Talk on "Engineering Applications of Seismic Refraction and Resistivity Techniques"

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MR. Ng Chak Ngoon, a practising engineering geologist and also the President of Malaysia Soil Investigation Association, presented the evening talk above at Wisma IEM on 15 May 2009. The talk was attended by 60 participants.

Geophysical survey methods have become increasingly important in engineering site investigation in recent years because of the continuous improvement in techniques and instruments. In particular, essential analytical techniques previously limited to mainframe computers are now possible with the immense power of the personal computer. Consequently, engineers are now discovering the advantages of engineering geophysics in terms of reliability, cost and speed.

The expanding role of engineering geophysics is also reflected by the increased coverage given to it in the latest (1999) edition of BS 5930: Code of Practice on Site Investigation; from a mere three pages in the preceding edition, it has now been expanded to 16 pages. However, this well established technique is somehow underutilised in Malaysia due to the users' unfamiliarity with the techniques and bad experience on the accuracy of the results. The main reasons for such an unhealthy outcome are mainly attributed to the wrong method adopted for the site condition, inappropriate specification and inappropriate interpretative method.

SEISMIC REFRACTION TECHNIQUE

In Malaysia, as well as elsewhere, seismic refraction is the most popular geophysical technique in engineering application. The advantages of the seismic refraction method are its ability to produce comprehensive continuous subsurface profile in a short duration and at relatively low cost. Mr. Ng gave a brief introduction on the underlying principles, methodology, applications and case studies of the seismic refraction method. This method relies on the measurement of travel times of P-waves through earth medium after the impact is generated on the ground.

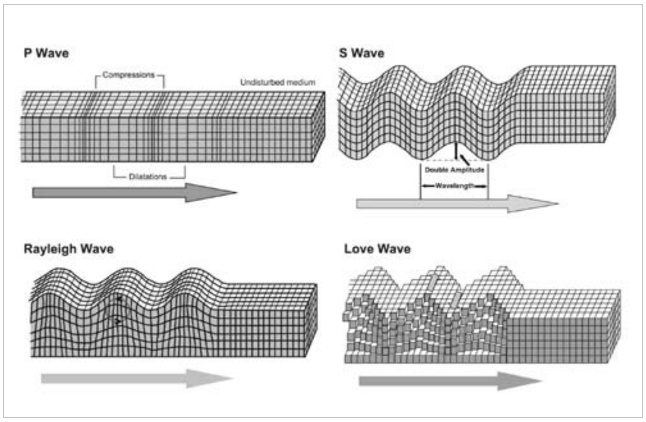

Figure 1: Types of mechanical waves generated from disturbance of ground surface

Figure 1 illustrates the models demonstrating the wave propagation of the body waves (P-wave and S-waves) and surface waves (surface rolling Rayleigh wave and horizontally polarised shear (SH) wave, which is also known as Love wave) in the semi-infinite elastic half space of earth materials. The identification of the first arrivals of seismic waves (*i.e.* P-waves) by geophones or hydrophones (see Figure 2) is the key to the interpretation of the seismic refraction method.

Figure 2: Geophone and its schematic details

Figure 3 illustrates the schematic diagram of the travelling wave front in various media under impact disturbance on ground surface. Due to the different travelling speeds in different underlying earth materials of varying densities and stiffness, the subsurface stratification boundaries are interpreted. The conventional interpretative method uses back-analysed P-wave travelling paths through the presumed sub-strata model with the mechanical properties of the earth materials inferred from correlation to best fit the measuring first wave arrival from a spread of geophone array.

This method is occasionally less accurate if the site geology is complicated. The new approach is to discretise the subsoils into smaller elements and adopting mathematical algorithms to compute the P-wave velocity field from which material types are identified on the basis of their P-wave velocities as presented in Figure 4 ('Velocity' is a commonly used terminology instead of 'speed' in seismic survey despite the fact that the direction

