COMPARISON OF ACSW TESTING WITH STIFFNESS MESUREMENT BY OTHER SEISMICS TECHNIQUES

Guidance Note SSGN016

Introduction

The accuracy and reliability of the Advanced Continuous Surface Wave (ACSW) testing data has been reviewed in detail in SoilSafe Guidance Note SSGN009. Here it was noted that seismic techniques, such as ACSW testing, measure stiffness in the very small-strain linear region of the strain stiffness response curve (*see Figure 1 below*). This has the advantage of providing a reference stiffness value which can be readily adjusted for design strain levels and makes seismic techniques attractive for accurate determination of soil stiffness properties.

This guidance note reviews the commercially available seismic techniques which can be used to determine ground stiffness and compares each with the ACSW testing technique. The range of seismic techniques has been divided into the intrusive techniques which require one or more boreholes and non-intrusive techniques which are undertaken entirely from the surface.

A summary table is provided at the end of the guidance note.

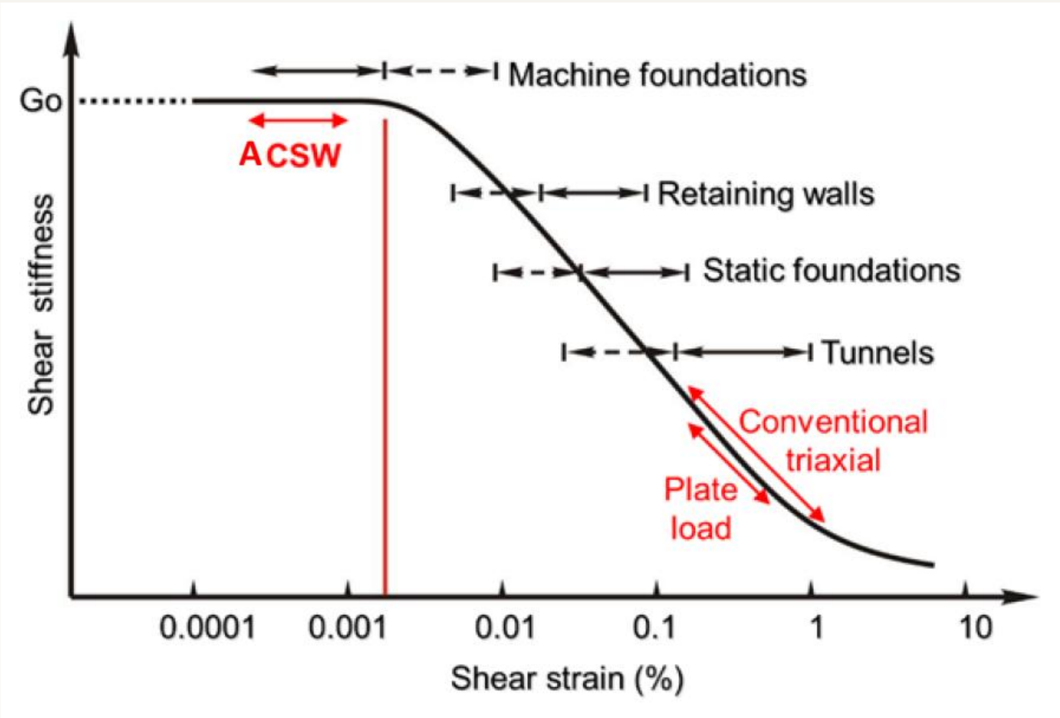


Figure 1 Typical strain stiffness response of soils showing strain levels associated with common geotechnical problems

Basic Seismic Principles

Seismic techniques rely on the characterisation of elastic waves as they propagate through the sub-surface. There are two categories of seismic wave; body waves and surface waves. The propagation of both types categories of waves is a function of the density and elastic properties of the ground.

Body waves propagate outwards from the source and comprise compressional (P) and shear (S) wave. P waves are the fastest seismic wave and are transmitted through both the pore water and soil skeleton. For soils the first arriving P waves will be transmitted by the pore water with waves travelling through the soil skeleton arriving later. The difficulty in accurately assessing the arrival time of the soil skeleton P waves makes them unattractive for stiffness measurement techniques. S waves are the second fasted seismic wave and are transmitted by the soil skeleton alone. As such the velocity of S waves (V_s) is a useful measurement for geotechnical investigations as it is directly related to shear stiffness through a relationship with density ($G = \rho.V_s^2$). Whilst the ray paths of body waves are straight, they may be refracted at boundaries of sharp stiffness contrast complicating the assessment of the wave paths necessary to calculate velocities.

