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SYNOPSIS In a study of wave propagation at the surface of soft and sensitive clay deposits, particle velocities were measured at five sites of Champlain clay deposits in the province of Quebec. Surface excitation was provided by the free fall of a mass and the measurements were obtained at different distances from the source at ground level and shallow depths. The major portion of the energy appears to be in the form of Rayleigh waves. Attention is focused on the effects of site parameters and in particular the depth of water table on the level of amplitude and the attenuation coefficient. As expected, measurements obtained at top of a slope show a significantly larger amplitude along the crest when compared to the amplitude away from the crest.

INTRODUCTION

The subject of wave propagation at the surface of an elastic half-space has been investigated for a number of years with emphasis placed on different aspects. Seismic refraction techniques have been used on a number of occasions to study layered soil deposits (Redpath, 1973). In situ shear wave velocity measurements are now available through cross-hole technology yielding realistic values of the shear and/or Young's modulus (Woods, 1978). The behavior of soil deposits in response to pile driving has also been investigated (Heckman and Hagerty, 1978). Finally, the effects of both explosions and impact loads have been studied (Kostyuchenko, 1974; and Skipp and Buckley, 1977).

The evaluation of energy transmitted to a soil deposit by an impact or through vibratory loading remains, nevertheless a difficult problem. Its importance is obvious in granular material where rapid and repeated stressing may cause liquefaction. Wave propagation in deposits of soft and sensitive clays is also of some concern in assessing the effect of impact or vibrating loads at a distance from the point of excitation and in evaluating the effect on the sensitive clay.

A laboratory program was started some years ago at the University of Sherbrooke to study the effect of repeated loading and vibration on soft sensitive clays typical of those found in eastern Canada (Lefebvre, Bossé and Béliveau, 1978; and Lefebvre and Demers, 1980). Concurrently, a field investigation was initiated to gain more insight into the subject of wave propagation at the surface of a deposit of soft sensitive clay.

Five sites within the province of Quebec were chosen for this aspect of the study, four located in the valley of the St. Lawrence river, the fifth site located in an area near lake St. John (fig. 1). Particle velocities at a number of different distances and depths from the point of impact were recorded and interpreted in light of the theory of wave propagation. The object of the study is to describe the mode of energy transmission occuring within a clay deposit subjected to a vertical impact load and to assess the influence of the site conditions, particularly the level of the water table.

The purpose of this paper is to describe the field experimental program, to present the interpretation of the data and to comment on the results obtained.

THEORY OF WAVE PROPAGATION

The theory of wave propagation in soils is based on the theory of elasticity and will be reviewed only to extent necessary for the interpretation of the field data. The ground is modeled as a linear, elastic, homogeneous, and isotropic half-space in which energy is transmitted by three types of waves. These are the compression, or P waves, the shear or SH and SV waves in the horizontal and vertical plan respectively and the surface waves also known as Rayleigh waves or R waves. Love waves or L waves are plausible at layered sites. For soft clay deposits the speed of the P waves are on the order of 1 500 m/s whereas the S and R waves travel at a tenth of this speed at around 150 m/s, the Rayleigh waves being slightly slower depending on the Poisson ratio of the soil (Richart, Hall and Woods, 1970).

The amplitude of the particle motion associated with these waves decreases as a function of distance from the source due to geometric or radiation damping and secondly due to material damping. The former is due to an increase of the surface which for no material damping would contain the same energy. Due to their cylindrical wave front, Rayleigh waves decrease proportionately to the inverse of the square root of distance. P and S waves, having a hemispherical wave front, decreases inversely to distance in the volume and as one over the square of distance along the surface (Miller and Pursey, 1955).

The path of a particle affected by a Rayleigh wave is a retrograde ellipse with the amplitude of the horizontal radial component decreasing much more rapidly as a function of depth than the vertical component. In addition, very little motion is observed at depths greater than one and a half times the wavelength typically on the order of one to two meters (Woods, 1978).

