Investigation of Unstable Slopes and Wind Turbine Sites with Surface and Borehole Seismic Technologies: Case Studies

Robert J Whiteley
Coffey Geotechnics, Sydney, Australia

Simon B Stewart
Coffey Geotechnics, Sydney, Australia

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ABSTRACT

Surface and borehole seismic imaging with both P and S waves enhance site assessments and reduce risks at difficult and complex geotechnical sites. These technologies increase the effective radius of investigation of boreholes alone and provide improved site parameters such as dynamic elastic modulus. Case studies illustrate applications at a major road project on unstable colluvial slopes and at wind turbine sites on variable, voided calcareous soils with calcarenites.

1 INTRODUCTION

Unstable slopes pose challenges for conventional geotechnical investigations as drilling sites are often limited or costly and may not be possible at preferred locations. For isolated wind turbine sites, that may also be on slopes, it is normal to drill a single borehole at or near the proposed tower location. In both situations it is desirable to extend the investigation radius of boreholes to test subsurface variability and to obtain more representative parameters such as dynamic elastic modulus. This can be achieved with appropriate combinations of surface and borehole seismic geophysical technologies using both compressional (P) and shear (S) waves. These technologies are discussed and applied at unstable slope and wind turbine sites.

2 SEISMIC TECHNOLOGIES

2.1 Surface Seismic Testing

Most geotechnical engineers know of the seismic refraction method (Whiteley, 1994) and its ability to determine rock depths, strengths and excavation conditions from relationships between rippability and seismic P wave velocity. This method is also widely applied to unstable slope sites alone, or integrated with, borehole methods (Whiteley, 2004). Recently, surface refraction technology has been enhanced by combining better field practice and advanced numerical interpretation methods (Whiteley and Eccleston, 2006). Refraction has also been supplemented with S wave seismic testing using the new Multi-Channel Analysis of Surface Waves (MASW) method (Park et al. 1999). Application of both seismic refraction and MASW now allows mapping of the limits of unstable masses from the typical lower seismic velocities that they exhibit, examination of site variability and in situ determination of Young's and Shear Dynamic Modulus from standard equations.

2.2 Borehole Seismic Imaging

The investigation radius of a single borehole, drilled at least to the depth of interest, can be extended using for P wave seismic imaging with the SUBS (Site Uniformity Borehole Seismic) test (Whiteley, 2000). For SUBS, an encased array of hydrophone detectors at 1 to 2m intervals is lowered into a water filled PVC-cased borehole. Seismic energy is generated by summed surface impacts or buried small charges at 1 to 5m intervals along 1 to 8 scan lines radiating from the borehole in different directions. The borehole log and a vertical seismic profile (Section 2.3) provides calibration. Conventional surface seismic refraction provides soil thicknesses away from the borehole and this information is incorporated into the SUBS image. If more than one borehole is available then crosshole seismic imaging can also be done. SUBS essentially tests the applicability of the initially assumed layered earth model to the actual conditions at the site by creating seismic tomographic images (STI) along the scan lines. STI are two-dimensional contoured sections of seismic velocity in the material between the seismic sources and borehole detectors and represent variations in density and dynamic stiffness properties of materials away from the borehole. The resolution of SUBS is about 1m vertically near the borehole to 2m at 20m distant and from 2m to 4m horizontally over the same range. Sometimes observed low velocity features near the borehole are due to ground disturbance from drilling or when shallow or perched aquifers are drained by the borehole. Higher velocities at the borehole can be caused by grout bulbs formed during installation of the PVC casing.

2.3 Vertical Seismic S-Wave Profiling (VSSP)

In addition to the surface MASW method (Section 2.1) detailed S wave velocities may be obtained in the borehole with Vertical Seismic Shear Wave Profiling (VSSP, Whiteley et al., 1990). This test is similar in concept to the Seismic Cone Penetrometer Test (SCPT, Robertson et al., 1986) but is completed in a PVC cased borehole and can accommodate a wider range of conditions. Horizontally polarised S waves (SH waves) are generated near the borehole collar using impacts on the ends of weighted plank. P waves are generated separately by impacting a metal plate. Both waves are detected by an in-hole, three-component geophone probe clamped against the hole wall at pre-selected depth intervals between 0.5 and 2m. Individual P and S wave travel times to this probe are used to determine average and interval seismic velocities and dynamic modulus. VSSP generally provides more detail at the borehole while MASW tests the applicability of these values to the overall site and quantifies the range of variation.

