Spectral Analysis of Surface Waves for Damage Detection in Layered Concrete Structures

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ABSTRACT

Spectral Analysis of Surface Waves (SASW) is a widely used and accepted method in Geotechnical and Civil Engineering applications for estimating material properties in layered structures based on the dispersion characteristics of surface waves. This project aims to extend existing half space theory to analyse layered structures of finite depth. The excitation frequency and signal analysis need to be adapted and optimised to suit the physical properties of the layered structures and associated wave interactions from the layer interfaces. The material properties of the layered substructure can be estimated by evaluating the Rayleigh Wave dispersion characteristics as a function of frequency. Layer thicknesses and the structural integrity of the samples being tested can be interpreted from the averaged dispersion curves. The application of the new SASW tool enables the estimation of the physical properties of concrete and hybrid structures of unknown layer configurations and the detection of damage in structures of known physical dimensions.

INTRODUCTION AND MOTIVATION

Non-destructive testing is becoming increasingly important for quality control during construction and maintenance and for safety assessment of existing structures for mechanical as well as civil infrastructure applications. For the latter, Palmer points out that “There is a great need by industry to externally assess the condition of the structure for safety and economical reasons” (Palmer, 2008).

Spectral Analysis of Surface Waves (SASW) is widely used in Geotechnical and Civil Engineering applications for estimating material properties in layered structures based on the dispersion characteristics of Rayleigh Waves (Surface Waves), e.g. (*Geovision*, 2010).

This project aims to extend existing SASW methods to analyse layered concrete and hybrid structures of finite depth, with a particular focus on layered refractory linings. The new SASW tool will enable the estimation of physical properties of structures of unknown layer configurations and the detection of damage in structures of known physical dimensions. This will provide a non-destructive method of measuring the integrity of concrete and hybrid structures such as layered refractory linings. This will have major benefits for maintenance scheduling or service life estimations and has the potential to drastically reduce the overall running costs and improve the reliability of these critical assets. In addition, the physical hazards associated with visual inspections of refractory linings including falling debris, confined spaces and physical access will be greatly reduced by allowing for inspections to be performed externally. Figure 1 illustrates typical layered refractory lining with a void between two layers.

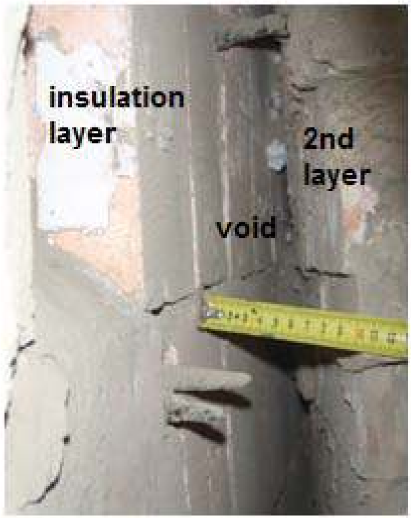

Figure 1: Layered refractory (Palmer, 2008)

The development of the new SASW tool requires that existing methodologies need to be adapted and optimised to suit the physical properties of the layered structures and associated wave interactions and noise from the layer interfaces. The measurement system including all aspects of data acquisition, signal processing and display of results are realised in LabView© incorporating innovative real-time graphical user feedback procedures.

This paper presents all details of the SASW methodolgy in general and the new tool for inspecting concrete and hybrid layered structures of finite depth in particular. It also reports on the current status of system development and outlines the experimental plan for testing and validation of results.

METHODOLOGY

For layered concrete structures pulse-echo or P-response modal testing can be used to detect voids around steel reinforcing bars of anchors, voids or disbonds between layers, uniformity of the concrete and for estimating concrete strength and elastic or shear modulus, e.g. (*Guidebook on non-destructive testing of concrete structures*, 2002), (Palmer, 2008).

A major disadvantage of the technique is that only the structure directly below the excitation point is assessed, which makes it a time consuming and costly method to inspect large structures. The benefit of surface waves is that they travel along the structure and hence can be used to assess the entire structure between two sensors separated laterally.

Variations in surface wave velocity can be used to capture variations within a concrete sample. Apart from material and environmental characteristics such as stiffness and density, many types of damage can also cause changes in velocities of ultrasonic waves, for example debonding of reinforcement, delaminations in layered systems and porosity or voids (Palmer, 2008).

