DETERMINATION OF SHEAR WAVE VELOCITY BY DIFFERENT CROSS-HOLE METHODS

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SUMMARY

Different types of cross-hole tests were carried out at two sites with overconsolidated and normally consolidated clays, respectively. Shear waves were generated by impulse excitation, steady state sinusoidal as well as random excitation. Shear waves were recorded and analyzed with respect to frequency content. It was found that significant dispersion occurs even in relatively homogeneous clay deposits. Good agreement was obtained between sinusoidal and random excitation. Shear wave velocities determined from conventional impulse excitation, using first arrival times yield up to 60 per cent higher values.

INTRODUCTION

The knowledge of dynamic soil properties is of great importance for dynamic respons analyses. In the field the cross-hole method has found wide practical application. In conventional cross-hole testing a vertically polarized shear wave is generated by an impact at the bottom of a borehole and the first arrival of the propagating wave at a point some distance away is measured. It is assumed that the velocity of wave propagation is the same for all frequencies, thus the medium is non-dispersive. If the wave travels in a dispersive medium, two different wave propagation velocities exist, phase velocity and group velocity. Individual "peaks" of a propagating wave travel at the speed of phase velocity. Energy propagates as group velocity which thus is of greatest interest for earthquake engineering problems. Dispersion of waves occurs in inhomogenous soils, e.g. if the wave velocity varies significantly within a depth interval of one wave length.

In order to investigate the frequency dependence of shear wave propagation, three different types of cross-hole tests were performed. In addition to impact loading (transient signal), also steady state sinusoidal vibrations and steady state random vibrations were used. This work was part of a larger project on the application of dynamic screwplate testing (Ref. 1).

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FIELD TESTS

Tests were carried out at two sites in Norway. The soil conditions at the Haga site consist of a medium stiff, overconsolidated clay. The overconsolidation ratio decreases from 20 near the surface to 3 at 5 m depth. Down to this depth, the clay deposit is very homogeneous. The undrained shear strength determined from field vane tests is about s_u = 45 kPa, the natural water content w = 38 per cent and the plasticity index PI = 25 per cent.

At the Onsøy test site a weathered crust of about 1 m is underlain by 8 m of soft, normally consolidated clay with iron spots, organic matter and shell fragments. The undrained shear strength is about s_u = 12 kPa, the natural water content w = 65 per cent, and the plasticity index PI = 35 per cent. In the present investigation, a cross-hole system with two screwplates was employed. The emitting screwplate (16 cm diameter) was attached to a rigid steel rod, provided with a casing. A transducer (geophone) inside the screwplate recorded and triggered the generated signal. Two receiving screwplates (diameter 8 cm) provided with geophones were installed at about 2.8 m distance, at approximately right angles. The signals were recorded by a digital oscilloscope and analyzed by a frequency analyzer.

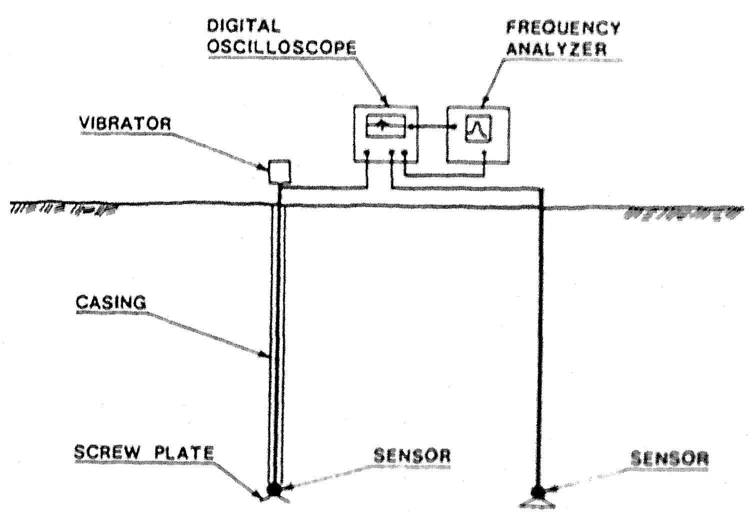

Figure 1 Schematic diagram of the cross-hole method

At each site, tests were made in two different directions and three different types of excitation were applied.