Surface waves are formed by the interaction of P and S waves in proximity to the ground surface and consist of Love and Rayleigh waves. Love waves travel with a motion perpendicular to the direction of travel and are the weakest seismic wave which limits their use in geophysical investigation. Rayleigh waves propagate with a retrograde elliptical path in the vertical plane and attenuate more slowly than other seismic waves. They also represent 2/3 of the source energy; the remaining 1/3 producing all other wave types. These two features make the use of Rayleigh waves particularly attractive for geotechnical investigation due to the ease with which high quality Rayleigh wave signals can be generated and Rayleigh wave velocity (V_r) measured. V_r can be simply converted to Vs (and hence shear stiffness) through an insensitive relationship with Poisson's Ratio. *Further information on this process is provided in Guidance Note SSGN009.*

Sources can either be user generated (Active) or natural ambient sources (Passive). The passage of seismic waves is measured using sensors which respond to either amplitude or acceleration of ground movement (accelerometers and geophones).

Intrusive Seismic Techniques

Intrusive techniques position either the source and or receiver within the ground for which seismic velocity (and hence stiffness) measurement is required. The range and configuration of the various methods available are

shown in Table 1. Reliability and resolution is influenced by ray path length and orientation between source and receiver. All intrusive methods endeavour to measure both V_s and P wave velocity (V_p), subject to the difficulties described above over selection of the correct first arrival times, which permits calculation of Poisson's ratio. Provided that the first arrival times are correctly picked, intrusive seismic techniques have an advantage over non-intrusive methods in not requiring complex interpretation and solution of an inverse mathematical problem.

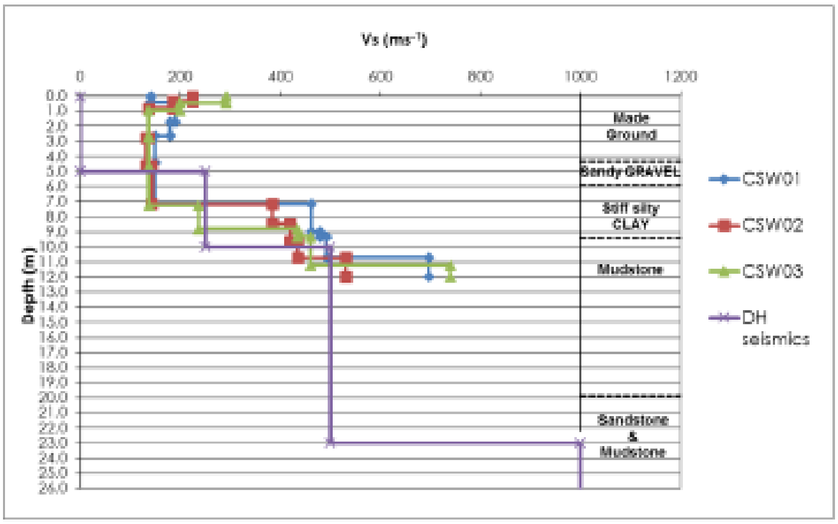


Figure 2: Blind trial between downhole seismic and ACSW data

In general, one or more boreholes are required for intrusive seismic techniques which makes them significantly more expensive than non-intrusive techniques. Whilst it has historically been considered that cross-hole measurements made between multiple boreholes are more reliable due to more simply interpreted ray paths, the recent InterPACIFIC research project (ref. Garofalo et al, 2015) found similar results and precision at a range of test sites using both down-hole and cross-hole methods.

Trials have been undertaken at the Surrey Research Park test site near Guildford, UK (see Figure 3). This site was the subject of intensive research into the use of field seismic geophysics (downhole, cross-hole and ACSW) for stiffness measurement during the early 1990's (Gordon,1997). Further testing was undertaken in 2011 to validate the performance of its in house ACSW testing equipment against the high-quality historical data available. Figure 3 shows both the historical and recently acquired ACSW data.

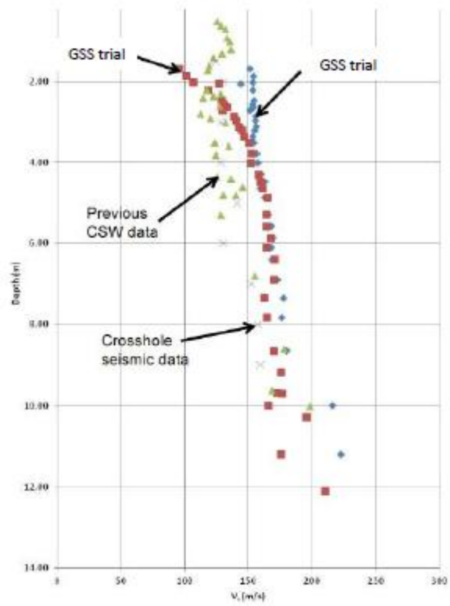


Figure 3: Comparison between published CSW test data (Gordon, 1997) and GSS test data at Surrey Research Park site 2011

The results show a close correlation between the ACSW data and the historically obtained CSW (a forerunner to ACSW) and cross hole data. It is noted that the ACSW data exhibits less scatter and a greater depth of penetration than the historical CSW data. Differences between the data sets at shallow depths relate to changes in groundwater levels since that time due to development of the Research Park. Similar close correlation between downhole seismic and ACSW data is shown in the results of the blind trial presented in Figure 2.