This section outlines all details of SASW and illustrates the application of the method to layered concrete structures.

Wave Mechanics in Solid Media

The fundamentals of wave propagation have been of interest for a number of centuries, however the existence of Rayleigh waves was only predicted in the late nineteenth century (Graff, 1991). The governing wave equation was derived from transverse wave propagation in strings where wave velocity is a function of the Young's modulus and density of the material. Pressure and shear waves are dispersive and travel in three dimensions in elastic solids. Wave velocity is a function of frequency as *"a harmonic wave of frequency ω can propagate only at a specific velocity c as governed by $\omega=\omega(c)$"* (Graff, 1991).

Unlike pressure (P waves) and shear waves (S waves), surface waves effectively travel in a 2 dimensional half space along the surface and at a lower velocity e.g (Graff, 1991). Rayleigh waves generate elliptical particle motion due to the bi-directional motion of surface waves. This elliptical motion is a function of depth and the direction of rotation reverses after a particular depth, for example 0.192 λ for a material with Poisson's ratio v = 0.3 where λ is the wavelength (Rose, J. L., 1999).

Due to non-dispersive propagation of surface waves constrained to a two dimensional half space, wave energy is dissipated at a much slower rate than pressure or shear waves. As a result, they can be used to effectively sample media over larger distances than P or S waves.

Generating surface waves

Surface waves can be generated both directly and indirectly using a variety of techniques. An impulse normal to the surface or shear wave transducers can both be used to excite surfaces wave directly. Indirectly, an incident wave, either pressure or shear, is converted into two waves when reflected off a surface. For a reflection angle above a critical incident angle θ_c, where θ_c is a function of Poisson's ratio, one of the reflected waves generated will propagate along the surface, e.g. (Rose, 1999).

Phase velocity & group velocity

Wave velocity can be estimated using the travel time (Δt) of the dominant frequencies in time domain. For a signal captured at multiple locations, the wave velocity can be calculated as a function of frequency using phase difference ($\Delta\varphi$) e.g. (Staudenmann, 1995). Figure 2 shows two receiver signals in the time domain and the corresponding phase difference of the cross power spectrum.

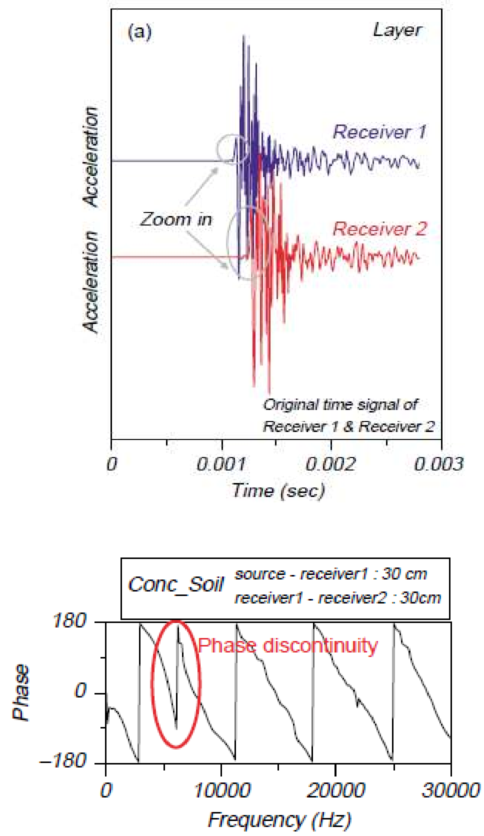

Figure 2: Phase difference between receiver signals (Kim, Seo, et al., 2006)

Unwrapping the phase to calculate travel time involves summing the fraction of the last cycle of the frequency and the number of 360° cycles preceeding it (Cho, Y. S., 2003). This method has been used in SASW applications to accurately calculate wave (phase) velocity as a function of frequency. By plotting velocity against wavelength a characteristic dispersion curve is created which can be used to determine the elastic properties of the structure along the depth (see Figure 6).

Spectral Analysis of Surface Waves

SASW has been widely used as a seismic method performed on the ground surface to estimate the variation in material stiffness with depth (*Geovision*, 2010). The material properties of the layered sub-structure can be estimated by evaluating the Rayleigh wave dispersion characteristics as a function of frequency.