Impulse excitation was generated by a hammer blow against the upper end of the emitter rod. The recording was triggered by the geophone at the screwplate. The travel time to the adjacent screwplate could be measured directly on the screen of the oscilloscope. A typical recording is shown in Figure 2. The travel times for the first arrival (T1) the first peak (T2) the first through (T3) and the second peak (T4) were measured.

Average of the frequencies of the different wave intervals were estimated from the time between the first arrival to the first peak (one half period), between the first peak and the first through and between the first through and the second peak, respectively.

Sinusoidal steady state excitation was accomplished by an electromagnetic vibrator, placed on top of the emitting rod, cf. Figure 1.

x

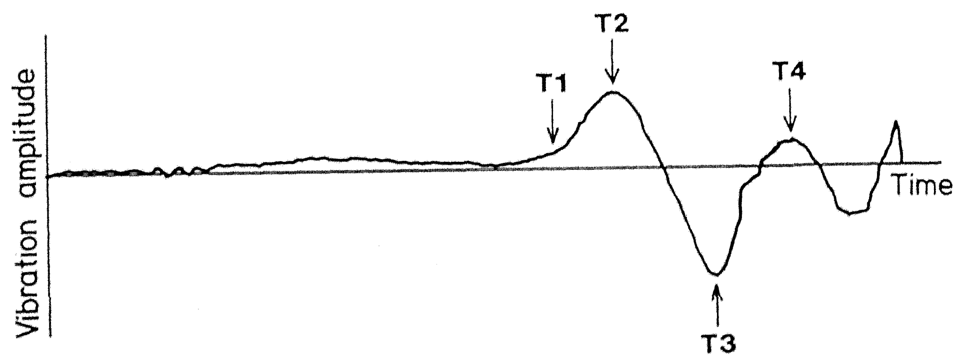

Figure 2 Typical record of impulse cross-hole test, with different arrival times of shear wave

The frequency of vibration was varied between 20 and 180 Hz by a signal generator. The signal from the emitter and the receiver were recorded simultanously. Four functions of the signals were recorded a) the magnitude of the velocity of the emitter, v_e, b) the magnitude of the velocity of the receiver, v_r, c) the ratio of the velocities i.e. v_r/v_e and finally d) the phase difference between the two velocities $\emptyset$.

Random steady state excitation was performed using the same equipment as for sinusoidal excitation. The frequency content was analyzed and the four functions mentioned above were calculated for the frequency band selected. The signal contained frequencies between 50 and 220 Hz. The coherence function was also recorded.

$$T_g = \frac{d\emptyset}{d\omega}; \qquad \omega = 2\pi f \qquad (1)$$

where T_g is the group travel time, $\emptyset$ is the phase difference, ω is the angular frequency of vibration and f is the cyclic frequency. In a phase-frequency diagram, the secant corresponds to the phase travel time and the slope of the curve to the group travel time.

TEST RESULTS

Impulse excitation: The results from tests with impulse excitation are shown in Table 1. The shear wave velocity is almost constant for both propagation directions (I, II). At the Haga site the shear wave velocity increases with depth. The estimated frequencies depicted from the recorded signal (cf Figure 2) also increases with depth.