The wavelength of the Rayleigh wave, L_R, is proportional to the speed of the wave, V_P, and inversely proportional to the frequency of the motion in herz, f.

$$L_R = V_R/f \qquad (1)$$

The additional damping, due to material behavior, is in general a function of the level of the amplitude of motion and is typically expressed as exponential in distance, which for the geometrical damping of the Rayleigh waves yields

$$\frac{A(r)}{A(r_o)} = \sqrt{\frac{r_o}{r}}\, e^{-\alpha(r - r_o)} \qquad r > r_o \qquad (2)$$

in which $A_{(r)}$ and $A_{(r_o)}$ are the amplitude of the particle motion at distance of r and r_o from the point of impact respectively. The attenuation coefficient α is typically on the order of 0,04 - 0,12 m^{-1} for saturated clays (Barkan, 1962).

DESCRIPTION OF SITES

The general geotechnical properties of the five sites chosen were already known based on previous tests. All sites were on horizontal ground with the site at St-Coeur-de-Marie overlooking a highway cut 7 m deep and a slope of about 24°. The excitation source was located at 3 m from the crest of the slope and all measurements were obtained on the level terrain at this particular site.

In all instances the clay deposits extended well beyond 10 m and had upper sections of fissured and weathered clays with a layer of top soil 20-30 cm thick, the effect of which for this comparative study is not considered. The clays are of marine origin and postglacial. The location of the sites is given in Figure 1 and the geotechnical properties are summarized in Table I. The thickness of the weathered zone varies from about 4 m at St-Coeur-de-Marie to a minimum of 1 m at St-Marcel. The depth of the water table varies from 1 m at St-Marcel to 2,4 m at St-Coeur-de-Marie.

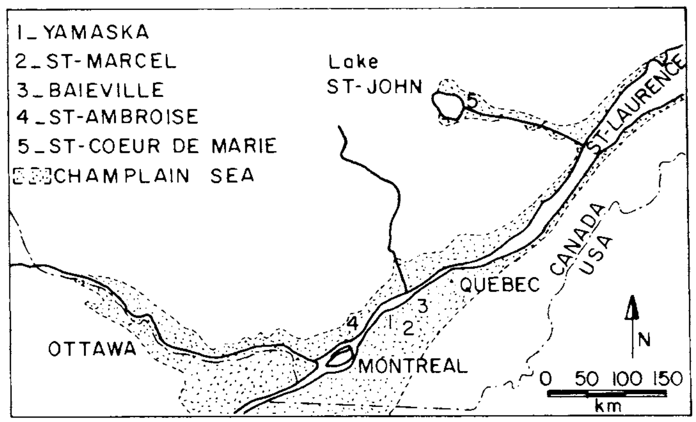

Fig. 1. Location of Experimental Sites

TABLE I. Geotechnical Properties

Location	W (%)	W_L (%)	W_p (%)	I_p (%)	I_L	Thickness of Weathered Section (m)	Test	Depth of Water Table (m)
Baieville	82	75	25	50	1,14	1,3	B	1,0
St-Marcel	80	63	25	38	1,44	1,3	M3	1,0
							M4[1]	1,0 (0,2)
							M1[2]	1,15
							M2	1,15
Yamaska	80	67	24	43	1,30	1,7	Y	1,4
St-Ambroise	69	47	24	23	1,96	2,1	SA	1,9
St-Coeur-de-Marie	50	41	20	21	1,43	5,1	SC1[3]	2,35
							SC2[4]	2,35

1 Impact in a hole 0,8 m deep thus at a distance 0,2 m from water table.
2 Results from the test are questionable due to effect of stones near point of impact.
3 Perpendicular to the crest of the slope in a direction away from the slope.
4 Parellel to crest of slope

The average water content is about 80% at St-Marcel, Baieville and Yamaska, 70% and 50% at St-Ambroise and St-Coeur-de-Marie respectively. The plasticity index varies from about 50 at Baieville to 20 at St-Coeur-de-Marie. The natural water content is higher than the liquid limit resulting in a high sensitivity and liquidity index going as high as 2 at St-Ambroise.

Tests B, M3, M1, Y and SA are the basic comparison tests. Tests M1 and M2 were performed in the summer 1979 and M3 and M4 were performed in the fall 1979 all at the same site. Results from M1 are questionable due to the presence of stones near the point of impact. M4 was used to determine the effect of impact closer to the water table 0,2 m versus 1 m in M3. Finally the tests at St-Coeur-de-Marie were to evaluate the effect of a slope on the particle motion with SC2 oriented parallel to the crest and SC1 perpendicular to the crest.