> Most of the Rayleigh Wave energy exists within one wavelength of depth and in layered media, the propagation velocity of surface wave depends on the frequency (or wavelength) of the wave because waves of different wavelengths sample different parts of the layered medium" (Kim, Seo et al. 2006).

High frequencies are quickly damped out while frequencies of longer wavelengths will penetrate deeper to sample material properties at a greater depth, e.g. (Kim, D. S., N. R. Kim, et al., 2004). The phenomenon is illustrated in Figure 3

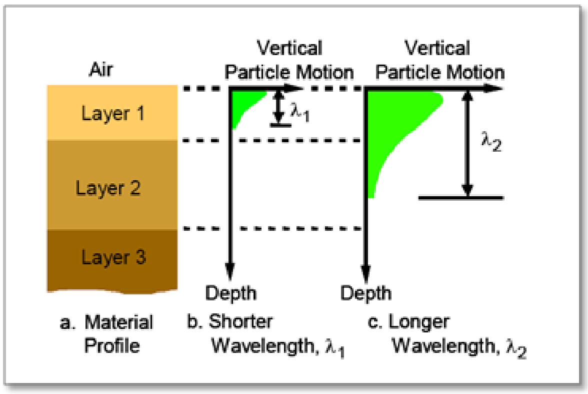

Figure 3: Rayleigh wave motion (Geovision, 2010)

For this project, surfaces waves will be generated directly using a variety of impacts from an impulse hammer to achieve the desired frequency range. The applied excitation will also generate Rayleigh waves indirectly as the resulting pressure waves reflect off the layer interfaces e.g. (Graff, 1991), (Rose, 1999). This process will be monitored to ensure the correct frequencies are excited for the sample being tested and that there is appropriate coherence between the input and receiver signals. The impact will be averaged to ensure a good signal to noise ratio and displayed to the user for review.

Environmental conditions need to be considered as a possible source of variation in results. Moisture content can provide misleading wave velocities due to water filling voids. Large temperature variations can also influence test readings but experimental tests on samples between 10°C and 30°C have been shown to have no significant effect on results (*Guidebook on non-destructive testing of concrete structures*, 2002). Environmental conditions will be recorded and considered when estimating concrete strength or material properties. Consistency in measurements will be vital in preventative maintenance applications were tests are performed at regular intervals and compared to baseline results.

To determine specific material properties, the SASW system must be provided with an accurate estimate of pressure or surface wave velocities for the sample being tested e.g (Kim, D. S., W. S. Seo, et al., 2006). This will be obtained using a separate calibration procedure built into the SASW program using an impact echo (IE) method. A generated stress impulse at the surface will propagate between the top and bottom surfaces of a sample of known thickness and the travel time will be recorded to provide experimental wave velocities. The same hardware as used in the SASW test will be reconfigured for the IE calibration as shown in Figure 4.

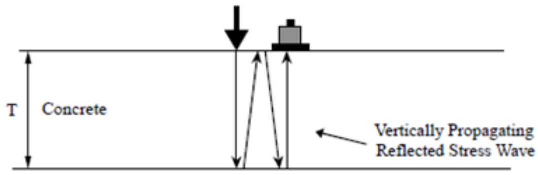

Figure 4: Impact echo test configuration
(Kim, Seo et al., 2006)

Rayleigh Wave velocity can then be measured using 2 receivers mounted in line with the impact source separated by a known distance. The SASW program can then calculate wave velocity as a function of frequency, *Vr(f)*, based on the phase difference between the two receivers which will then be plotted against wavelength to create a dispersion curve (figure 7). Figure 2 is a typical plot of phase difference between two receiver signals. The proposed SASW test configuration is shown in Figure 5

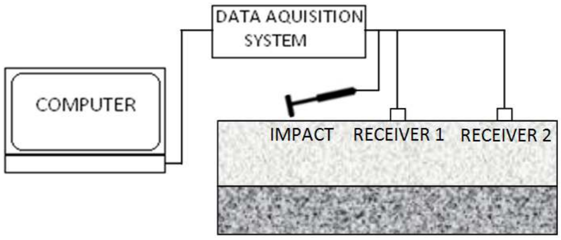

Figure 5: SASW test configuration

Layer thicknesses and the structural integrity of the samples being tested can be interpreted from the dispersion curves. For example, Figure 6 shows an experimental dispersion curve for an SASW test of a thin concrete slab sitting on soil. The sudden step in velocity and corresponding phase discontinuity represents the interface between the concrete slab and soil.

