MULTICHANNEL ANALYSIS OF SURFACE WAVES (MASW) FOR INVESTIGATION OF GROUND COMPETENCE: AN INTRODUCTION

Koya Suto
Terra Australis Geophysica Pty Ltd

ABSTRACT

The Multichannel Analysis of Surface Waves (MASW) is a seismic method to investigate the competence of the ground, one of the essential geotechnical interests. It can provide dense coverage of data of ground competence quickly and economically in various stages of development projects.

This method, developed in the 1990s and first commercialized in 1999, analyses propagation of the seismic surface wave in the frequency domain and estimates the underground shear wave (S-wave) velocity structure. The S-wave velocity is an elastic parameter closely related to Young’s modulus, an important property to derive load bearing capacity of the ground.

Geometry for data collection for the MASW analysis is similar to the seismic refraction survey but simpler. It does not require a range of long offsets or a large geophone array for equivalent depth of investigation. As the MASW processing involves data transformation into the frequency-velocity domain, it is relatively CPU intensive. This is the reason why the method could not be put into practice until the 1990s, while the theory and possible use was speculated since 1950s. Through this processing, a dispersion curve of the seismic wave propagation is analysed and then inverted to the S-wave velocity structure.

This paper presents an introduction to the MASW method outlining its concept and application in a variety of geotechnical settings.

1 INTRODUCTION

In preparation of construction sites and design of buildings, the competence or supporting capacity of the ground is essential information.

The competence of ground is traditionally tested at point sampling, typically by standard penetration test (SPT), cone penetration test (CPT), seismic cone penetration test (SCPT) or downhole logging. While these are direct measurements and present concrete values, it is often not economically feasible to sample points dense enough to represent the entire area. The values for the rest of the area are estimated by interpolation and there is always a risk of missing local anomalies between the sample points.

Geophysical survey methods help to estimate the geotechnical parameters of the ground by measuring the physical parameters from the surface. Amongst them, the seismic methods are useful in estimating elastic properties of the ground, as the seismic motion, the phenomenon it observes, is an elastic wave. The seismic refraction method, which estimates the P-wave velocities of the underground layers, is commonly employed in geotechnical application.

The Multichannel Analysis of Surface Waves (MASW) method is a newly-developed seismic method which analyses surface waves in the frequency domain to estimate the underground S-wave velocity structure. The S-wave velocity is closely related to other elastic parameters important to describe competence of the ground, particularly Young’s modulus.

The seismic data are collected along a seismic line on the surface; the data are processed and analysed along the line. This provides a 2D coverage and the information is expressed as a cross section of S-wave velocity. If the area is covered with a sufficient density of survey lines, the S-wave distribution can be drawn in plan view.

The MASW method can be applied to areas including the investigation of overburden thickness, depth to bedrock, buried channels, delineating cavities and compaction monitoring.

It is a non-destructive and non-invasive method. The survey is carried out with standard 4WD vehicles, does not require large equipment and causes minimal environmental impact. The interruption to the site operation is minimal, considering the value and volume of the underground information obtained from this survey.

2 SURFACE WAVE SEISMIC METHODS

Seismic surface waves are known to researchers of conventional seismic reflection as ground roll “noise”. They are produced by natural seismic sources, human activities such as traffic and machinery, or the deliberate effort of generating seismic signals. The nature of this “noise” differs from place to place reflecting the nature of the ground. In other words, this noise contains information about the ground, particularly near surface physical properties.

Several methods to analyse the surface wave have been devised in recent years. Some methods passively observe the natural vibration of the ground, and others actively generate the surface waves to be recorded. In general, natural ground motions, called microtremors, have longer wavelengths and are suited to survey the deeper part of the ground, while active seismic sources generate surface waves with shorter wavelengths more suitable for shallow investigation. The passive methods include the Spatial Autocorrelation (SPAC) method (Okada, 2003) and the Refraction Microtremor (ReMi) method (Louie, 2001), and the active methods are the Spectral Analysis of Surface Waves (SASW) method (Nazarian *et al*., 1986) and the Multichannel Analysis of Surface Wave (MASW) (Park *et al*., 1999). Table 1 lists these methods in terms of the surface waves and observation arrays used. The MASW method is an active method using linear geophone arrays

Table 1: Geophysical surveys using surface waves.

Active Methods Uses active seismic sources	Passive Methods Observes ambient vibration (Microtremor Surveys)
(Point Measurement) Spectral Analysis of Surface Wave (SASW) Continuous Spectral Analysis of Surface Wave (CSW)	(Circular Array) Spatial Autocorrelation (SPAC) Frequency-wavenumber (F-K)
(Linear Array) Multichannel Analysis of Surface Wave (MASW)	(Linear Array) Refraction Microtremor (ReMi)

The fundamental concept of the analysis of the surface wave is based on the frequency dependent velocity. The theoretical basis was developed in the late 1950s by authors such as Aki (1957). This analyses involves relatively intensive computer power and is the reason the method did not become commonplace until recently.