3 CASE STUDIES

3.1 Unstable Slope Site: Lawrence Hargraves Drive, New South Wales

Lawrence Hargrave Drive (LHD) is part of the main coastal link between Sydney and Wollongong. The original road between Clifton and Coalcliff was constructed in 1878 about 20 to 45m above sea level through a coastal escarpment with steep cliffs rising to a height of some 300m. Aggressive marine weathering and erosion has undercut this escarpment and induced instability problems. Since construction, this road had a history of severe embankment instability, rock fall, debris slide and debris flow problems and was rated as the highest for slope instability risk to roads in New South Wales. For safety reasons it was closed in August, 2003. Over the next 2.5 years an engineering solution was devised and constructed to reduce risks to ‘acceptable’ levels. Geologically, LHD is on the southeastern margin of the Sydney Basin that contains essentially flat-lying interlayered sandstone, mudstone and coal beds, overlain by interbedded sandstones and mudstones/claystones and quartzose sandstone (Bowman 1974). Over the closed section of road the coastline has two prominent bays with their associated headlands. The landward sides of these bays form irregular amphitheatres, designated as Geotechnical Domains (GD2 and GD4, Hendrickx et al. 2005). This paper deals only with GD2 which is an east facing bay 300m long and 100m deep, and the highest risk area to road users. The main hazards included rock avalanches from the sandstone cliffs beside the road, rock falls from cliffs and debris flows from the higher claystone slopes. The road traversed thick colluvium extending to the sea, comprising a mix of rocky debris with some extremely large boulders. This has experienced long-lasting failures with rotational and translational slides common below the road since it was opened. During 2003, the road at GD2 started moving again and was a major contributing factor to the closure decision.

As part of the geotechnical investigations, SUBS imaging of the colluvium on the seaward side of the road was completed from a series of boreholes to map the bedrock interface. In this very steep, unstable area drilling was not permitted and inclined boreholes from the road were considered too costly. Seismic data was acquired using energy sources that were small explosive charges in shallow holes augered along individual scan lines that both paralleled and crossed the road. On the very steep slope these were deployed by crews tethered with safety ropes. The SUBS image from a single scan at one borehole (BLA5) drilled beside the road at GD2 is discussed. This was obtained along Line 2, oriented down the steep slope and is representative of the site conditions. Correlation of the seismic velocities with the borehole log is provided on Table 1 with three general seismic layers extending from the ground surface.

Table 1: Calibration of seismic velocities with borehole log for BLA5

Seismic Layer	P-wave velocity (km/s)	Thickness range (m)	Simplified borehole log
1	0.4-0.7	1-12	Silty sand (fill & colluvium)
2	0.8-2.5	6-23	EW to HW sandstone, conglomerate, sandy clay, some boulders
3	2.6-3.7	-	SW to F siltstone/sandstone with coal seams

EW- Extremely Weathered, HW- Highly Weathered, MW – Moderately Weathered, SW- Slightly Weathered, F- Fresh

