VALIDITY OF ACSW DATA

Guidance Note SSGN029

Introduction

Advanced Continuous Surface Wave (ACSW) is an engineering ground stiffness testing system developed by SoilSafe Limited. ACSW uses Rayleigh wave velocity (V_r) measured over a range of discrete frequencies (wavelengths) to determine ground stiffness. A surface vibrating source ('shaker') generates a range of test frequencies and Rayleigh wave velocities are progressively measured as change in wave phase angle along a short array of 6 geophones with known spacings.

The ACSW source and data collection are controlled by SoilSafe C-DAS software which undertakes automatic quality checks on data. C-DAS automatically processes the digital test output to generate a dispersion curve (V_r against f), from which an approximate average shear wave velocity (V_s) with depth profile for each data point is generated (the 'simple inversion'). C-DAS is subsequently used to invert the dispersion curve data by mathematical modelling ('advanced inversion') to provide a layered shear wave velocity profile (V_s against depth), which is the ultimate output. This shear wave velocity profile can be converted using well-understood relationships to a stiffness profile (e.g. E or G against depth).

This guidance note summarises the theoretical errors for ACSW based on validation studies completed by SoilSafe and explains qualitatively the controls which limit the effects of these errors on the stiffness profiles generated by ACSW.

Key Features of ACSW

There is extensive data to support the accuracy of ACSW stiffness data when compared against other forms of in situ stiffness measurement (see SoilSafe Guidance Notes SSGN013 & SSGN016). ACSW data can be readily shown to provide better stiffness data than commonly used empirical relationships (for example between SPT N and stiffness) and to demonstrate ACSW data equivalence with more expensive high-quality stiffness data, such as large-scale load test data (see SoilSafe Guidance Note SSGN018) and pressuremeter data (see figure 1).

ACSW theory assumes cross-isotropic ground conditions with a consistent Vr value over the length of the geophone array and that the dominant measured frequency is that being generated by the shaker. Consistency of phase shift across the geophone array and match of dominant frequency to shaker frequency are automatically checked by C-DAS. Any out-of-tolerance performance of any or all geophones is therefore automatically highlighted and can be discounted in considering the accuracy of data. C-DAS also provides

automatic display features which allow easy data comparison and assessment in the field to identify and evaluate discrepancies in profiles generated.

Advanced inversion involves applying a forward model to an assumed layered Vs profile to generate a synthetic dispersion curve which is then compared against the field dispersion curve (edited to remove data not meeting quality checks, debatable data or outliers). The layered V_s profile is then iteratively adjusted using an automated search method in order to determine the best fit profile meeting pre-set termination criteria.