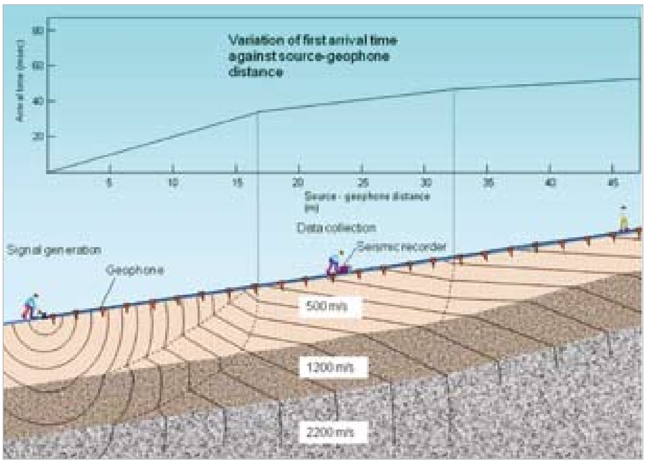

Figure 3: Propagation of P-wave through various media of different wave speed under impacting disturbance on ground surface

of the measured quantity is not of any significance in the interpretation).

A case study shown in Figure 5 comparing the two interpretation approaches mentioned earlier obviously implies that better accuracy is achieved in the new approach. The newer interpretation technique has also shown promising results on meta-sedimentary formations, in which interpretation using the older technique is far more complicated. The wave travelling speed interpreted for the respective subsurface materials can serve as an indication of the rippability of the materials.

This is very important for earthwork design as excavability of the materials above the cut platform will have direct impact to the entire earthwork cost and construction time. For the detection of the bedrock profile of a sloping ground, particularly across the ridge, it is usually advisable to have seismic lines running perpendicular to the contour lines. The same technique has been less successful in limestone areas, especially where the limestone surface is excessively irregular and far deviated from theoretical bases of the technique.

One common problem is the detection of a limestone surface closer to the line of geophones, but off the vertical plane through the lines of geophones as illustrated in Figure 6 in which case a borehole, which is normally vertical, would indicate the limestone to be much deeper. Therefore, in limestone, it is usually necessary to have seismic lines in two perpendicular directions to verify this possibility.

There is always a strong perception within the engineering fraternity to assume a detected cavity in the form of continuous channel or void in the intact limestone. However, observations of limestone surfaces exposed in tin mines suggest that a so-called 'cavity' usually exists in the form of a depression or sub-vertical solution notches (see Figure 7) in the walls of solution channels cut into the limestone bedrock. In some cases where the solution notches are very well developed, the intact limestone between the networks of solution notches become pinnacle clusters as shown in Figure 8.

A recent P-wave application is the determination of as-built lengths of constructed piles in abandoned projects being revived. In the example illustrated in Figure 9, the as-built pile construction records were unavailable and the interpretation