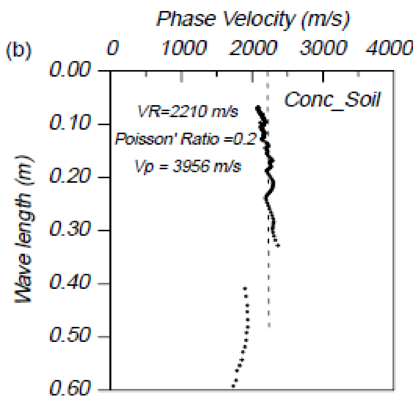

Figure 6: Concrete slab Dispersion Curve example
(Kim, D. S., W. S. Seo, et al., 2006)

This project extends existing half space methodology to detect voids, cracks or delamination between individual concrete layers of known thickness. The main outputs of the SASW analysis system is the wavelength-phase velocity dispersion curve along with receiver signal coherence evaluation in both frequency and time domain to improve the reliability of the measurement results.

Signal Processing

The experimental data measured in the time domain can be transferred to frequency domain using Fast Fourier Transform (FFT). The sample size and sample rate determines the usable frequencies and frequency resolution (Δf) e.g. (*MECH3200 Course Reader,* 2010). The resolution in the frequency spectrum is limited by the sample size, nΔt of the signal as at least two datapoints are required to capture a resonance (1). The maximum usable frequency (Nyquist frequency)(2) is half the sample rate, anything higher than this will not be captured and can lead to artificial lower frequencies (Aliasing). To avoid aliasing, the input signal will be monitored to ensure the correct frequencies are excited based on the desired frequency resolution and sample rate limitations.

$$\Delta f = 1/(n\Delta t) \quad (1)$$

$$f_{max} = 1/(2\Delta t) \quad (2)$$

Where n is the number of samples, Δt is the sample time and nΔt is the sample size (T).

A Discrete Fourier Transform can only capture a finite number of frequencies which is governed by the sample size. "Spectral leakage" can occur as a result of trying to capture a continuous frequency spectrum with a finite number of points. The length of the signal can be maximised until the Nyquist frequency reaches the maximum desired frequency for the sample being tested.

Leakage can be further reduced or eliminated by setting the signal length to an integer number of periods of desired frequencies or by applying a windowing function. Windowing uses a weighting function on the signal in the time domain to minimise discontinuities at the endpoints of the signal. Specific excitation frequency requirements for samples being tested are pre-determined to ensure accurate signal analysis results within the desired frequency range.

SYSTEM DEVELOPMENT

Program Outline

The new tool consists of a complete SASW package with a simple graphical user interface realised in LabView© incorporating innovative real-time graphical user feedback procedures. The step by step procedure to display the relevant output data will prompt the user to repeat steps as required to guarantee accurate measurement results. This includes instant operator feedback regarding quality of impact excitation and signal averaging to optimise signal to noise ratio and correct evaluation depth.

The SASW Program has been broken down into 4 distinct modules. An overview of the program outline has been included in Figure 7.