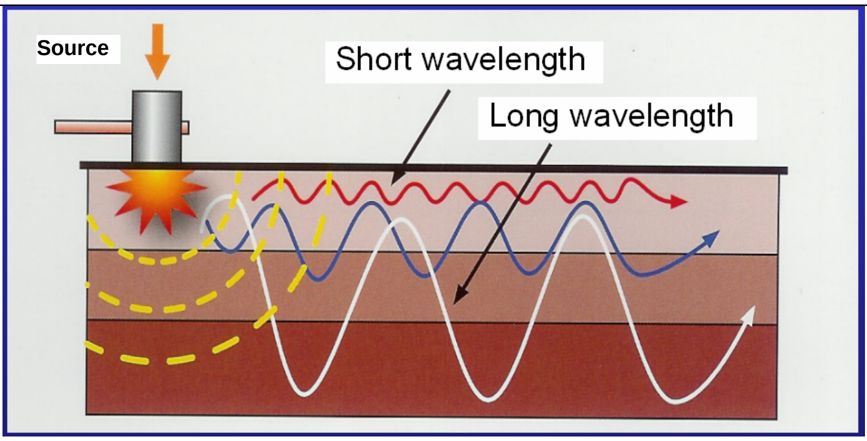

Figure 1: Conceptual diagram of analysis of surface wave (from a brochure of OYO Corporation).

Figure 1 illustrates the concept of the surface wave survey method. In this illustration, an impact is made by an active seismic source, but the principle is the same for the natural source. The seismic waves contain components of a range of wavelengths. The short wavelength components of the seismic wave attenuate quickly near the surface and the deeper part of the ground is dominated by the long wavelength components. Therefore, the velocity of the short wavelength components of the seismic waves contains information about the elastic property of the shallower part of the ground while that of long wavelength indicates the deeper part. In practice, an observed seismic record is transformed into the frequency-phase velocity domain to obtain a curve of variation of velocity along frequency (called “dispersion curve”), and it is inverted to depth versus S-wave velocity profile through estimation of wavelength. This process is detailed in Okada (2003) and Park, *et al.* (1999) for passive and active methods, respectively.

3 WHY S-WAVE?

An earthquake is caused by a stress/strain adjustment in the earth's crust. When it occurs, a large amount of energy is released and propagates as seismic waves. The seismic wave particle motion parallel to the direction of propagation is known as the compressional or primary P wave and travels faster than the particle motion perpendicular to the direction of propagation (the shear wave or secondary S wave). The S-waves carry far larger energy than the P-waves and cause greater damage. Therefore knowledge of the ground's response to the S-wave is essential to earthquake engineering.

The S-wave velocity has another significance in geotechnical engineering. In designing infrastructure in civil engineering, Young's modulus is one of the most important geotechnical parameters. Mathematical relationships among elastic parameters are found in many references and text books (Sheriff, 2002, for example). Young's modulus has a basic relationship with shear modulus, μ, and Poisson's ratio, σ:

$$E = 2\mu(1+\sigma)\ . \qquad \textbf{(1)}$$

The dynamic definition of Poisson's ratio is:

$$\sigma = \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - V_s^2\right)}\ , \qquad \textbf{(2)}$$

where Vp and Vs are P-wave velocity and S-wave velocity of the material, respectively.

The S-wave velocity is a function of shear modulus, and density, ρ:

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad . \qquad \textbf{(3)}$$

Therefore:

$$\mu = \rho V_s^2 \quad . \qquad \textbf{(4)}$$

Substituting μ and σ in Equation (1) with Equations (2) and (4),

$$E = 2\rho V_s^2 \left(1 + \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - V_s^2\right)}\right). \qquad \textbf{(5)}$$

$$\therefore E = \rho V_s^2 \frac{3\left(\frac{V_p}{V_s}\right)^2 - 4}{\left(\frac{V_p}{V_s}\right)^2 - 1}\ . \qquad \textbf{(6)}$$

In Equation (6), it is apparent that Young's modulus, E, is linearly proportional to density ρ and is neutral or is little influenced by Vp/Vs ratio, while Vs affects Young's modulus by the square of its variation. Therefore, investigating variations of Vs provides a significant insight into the competence of the ground through Young's modulus.

Table 2 shows actual calculations of Young's modulus according to Equation (6) within the likely range of the Vp/Vs ratio and density. Note that the range of the variation of S-wave velocity is far larger than that of density, and it affects Young's modulus vastly. Note also that the value of Young's modulus is around 100 MPa for Vs=150 m/s and around 300 MPa for Vs=250 m/s with relatively small variation along Poisson's ratio and density. These values roughly correspond to Young's modulus of competent soil and bedrock, respectively.

Figure 2 plots seismic wave velocity against standard penetration test "N-values" for clays and soil. S-wave velocity displays a good correlation with N-values while P-wave velocity shows little significant correlation.