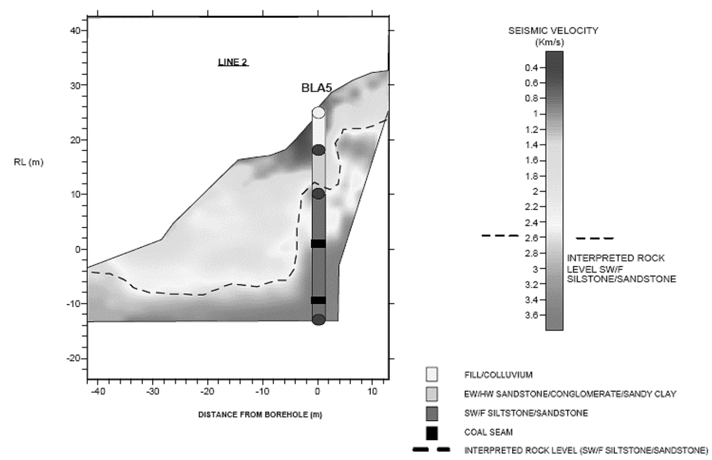

Figure 1: SUBS seismic image for Line 2

Figure 1 shows the seismic image obtained beneath Line 2 with the interpreted level to SW to F siltstone/sandstone marked where the seismic velocities increase rapidly with depth, suggesting an abrupt transition from colluvium to SW to F rock, as encountered at the borehole (Table 1). The bedrock profile appears as three steep steps with the borehole on the second narrow step. This image also shows that the seismic velocities in the bedrock near the borehole are relatively low suggesting increased fracturing and instability. The bedrock deepens rapidly on the downslope side of the borehole to about 8m below mean sea level (RL 0m) and is relatively flat, possibly due to scouring by the combination rapid toe erosion at the shoreline and lateral movement of the overlying unstable colluvial mass due to slumping. The bedrock also appears to shallow near the limit of the image but this could be a region where large boulders are present as can be observed at low tide.

3.2 Wind Turbine Sites, Portland, Victoria

One of Australia's largest windfarm projects is currently under construction on the south-west Victorian coast near the city of Portland. While many factors governing the siting of wind turbine towers, significant geotechnical factors relate to the design of the footings. This normally requires site-specific information on dynamic elastic properties of the soils and rocks and their variability and condition beneath each proposed turbine site.

This region of Victoria is formed as a series of NW to SE trending sandy ridges, relict beach dunes with broad interdunal flats. The ridges contain calcareous sands of the Bridgewater Formation that is a poorly graded, fine to coarse sands with little or no fines and the geological conditions are highly variable with sandy soils containing calcarenite layers and exposures of massive and voided calcarenite, often on the ridges. The continuity and degree of calcareous cementation is extremely variable with strengths ranging from those of uncemented, medium dense or dense sands to strong calcarenite/sandstone. The strongly cemented zones often have a high void ratio and sinkholes, cavities, solution pipes and other karstic soils can be present, particularly, in the more strongly cemented soils.

Recently, Bowling and Ditchfield (2007) describe an approach to wind turbine footing design in similar materials that is almost entirely reactive and based on initial drilling, typically to 15-20m depth, then observation, further shallow drilling and geotechnical assessment during construction. Our approach is more proactive, combining geophysics with geotechnical investigation. This uses single deep borehole is drilled and cased to 25m near the proposed tower location, geotechnical assessment of the materials encountered, SUBS seismic imaging along radiating scan lines to at least 20m distance from the borehole where substantial rock is encountered and S-wave measurements, generally where very thick soil sections are present. This permits more rapid site assessments and local adjustments of tower placement where improved foundation conditions are indicated, potentially significantly reducing geotechnical risks and construction costs. Case studies are presented at two wind turbine sites near Portland, one in mainly rock conditions and the other in soils. At both locations the tower was to be supported by an octagonal pad footing 16m across, founded at 2m depth.

Table 2: Simplified borehole log of BH2

Depth (m)	Simplified borehole log
0-8	Calcrete cap to 1m, dense to very dense calcareous sands
8-25	Calcarenite layers, high to very high strength, substantial core loss over 0.4 to 0.8 m intervals, large cavities from 13 to 16m

The set of SUBS images on the radiating scan lines from the first site is shown in Figure 2. Table 2 provides a simplified borehole log. The images show highly variable subsurface conditions. Relatively low seismic velocities (< 0.9km/s) to about 8m to 10m depth reflect mainly dry dense sands and higher to the east and south-east of the borehole suggest increased thickness or occurrence of calcarenite layers. Below this depth velocities increase significantly consistent with increased thicknesses of strong calcarenite layers encountered in the borehole (Table 2). Substantial cavities from 13 to 16m (Table 2) appear as higher velocity regions on most of the images presumably due to void filling by casing grouting operations. Below 8m depth there is quite a different velocity distribution on either side of the borehole indicating substantial lateral variability at this site with possible increased voiding mainly on the western side of the borehole indicated by the lower values. The higher velocities extending laterally mainly to the east and south-east of the proposed tower location indicate improved foundation conditions in this region, consequently, a new tower location was suggested as shown on Figure 3.

