Mapping shallow bedrock at an urban development site with the multichannel analysis of surface waves (MASW) method

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ABSTRACT

The multichannel analysis of surface waves (MASW) method is an advanced method for investigation of elastic properties of near-surface materials. It analyses seismic response of the ground in the frequency-velocity domain and estimates the underground S-wave velocity structure. This case history demonstrates the effectiveness of MASW in mapping a shallow bedrock feature which was critical to foundation assessment on a Gold Coast development site.

A closely-spaced CPTu tests at the site found relatively deep and variable soft soils typically 6-20 metres thick. However, one CPTu test pit indicated a localised hard anomaly at an unexpected very shallow depth of 1.4m. Several check test pits showed the bedrock is sandstone. It was critical to this project to know the lateral extent of this feature, as building across an abrupt change in ground stiffnesses could cause differential settlement problems.

MASW seismic survey lines were sited in a radial pattern from where the shallow bedrock was encountered to determine the extent of this feature. The results of the analysis were displayed in the form of S-wave velocity cross sections. These clearly showed the extent of the shallow bedrock. This demonstrates a case where the MASW method is used effectively and cost-efficiently in mapping this shallow bedrock.

1 INTRODUCTION

Seismic survey methods are often used in investigation of geological structure and the determination of elastic properties of soils and rocks. The reflection seismic survey is commonly used for petroleum exploration mainly for geological structure and petroleum traps; it is suited for relatively deep structures. For shallower applications, typically in the geotechnical field, the refraction method is more often employed. (SEGJ, 1998)

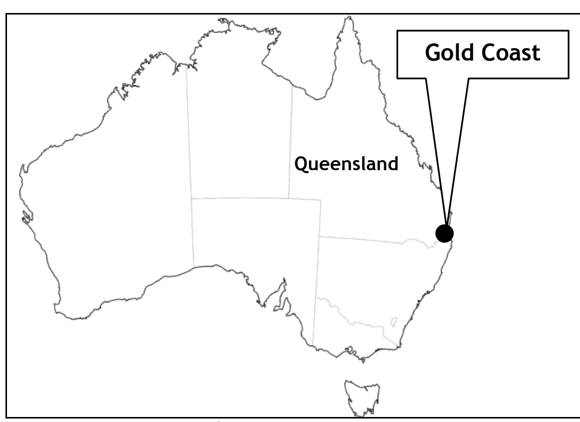

Figure 1: Project location

Recent research of seismic waves in the frequency domain has led to the development of other kinds of seismic survey technologies using the surface wave analysis. These new methods include the Microtremor Survey Method (MSM) (Okada, 2003); the Refraction Microtremor (ReMi) method (Louie, 2001) that analyse ambient seismic signals, the Spectral Analysis of Surface Waves (SASW) method (Nazarian et al., 1986) and the Multichannel Analysis of Surface Wave (Park et al., 1999) which use active seismic sources. All of these methods analyse the dispersive properties of Rayleigh waves in the frequency-phase velocity domain, and estimate the subsurface S-wave velocity structure. Each of these methods has its own merit depending on lateral scale of the survey, required depth and resolution of investigation, nature of environmental noise and site access for seismic source.

Among these methods, MASW is recognised as being efficient in investigation of relatively shallow depths (to 30-50m with current data acquisition parameters) over relatively small areas. The recent applications to building sites include estimation of depth of bedrock (Miller et al., 1999), detection of sinkholes (Miller and Xia, 1999) and assessment of soil competence (Park and Miller, 2005).

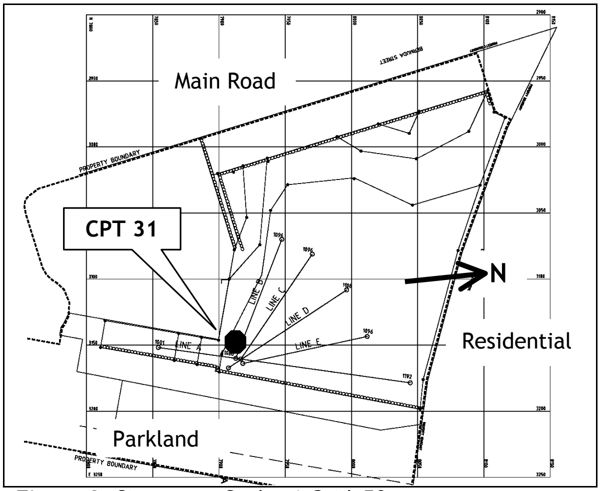

Figure 2: Site map. Scale: 1 Grid=50m

The present paper is concerned with the application of the MASW method to delineating the extent of the shallow bedrock in a construction site, where cone penetration tests (CPTu) and test pits encountered bedrock at an unusually shallow depth. Construction straddling the shallow and deep bedrock may risk damage due to differential settlement, therefore it is important to delineate the extent of the shallow bedrock.