Table 2. Young's modulus calculated from *Vp/Vs* ratio, density and S-wave velocity

	Vp/Vs=	2.4		σ=	0.40		
Youngs Modulus (MPa)		S-wave Velocity (m/s)					
	density (Mg/m^3)	100	150	200	250	300	500
	1.4	39.1	87.9	156.2	244.1	351.5	976.5
	1.6	44.6	100.4	178.6	279.0	401.7	1116.0
	1.8	50.2	113.0	200.9	313.9	452.0	1255.5
	2.0	55.8	125.5	223.2	348.7	502.2	1395.0
	2.2	61.4	138.1	245.5	383.6	552.4	1534.5

	Vp/Vs=	3.7		σ=	0.46		
Youngs Modulus (MPa)		S-wave Velocity (m/s)					
	density (Mg/m^3)	100	150	200	250	300	500
	1.4	40.9	92.0	163.6	255.6	368.1	1022.4
	1.6	46.7	105.2	187.0	292.1	420.7	1168.5
	1.8	52.6	118.3	210.3	328.6	473.2	1314.5
	2.0	58.4	131.5	233.7	365.1	525.8	1460.6
	2.2	64.3	144.6	257.1	401.7	578.4	1606.7

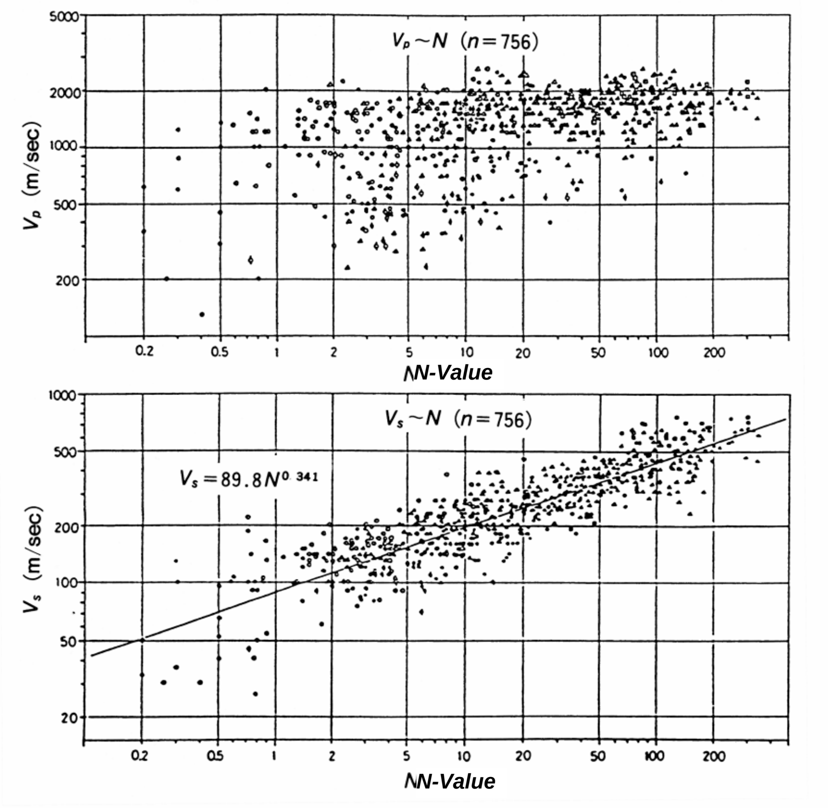

Figure 2: Correlation between elastic wave velocity and N-value of standard penetration test. (after SEGJ, 2004).

4 FIELD PROCEDURE

4.1 DATA ACQUISITION PARAMETERS

The field procedure of the MASW survey is similar to that of a seismic refraction survey but simpler since only one shot is required into the geophone array (Figure 3). The geophone array, usually 24 or 48-channel, is laid in a straight line at regular intervals as adopted in the refraction survey. The interval between geophones is designed to capture the shortest wavelength which is approximately equal to the shallowest resolvable depth desired (Kansas Geological Survey, 2007). The distance of the source from the nearest geophone of the array ("near offset") should be greater than the maximum depth of interest (Park *et al.*, 1999).

As the procedure of the MASW method requires a broad spectrum of data, the geophones used for data acquisition generally have a natural frequency lower than 10Hz and 4.5Hz geophones are commonly used. The log-cut analog filter commonly used for the refraction survey is never to be used for data acquisition.

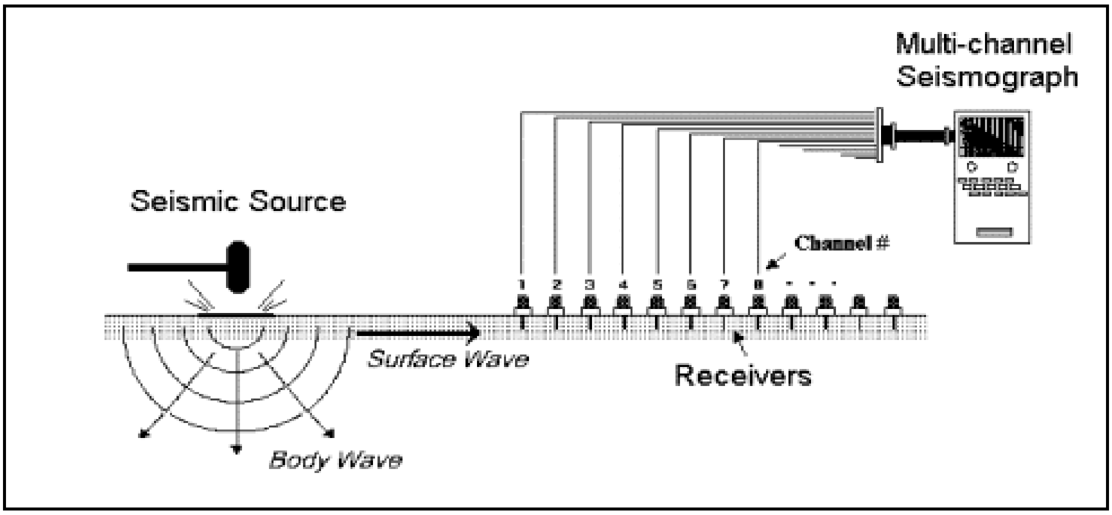

Figure 3. Field geometry of the MASW survey. (from Kansas Geological Survey, 2007).