The InterPACIFIC project (Garofalo *et al,* 2015) was undertaken to independently compare the results of surface wave methods (non-invasive) and downhole seismic techniques (invasive). The results shown in Figure 4 below demonstrate the close correlation in the results obtained by these two techniques. Since downhole seismic techniques directly measure Vs velocities correlation between this data and surface wave techniques conclusively confirm the validity of the ACSW technique in measuring V_s.

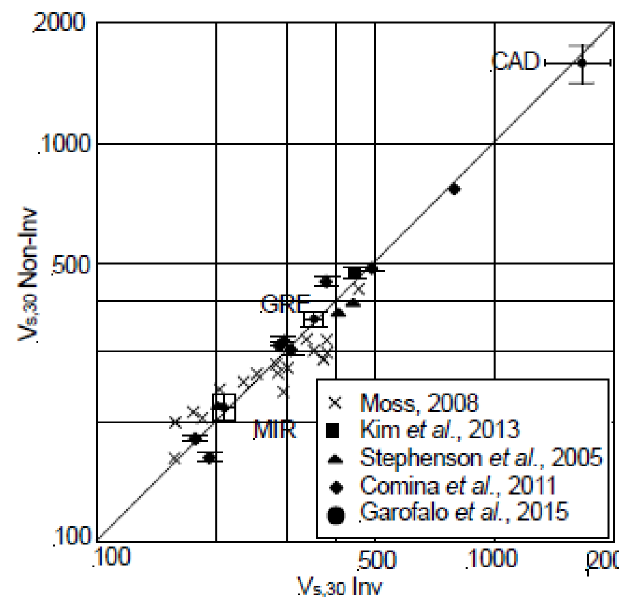


Figure 4: Comparison of $V_{s,30}$ values (standardised V_s to a depth of 30m) from invasive and non-invasive methods in the study InterPACIFIC study and others from Garofalo *et al*, 2015

It must be noted however that in contrast to the ACSW measurements down hole seismic techniques endeavour to measure both P wave and S wave velocities permitting calculation of Poisson's Ratio which cannot be determined from ACSW testing. Cross hole seismic techniques also provide greater resolution at depth than surface techniques such as ACSW and downhole seismic.

Non-Intrusive Seismic Techniques

Non-intrusive techniques are particularly attractive due to the absence of any need for the construction of boreholes. However, as testing is undertaken from the ground surface, the depth of investigation is limited by the ability to generate, receive and interpret signals which engage sufficiently with deeper soils to permit assessment of their stiffness.

The long-established techniques of refraction and reflection are rarely used for onshore geotechnical parameter measurement due to the difficulties associated with the processing of layered profiles

The use of surface wave techniques has a number of attractions founded upon the ease with which strong, coherent source waves may be generated and the

dispersive nature of their propagation (causing the velocity of different wavelength surface waves to be a function of the stiffness depth profile). Surface waves may be generated simply using a surface hammer source as normally used in the Spectral Analysis of Surface Waves (SASW) and Multi-station Analysis of Surface Waves (MASW) techniques. However, a hammer source also creates P & S waves in addition to surface waves which can obscure surface wave detection and may only create surface waves over limited ranges of frequency. In addition, the weak and transient nature of a hammer source over certain frequencies is susceptible to interference by background noise sources.

The use of a continuous sinusoidal source as used by the ACSW technique overcomes these limitations by generating only Rayleigh waves at user determined frequencies. Acquisition at monotonic frequencies provides an effective 'stacking' of data and makes the technique remarkably insensitive to even strong ambient noise such as that generated by nearby construction plant. The facility to undertake automated data analysis permits real time reporting of stiffness profiles. Unlike SASW and MASW techniques, ACSW has been designed as a rapid, integrated construction testing system capable of operation on active construction sites or infrastructure.