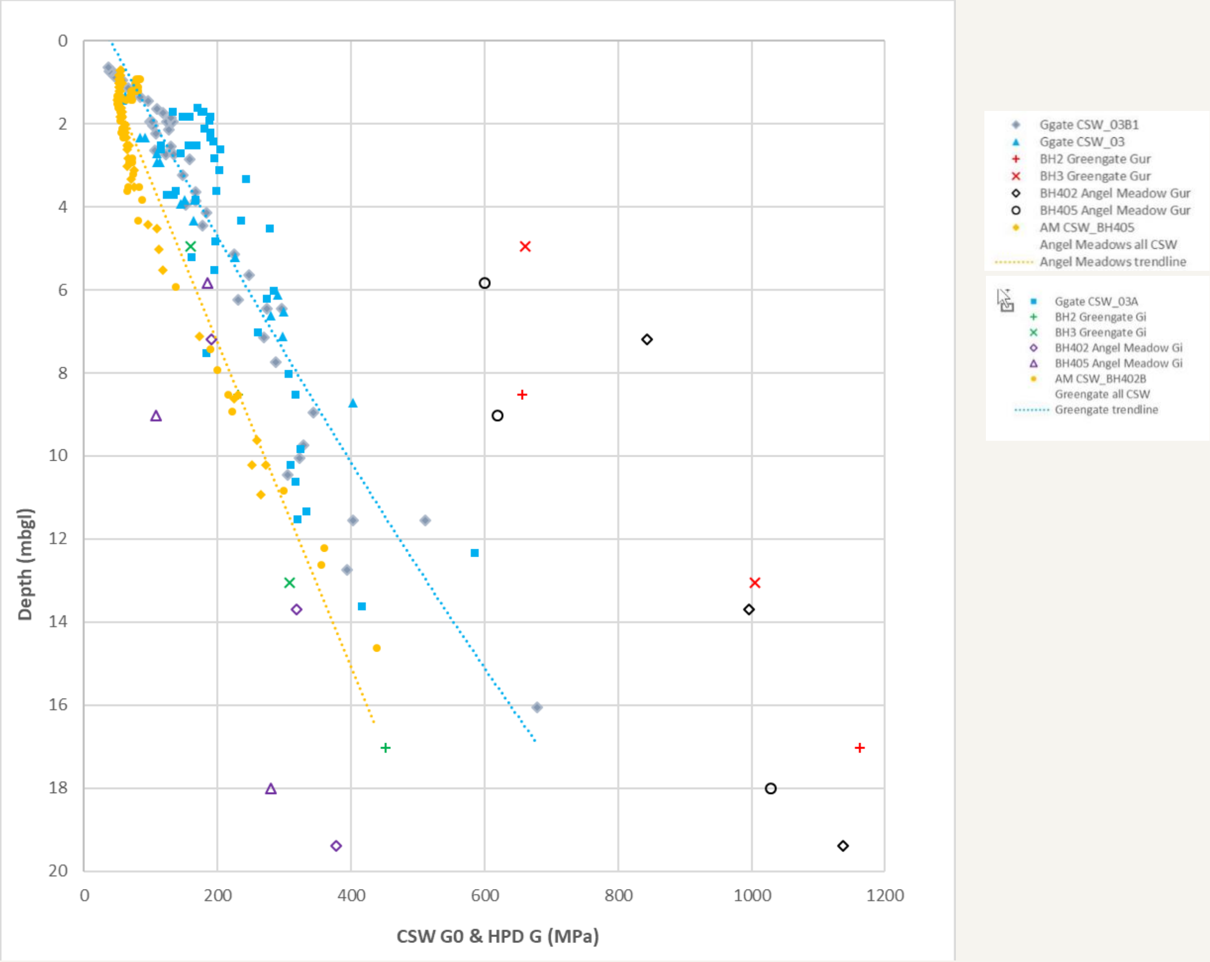

Figure 1: Comparison between ACSW simple inversion data (in blue & orange) and pressuremeter data in Sherwood Sandstone – note scatter in pressuremeter data.

The theoretical accuracy of ACSW data is therefore a combination of:

- **The accuracy of measurements made by the testing system used to generate the field dispersion curve**
- **The accuracy of the numerical inversion process used to translate the field dispersion curve into a stiffness profile**

Some of these theoretical errors are significant but are inconsistent with the demonstrated accuracy of ACSW data compared to other types of test data.

This is explained by the constraints which restrict errors introduced in the measurement and analysis of ACSW data as follows;

- Optimised test methodology
- Continuous data acquisition at monotonic frequencies across 6 geophones providing significant data redundancy and causing random system noise to be attenuated
- Advanced control features within C-DAS undertaking automated data quality checks and providing real-time visual output
- Sophisticated inversion software providing a range of search algorithms and forward models permitting the widest range of field data to be inverted
- Ability to stack field data to assist identification of spurious data

Field Measurement Accuracy

The field data acquired is used to generate a dispersion curve which is the basis for all subsequent data processing. Generation of the dispersion curve relies on the accurate definition of three parameters;

1. Geophone spacing
2. Phase shift
3. Test frequency

System accuracy in the field is assessed by both automatic data quality checks within C-DAS and experienced user checks made via interrogation of data using C-DAS displays in the field and prior to inversion. A key control is the ability in C-DAS to compare test data in the field, including continuously plotting data against previous tests to identify variations in data quality. The speed of data collection (approx. 6 minutes for 60 test frequencies between 8-91Hz) means that tests can be rapidly repeated allowing for ready stacking of data. The ability to easily compare similar test locations is an important control to potential dispersion curve data errors; multiple tests are always recommended by SoilSafe for this purpose.