Unlike refraction surveys, in which only the first arrival of the signal is analysed, the MASW requires a data record length sufficient for transformation from the temporal domain to frequency domain. In many cases a data length of two seconds is considered sufficient. Sampling interval dictates the upper limit of the frequency range contained in the data. An interval of 0.5 ms (Nyquist frequency 2000Hz) is generally used. This represents about ten or more times oversampling of the likely frequency response of the earth, ensuring good data redundancy for the transform.

To generate the seismic wave, an impulse source such as a sledge hammer or weight dropping system (Figure 4) is commonly used for its simple operation. If the depth of interest is great requiring a large offset, a larger energy source such as explosive may be used. An uncorrelated vibrator source may be used to directly obtain swept frequency data (Park *et al.*, 1999).

Figure 4: A vehicle-mounted weight dropping system.

Figure 5: A land streamer.

4.2 SURVEYING ALONG A SEISMIC LINE

To investigate the variation of the S-wave velocity structure, the geophone array is moved and data are acquired normally but not necessarily, continuously along a survey line. Moving a conventional seismic data acquisition system with spiked geophones involves retrieving the geophones, "re-planting" them and re-connecting to the data cable. This is a labour-intensive time-consuming process. To improve productivity in data acquisition, several types of seismic land streamers were devised (O'Neill, *et al.*, 2006 for example). Figure 5 shows a land streamer developed by the author. With a land streamer, the entire array is towed to the next location without disconnecting the geophones from the cable.

5 DATA ANALYSIS

One data record acquired with an array is used to produce a 1-dimensional S-wave velocity profile (depth vs. velocity) at the centre point of the array through the inversion process. However it is possible to produce 1-D profiles at different locations in the same array by selecting appropriate traces of the array (Suto, *et al.*, 2006).

The seismic data is collected in the time domain. Figure 6 is a sample seismic record collected with a 24-channel recording system, and the station interval is 1 m. The seismic source is 12.5 m away from the array to the left. This record is transformed into a frequency-phase velocity domain using a process called "overtone" analysis. Figure 7 is an example of an overtone analysis display. The colour indicates the energy level of the surface wave of a particular frequency-phase velocity combination in the quadrant. For example, the 20 Hz component of the surface waves has the highest energy at about 100 m/s. This is the fundamental mode Rayleigh wave, a type of surface wave. A lesser energy is traveling at about 150 m/s. This trend and those repeated above are higher mode Rayleigh waves, which are not used in the current algorithm.

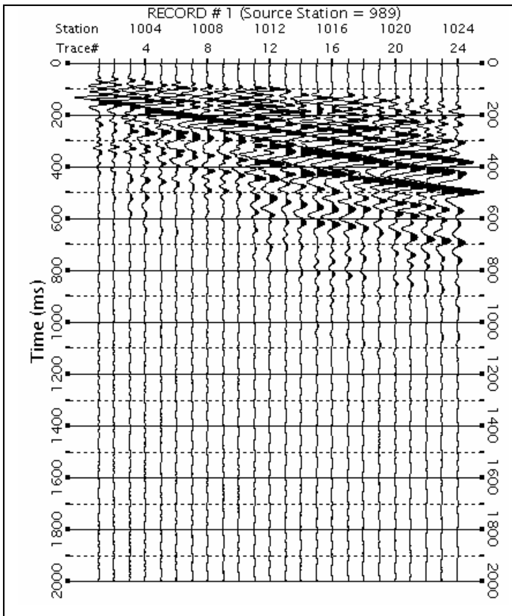

Figure 6: A seismic record.

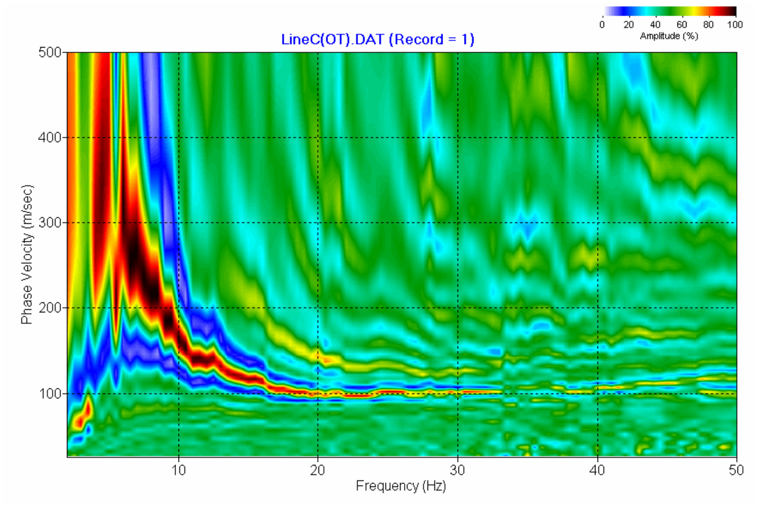

Figure 7: Overtone analysis of the seismic record of Figure 6.