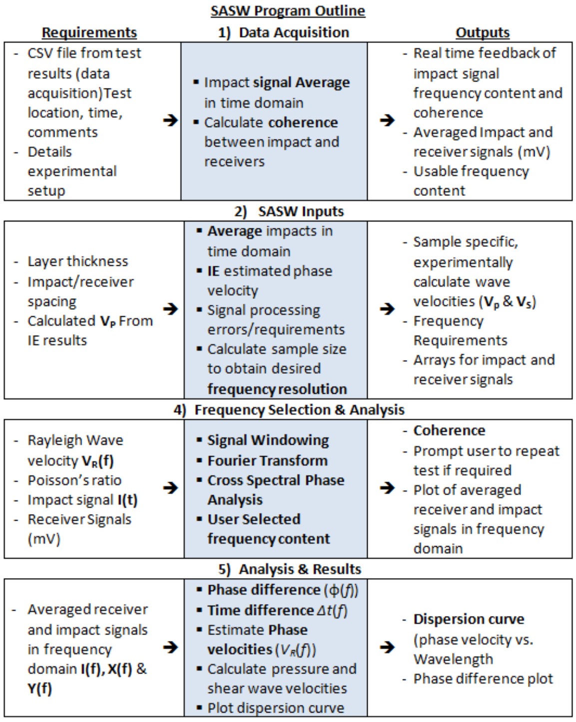

Figure 7: SASW program outline

A screen shot of the analysis and results page is included in Figure 8.

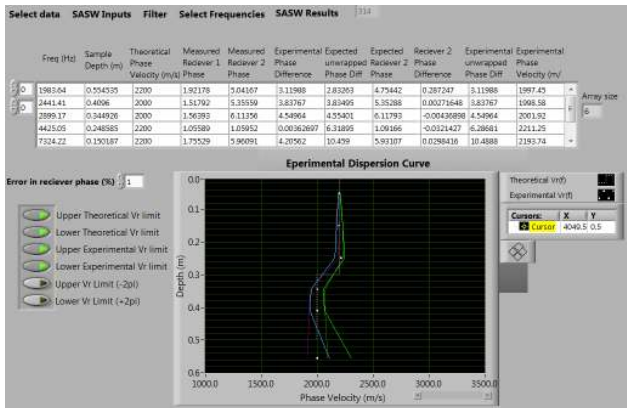

Figure 8: SASW Analysis and Results page

The user interface was developed in a series of distinct logical stages. While reviewing results, the operator can export data or add comments before progressing to the next stage.

Analysis of Artifical Data

Artificial data was developed as a means to validate the SASW process and LabView© program. An artificial signal generator was constructed using six discrete sinusoidal frequencies with a phase shift based on a receiver spacing of 0.5m and specified wave speed $V_R(f)$. The wave velocities and wave lengths were based on theoretical dispersions curves such as the two layered system in Figure 9.

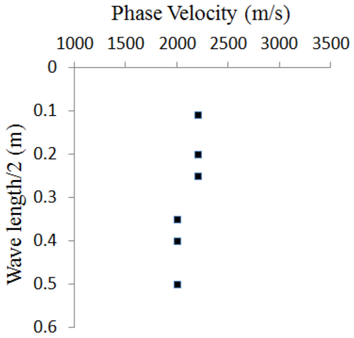

Figure 9: Theoretical dispersion curve

Two different wave speeds were set to replicate a typical layered concrete structure, the first 300mm thick and the second 200mm thick. Six discrete frequencies were calculated from the two hypothetical wave speeds and from wave lengths based on the desired sample depths. Figure 10 shows an artificial signal in time domain and its corresponding frequency spectrum highlighting the six discrete frequencies.

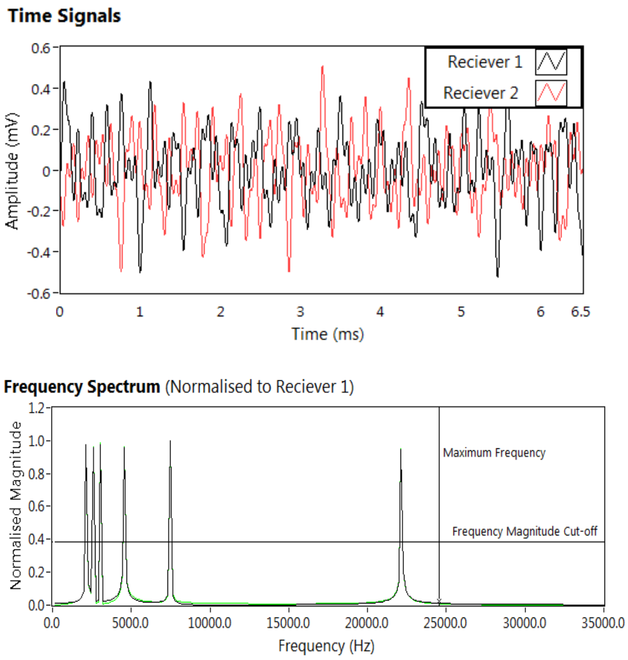

Figure 10: Artificial sample data

Figure 11 shows the output dispersion curve from the SASW program for the two layered artificial signal. These signals were also analysed in Matlab© to validate the LabView© results.