Due to the averaging effect of the ACSW data acquisition system which measures velocity across 6 geophones (only 2 required) and over 100 wave cycles (only a single cycle required) theoretical total system errors with a 95% confidence level can be shown to be better than 15% at 10Hz reducing rapidly with increasing frequency to around 5% at 90Hz for a typical geomaterial with mid-range V_r value of 200m/s. Accuracy improves for lower velocity (lower stiffness) materials which are typically the materials of greatest concern to Geotechnical Engineers. The sources of error in field measurement and their controls are summarised in Table 1 below.

In addition to inherent errors in field measurement spurious data may be generated by a number of sources. These sources and the controls implemented to limit their effect are summarised in Table 2 below.

Table 1: Sources of error in field measurement and their controls.

Parameter	**Source of error**	**Control**	**95% confidence error**
Geophone spacing	**Inaccuracy in geophone spacing**	**Careful field technique reduces typical spacing error to better than ±5mm** **Cumulative error from random variations in geophone spacings over 6 geophones reduced from individual pair error**	**<0.5%**
Phase shift	**Phase lag response differences between geophones**	**Calculated phase angle for each geophone at dominant frequency averaged over 100 cycles improving numerical precision and reducing cumulative effect of random errors in geophone mechanical system** **Errors are averaged over 6 geophones via use of best fit line to phase shift data**	**<9% (10Hz)** **<5% (90Hz)**
	Numerical imprecision due to limitations of A/D sampling frequency	**High speed sample rate combined with averaging of calculation over 100 wave cycles and 6 geophones**	
Frequency	**FFT theory limitations**	**Use of numerically efficient FFT methodology**	**<1% (>45Hz)** **<3% (<45Hz)**
	Source signal generation, shaker response, geophone accuracy,	**Use of high-quality system components**	

	signal amplification		
	Numerical imprecision due to limitations of A/D sampling frequency	High speed sample rate combined with averaging of calculation over 100 wave cycles and 6 geophones	

Remaining inaccuracies are further reduced through the plotting of data as part of a continuous dispersion curve as considered by the inversion process, including the appropriate editing and stacking of data which limit the effects of scatter in the data resulting from individual datapoint inaccuracies. In addition, errors in a limited number of frequencies are not significant to defining the dispersion curve due to the large number of frequency points measured.

The low level of system measurement error is illustrated in Figure 2 below which shows the results of two repeated tests at the same test location with individual frequency/velocity measurements showing a high degree of repeatability.

Table 2: Sources of spurious dispersion curve data.

Source of error	Control
Aliasing at high frequencies	Isolated data points or highly scattered data at the extreme high frequency range normally discounted Data edited with reference to adjacent tests allowing potentially spurious profiles to be identified Where appropriate, stacking repeat test data and/or curve fitting to define reliable dispersion curves Geophone spacing reduced where high frequency data of particular importance
Inaccurate wave definition at low frequencies	Use of low natural frequency geophones Isolated data points or highly scattered data at the extreme low frequency range normally discounted Geophone spacing increased where high frequency data of particular importance Use of high energy shaker to improve signal strength at geophones

Dominant frequency recorded due to other nearby sources	Automated removal of dominant signal frequencies beyond pre-set limits from generated frequency Energy sources not aligned with geophones will fail the phase shift consistency test due to inconsistent distances to source
Dominant frequency recorded represents P/S wave propagation	Data points generated easily identified as due to other seismic wave activity
Higher mode ground response	Data points generated generally readily identified and largely confined to higher test frequencies Available forward models in CDAS permit analysis of multi-modal data