The frequency-phase velocity trend of the fundamental mode Rayleigh wave is recognized as a high energy "train" in the overtone analysis display. This trend is "picked" and saved as a continuous curve (Figure 8). This curve is called a "dispersion curve". The dispersion curve characterises the underground S-wave velocity structure.

The dispersion curve is inverted to a one-dimensional (1D) S-wave velocity profile (Figure 9). The inversion algorithm is described in Park *et al.* (1999) and Xia *et al.* (1999), While a particular S-wave velocity structure produces a particular dispersion curve, one dispersion curve is not necessarily inverted to one unique S-wave velocity structure and some parameters such as depth to half-space and number of layers have to be entered. If a velocity structure is known at a nearby drilling location, the drilling data can be used as a 'seed' to start inversion modelling. Otherwise an initial model must be made from the interpreted dispersion curve. While the inversion algorithm reaches good results, a better initial model, of course, leads to a more accurate S-wave velocity profile. The resultant model must be examined in terms of known geological or geotechnical knowledge of the site and any anomaly must be checked for its validity.

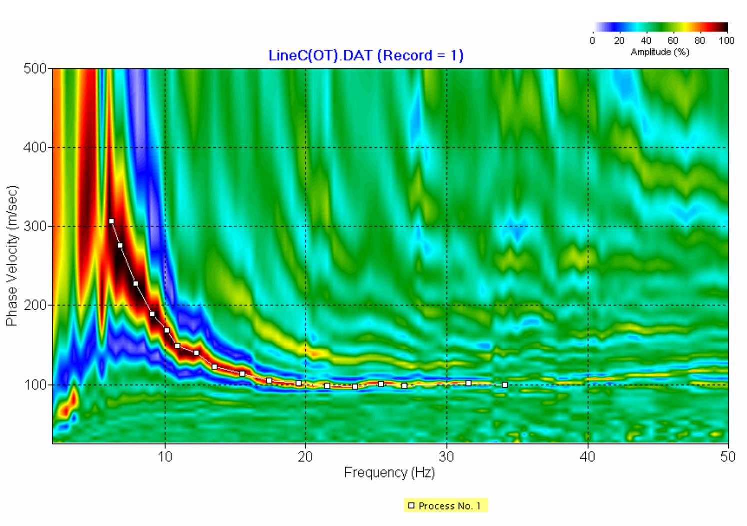

Figure 8: A dispersion curve is picked on the overtone analysis display.

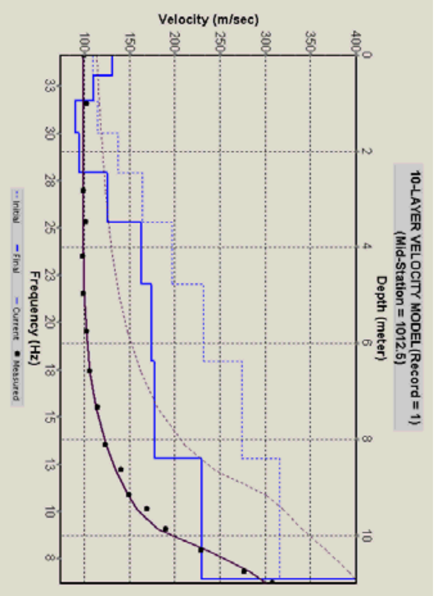

Figure 9: Depth versus S-wave velocity profile inverted from the dispersion curve in Figure 8.

The series of 1D profiles along a seismic line are then interpreted to form a 2D S-wave velocity cross section. Figure 10 is an example of an S-wave velocity cross section. Dark colours represent high S-wave velocity. In this example most areas shallower than 3 metres are considered to be low competence (<150 m/s).