EXPERIMENTAL PROCEDURE

Since the level of energy input had to be determined for comparison purposes, the testing program required an excitation procedure which was reproducable and readily obtained. A system with a free falling mass was adopted. Two masses respectively of 25,25 kg and 58,25 kg were dropped from heights of 0,3, 0,6, 0,91, 1,22, 1,52 and 1,83 m in order to have a reasonable range of energy. In order to assure a good contact, the falling mass fell onto a steel circular plate 3 cm thick and 31 cm in diameter. The impact was always produced at the ground surface except for test M4 where the impact was in the bottom of a hole 0,8 m deep.

Standard seismic geophones with a natural frequency of 4,5 kz were used to measure the velocity component in three directions, vertically, radially and tangentially from the point of impact. The geophones were mounted on a cubic block and then placed on support blocks in order to be able to lower the sensor into shallow boreholes 0,5 m and 1 m deep at each site. The effect of the support blocks was found insignificant. The geophones were placed at distances of 4,5m, 6,75 m, 9,0 and 11,25 m from the point of impact. At each test these velocities were recorded at twelve points (four distances and three depths) and twelve energy levels were used in generating the impact. The three components of the two points nearest to the source were recorded on a six channel oscillograph RAPET RMS II followed by identical measurement for the two furthest points in order to evaluate the effect of distance in the results. A typical recording is shown in Figure 2.

DATA ANALYSIS

The amplitude of the measured velocity components in the tangential direction are generally much smaller then those in the vertical or radial directions as might be expected in an axisymmetric phenomenon. The maximum velocity

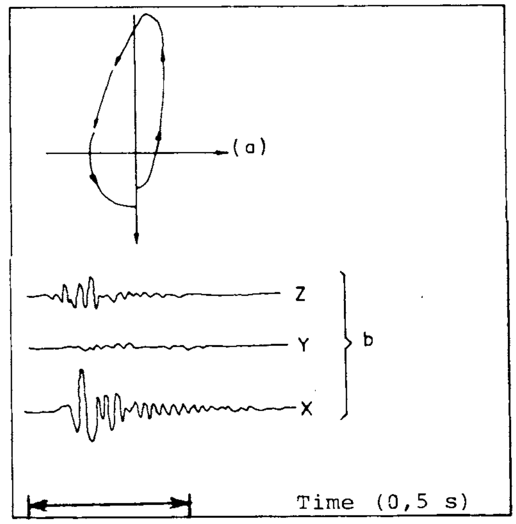

Fig. 2. a) Retrograde Ellipse
b) Typical Recording

a) A_x, $-A_z$ b) x: radial
y: tangential
z: vertical

amplitude was taken as the square root of the squares of the maximum of each of the components, which though conservative, is nevertheless reasonable due to the relative insignificance of the tangential motion and the short time lag observed between the maximum amplitudes in the other two directions

$$A = \sqrt{A_x^2 + A_y^2 + A_z^2} \qquad (3)$$

in which A_x, A_y, A_z are the velocity amplitudes in the radial, tangential and vertical directions respectively.

This information was then processed by computer in order to determine the factor γ by a least squares procedure in which

$$A = \gamma \sqrt{E/d} \qquad (4)$$

$$E = m\ g\ h \qquad (5)$$

E is the energy at impact, m is the mass, g is the acceleration of gravity, h is the free fall of the mass, d is the distance of the sensor from the point of impact and A is the level of particle velocity as obtained from equation 3.

EXPERIMENTAL RESULTS

Type of Wave

Based on the recordings obtained, the speed of the oncoming wave was measured for four of the nine tests and are recorded as a function of depth in Table II.