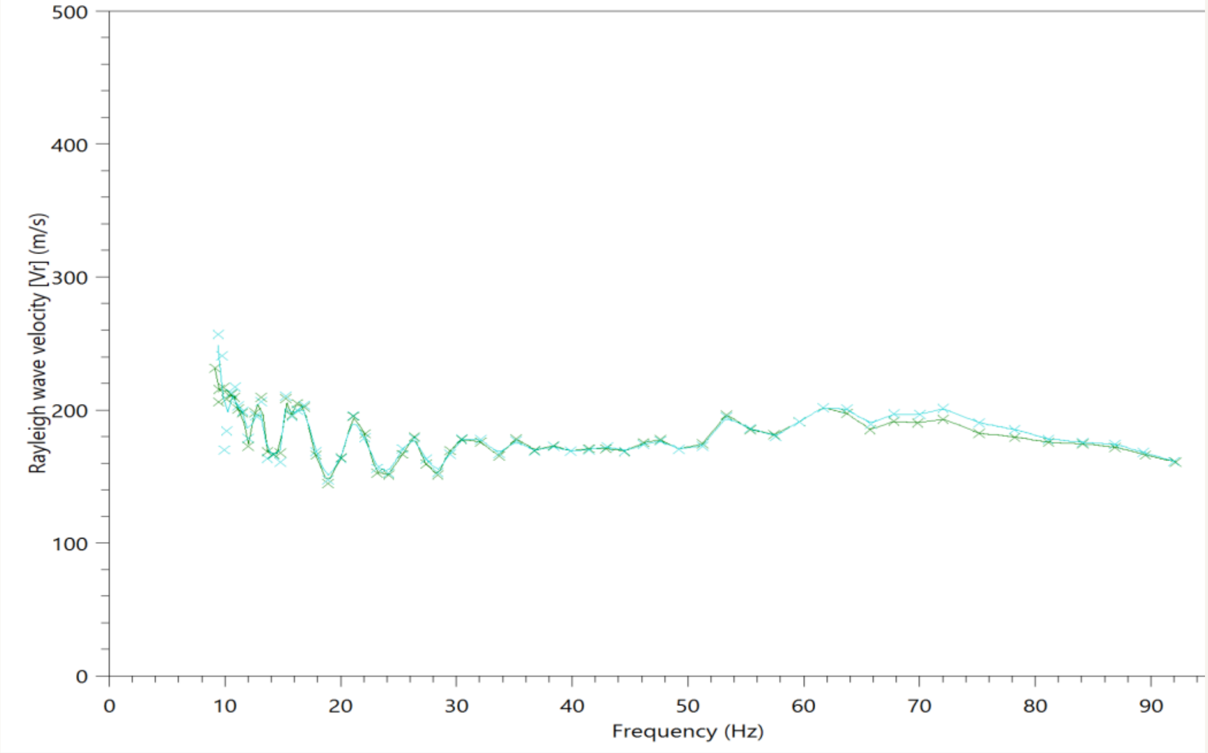

Figure 2: Field data repeatability in C-DAS – dispersion curve for repeated tests.

Inversion Accuracy

Advanced inversion accuracy is determined by the extent to which the modelling employed generates a stiffness profile which is consistent with the known ground conditions. In practice reliable stiffness data is normally not available to assess the results of inversion and evaluation of accuracy/reliability must be undertaken by a combination of comparisons between:

- **fit of the synthetic dispersion curve model & the field data**
- **the independently generated simple inversion profile & the layered model profile**
- **available information on ground conditions & the layered model profile**
- **the layered model profile & those for similar test locations**

Table 3: Sources of spurious dispersion curve data.