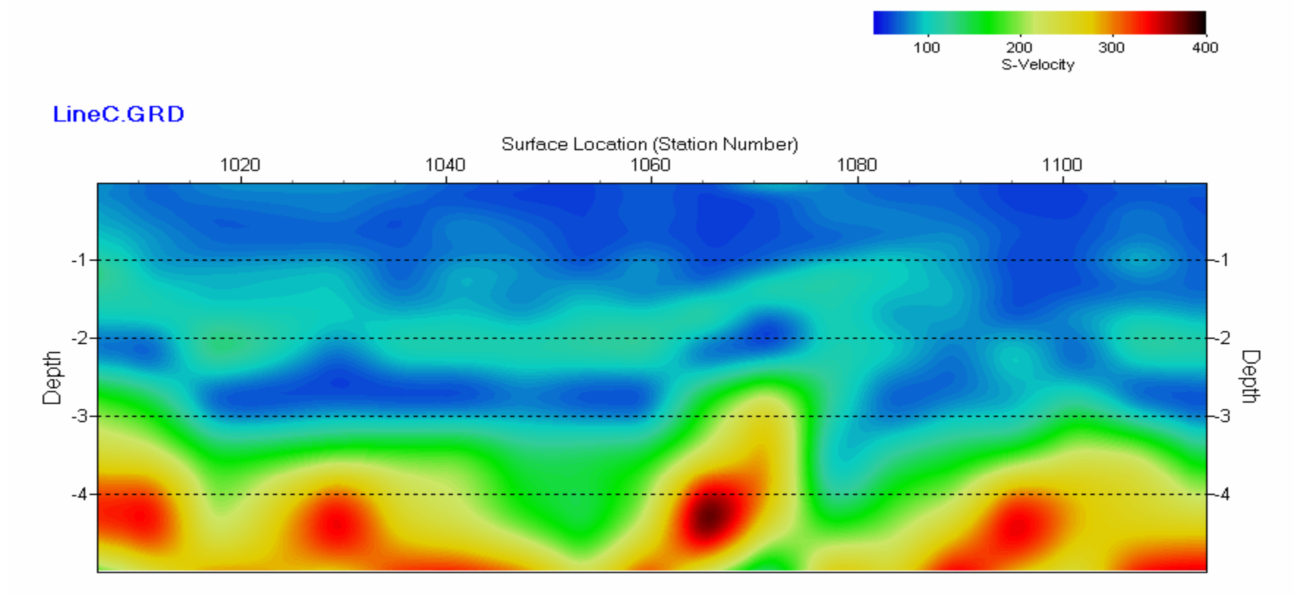

Figure 10: An example of S-wave velocity section. Vertical axis is depth 0-5 m; Horizontal axis is 110 m long.

6 AREAS OF APPLICATION

To date the MASW method has been used in various applications in various areas. Typical applications include compaction monitoring (Park and Miller, 2004), bedrock mapping (Miller and Xia, 1999), cavity detection (Park *et al,* 1998), subsidence investigation (Miller *et al.*, 1999), aquifer search (Xia, 2006) and geological mapping (Westerhoff, 2004). Some examples are presented from applications in Australia.

Figure 10 in the previous section is from a football ground built on a landfill site. Uneven unconsolidated material near the surface is causing subsidence and cavities in the field especially in dry condition.

Figure 11 shows an example of a hard sandstone bedrock under a construction site abruptly changing depth. In this site, only one CPTu test encountered the shallow bedrock and the MASW survey successfully mapped its extent.

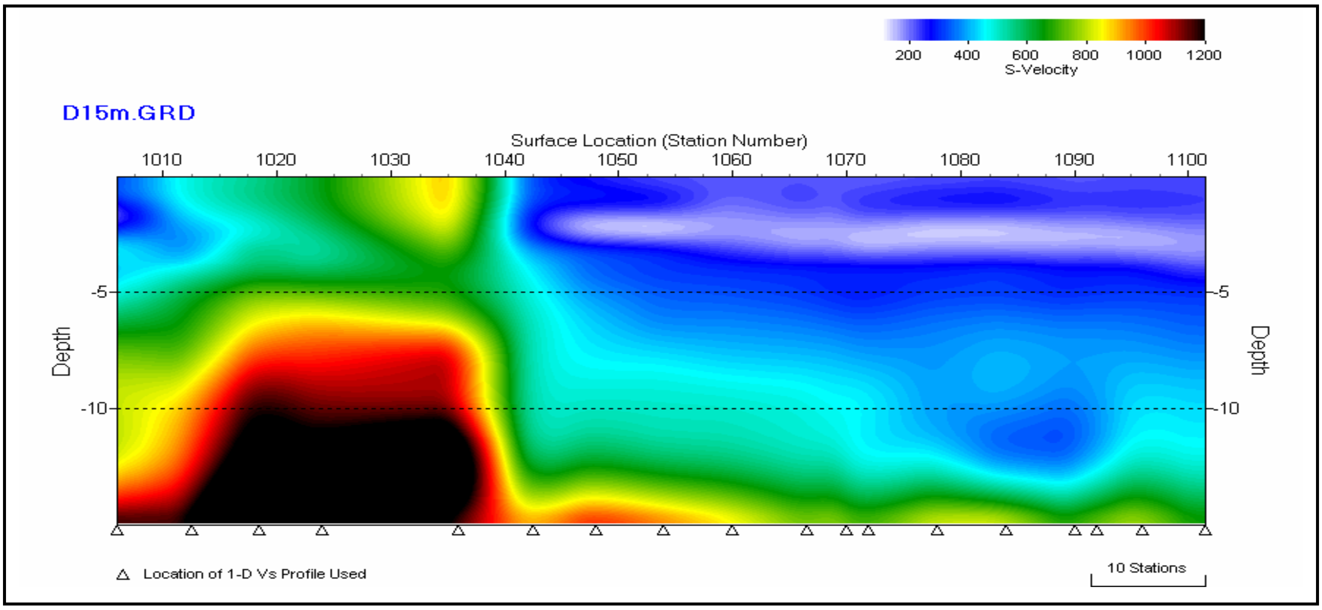

Figure 11: Variation of depth of bedrock mapped by MASW. Vertical axis is depth 0-15 m. Horizontal axis is 100 m long. (from Suto *et al.,* 2007)

Monitoring the quality of compaction for building sites is another engineering application of MASW. Figure 12 is an S-wave velocity cross section at a construction site after compaction by impact roller. This line shows a poorly compacted area remaining to the left of the section.