Obviously, these are not compression waves due

TABLE II. Wave Velocity (m/s)

Site	H = 0 m	H = 0,5 m	H = 1,0 m
M3	109	107	96
M4	116	111	112
B	123	118	102
Y	116	108	95

to their relatively low speed and correspond either to shear or Rayleigh waves. Typical observation of the velocity as shown on Figure 2 demonstrate the retrograde elliptical behavior of Rayleigh waves. The measured frequency of Yamaska was 40 hz near the point of impact yielding from Equation 1 a wavelength of around 2,75 m. The frequency decreased as a function of distance from the source as demonstrated earlier (Kostynchenko, 1974). These observations, together with the fact that the geometrical damping goes as one over the square root of distance as shown in the next section, suggest that the major portion of the energy is transmitted in the form of Rayleigh waves.

Effect of Energy

The examination of individual records shows a good relation of the amplitude of motion as a function of the linear momentum of the falling mass at impact. However, to be consistent with existing litterature on wave propagation, particularly in the case of pile driving, results were evaluated in terms of the square root of the energy at impact divided by distance from the source, rather than linear momentum divided by this distance. A typical cluster of the results is given in Figure 3 where both the ordinate and abscissa are on logarithmic scales. The slope of a straight line through the cluster would then correspond to γ of Equation 4.

As observed from this figure the amplitude of motion is larger near the surface and lower at a depth of 1 m. The slope of the line, γ, seems also to be a function of depth as shown in Table III, values being generally higher at the ground surface.

Attenuation Coefficient

An estimate of the attenuation coefficient, α, may be obtained by rearranging Equation 2. Estimates for this parameter was obtained for the three depths studied for all the energy combinations investigated at each site both near the impact i.e. between the sensors at 4,5 and 6,75 m, and further away between the measurements taken at 9 and 11,25 m. In general the attenuation was larger, the larger the level of motion, i.e. near the point of impact and near the surface. Rather than attempt to estimate values of α for each depth studied, each site is characterized by an average value (Table III). This corresponds to an average distance between the curve for geometrical damping and measured amplitude levels as shown in Figure 4 for the test at Yamaska.

The values at St-Coeur-de-Marie are neglected, since the formula used for geometric damping is

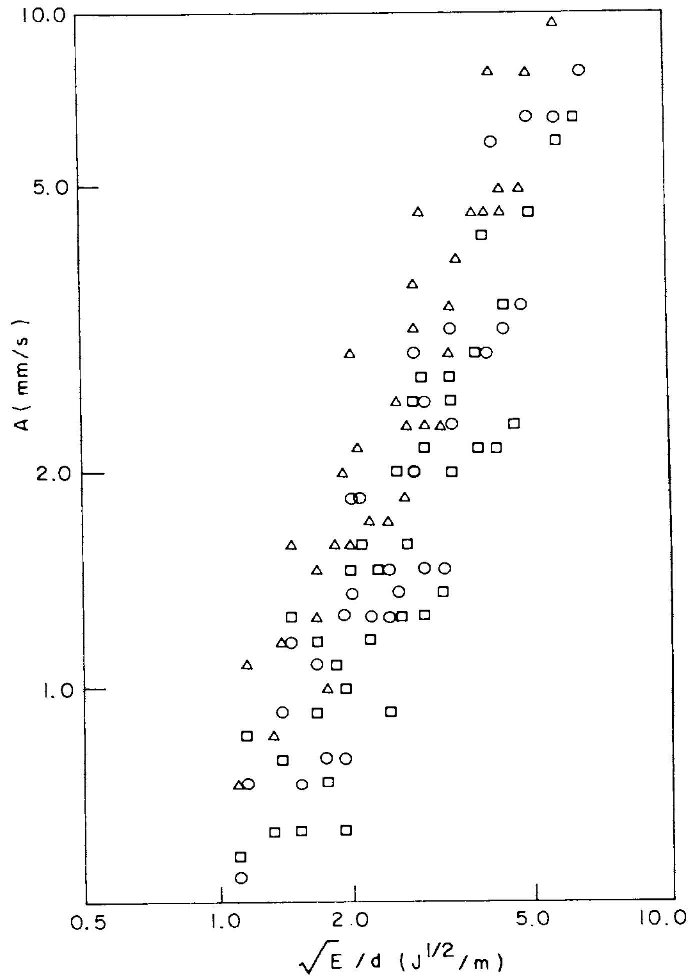

Fig. 3. Amplitude of Maximum Velocity as a Function of $\sqrt{E}/d$ (Yamaska, △ - surface
○ - 0,5 m
□ - 1,0 m

