a "*frequency grouping*") may be applied if it improves the result in terms of the appearance of the higher modes. These are picked and included in the inversion because "*it's just extra information that will help deliver the best ground model*". A further company applies minimal and cautious windowing and muting techniques to improve the low frequency part of the dispersion image. However, it should be noted that caution is needed here in any smoothing as these may change the apparent velocity. They also interpret each dispersion image individually and do not stack them, as it can be misleading if they get one or two shots that are showing up a higher order mode which can pollute the image. As input parameters for the construction of the starting model, all used P-wave velocity (Vp), Vs, Poisson's ratio, number of layers and soil density, derived from nearby borehole logs if available or other desk study sources if not to give a starting point for iteration.

Within the construction of the final Vs model, an initial ground model for the site is required and fitted to the site data, and most firms generally follow a broadly similar process. One company primarily inputs the measured Rayleigh wave curve, derived directly from the experimental data, and then inputs the chosen ground model used to run the inversion.

Within their software, they can also add water table depth, whereas others may not. Another explained that sometimes, in case of absence of borehole logs for the input parameters to the ground model they just make their best estimate based on the expected geology. They would also use if required data from geological maps, these being a good guide but lacking detail for very shallow MASW work. Nevertheless, if a ground investigation has already been done, providing specific density values, then all firms use them in their analysis (significant for earthworks and made ground). Another added that the parameters "*are derived from a combination of known geology, textbook values, site conditions and the experimental dispersion curves*". Their approach is to always use as much a priori geotechnical information as possible when building their initial model, and then it goes through an iterative process of varying these parameters to provide the best fit to the data, that is "geologically plausible". One firm added that "*if we are trying to determine the number of ground layers to use, this must be primarily done through boreholes*". Yet, they also do parameterisation testing within their modelling, by mainly "*holding a fixed number of iterations within a model and then create models with for example 2-10 layers, then compare the RMS misfit as a function of the number of layers and look at where the difference changes*". This is regarded as important to look at, even with available borehole data, "*because a visual change, defined in a borehole log, doesn't necessarily correspond to a density or a measurable change in Vs*". One company also re-informs the initial model to adjust it and re-run the inversion if they are unsatisfied with the first iteration results. They would also test the number of layers by starting with typically a 10-layer model and if they find that their dispersion curves do not have many points on them (i.e., they have not resolved a wide range of frequencies and the model is unstable), then they might reduce the number of layers.

As for the number of runs and the threshold of fit imposed, one company said that the software defaults to 5 iterations, which are sufficient to derive a suitable model for most purposes. However, they believe that to derive arguably the best fit model, doing some testing is also sensible. This means that they would run some models with an iteration range "*but would always aim for the simplest best fit model to the data, by checking whether subsequent iterations are no longer drastically reducing the RMS misfit*". Another agreed that the iteration's number is variable for each shot, but generally they are aiming at an RMS error of less than 5-10%. Another uses all 30 iterations that the software goes up to, as there is no option to put in a convergent limit. Another uses 10 iterations, as a default maximum. Most (if they can) stop the iteration when they see that the model is not improving its convergence. Therefore, while a similar process is used, there is a clear difference in the choices taken to assess the final Vs information based on the nature of the ground models used. This can be due to the number of layers put into the model, the number of steps in the processing to gain convergence or best fit to the initial model and the availability or assumptions made about initial soil properties (and which properties to include).

For CSW data processing, according to one firm, the output is like MASW, as they both work on the same principle. They use an in-house MATLAB code, and the model input parameters are similar to MASW, based ideally on borehole data. Another checks each receiver's signal and cleans up any background noise within the software. They then plot either shear modulus or Vs and V_R against depth in Excel. They commence by looking at the stiffness against depth plots and the coherence values of each geophone at each frequency. Shear modulus and wave velocities are calculated within their software, from the time domain data, through a fast Fourier transform.

So again, the processing of data varies and relies heavily on the experience of those doing the analysis, the way the data has been collected, the software and any smoothing needed. This again could lead to areas of variability in the final results and shows that during data collection consideration must be given to subsequent processing.

4. Conclusions

This study revealed that companies undertaking seismic surface waves surveys for railway earthwork compliance follow the specific survey specifications (based on understanding the survey's purpose), in conjunction with their experience of similar testing in similar soils. While some survey methods may be quicker to implement, the quality of the results depends on the staff's experience obtaining good site data and adapting the survey as they proceed, but also consider subsequent analysis during collection.

The design element and expert's input from the beginning until the end of each survey is crucial with the test protocol depending on two parameters, the site materials and the purpose of the test. Data quality control on site is important, as specific techniques can reduce data noise and help analysis and interpretation in the office. Each firm has broadly similar but slightly different approaches to collecting, smoothing and processing data. However, it appears there is no individual process to follow for seismic surface wave methods, as one specific method would not always be useful and relevant to every site.

The interviews showed there are differences in array lengths used, shot locations, extent of data collected and data processing. There were differences in the inversions assessed and the models then used based on available ground information and survey quality. This leads to firms using different numbers of layers in models and different number of calculation iterations to get best fit. All these factors may influence the final output data.