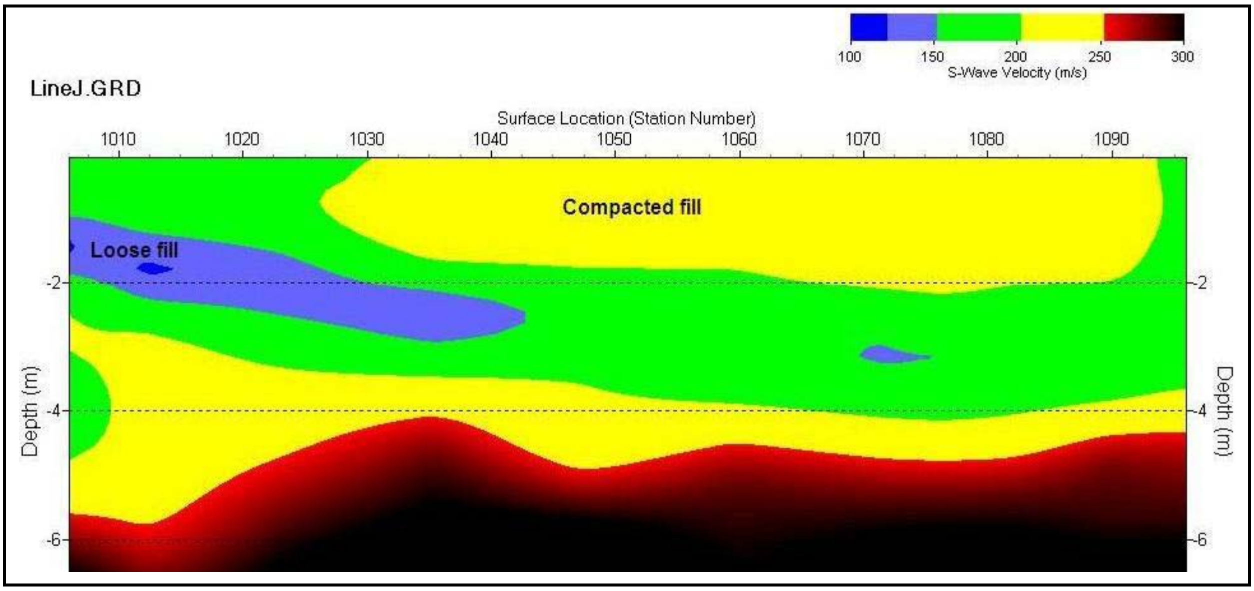

Figure 12: Competence of the ground after compaction mapped by MASW. Vertical axis is depth 0-6.2 m. Horizontal axis is 90 m long. (from Scott *et al.,* 2007)

In this example the survey lines were closely arranged to enable mapping in plan view. Figure 13 shows the distribution of S-wave velocity at a depth of 1m below ground surface. It is superimposed on the results of DCP tests at the site. The two results agree with each other very well and the MASW gives more details of the spatial variation of the competence of the ground. The area circled as an “anomaly” is a location where S-wave velocity map did not agree with the DCP results. Later, it was found that this location had been filled with building rubble bridging fill within 0.4 m depth. The MASW map represents the competent ground below the rubble.

