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Estimation of *in-situ* moduli of deep soil cement using P-S logger

Estimation du module *in situ* de sol-ciment en grande profondeur à l'aide de l'enregistreur P-S

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ABSTRACT

This study applies the borehole geophysical technique using P-S suspension seismic velocity logger to measure the in-situ compression (P) and shear (S) wave seismic velocity of a deep mixed soil cement treated ground. The wave velocity profiles obtained from the field are used to estimate the in-situ elastic properties, such as Young's modulus, shear modulus, and bulk modulus to be used in seismic design. The concept of P-S suspension log, details of the instrumentation, testing procedure and analysis are presented in detail.

RÉSUMÉ

Cette étude met en application la technique de trou de sonde géophysique utilisant l'enregistreur de suspension vélocité sismique P-S pour mesurer la compression et le cisaillement de vélocité d'onde sismique des terrains traités en grande profondeur à l'aide de mélange sol-ciment. Les profiles de propagation des ondes de vélocité obtenus sur le terrain sont utilisés pour estimer les propriétés élastiques *in situ*, notamment le module de Young, le module de cisaillement et le module de volume utilisés dans la conception sismique. Le concept d'enregistrement de suspension P-S, les détails de l'instrumentation, la procédure d'essai et l'analyse sont présentés en détails.

1 INTRODUCTION

A variety of non-invasive and minimally invasive methods such as remote sensing, surface geophysics, borehole geophysics and various push technology can be used to determine subsurface geologic conditions of roads, bridges and their associated structures. Some of these methods can be utilized to determine subsurface geologic conditions prior to construction. Some can be applied to QC measurements during construction and many can be applied after construction to determine as-built conditions, as well as degradation (See ASTM, 1995, Benson 2000, Anderson and Cardinoma, 2000, Porbaha 2002)

The benefits of such measurements include: non-destructive sampling, in-situ measurements of a wide range of physical properties, sampling larger areas or volumes and providing continuous measurements in some cases. These benefits result in a greater sample density, which can more readily identify uniform conditions as well as locate anomalous conditions. Once anomalies conditions are identified, those areas requiring further tests, borings or repairs can be accurately and quickly located. These methods can also provide temporal measurements (detecting changes in conditions with time). Such data can be used in a database to guide management decisions for maintenance and repairs. (Benson 2000)

The objective of this paper is to estimate elastic properties of deep mixed soil cement columns using P-S suspension seismic velocity log method, a borehole geophysical approach. For this study soil cement columns of 900 mm in diameter were installed using a triple auger deep mixing machine, as part of an on-going project. Table 1 illustrates the profile of the ground at the project site. To characterize the soil properties at the site Cone Penetration Test (CPT) was conducted. The design strength of soil cement was 2000 kPa. Core samples of 84 mm in diameter were obtained using triple tube sampler. The holes from the core sampling were filled with water and geophysical tests were conducted. The concept of P-S suspension log, background, details of the instrumentation, testing procedure and analysis are presented in detail.

Table 1: Description of soil profile

Depth range (m)	Soil type
0-1.5	Silty sand (SM), trace of rounded cobbles (<5%), artificial fill, medium dense, light yellowish brown, dry.
1.5-6	Poorly graded fine sand (SP), medium dense, brown (10yr5/3), moist, occasional lenses of silt ranging from 10 to 30 mm thick.
6-8.7	SANDY SILT (ML)/ CLAYEY SAND (SC), medium dense to loose, medium brown (10YR5/3), moist, interbedded with SANDY CLAY lenses (30 to 50 mm thick) q_u =96 kPa, Su=29 kPa (for SANDY CLAY)
8.7-10.5	Lean CLAY (CL), stiff, dark gray , moist, medium plasticity, qu 144 kPa, Su=62 kPa
10.5-10.8	SILT (ML), minor fine SAND (10%), medium dense, yellowish brown, (10YR5/4), moist, non plastic.
10.8-11.3	Poorly graded fine sand (SP), medium dense, brown (10yr5/3), moist.
11.3-13.8	COBBLES (50%) and well graded GRAVEL (GW) with sand (15%) matrix, dense, varicolored, wet, COBBLES range from 75-159 mm diameter (metavolcanic, subrounded).
13.8-14.6	Well graded SAND (SW)with fine to coarse GRAVEL, 55% SAND, very dense, varicolored.