Error	Source	Control
Inappropriate forward mode	Incorrect identification or consideration of modes (e.g. treating higher mode as fundamental or vice-versa)	Information on ground conditions will highlight the potential for higher mode data. The presence of higher modes is normally readily identified as steps or sharp jumps in the dispersion curve. Variations between similar test locations highlights potential mode differences. Data is conservatively edited to remove data where the mode is unclear (e.g. very scattered or outlying data). Forward model output considered as part of overall quality control by comparing outputs for similar test locations against known ground conditions and against the simple inversion profile.
Forward model limitations	Oversimplification of Vs profile due to mathematical limitations of available forward models	Layers thinner than those that can assumed by the model will be averaged. Data generated by sharp boundaries will not be considered by models but is highlighted in the simple inversion data for assessment against available information on ground conditions. Where these are affecting model fits the dispersion curve is suitably edited.
Misfit to data	The synthetic dispersion curve does not provide a good fit to the field dispersion curve	The significance of the level of misfit can be assessed by comparison of the model against known ground conditions, the simple inversion profile and adjacent tests.

Whilst the inversion of dispersion curve data is considered to be a mathematically 'ill posed problem' (meaning that there is no unique solution using the dispersion curve data alone), in reality modelling can be constrained using readily justified assumptions and an experienced modeller. In particular:

- **The range of test frequencies limits the number and thicknesses of layers that can be reliably modelled. Allowing for this (by using appropriate numbers of layers and thicknesses derived empirically) limits the achievable model resolution but removes the potential for the generation of unrepresentative extreme stiffness values for very thin layers. Initial sensitivity analysis is used to optimise model layer constraints within the empirically derived layer number and thickness defaults**
- **The potential variation in soil properties used for modelling are relatively small (e.g. soil density, Poisson's ratio, maximum and minimum Vs values)**
- **Some information on ground conditions is always available in the form of site observations and geological mapping from which some information on soil properties, boundaries and likely Vs profile can often be obtained. In addition, some intrusive information (e.g. nearby published boreholes) is often available to supplement this**
- **The simple inversion describes the average Vs profile and hence indicates whether profiles are normally or inversely dispersive, a significant modelling constraint**
- **The simple inversion profile provides an additional limit on the extent to which the modelled layered advanced inversion Vs profile can reasonably deviate from the average. This allows a further modelling constraint (the Simple Inversion Weighting) to be employed removing any extreme modelling artefacts and hence further limiting the valid models possible**
- **Simple inversion data gives an indication of boundary depths which can be correlated with any available information on ground conditions for model evaluation/constraint (see figure 3)**
- **The consistent application of constraints for tests with similar expected ground conditions allows the applicability of inversion models to be assessed by comparing the resulting Vs profiles. Since similar profiles would be expected for tests on similar ground conditions, this evaluation effectively provides a further modelling constraint. For this reason, multiple tests are always recommended so that tests where results are anomalous potentially requiring further investigation or consideration may be identified (see figure 4)**
- **Undertaking inversion on combined test data with similar ground conditions provides a check on the significance of any differences in the field data at individual test locations and thereby the robustness of the model used.**

VALIDITY OF ACSW DATA

Validation analyses undertaken assuming good quality effective dispersion curve data and a simple, maximum 20m depth ground model with layer stiffness contrasts in excess of 25%, confirms that using C-DAS:

- **Vs can be determined with a very high degree of accuracy (within 1.5%) where layer boundaries & Poisson's ratio are known.**
- **Vs and layer boundaries can be determined within 30% with no prior information on boundaries and an assumed Poisson's ratio.**