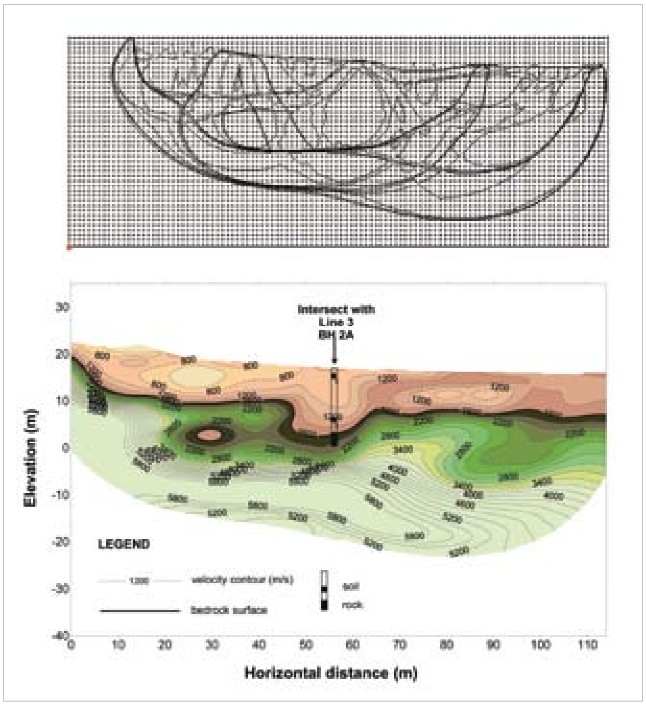

Figure 4: Interpreted wave speed field for materials identification

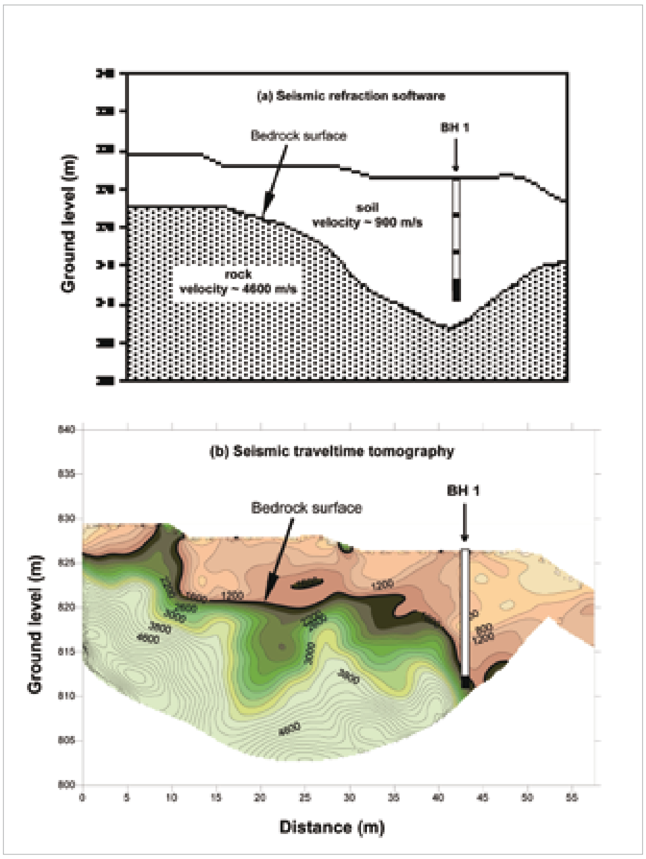

Figure 5: Comparison of conventional and recent interpretative approaches

of normal dynamic pile testing was difficult because the pile was connected by the capping beam to other piles forming a contiguous bored pile (CBP) wall, which was in turn connected to the concrete basement slab.

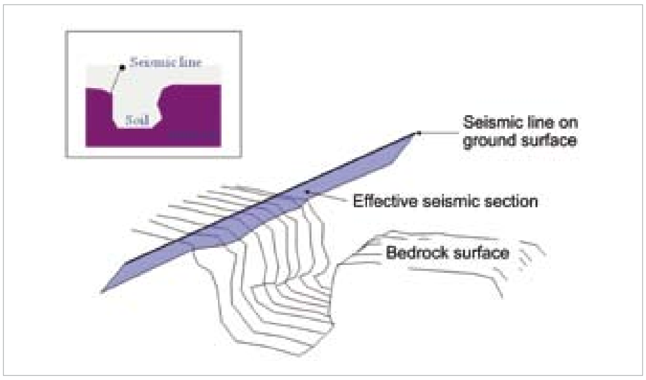

Figure 6: False first wave arrival from non-presumed survey section due to close proximity of refraction surface irregularity to the seismic array