2 BACKGROUND

In the borehole geophysical technique using P-S suspension, the in-situ compression (P) and shear (S) wave seismic velocity logs are collected using a downhole probe connected to a surface seismograph. The probe contains a seismic source and two sets of oriented geophones separated by a fixed one meter distance. The tool measures S-wave velocity in hard rock. In soft rock and soil, equivalent S-wave velocity is obtained through measurement of the dispersive, flexural mode. Measurements can be obtained through a fluid-filled, grouted, PVC casing, but best results are obtained in a fluid-filled uncased borehole. Evidently, for case of soil cement column there is no need for casing. In P-S Suspension technique the source is at a constant distance from the receivers, and therefore the interval velocities can be recorded with greater detail and at greater depths than conventional (surface-to-borehole) shear wave surveys.

Currently, P-S suspension data are examined and processed semi-automatically. This allows greater control over identification of events on the velocity records and helps to minimize potential for error. The P and S wave velocities are graphically shown on a plot of velocity versus depth (or elevation). Velocity data are used to calculate low-strain, in-situ values for Poisson's ratio and shear modulus. These material properties and velocities are used to derive seismic ground response models for structure design. Interpretations of material composition are made in combination with the above geophysical logs (Hughes 1998).

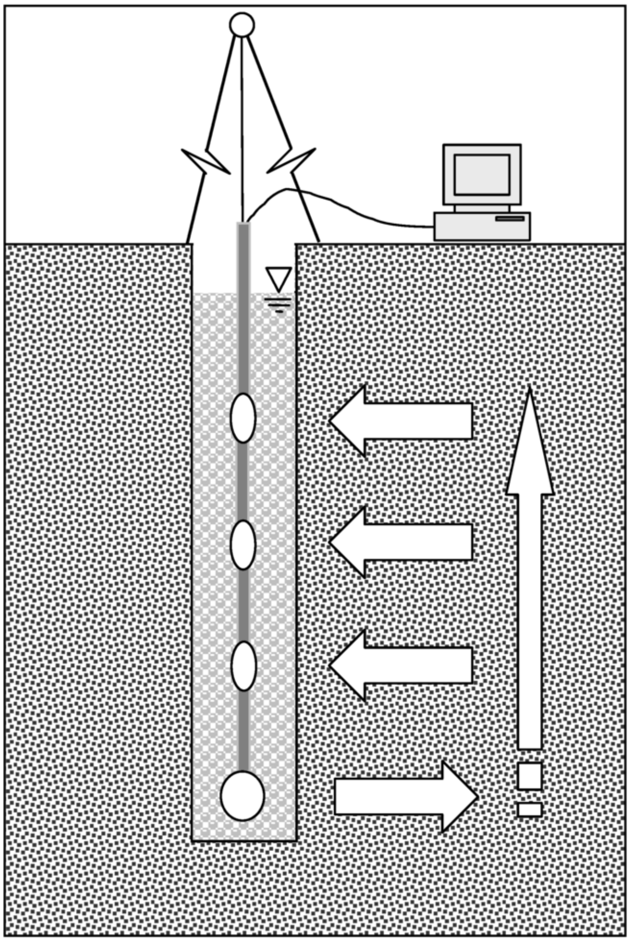

Figure 1:.Set up of the P-S suspension log

3 INSTRUMENTATION

The OYO P-S Logger, Model 170 Suspension P-S Logging system was used to obtain in-situ shear and compression wave velocity (Vs and Vp) measurements. The logging system consists of a downhole probe connected to a surface winch and seismograph. The probe contains a seismic source and two sets of oriented geophones separated by a fixed one meter distance. Because the source is at a constant distance from the receivers, interval velocities can be recorded with greater detail and at greater depths than conventional (surface-source) downhole shear wave surveys.