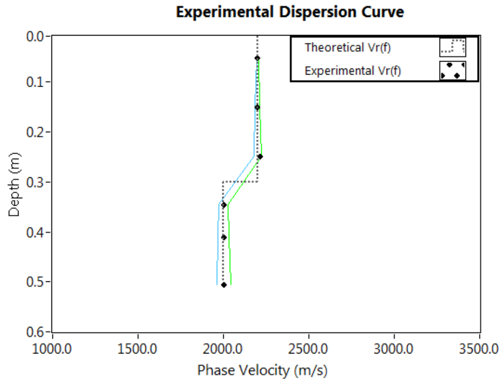

Figure 11: Two layer artificial data dispersion curve (with error bands)

An error analysis was performed on the phase calculations by comparing the FFT results to the expected results based on the specified phase shifts $\Delta\varphi(f)$ in the artificial signal. Assuming an accuracy of 99% in receiver spacing measurements, the receiver phase information was found to be the most sensitive parameter in the phase velocity calculations. A variety of artificial samples with known phase shifts were analysed to quantify the error in the receiver 2 phase. The results were found to be within 0.5-0.74% (for 95% confidence interval) and the resultant resolution in phase velocity has been incorporated into the program by adding error bands to the calculated dispersion curve data points.

Analysis of Preliminary Experimental Data

The new SASW tool was also used to analyse experimental data from testing samples of known geometry and with known flaws. Palmer Technologies provided SASW data for a concrete water tank, 600mm thick with a receiver spacing of 0.3m. Figure 12 shows the two receiver signals overlaid in time domain to highlight the time shift and signal decay. Figure 13 shows the frequency spectrum of the signals.

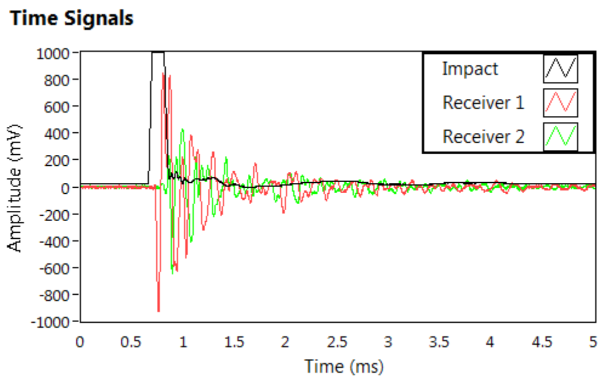

Figure 12: Experimental SASW Data Time Signal

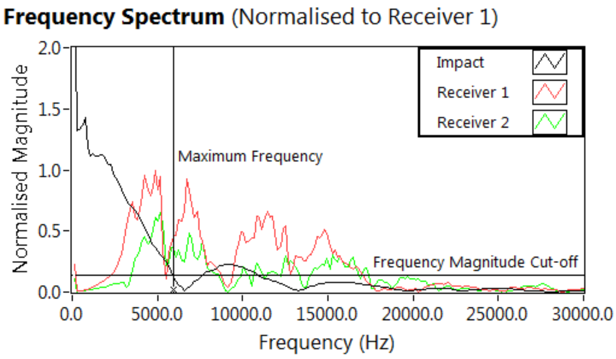

Figure 13: Experimental SASW Data Frequency Spectrum

Experimental Testing

A number of specially designed test samples were made available by Palmer Technologies for experimental testing. The hardware and data acquisition package used was developed by Palmer Techlogies. Initial testing has been performed on both single and multilayered test samples including the single layered sample with honeycomb flaw in Figure 14.

Figure 14: Single layer concrete sample with honeycomb flaw

Multilayer concrete samples of known physical properties and know wave velocity have also been used for initial testing. Figure 15 shows one of the multi-layered sample configurations.