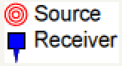
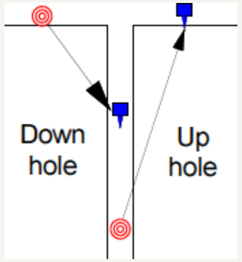
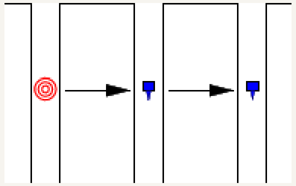
The depth of investigation of surface wave techniques is limited by the maximum wavelength (and minimum frequency) that can be generated. This typically limits the depth of investigation to around 10-15m depending on the ground stiffness (assuming a minimum frequency of 10Hz in a stiff material). Deeper investigation is possible where low frequency ambient noise or microtremors are used as a seismic source. This can permit investigation to depths in excess of 100m, however successful use of the technique requires large area geophone arrays and length data acquisition periods which are impractical in most routine situations. In addition, processing of data is complex and highly specialised. As a result, the technique tends to be reserved for research applications only.

Falling Weight Deflectometer (FWD)

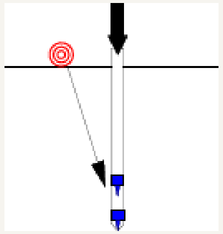
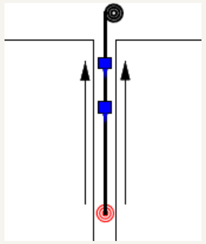
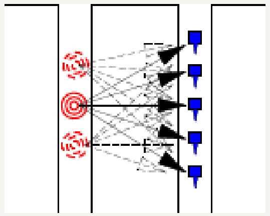
The FWD and by association the Lightweight Deflectometer (LWD) are discussed separately as they are not true seismic techniques, as instead of measuring seismic wave velocities the surface deflection profile due to a known impact force on the ground surface is measured. The test was originally developed to estimate the structural capacity of road pavements but has more recently been used to determine the stiffness of railway track.

The technique involves the measurement of surface deflections at a range of distances from the point of impact of a standardised energy source to permit the construction of a surface settlement curve. Subsoil stiffness can then be determined through an inversion process whereby stiffness values are adjusted in a simple elastic model until a satisfactory solution is attained. More commonly soil stiffness is assessed using simple empirical relationships. Due to the small diameter of the load plate (typically 300-450mm) the test only provides information relating to the stiffness to a depth of approximately 1m

Intrusive methods

Seismic method	Diagram 	Measured value	Advantages	Disadvantages	Relative Cost	Commentary
Up-hole Down- hole		V_p, V_s	• Applicable to all soil and rock types • Permits determination of Poisson's ratio	• Penetration limited by energy of seismic source • Requires a cased borehole	Moderate to high	Data quality has been shown to be comparable to cross holes. Downhole method allows use of higher power surface sources and greater depth of investigation Rely on well-grouted casing which can be difficult to achieve in some ground conditions. Frequently used on high profile projects due to long history of use and confidence in results.
Cross hole		V_p, V_s	• Applicable to all soil and rock types • Theoretically resolution unaffected by depth • Can detect softer layers at depth • Permits determination of Poisson's ratio	• Requires 2 or more cased boreholes •	High	Rely on well-grouted casing which can be difficult to achieve in some ground conditions. Less commonly used than Down/Up hole methods due to onerous requirement for 2 or more boreholes and tends to be reserved for high profile projects of where deep investigation is required.

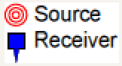
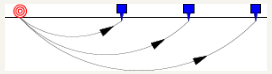
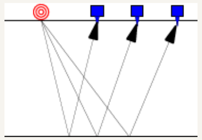
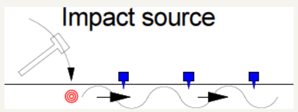
Intrusive methods *contd*

Seismic method	Diagram 	Measured value	Advantages	Disadvantages	Relative Cost	Commentary
Seismic cone		V_p, V_s	• No BH required • Rapid where ground conditions suitable • Permits determination of Poisson's ratio	• Penetration can be limited in stiff/hard ground • Unsuitable for rock	Moderate	Provides other geotechnical parameters in addition to measurement of V_p, V_s. Attractive technique where ground conditions suitable for investigation to 20-30m depth.
P-S Suspension logging		V_p, V_s	• Applicable to all soil and rock types • Resolution unaffected by depth • Can detect softer layers at depth • Permits determination of Poisson's ratio	• Requires a cased borehole	High	Best results obtained in uncased holes not normally possible in superficial soils High cost tends to restrict use to projects where measurement in deep boreholes is required.
Cross hole tomography		V_p, V_s	• Can produce 2D distribution of stiffness • Applicable to all soil and rock types • Permits determination of Poisson's ratio	• Requires 2 or more cased boreholes • Data processing and interpretation are complex and difficult	High	High cost tends to restrict use to research applications.