The source is a self-contained, electronically activated hammer. The hammer transmits pulses through the borehole fluid into the adjacent medium. The pulse generates refracted P waves and converted shear waves. In addition to P waves and converted S waves, the pulse generates a surface wave on the borehole wall with a velocity equivalent to the formation shear wave. this wave is often referred to as a flexural wave. Other waves are also generated, but only those pertinent to our investigation are presented here. The refracted P wave, P-converted S wave and flexural wave are transmitted back into the borehole fluid, where they are detected by the geophones. The arrival times of the different waves at each geophone are then used to calculate P- and S- wave velocities for the interval between them. To aid in identification of S waves, the hammer fires two oppositely-polarized pulses. The resulting change in S-wave polarity, recorded on separate geophone channels, can then be used to determine the onset of the S-wave and flexural wave. In low-velocity materials ($V_p \leq 1500$ m/s), body waves (P and S waves) cannot be directly measured due to refraction of those waves into the formation and away from the borehole. The ability to generate and detect the flexural wave enables measurement of shear-wave velocity for those materials.

To accommodate site-specific conditions, the distance between the source and the geophones can be varied via detachable spacers, i.e., filter tubes of fixed lengths. The distance between source and geophones can be varied up to 3 meters, to maximize signal amplitude, minimize record length and provide a sufficient measurement interval to allow recognition of the source pulse at the geophones.

The seismograph consists of a central processing unit connected to a signal monitor and printer. Six channels (three for each geophone) are recorded with each measurement and displayed on the monitor. Recording gains are individually adjustable for each channel. Additionally, multiple shots may be recorded and stacked with each measurement for additional signal enhancement (Hughes, 1998).

Figure 2: P-S-suspension lowered in the hole filled with water

4 FIELD TESTING PROCEDURE

The general operation of the P-S logger is as follows: 1) the probe is lowered to a selected depth in the hole, 2) gains, number of stacks and display parameters are optimized, 3) the probe is then lowered to the bottom of the hole, and 4) measurement proceeds. Measurement usually proceeds from the bottom up. The probe is incrementally raised and measurements are collected and stored on floppy disk and hard copy printout. Signal quality is monitored throughout the process and recording parameters are re-adjusted as necessary.

Once collected and stored, data are processed using PSLog, a proprietary software package developed by OYO Corporation. PSLog is used to examine the trace data, pick arrival times and calculate P and S interval velocities. Arrival times are picked manually. To refine arrival picks, signal filtering can be used to attenuate undesirable frequencies and enhance the S-wave signal. Pick quality can be grouped into four general categories based on shear wave observation:

- Excellent: first breaks easily identifiable from a single shot without filtering; little or no background noise;
- Good: decreasing signal-to-noise ratio; amplitude peaks (immediately following first break) identifiable without filtering, but filtering required for accurate picking of arrivals; stacking of multiple shots may be needed;
- Fair: low signal-to-noise ratio; filtering required for recognition of amplitude peaks; stacking required;
- Poor: very noisy; filtering and stacking required for recognition of amplitude peaks; picking of identical peaks (or troughs) at upper and lower geophones possible by comparison to adjacent records;
- Not Detected: no recognizable shear waves, or recognition of identical amplitude peaks at upper and lower geophones not possible; extremely noisy.

Once velocities have been obtained, the data are exported to a spreadsheet for additional calculations. These calculations may include mean velocities, cumulative travel times and elastic moduli. These data are subsequently tabulated and exported to a graphing program for final printing and reporting.