2 BACKGROUND OF DEVELOPMENT PROJECT

The site of this project is a new residential development on the Gold Coast in southeast Queensland (Figure 1). Development of this part of Gold Coast started in late 1980s and it took until late 1990s to landscape the swamp to a lakeside business and residential centre.

The terrain is a largely flat recent sedimentary floodplain which overlies the Tertiary bedrock consisting mainly of sandstone. The bedrock is, however, eroded by ancient creeks and tributaries in a complex pattern resulting in its depth varying in a complextern.

The site is in a well-developed suburban area along a main road, surrounded by a shopping complex, established residential properties and an extensive parkland. The development of this site started in 2005 as one of the last major residential properties in the area. Site investigation by the MASW method took place in January 2006.

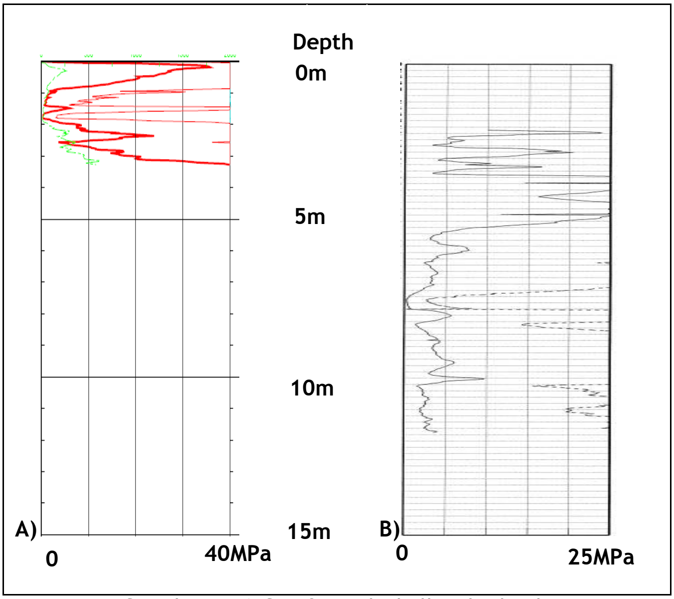

Figure 3: CPT data. **A)** CPT 31 with shallow bedrock; **B)** Typical CPT without shallow bedrock.

3 GEOTECHNICAL INVESTIGATION

During the initial site investigation, 42 cone penetration tests (CPTu) were conducted over the area of approximately 5 hectare. Among them, CPT 31 encountered refusal at shallow depth that was later discovered to be sandstone rock (Figure 2). This CPT profile and another "typical" CPT profile in an area with thicker soil for comparison are shown in Figure 3.

To investigate the extent of this feature, five seismic lines were surveyed using the MASW method as shown in Figure 2. The fan pattern arrangement, rather than grid, was chosen to ensure each line captured the edge of the shallow bedrock. The lines could not be extended to the parkland to the east because there was a drain parallel to the eastern boundary.

4 DATA ACQUISITION FOR MASW

A total of 667 metres of seismic data was recorded on five lines for the MASW method on 11th January 2006. The acquisition parameters used are listed in Table 1. Acquiring two records with the source points separated by the length of the streamer enables the combination of two 24-channel records to form one 48-channel record for analysis. This ensures a continuous data coverage along the lines.