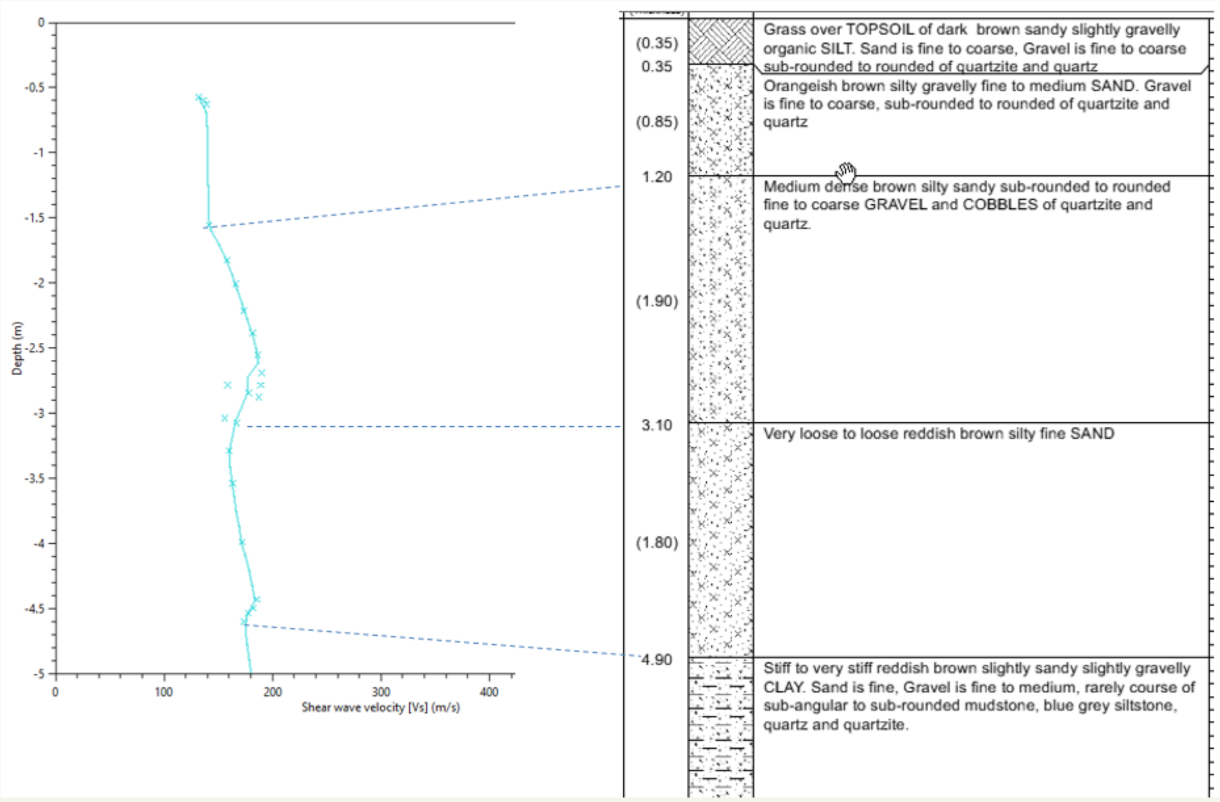

Figure 3: Boundaries indicated by simple inversion data.