5 ANALYSIS & DISCUSSION

The digital time series records from each depth are transferred to a personal computer for analysis. These digital records are analyzed to locate the first minima on the vertical axis records, indicating the arrival of P-wave energy. The difference in travel time between these arrivals is used to calculate the P-wave velocity for that 1-meter interval. When observable, P-wave arrivals on the horizontal axis records are used to verify the velocities determined from the vertical axis data. In addition, the soil velocity calculated from the travel time from source to first receiver is compared to the velocity derived from the travel time between receivers.

The digital records are studied to establish the presence of clear SH-wave pulses, as indicated by the presence of opposite polarity pulses on each pair of horizontal records. Ideally, the SH-wave signals from the 'normal' and 'reverse' source pulses are very nearly inverted images of each other. Digital FFT – IFFT lowpass filtering are used to remove the higher frequency P-wave signal from the SH-wave signal.

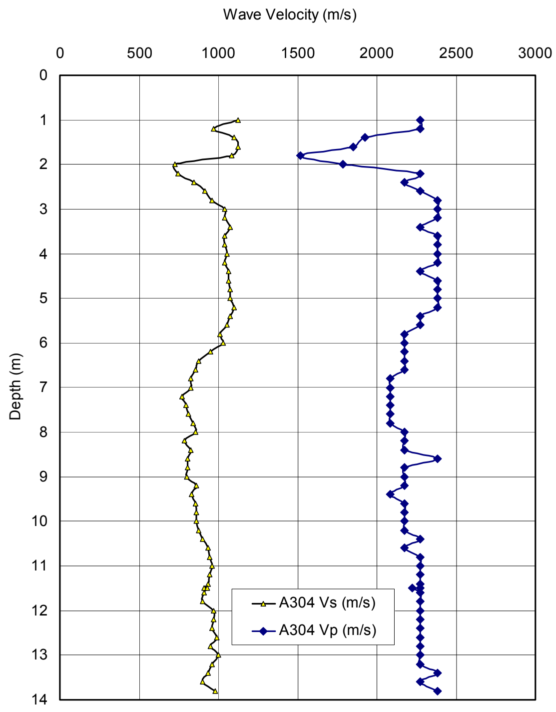

Figure 3: Seismic data from p-s suspension log for column A304

The first maxima are picked for the 'normal' signals and the first minima are picked for the 'reverse' signals. The absolute arrival time of the 'normal' and 'reverse' signals may vary by +/- 0.2 milliseconds, due to differences in actuation time of the solenoid source caused by constant mechanical bias in the source or by borehole inclination. This variation does not affect the velocity determinations, as the differential time is measured between arrivals of waves created by the same source actuation. The final velocity value is the average of the values obtained from the 'normal' and 'reverse' source actuations.

Once the proper picks are entered, PSLOG automatically calculates both Vs and Vp for each depth. The program allows spreadsheet output for presentation in either charts or tables or both. Standard analysis is performed on receiver 1 to receiver 2 data, with separate analysis performed on source to receiver data as a quality assurance procedure (Geo-vision).

Sample results obtained from the field are shown in Figure 3. The elastic properties of deep soil cement are calculated from the P and S wave velocities using the following equations:

$$\nu = [1-2(Vs/Vp)2]/[2-2(Vs/Vp)2] \quad (1)$$

$$G = Vs \times \rho \quad (2)$$

$$E = 2Vs2\ \rho\ (2+\nu)(1+\nu)/\nu \quad (3)$$

$$K = E / 3(1-2\nu) \quad (4)$$

Where ν =Poisson's ratio, G=Shear modulus, E=Young's modulus, K=Bulk modulus and ρ=Mass density. Figure 4 shows the variation of moduli with depth for soil cement columns.