Table 1: Data acquisition parameters

Seismic source:	50kg accelerated weight drop onto a steel plate
Source interval:	24 m
Source points	2 per spread: 12.5m and 36.5m from closest geophone
Receiver system	Purpose-built land streamer
Far offset	60.5m
Recording channels:	24
Geophone interval:	1 m
Geophone type:	Geospace 4.5 Hz single geophones
Record length:	2 seconds
Sampling rate:	0.5 ms
Filters:	No Low-cut or High-cut filters were used
Data format:	SEG2
Recording system:	Seistronix RAS-24 distributed seismic system
Vertical stacking:	1

Two examples of seismic record are shown in Figure 4. Only the nearest 24 traces of each record are displayed here. Note that the gradient of the seismic signal train in Figure 4A at the left is far gentler than in Figure

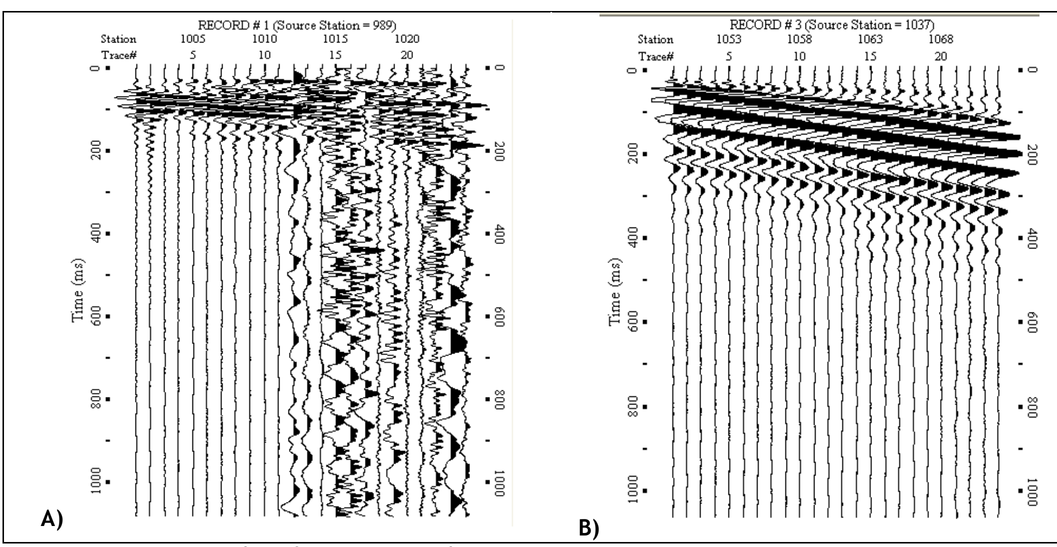

Figure 4: Two examples of seismic records.
A) Eastern end of Line B where bedrock is near the surface.
B) Western end of Line B where bedrock is estimated to be about 10m deep.

4B at the right, indicating high seismic velocity. It is also noted that the high-frequency components are more dominant and that noise level is higher in Figure 4A. All these features indicate there is hard material with high seismic velocity near the surface.

5 DATA ANALYSIS

Data analysis was carried out using the SurfSeis® software developed by the Kansas Geological Survey. The process consists of two steps: analysis of dispersion curves in frequency-phase velocity domain; and inversion of the dispersion curves to S-wave velocity structures.

5.1 Overtone Analysis and Dispersion Curve

Data collected in the time-space domain were transformed into the frequency-phase velocity domain through the process called overtone analysis. This transform calculates the energy level of each frequency component of the Rayleigh wave travelling at certain velocities, and displays it in colour. Figure 5 shows examples of the overtone analysis displays from the areas of the site where the bedrock is relatively shallow and deep. In Figure 5, which is normally displayed in full colour, the darker grey indicates high-energy spectrum of Rayleigh wave in the frequency-phase velocity domain.

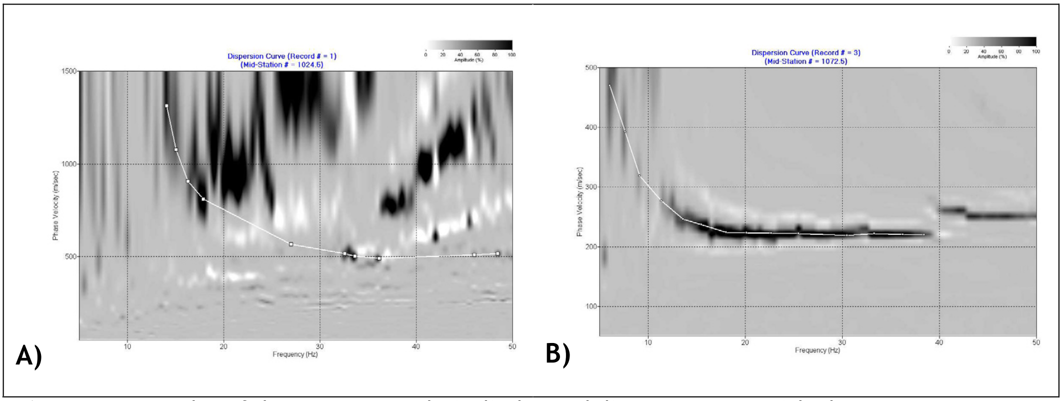

Figure 5: Examples of the overtone analysis display and dispersion curve picked.
Horizontal scale: 5-50Hz.
A) Eastern end of Line B where bedrock is near the surface. Vertical scale: 50-1500m/s
B) Western end of Line B where bedrock is estimated to be about 10m deep. Vertical scale: 50-500m/s