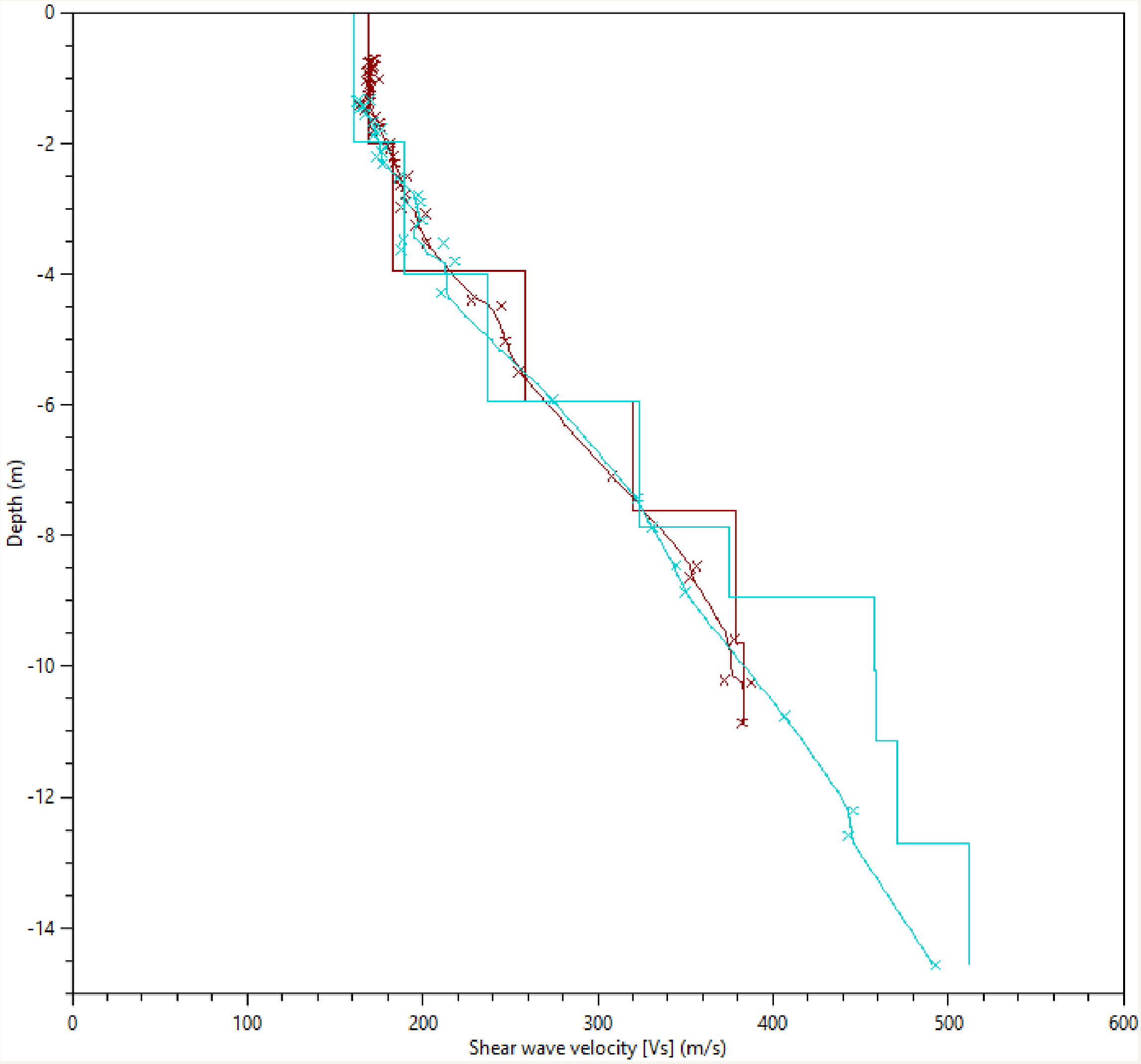

Figure 4: Evaluation of inversion modelling in C-DAS by comparison with similar adjacent tests and simple inversion data.

Resultant Accuracy

No stiffness test data can be considered as objectively accurate given than the 'true' bulk stiffness

of the ground for geotechnical design can only be determined by the long-term performance of specific structures once built. In considering the theoretical accuracy of ACSW data it is important

to remember the fundamental limitations of many other stiffness measurements which may be influenced by effects which do not apply to ACSW data, namely:

- **inaccurate or difficult to define empirical relationships (e.g. SPT data)**
- **uncertain strain levels (e.g. plate load tests)**
- **soil disturbance (e.g. sampling for laboratory testing)**

- **small scale local stiffness variations which may not represent the bulk properties of the soil (e.g. intrusive testing)**

These effects are likely to be the most significant influence on the accuracy of stiffness measurement for design purposes and explain the large degree of scatter often seen in commonly obtained stiffness data and which often leads to calculated and actual ground movements differing by a factor of 2 or more. Even where stiffness measurements are of the highest quality (e.g. Crosshole seismic testing or large-scale load tests) the cost and time involved with obtaining these limits their application compared to more rapid and cost-effective ACSW testing.

Whilst there are a number of elements which can introduce significant theoretical errors to ACSW data, the range of controls employed in analysis of the data by experienced users support the conclusion from empirical comparison that ACSW stiffness data is at least as accurate as that derived from other commonly used high quality in-situ stiffness testing (see figure 5).