Figure 7: Exposed limestone mining surface

Figure 8: Pinnacle clusters in massive development of solution notches

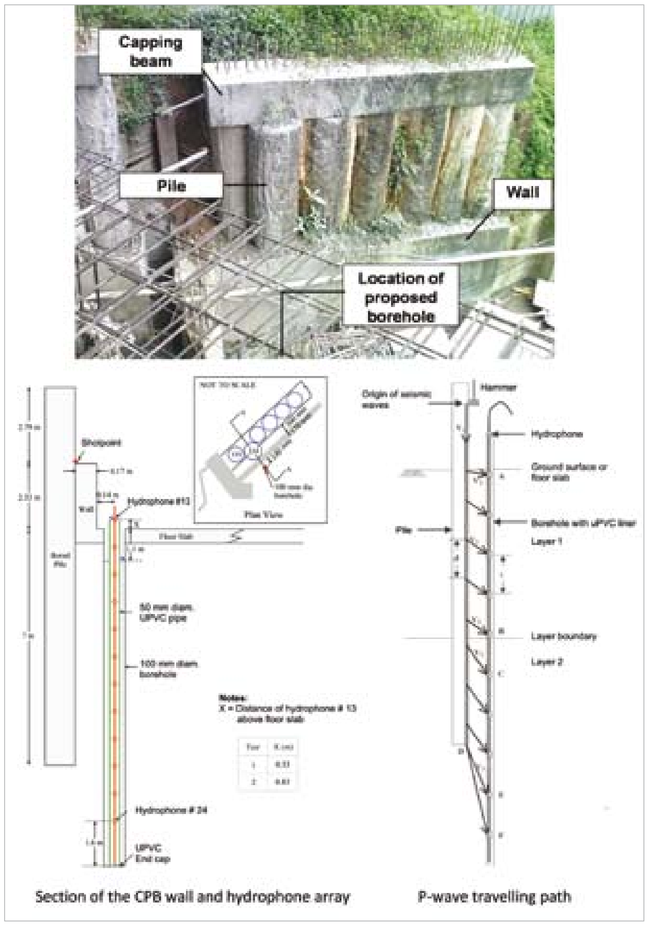

Figure 9: Use of P-wave for pile length detection

For the test, a borehole was drilled 300mm from the edge of the pile reaching a depth beyond the design length of the pile. An array of hydrophones at 1m intervals in the borehole filled with water detected the seismic signal created with a sledge hammer impacting at the upper portion of the pile. The test was repeated with the hydrophone array raised by 0.5m in the hole. In Figure 10, the first arrivals from the two tests are combined and plotted against the depths of the hydrophones to yield the equivalent of a single set from a string of 48 hydrophones of 0.5m intervals.

The boundaries between the three subsoil layers were identified by offsets (flatter sections) of the resulting line, each indicating a change in velocity from one soil layer to another. The depth of the pile toe was where the plot deviated from a straight line because seismic wave travels at a lower velocity in the soil beyond the pile toe compared to a higher velocity in the pile concrete material. Figure 9 shows the P-wave travelling path through pile and various layers of subsoils.

There is also increasing demand for cross-hole, down-hole and up-hole seismic technique to determine S-wave velocities from which the shear modulus is obtained. The speaker's personal experience indicates that the cross-hole seismic technique show less satisfactory accuracy than the refraction technique in detecting the stratification interface of the ground formation.

Depending on the impact energy required, the energy source used to create the impact can range from sledge hammer, drop hammer, shotgun firing and explosives. Mr. Ng reckons that a normal sledge hammer impact is sufficient for most civil engineering applications and typical seismic geophone array. An explosive impact would be ideal for the seismic technique, however, it is troublesome due to the strict requirements and permit application from the police department. The interval between the geophones is typically 5m. Of course, one can always increase or decrease the interval to suit the survey requirements. For closer intervals, a higher resolution is achieved, but the depth of detection is also reduced due to shorter array spread.

There are always questions about whether the acquired geophysical data should be interpreted by the geophysicist or engineering geologist. Mr. Ng's opinion on this matter is that the interpretation will undoubtedly need a combined knowledge in both areas. An engineering geologist with the right experience in geophysical survey will probably do a better task as

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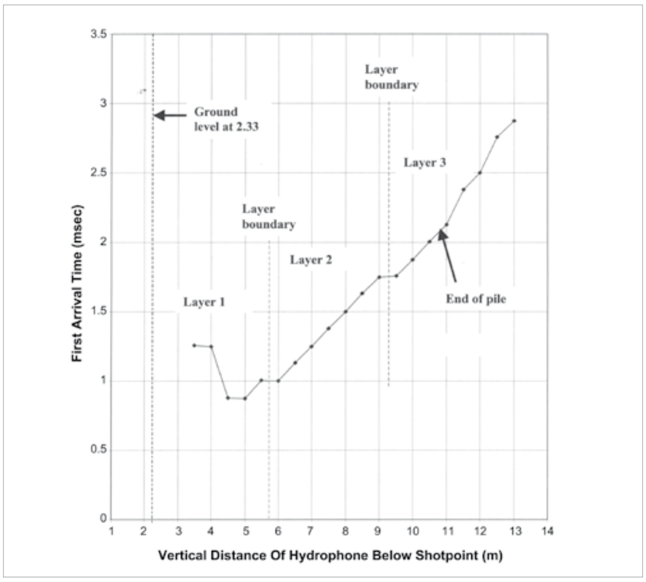

Figure 10: The record of first wave arrival of hydrophones at different depth location