A dispersion curve of the fundamental mode Rayleigh wave is picked on the overtone analysis display, following the high-energy trend. Where there is a thick low-velocity surface layer, the overtone analysis displays a clear trend in the frequency-velocity domain and a dispersion curve is unambiguously analysed (Figure 5B). The high-energy trend over 40Hz in Figure5B is that of a higher mode Rayleigh wave and is not included in the pick of the dispersion curve. Where the high-velocity bedrock is near the surface, the overtone display is dominated by energy other than the fundamental mode Rayleigh wave namely higher mode waves and body waves (Figure 5A). As a result the display appears noisy, and the analysis of dispersion curve becomes interpretive. Note that the energy concentrates in the higher velocity region of the display.

Figure 5A shows high-energy in the high frequency (above 35Hz) high-velocity (over 750m/s) area trending upward with increasing frequency. This is perhaps due to a fast body wave travelling near the surface through a high-velocity medium. This strong energy obscures the dispersion curve of the fundamental mode Rayleigh wave above 35Hz. The dispersion curve energy was recognised up to 50Hz, where phase velocity of 500m/s was picked. Xia et al. (1999) suggests that first-pass estimates of the depth and S-wave velocity represented by a point on a dispersion curve are 0.63 times the wavelength and 0.88 times the Rayleigh wave phase velocity, respectively, as. Accordingly, the point of the highest frequency on the dispersion curve in Figure 5A represents depth about 6m and its velocity is about 440m/s. Iterative inversion further refines the depth model. This analysis was carried out on the seismic data at approximately 6m intervals.

5.2 Inversion

Each dispersion curve was inverted to an S-wave velocity structure model at the analysis location. This is a one-dimensional (1D) structure, *i.e.* it models S-wave velocity versus depth at the chosen location. An initial layered earth model is required for the inversion process. In this case a 20-layer variable thickness model with a depth to half space of 35m was used. Apart from these two parameters, the iterative inversion is performed automatically by SurfSeis.

Where high-velocity material is near the surface, such as the location of Figure 5a, the inversion process does not give detailed S-wave velocity structure shallower than the minimum depth defined by the pick at the highest frequency of the dispersion curve. Further The depth model in shallower depths are refined by iterative inversion process to match minor inflections in the curve.

Along each seismic line, a series of 1D S-wave velocity structures are obtained through the inversion process. These 1D velocity structures are gridded in the 2-dimensional space to show a final S-wave velocity section for each line. Figure 6 is a grey scale display of S-wave velocity section of Line D. This is normally in full colour. The extent of the bedrock is indicated by dark grey, which represents the S-wave velocities greater than 450m/s.

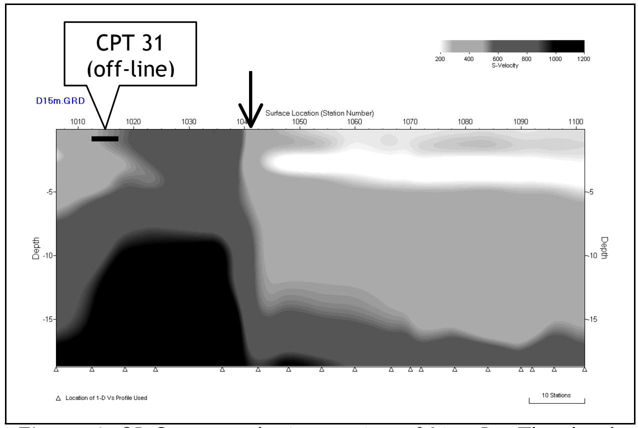

Figure 6: 2D S-wave velocity section of Line D. The depth of refusal at CPT 31 is shown by short black line. The triangles at the bottom are analysis points.