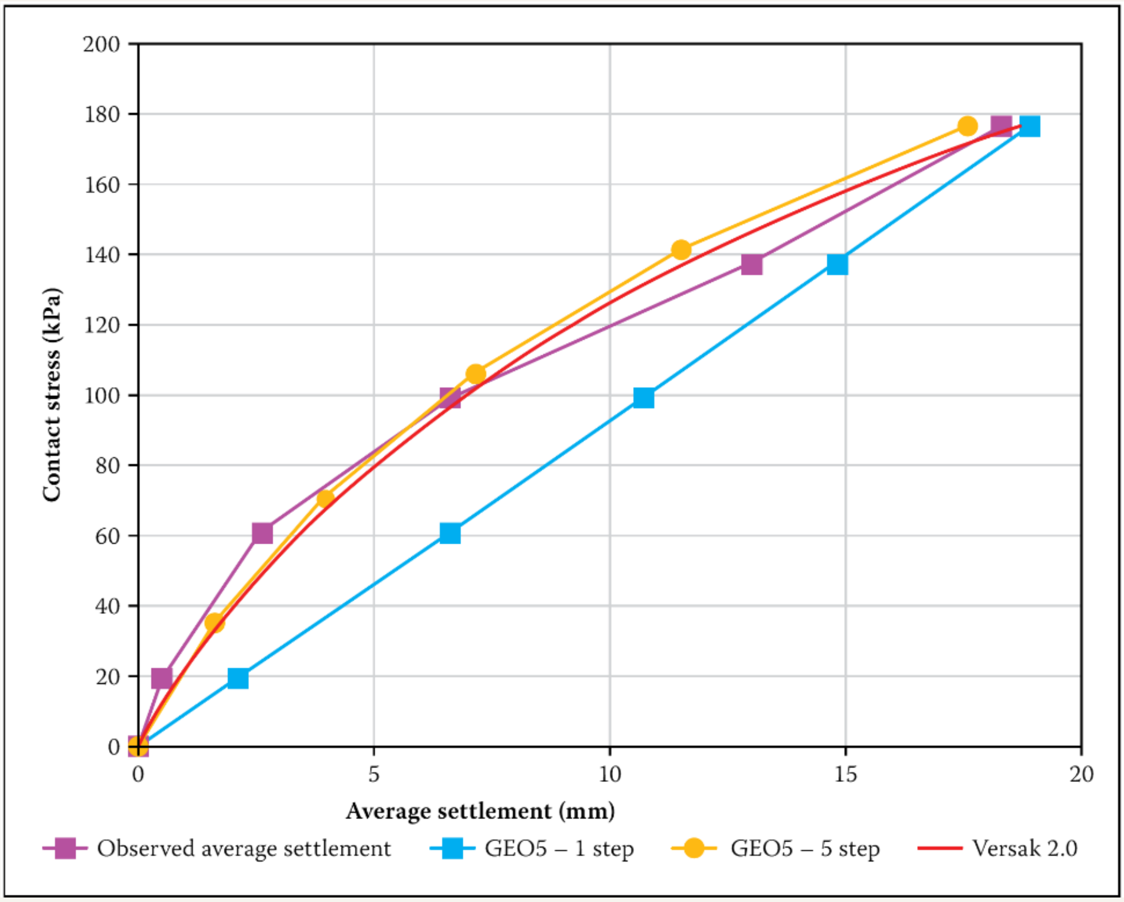

Figure 5: Comparison between predicted settlement using ACSW data using standard linear elastic software and actual settlement for large scale load test.

Heymann, G., Rigby-Jones, J., Milne, C.A. (2017) The application of Continuous Surface Wave testing for settlement analysis with reference to a full-scale load test for a bridge at Pont Mein Rûg, Wales. SAICE journal.

References

- **SSGN013 Comparison of ACSW testing with stiffness measurement by empirical relationships with other soil properties**
- **SSGN016 Comparison of ACSW testing with stiffness measurement by other seismic techniques**