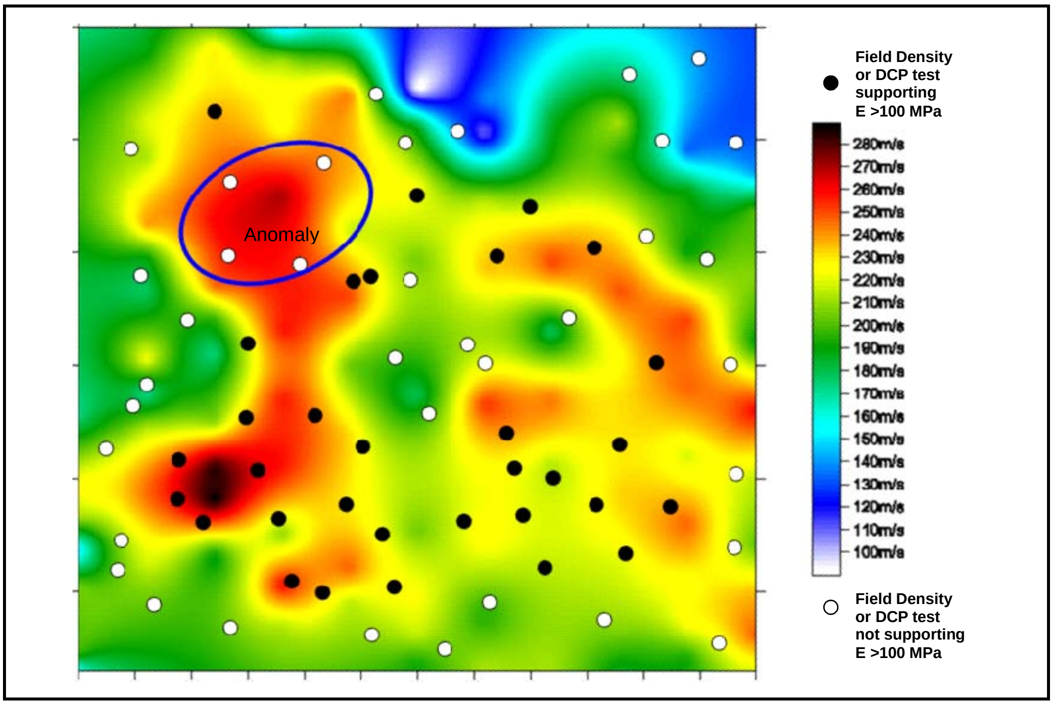

Figure 13: Plan view of competence after compaction at the depth of 1 m below ground mapped by MASW. The area is approximately 120 m by 120 m. (from Scott *et al.*, 2007)

Another example (Figure 14) is an investigation in a tailings dam where tailing material, original surface and bedrock are differentiated by the MASW method. Lithology from the borehole logs along the line is posted in Figure 14. In the tailing on the top, some parts are allowed to dry and are harder than other parts. The S-wave velocity of the harder tailings approaches that of underlying clay of the original surface.

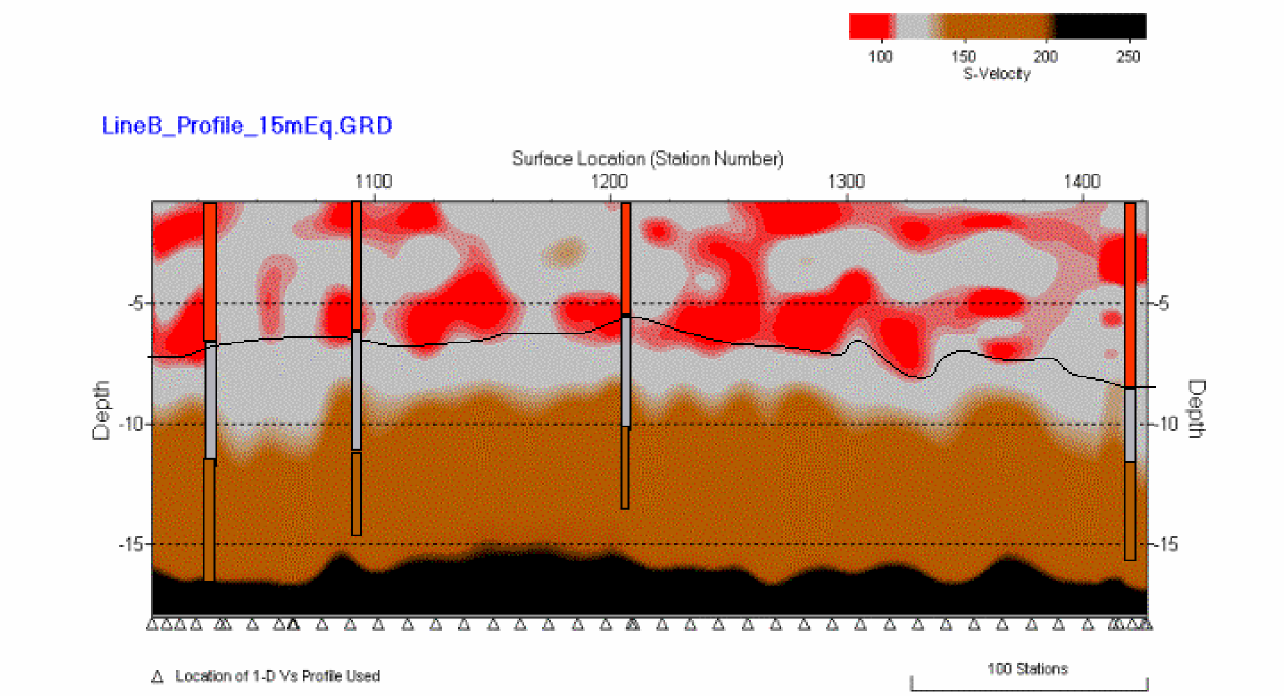

Figure 14: S-wave velocity section from a tailings dam showing from the top: tailings, stiff clay and shaley bedrock. Vertical axis is depth 0-20 m. Horizontal axis is 420 m long. (from Suto, *et al.*, 2006)

7 DISCUSSION AND CONCLUSION

The MASW method can estimate the competence of the ground by S-wave velocity, which is closely related to Young's modulus. As the method uses survey lines on the ground surface, it can profile the competence of ground continuously. Surveying along closely spaced lines can map the distribution of S-wave velocity in plan view with dense sampling. The areas of application include investigation of natural ground, monitoring of construction operations and their combination.

As seen in the examples the S-wave velocity distribution mapped by MASW method generally agree with the results of borehole logging and other geotechnical tests. Precise comparison of these methods is beyond the scope of this paper, and readers interested are referred to other publications such as Xia *et al.* (2000), Anderson *et al.*(2004) and Anderson *et al.*(2005).

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