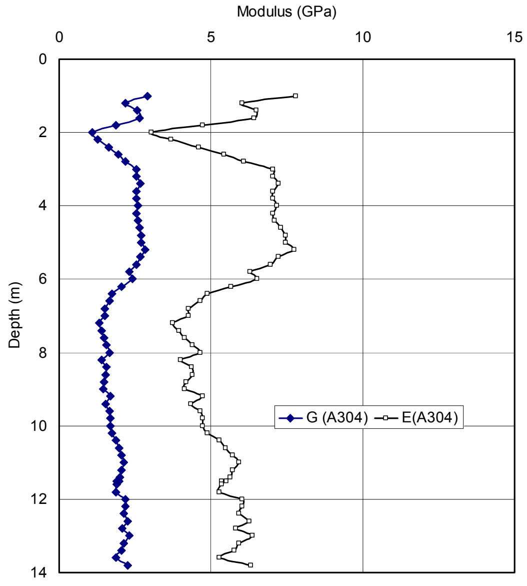

Figure 4: Variation of modulus with depth for Column A304

6 ADVANTAGES AND LIMITATIONS

Because the source is a constant distance from the geophones, an advantage of the P-S Logger over shear wave loggers using a surface source is the ability to collect data from greater depths in shorter times. Additionally, since the interval velocity is obtained over a shorter total distance, more detailed interval velocity data can be obtained. Data can be obtained from cased holes, provided plastic (e.g., PVC) casing is used. Because the difference in arrival times between the two geophones is used to calculate interval velocity, timing errors caused by shot delay and P-wave travel within the borehole fluid are eliminated, and pick accuracy up to $\pm$0.01 ms can be obtained. Finally, stacking and filtering capabilities allow optimal data collection in marginal environments.

The primary limitation of the P-S Logger is velocity error due to misalignment of the geophones in the borehole, lithologic heterogeneity between geophones, and borehole eccentricity. This error can be partially compensated by averaging normal and reversed shear wave velocities and by increasing measurement density, but cannot be completely eliminated. Additional limitations are related to measurement environment and are not unique to the P-S Logger. These include noisy environments (low signal to noise ratio), hard rock (difficult P and S differentiation due to high S velocities) and borehole instability (for untreated soil). Despite these limitations, the P-S Logger remains an efficient tool for in-situ determination of P and S velocities. (Hughes 1998).

Core samples were also taken using a triple tube sampler to allow laboratory testing and finding correlations of field and lab tests. However, the results of laboratory tests are not available at the time of this publication. Table 2 (Imamura et al., 1996) presents both shear wave (S-wave) and compression wave (P-wave) velocity magnitudes and their correlations with strength parameters of treated soil columns. This table is compiled from case studies' results reported on soil columns by Imamura et al. (1996). The values shown in the table may not be representative for all other soil types and conditions of other DM projects since these properties and magnitudes are known to vary from site to site. In practice, however, it is prudent to conduct a few laboratory tests on local treated soil samples and establish the relevant geophysical parameters for both treated and untreated soils for better quality assessments in the field.

Table 2: Approximate geophysical parameters for strength interpretation

P Wave Velocity (m/s)	S Wave Velocity (m/s)	UCS (kPa)
1200 - 1300	300 – 700	300 – 400
1400 - 1700	700 - 1000	400 – 2000
1700 - 2400	1000 – 1500	2000 – 4000
2400 - 2600	1500 - 1600	4000 – 5000

7 SUMMARY & CONCLUDING REMARKS

In this study the wave velocity profiles obtained from the P-S suspension seismic velocity logger are used to estimate the in-situ elastic properties, such as Young's modulus, shear modulus, and bulk modulus. Geophysics could be a cost-effective supplement to a traditional core sampling program for estimation of elastic properties and a means to assess quality of the treated soil. Borehole geophysics, by a relatively minor increase in project cost, increase both the type and amount of data obtainable from a borehole, aiding in characterization of the treated soil. In some instances, a geophysical logging program may save money by reducing the scope of investigations, the number of lab tests needed or checking the uniformity of the treated ground along the depth. Attempts are underway to use geostatistical concepts to understand the spatial variability of soil cement in the field.

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