TABLE III. α and γ as a Function of Depth for Each Test

Test	γ Depth 0 m	0,5 m	1,0 m	α
B	0,97	0,75	0,71	0,14
M3	1,03	0,83	1,15	0,11
M2	1,04	1,05	1,16	0,17
Y	1,20	0,90	0,77	0,17
SA	1,62	1,27	0,67	0,28
M4	1,01	0,80	0,75	0,05
M1	0,91	0,58	0,83	0,10
SC1	1,80	0,92	0,65	0,07
SC2	2,66	1,31	-	0,08

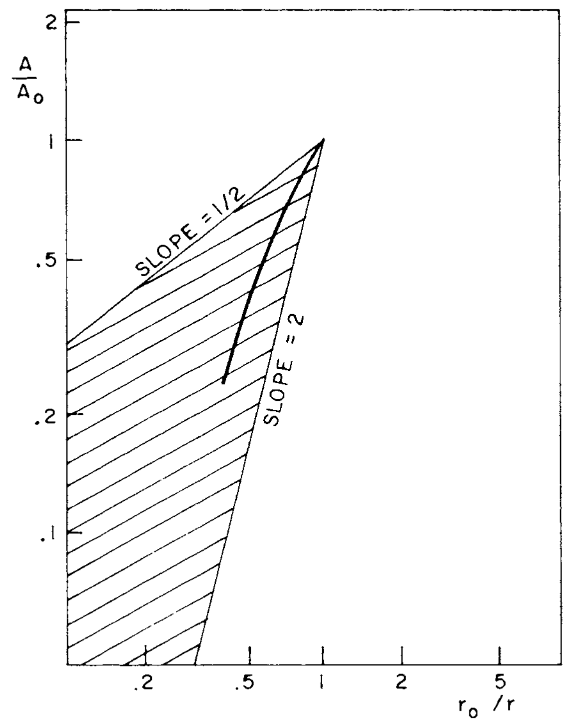

Fig. 4. Non-dimensional Amplitude as a Function of Non-dimensional Distance from Point of Impact (Yamaska)
Slope = ½: geometric damping for Rayleigh waves;
Slope = 2: geometric damping for body waves.

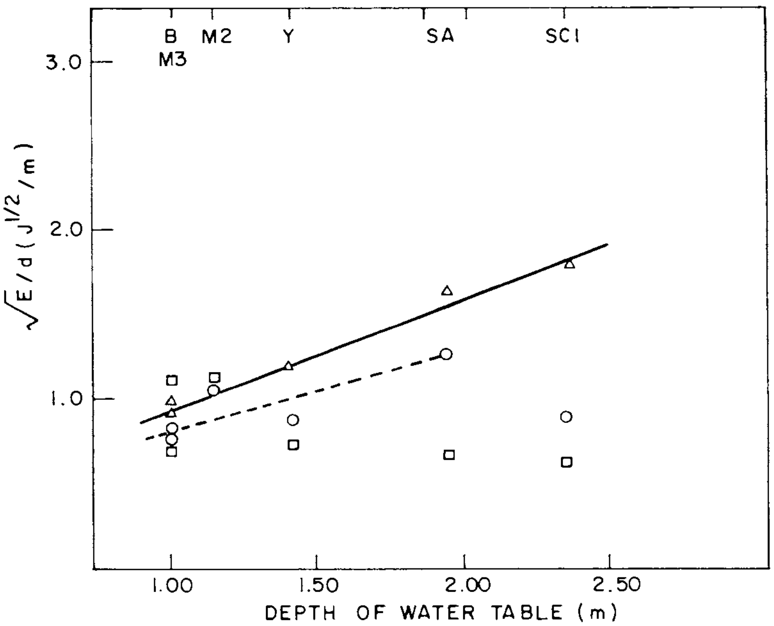

Fig. 5. γ as a Function of Depth of Water Table
(△ ground level, ○ 0,5 m deep, □ 1 m deep)

not appropriate. The correlation between the amplitude levels and attenuation coefficients is consistent (Table III), considering the scatter in the results and the fact that average values are used. Nevertheless, the larger the amplitude, the larger the attenuation coefficient is as evidenced by the results obtained. Secondly, the effect of dropping the mass inside a hole 0,8 m deep seems to have little effect on the amplitude of motion at the surface and at 0,5 m deep, but seems to decrease the attenuation coefficient considerably as evidenced from results for M3 and M4.