COMPARISON OF ACSW TESTING WITH STIFFNESS MESUREMENT BY OTHER SEISMICS TECHNIQUES

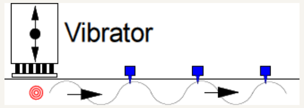
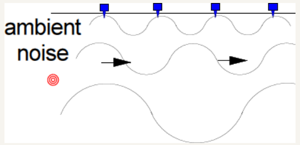
Guidance Note SSGN016

Non-intrusive methods

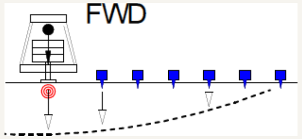
Seismic method	Diagram 	Measured value	Advantages	Disadvantages	Relative Cost	Commentary
Refraction		V_p, V_s	• No borehole required • Permits determination of Poisson's ratio	• Cannot operate where stiffness reduces with depth • Sensitive to background noise	Moderate	Rarely used for stiffness profiling due to limitations in dealing with layered soil profiles.
Reflection		V_p, V_s	• No borehole required • Permits determination of Poisson's ratio	• Only effective in layered ground • Sensitive to background noise	Moderate	Rarely used in shallow onshore investigations due to requirement for layered profile and complex processing required.
SASW (Spectral Analysis of Surface Waves) **MASW** (Multistation Analysis of Surface Waves)		V_R	• Portable • Can be adapted for continuously vibrating source to improve data quality	• Cannot determine Poisson's ratio • Not designed for normal construction testing • Background noise filtration can be problematic • Complex post processing arrangements	Low	Surface Rayleigh Waves attenuate far slower than Body P & S waves and represent 2/3 of impact energy. Dispersive nature of Rayleigh waves in heterogeneous soils permits determination of a layered stiffness profile. *More recently SoilSafe ACSW uses similar principles but with integrated construction testing application*

COMPARISON OF ACSW TESTING WITH STIFFNESS MESUREMENT BY OTHER SEISMICS TECHNIQUES

Non-intrusive methods *contd*

Seismic method	Diagram (Source / Receiver)	Measured value	Advantages	Disadvantages	Relative Cost	Commentary
Advanced Continuous Surface Wave (ACSW)		V_R	• Rapid (0.5hr/test) • Portable • Robust integrated construction testing system • Permits production of immediate stiffness profiles on site	• Depth of penetration limited by seismic source energy (typically 10-15m for standard source) • Cannot determine Poisson's ratio	Low	GSS construction testing system development of earlier Continuous Surface Wave (CSW) system, incorporating integrated software controlling, calibration, analysing and reporting tests. Recent research has shown that ACSW testing provides the same quality of data as downhole seismic testing for the same cost as empirical testing.
Microtremor/ Ambient noise surveys		V_R	• Can permit investigation to significant depth (>100m)	• Typically, large open spaces are required for geophone arrays • No control over frequency source spectrum • Cannot determine Poisson's ratio	Moderate	Relies on measurement of surface waves emanating from natural or human activities unrelated to the testing typically rich in low frequency content. Rarely used for shallow ground investigation due to requirement for large arrays and complex processing.

Non-intrusive methods *contd*

Seismic method	Diagram (Source / Receiver)	Measured value	Advantages	Disadvantages	Relative Cost	Commentary
Falling Weight Deflectometer (FWD) and Lightweight Deflectometer (LWD)		D_{xxx} mm (deflection at xxx mm from source)	• Routinely used test, especially on the railway • NR and HA have produced empirical design guidance based upon FWD measurements	• Test strain level variable and difficult to interpret • Interpretation difficult without knowledge of layered profile • On railway requires unclipping of the load sleeper • Depth of investigation limited to approximately 1m • Cannot determine Poisson's ratio	Moderate	Not a true seismic test as it measures deflections not wave velocities. Use of geophones to measure deflections on ballast problematic and data quality frequently unacceptable. URS have developed a rail specific FWD termed the Rail Trackform Stiffness Tester (RTST). This can be tracked onto/off the track in 15 mins but testing still requires unclipping of the load sleeper.

References

- BS5930:2015 British Standard Code of Practice for Ground Investigations, BSI
- Garofalo, F. et al (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, pp241-254
- Gordon, M.A. (1997) Applications of field seismic geophysics to the measurement of geotechnical stiffness parameters. PhD thesis, University of Surrey.
- Heymann, G. (2007) Ground stiffness measurement by the continuous surface wave test. *Journal of the South African Institution of Civil Engineering.* Vol.49, No.1, p25-31.