While there can perhaps be no standard overall process, there is scope to inform best practice guidance or standardise elements of testing for surveys used for railway earthworks compliance (where the survey is linear over an extended length but limited in depth, and the evaluation is specified against pass and fail criteria for the works). Such standardisation could centre around defining best practice for the survey sample rate, the sample time, the length of geophone string to be used, the shot locations/offsets, the geophone spacing and the target wave frequencies to be assessed. There may also be scope to inform best practice guidance for the analysis, in terms of steps of data quality assessment for smoothing or ground model inputs. This would then give more comfort that different contractors have handled data in a similar way or followed best industry practice. Additionally, standardisation for best practice would allow for optimisation of surveys in terms of time or resources required on site.

As a next step in the research, the interviews have been used to design an experimental study including MASW and CSW on a trial embankment including testing by several firms, to check the reliability and the repeatability of the methods and inform the development of best practice.

Acknowledgements

The authors would like to acknowledge all companies for accepting to participate anonymously in this study and sharing their experience.

References

[1] Gao, Y., Huang, H., Ho, C. L., & Hyslip, J. P. (2017). High speed railway track dynamic behavior near critical speed. *Soil Dynamics and Earthquake Engineering*, *101*. https://doi.org/10.1016/j.soildyn.2017.08.001

[2] Woodward, P. K., Laghrouche, O., & El-Kacimi, A. (2013). *THE DEVELOPMENT AND MITIGATION OF GROUND MACH CONES FOR HIGH-SPEED RAILWAYS*.

[3] Foti, S., Hollender, F., Garofalo, F., Albarello, D., Asten, M., Bard, P. Y., Comina, C., Cornou, C., Cox, B., di Giulio, G., Forbriger, T., Hayashi, K., Lunedei, E., Martin, A., Mercerat, D., Ohrnberger, M., Poggi, V., Renalier, F., Sicilia, D., & Socco, V. (2018). Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project. *Bulletin of Earthquake Engineering*, *16*(6), 2367–2420. https://doi.org/10.1007/s10518-017-0206-7

[4] Park, C. B., Miller, R. D., Xia, J., & Ivanov, J. (2007). Multichannel analysis of surface waves (MASW) - Active and passive methods. *Leading Edge (Tulsa, OK)*, *26*(1). https://doi.org/10.1190/1.2431832

[5] Foti, S., Lai, C., Rix, G. J., & Strobbia, C. (2014). Overview of surface wave methods. In *Surface Wave Methods for Near-Surface Site Characterization*. https://doi.org/10.1201/b17268-5

[6] Anderson, N., Thitimakorn, T., Hoffman, D., Stephenson, R., & Luna, R. (2007). *A Comparison of Four Geophysical Methods for Determining the Shear Wave Velocity of Soils*.

[7] Xia, J., Miller, R. D., Park, C. B., Hunter, J. A., Harris, J. B., & Ivanov, J. (2002). Comparing shear-wave velocity profiles inverted from multichannel surface wave with borehole measurements. *Soil Dynamics and Earthquake Engineering*, *22*(3). https://doi.org/10.1016/S0267-7261(02)00008-8

[8] Dietrich, P., Kretschmer, F., Vienken, T., & Popp, S. (2009). Combination of different seismic methods and geotechnical sounding for a rapid characterization of the near-surface ground. *EGU General Assembly Conference Abstracts*, *11*.

[9] Garofalo, F., Foti, S., Hollender, F., Bard, P. Y., Cornou, C., Cox, B. R., Dechamp, A., Ohrnberger, M., Perron, V., Sicilia, D., Teague, D., & Vergniault, C. (2016). InterPACIFIC project: Comparison of invasive and non-invasive methods for seismic site characterization. Part II: Inter-comparison between surface-wave and borehole methods. *Soil Dynamics and Earthquake Engineering*, *82*. https://doi.org/10.1016/j.soildyn.2015.12.009

[10] Bodet, L., Pasquet, S., Dhemaied, A., Boisson-Gaboriau, J., Cui, Y. J., Leroux, P., Nebieridze, S., Tang, A. M., Terpereau, J. M., & Vitale, Q. (2015). Seismic surface-wave analysis for railway platform auscultation. *Near Surface Geoscience 2015 - 21st European Meeting of Environmental and Engineering Geophysics*. https://doi.org/10.3997/2214-4609.201413802

[11] Donohue, S., Gavin, K., & Tolooiyan, A. (2011). Geophysical and geotechnical assessment of a railway embankment failure. *Near Surface Geophysics*, *9*(1). https://doi.org/10.3997/1873-0604.2010040

[12] Gunn, D. A., Donohue, S., Dashwood, B. A. J., Bergamo, P., Raines, M. G., Uhlemann, S., & Chambers, J. E. (2015). Earthworks ground model development using surface wave surveys. *Geotechnical Engineering for Infrastructure and Development - Proceedings of the XVI European Conference on Soil Mechanics and Geotechnical Engineering, ECSMGE 2015*, *6*.
[13] Collis, J., & Hussey, R. (2013). Business Research A Practical Guide for Undergraduate and Postgraduate Students 3rd edition. In *palgrave* (Vol. 142).