Depth of the Water Table

The level of the water table appears to have a major influence on the factor γ which is a measure of the amount of energy transmitted near the surface and the attenuation coefficient α related to material damping as demonstrated graphically in Figures 5 and 6 respectively.

From Figure 5 it is seen that the factor γ increases with the depth of the water table, i.e. there is less motion recorded at the ground surface when the water table is high. The effect is less pronounced for measurements at a depth of 0,5 m and goes in the opposite sense at 1 m. Thus, when the water table is near the ground surface a smaller portion of the energy is transmitted at the surface.

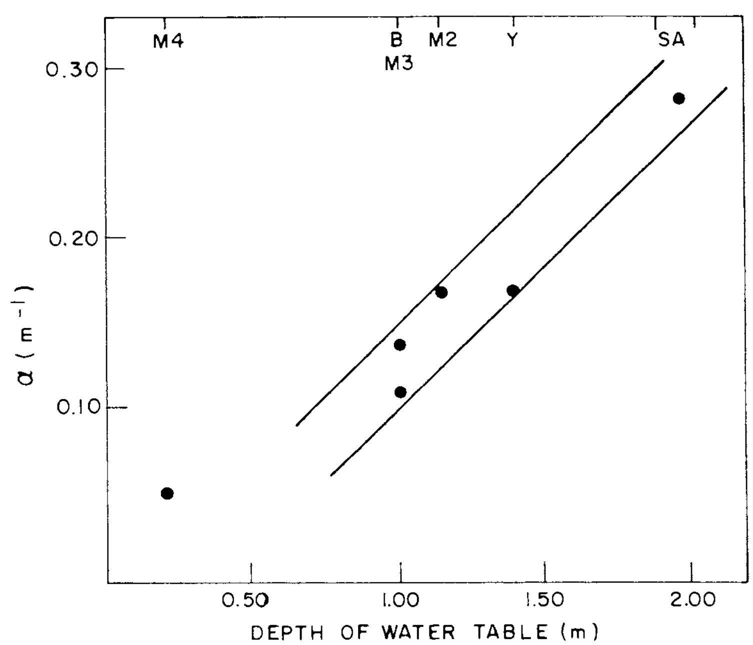

Fig. 6. Attenuation Coefficient as a Function of Depth of Water Table

From Figure 6, it is seen that the attenuation coefficient characteristic of the site increases as the depth of the water table increases. Though a portion of this trend is conceivably due to the higher level of motion at the ground surface this confirms the fact that fissured clay is more absorbent when not saturated.

Effect of the Proximity of a Slope

The particle motion recorded on a line parallel to the crest of a slope is greater than the corresponding motion perpendicular to the crest by about fifty percent for the same distance from the source. This suggests that a larger portion of the energy is transmitted along the crest due to the smaller geometrical and material damping. The attenuation of the motion, though admittedly no correctly modeled for this case, nevertheless suggests that the damping of the amplitude is small along the crest of a slope.

CONCLUSION

Particle velocities were recorded at the ground surface and at depths of 0,5 and 1 m for five sites consisting of soft sensitive clay deposits at four distances from an impact resulting from a free falling mass dropped from different heights. The data is interpreted based on the theory of wave propagation in an elastic half-space. The limited number of tests indicates some trends which confirm this theory and which could be summarized as follows:

1. The amplitude of the particle velocity is a function of the linear momentum of the falling mass at impact;

2. The major portion of the energy is in the form of Rayleigh waves;

3. The effect of the depth of the water table is instrumental in affecting both the level of motion and the corresponding attenuation. The lower is the water table, the larger are the particle velocities at the surface and the larger is the corresponding attenuation.

4. The larger the motion, the larger is the attenuation coefficient.

5. Larger particle motions are measured along the crest of a slope than perpendicular to the crest.

ACKNOWLEDGMENT

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