Table 1 Shear wave velocities for different frequencies from cross-hole tests with impulse excitation (wave arrival times, cf Figure 2)

Shear	Depth	Direction	Shear Wave Velocity (m/s)						
			Arrival	Times					
	m		T1	T2		T3		T4	
Haga	1.5	I	116	103	(140)*)	87	(89)	74	(75)
	1.5	II	118	102	(140)	88	(116)	-	
	2.5	I	132	120	(200)	-		-	
	2.5	II	137	122	(210)	-		-	
Onsøy	2.0	I	86	74	(120)	64	(91)	54	(70)
	2.0	II	81	69	(110)	58	(85)	50	(88)

*) Estimated frequencies (Hz)

In normally consolidated clay (Onsøy) the shear wave velocity is less than in overconsolidated clay (Haga). Also the predominant frequency of the signal is less at Onsøy than at Haga.

It is interesting to note that the shear wave velocity decreases significantly with the predominant frequency for the different arrival times of the signal.

Sinusoidal excitation: In Figure 3 typical test results of harmonic vibration excitation are shown for the Haga site, 1.5 m depth. In the upper left diagram the magnitude of the transfer function between the receiver and the emitter is shown and below the measured phase. In the upper right diagram the stacked phase ($x2\pi$) is presented. An approximated straight least square line was calculated. Finally, the lower right diagram shows the velocity calculated from equation (1) as a function of frequency. The value of the average shear wave velocity calculated from the straight line is also given. In this calculation the differentiation interval includes five measuring points, corresponding to a frequency interval of about 20 Hz. Although this interval is large, a clear variation of the group velocity with frequency can be observed. This implies that dispersion occurs. A peak exists

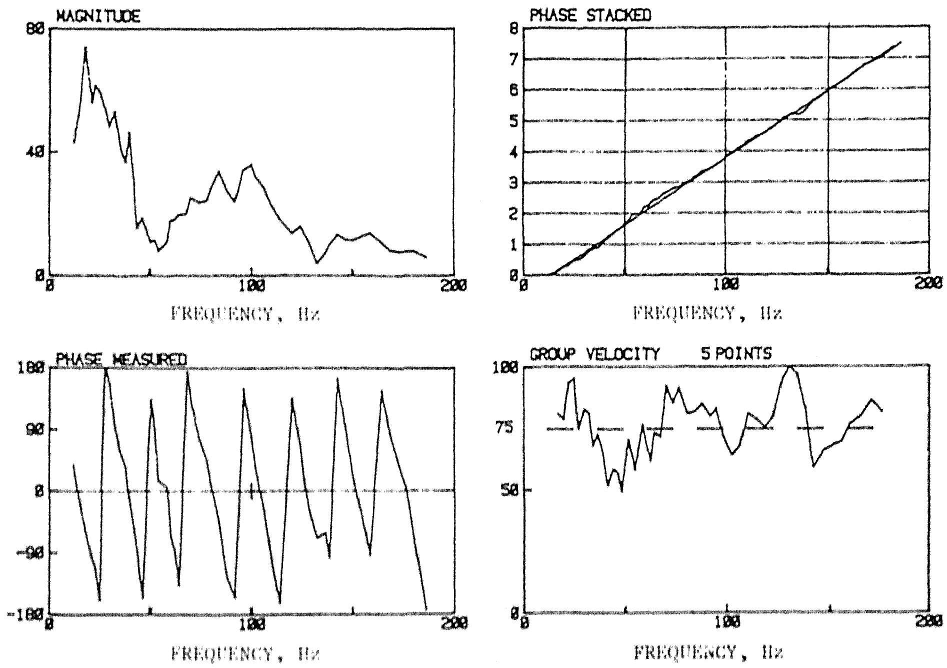

Figure 3 Result of cross-hole test for sinusoidal excitation, Haga (1.5 m depth)

at about 135 Hz, i.e. waves with a frequency of 135 Hz travel fastest. From Table 1 can be seen that the impulse test gave a frequency about 140 Hz for the first arrival wave. Shear wave velocities within a frequency interval of 40 to 70 Hz are less than 50 per cent (as low as 50 m/s) of the peak wave velocity (116 m/s). Similar results have been obtained at all test sites.