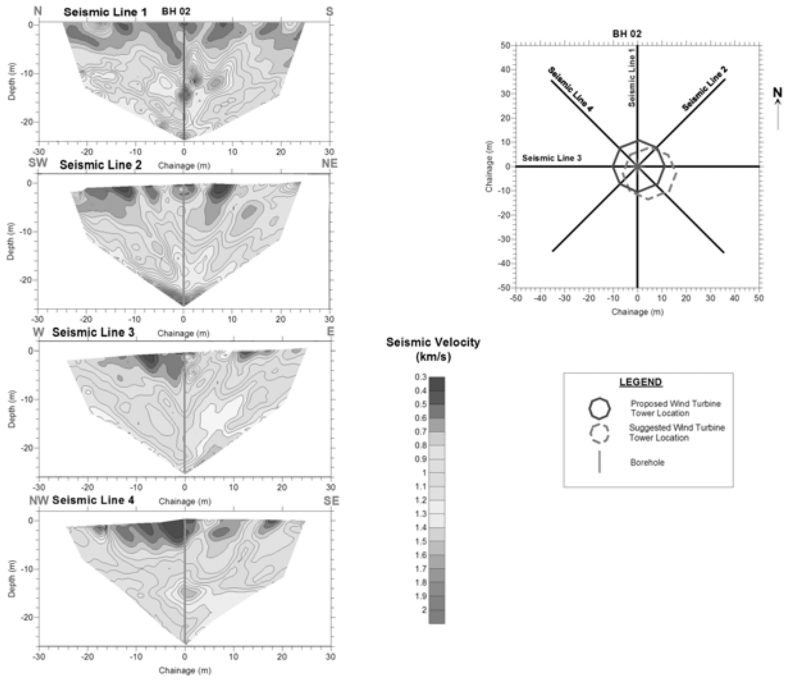

Figure 2: SUBS images around BH2

The second turbine site was on interdunal flats where no rock was expected nor encountered in drilling. Only VSSP was completed at this site for dynamic shear modulus (G) determination. The simplified borehole log with measured SPT (N_{60}) values and Swave velocities (V_s) are listed in Table 3 with computed G values assuming typical average dense sand densities. In order to provide some further confidence in the measured SPT values Figure 3 (from Whiteley et al., ibid.) was used to predict SPT values independently from the measured S-wave velocities (Line A, Figure 3).

Table 3: Simplified borehole log, S-wave velocities and SPT results

Depth (m)	Description	N_{60} measured	N_{60} predicted	V_s (m/s) measured	G (MPa)
0-8	Dense sands, minor cemented layers	21-69	6-27	125-270	25-145
8-20	Dense to very dense calcareous sands; SPT refusal at 13, 14 & 17m	49-61	42-51	300-340	150-210

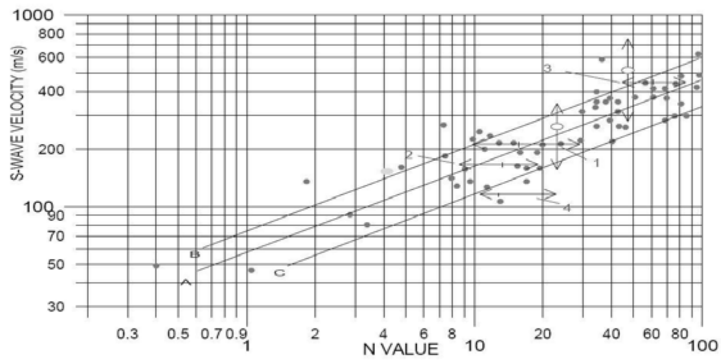

Figure 3: S-wave velocity versus SPT N-value

Predicted values agree with measured SPT values below 8m depth but are lower at shallower depth, probably due to effect of the near-surface cemented cap materials on the SPT tool.

4 CONCLUSIONS

Combined geotechnical drilling, enhanced surface and borehole seismic imaging technologies have the ability to improve site characterisation, reduce risks and increase engineering design opportunity at unstable slope and wind turbine sites in complex and variable conditions. This approach appears to be superior to drilling and observation alone.

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