The arrow in Figure 6 indicates the limit of the shallow bedrock. As the overtone analysis uses a number of traces, some lateral smearing was expected over the range of the races. However, in the present case, such smearing does not seem to be an issue. As seen in figure 6, a very sharp boundary of the areas of shallow and deep bedrock is produced. This suggests smearing over the traces is not significant. The lateral resolution in this case is achieved by the density of analysis points.

6 MAPPING

The limits of the region of shallow bedrock interpreted in the S-wave velocity sections were marked on a plan and connected to provide an estimate of the extent of the shallow bedrock. Contouring the depth of the top of bedrock was not attempted, because the observation on the 2D sections showed that the edge is well defined and it drops sharply as seen in Figure 6.

Figure 7 is the plan view of the estimated extent of the shallow bedrock. The feature observed on the seismic lines are consistent from line to line and encloses an area with the longest lateral extent about 60m along line A. The area to the east of the survey is outside of the development site.

7 DISCUSSION AND CONCLUSION

The MASW method was successfully used to map the extent of the shallow bedrock which CPT tests and test pits indicated at the construction site in Gold Coast, Queensland. The result contributed to an accurate settlement analysis being conducted ensuring there would be no unexpected differential settlement.

In this application, the edge of the bedrock dropped sharply, and depth contouring was not necessary. If the bedrock had gently-sloping edges, a depth contour map may be desired. Then, a more detailed S-wave velocity structure would be investigated by improving the quality of dispersion curve particularly in the high-frequency band. This may be achieved by reducing the geophone spacing in acquisition and/or applying appropriate mute and filtering in processing.

The MASW survey took only two days: one day for field data acquisition and one day for data analysis. The number of the analysis points in this survey is 100. Should this amount of information be obtained by other methods such as CPT or drilling, the time and hence cost would be an order of magnitude higher.

With the knowledge of the limit of the shallow bedrock, a more realistic settlement model was used to assess the influence of the near surface rock on surrounding structures.

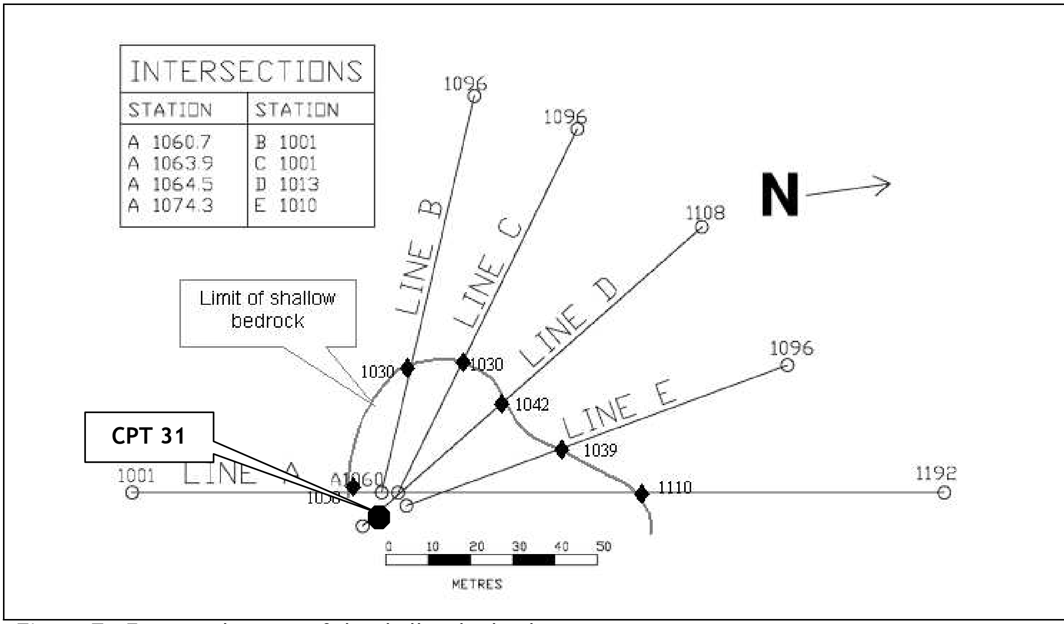

Figure 7. Estimated extent of the shallow bedrock.

This case history demonstrated that the MASW method is an economical way of checking the structure and competence of subsurface ground conditions and that it is an effective risk reduction tool available to the construction industry.

8 ACKNOWLEDGEMENTS

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