Random excitation. An example of a signal analysis for random excitation is given in Figure 4. The results are similar to those of sinusoidal excitation. However, only frequencies above 60 Hz could be generated in this experiment.

In Table 2, shear wave velocities determined from the different types of cross-hole tests are summarized. The wave velocities using conventional "first arrival" times are in general about 50 per cent higher than the group velocities determined from steady state vibrations.

Table 2 Comparison of shear wave velocities from cross-hole tests

Site	Depth m	Direction	Impulse C_s m/s	Sinusoidal C_s m/s	Random C_s m/s
Haga	1.5	I	116	76	75
	1.5	II	118	99	98
	2.5	I	132	83	-
	2.5	II	137	97	-
Onsøy	2.0	I	86	75	73
	2.0	II	81	67	59

In all cases good agreement was obtained for random and harmonic vibration excitation.

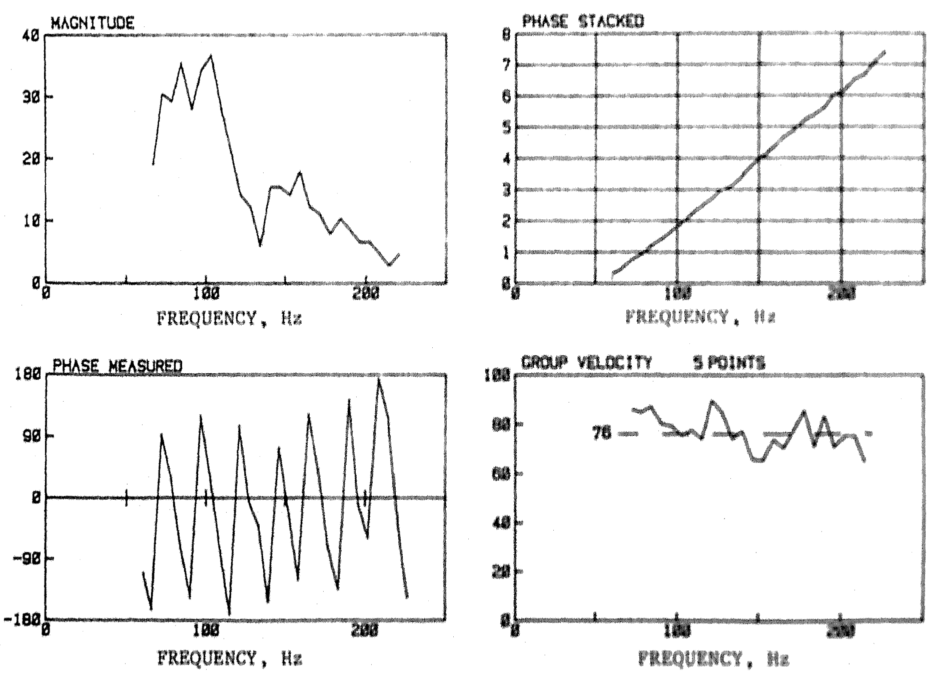

Figure 4 Results of cross-hole test for random excitation, Haga (1.5 m depth)

CONCLUSIONS

Different types of cross-hole tests were performed at two sites with homogeneous clay deposits. It was found that shear waves velocities are frequency dependent. Thus dispersion can occur even in homogeneous soil deposits without pronounced layering or stratifacation. The difference between wave velocities using first arrival times and average group velocities can be as high as 40-50 per cent.

Good agreement was obtained between wave velocities using steady state sinusoidal and random excitation. Also in the case of impulse excitation, shear wave velocities determined from different wave arrival times and respective predominant frequencies agree with steady state excitation.

ACKNOWLEDGEMENT

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1. Bodare A., (1983). "Dynamic Screwplate for Determination of Soil Modulus In Situ" Doctoral Dissertation, Institute of Technology, Uppsala University, Sweden, UPTEC 8379R, 273 p.