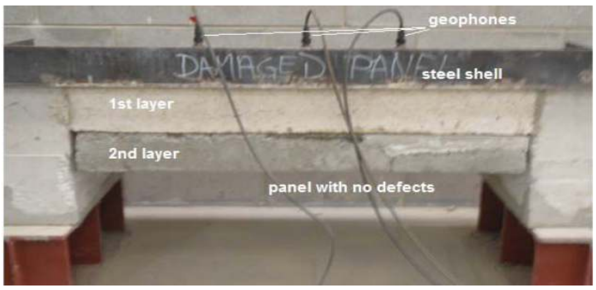

Figure 15: Layered concrete test sample with no defects

Figure 16 depicts the same experimental setup as Figure 15 with a section missing on the bottom layer to represent a void.

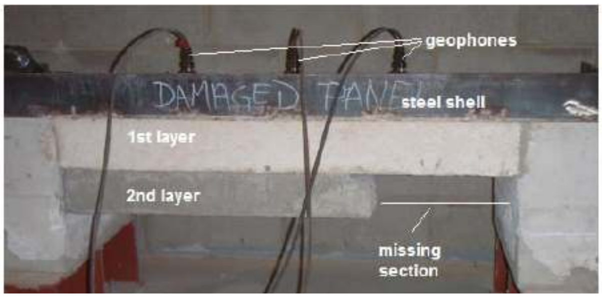

Figure 16: Layered concrete test sample with void

Current Status and Future Plans

The baseline SASW program outlined in Figure 7 is operational and working with artificial signals as expected. The analysis results for the artificial signals have also been validated using a separate program developed in Matlab©. Initial experimental testing identified difficulties associated with exciting surface waves in the desired frequency range when using an impulse hammer. Exciting the higher frequencies proved difficult on the concrete samples. The second difficulty identified during testing was in ensuring the excitation generates surface waves through the entire thickness of the sample. The lower frequencies required for the multilayerd samples could not be generated through the steel outer shell where disbond between layers was present. Undesired higher frequencies in the steel shell also tended to dominate the receiver response.

Initial testing also identified the need to determine the wave type associated with each frequency so that surface waves can be isolated. The process used to determine phase velocity is only accurate for discrete frequencies with a maximum variation in wavespeed corresponding to plus or minus 2π of the expected unwrapped phase. This limitation can be addressed but varying the receiver spacing to sample a number of specific frequency bands. Each frequency band would be limited to a maximum range of 5 times the lowest desired frequency. By setting this maxium limit on the unwrapped phase difference the potential for error in phase velocity calculations can be controlled.

An alternative approach is to investigate more robust methods for calculating phase velocity. Developing an iterative real time Fourier transform may allow for time signal analysis triggered at discrete frequencies to be investigated. An alternative and potentially more robust approach would be to investigate Wavelet analysis, which can capture both time and frequency content, e.g. Ni, Xiao et al. 2010). Eliminating the reliance of unwrapped phase difference for wave speed calculations will be the focus of the future development of the SASW tool.

Finally, wave interactions at layer interfaces will also need to be further investigated to analyse results and interpret the experimental dispersion curves during testing. This will be realised through continued experimental testing.

CONCLUSION

Non-destructive testing is becoming increasingly important for quality control during construction and maintenance and for safety in existing structures. The application of the new SASW tool will be in estimating physical properties of existing concrete structures of unknown layer configurations and also as a maintenance strategy for damage detection in structure of known physical dimension. This tool will provide a non-destructive method of measuring the integrity of concrete structures or refractory linings for maintenance scheduling or service life estimations with the potential to drastically reduce the overall running costs and improve the reliability of these critical assets. In addition, the physical hazards associated with visual inspections of refractory linings including falling debris, confined spaces and physical access will be greatly reduced by allowing for inspections to be performed externally.

SASW is already a widely used and accepted method in Geotechnical and Civil Engineering applications for estimating material properties in layered structures based on the dispersion characteristics of Surface Waves. This project extends existing half space theory to analyse layered structures of finite depth. The impact and receiver signal analysis will be adapted and optimised to suit the physical properties of the layered structures and associated wave interactions and noise from the layer interfaces. Through further testing, the impact excitation will be optimised to suit individual test conditions through instant operator feedback and signal averaging. Initial testing has shown the current method for phase velocity caculations needs to be further developed. The measurement system including all aspects of data acquisition, signal processing and display of results will be realised in LabView© incorporating innovative real-time graphical user feedback procedures.

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