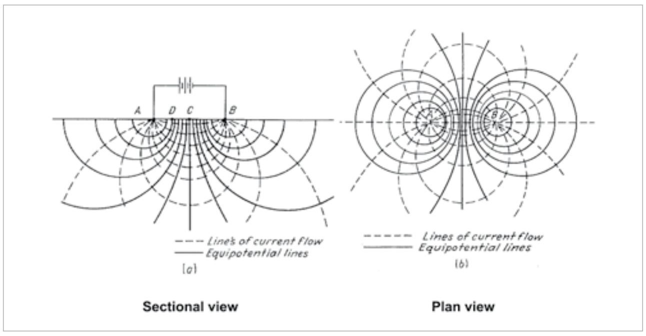

Figure 11: The electrical field of two point electrodes

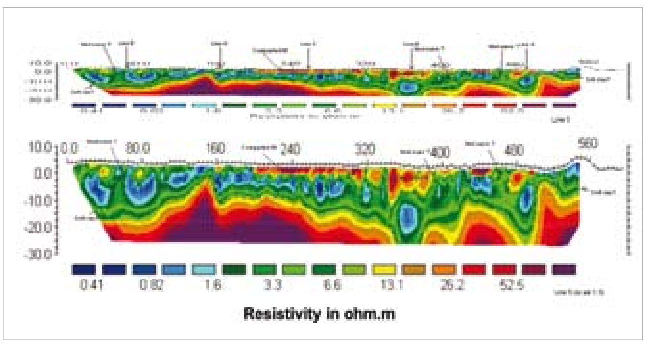

Figure 12: Identification of mud wave profile and the soft clay layer beneath the fill

the interpretation of subsurface conditions requires a reasonably established geological model to start off.

The speaker presented a case study in Oman in which the upper subsoil with cementation of mineral salts in the soil particles through the evaporation of capillary water had resulted in high wave speed in such materials in the seismic survey data. This may give a false perception that the subsurface is competent. With local geological knowledge, it is known that the sandy materials beneath the cemented crust are much weaker. The seismic refraction technique has a problem in correctly detecting the underlying weaker materials beneath a more competent material as the first arrival of the refraction wave is usually from the higher competent materials.

RESISTIVITY PROFILING TECHNIQUE

In a resistivity survey, four electrodes are planted at the ground surface, two of which pass an electric current into the ground while another two measure the potential difference between them as illustrated in Figure 11. Among the several possible electrode configurations, the two most commonly used are the Wenner configuration, in which electrodes are equally spaced, and the Schlumberger configuration in which the distance between a current electrode and the nearer potential electrode is several multiples of the distance between the two potential electrodes. In vertical electrical profiling, the variation of resistivity with depth is determined by measuring the apparent resistivity with various electrode separations. It is most commonly used to determine ground resistivity for the design of lighting conductor systems, metal pipe corrosivity assessment, water table determination and pipe leakage detection.

Lateral variations of ground resistivity can be determined by means of 2D resistivity in which electrodes are planted at regular intervals along a straight line or 3D resistivity with electrodes in a square grid. The electrodes are connected by wires to a resistivity meter via a switching device which can select any four electrodes at a time for resistivity measurement. Resistivity is effective in mapping subsurface geology especially in differentiating between clayey and sandy materials as illustrated by a case study for detecting mud waves generated by an earth filling operation over soft compressive clay as shown in Figure 12. In one survey section (the lower figure of Figure 12), the irregular mud wave was clearly evident. Resistivity technique has also been used to determine the water table, the limits of seawater intrusion, groundwater seepage zones and pipe leakages. In some applications, the resistivity method can be used to map subsurface bedrock surfaces over large project areas for the design of cut and fill.

Before considering the 2D resistivity application, a careful assessment should be carried out to evaluate the appropriateness of this technique to solving the problem. The interval of the electrodes should also be carefully evaluated for the problem. The limitations of the resistivity profiling technique are: (a) Lateral variation of the ground electrical properties and boundary will severely affect the accuracy of the 2D resistivity profiling results, (b) There is an inherent problem of decreasing accuracy in the 3D resistivity profiling method when approaching the boundary, (c) Input of engineering geologist is essential in the interpretation. In the specification of the resistivity survey, the following aspects should be clearly mentioned:

a) Length/area of survey
b) Depth of investigation
c) Verification boreholes
d) Line orientations
e) Geological assessment ■

Acknowledgement: The author wishes to express his thanks to Mr. Ng Chak Ngoon for the use the figures in his presentation and his valuable comments on this report. Some of these figures have been modified for the clarity of presentation.