14 Mar 1991, 2:00 pm - 3:30 pm

General Report Session 10: Wave Propagation in Soils

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Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991 St. Louis, Missouri, General Report Session No. X

Wave Propagation in Soils

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CLASSIFICATION OF PAPERS

The eight papers can be classified as follows:

Experimental Results	2
Theoretical Analysis	3
Applications for Soil Exploration	3

The papars can also be classified according to the type of waves that were studied, as follows:

Shear and Compression Waves	3
Surface (Rayleigh) and Boundary Waves	5

EXPERIMENTAL RESULTS

Impact Response of Granular Soils

In their paper, Poran et al. present the results of an extensive laboratory study of dynamic compaction of dry sand. The dynamic compaction was achieved by repeated dropping of steel pounders.

Tests were conducted in a cubic tank with 1.2 m sides. The sand was placed in the tank at an initial relative density of 25%. Effects of different pounder size, weight and drop height were investigated. Pounder deceleration at impact was measured by two accelerometers mounted on the pounder top. Dynamic pressures in the soil during impact were also measured. The final density distribution in the sand was measured with a nuclear instrument. Soil strains were measured at several points within the sand mass by using electromagnetic induction sensors. These strain measurement were conducted before and after each pounder impact. In addition, static plate load tests were conducted for comparison, under similar conditions.

As expected, test results show that the dynamic stiffness increases with the number of pounder impacts. The acceleration-time record during impact is integrated once with respect to time to obtain the velocity where the integration constants are based on known initial and final velocities. The velocity-time record is then integrated again to determine pounder displacement with an integration constant which is based on the known final "at-rest" pounder displacement.

Impact stress is computed and a dynamic stress-strain plot is used to determine a Dynamic Settlement Modulus (DSM). The DSM increases with the number of pounder drops and the rate of increase is proportional to the rate of densification. The paper shows that DSM may be correlated to static elasticity modulus for the sand. DSM concept is based on the global dynamic response of the affected soil mass. The concept may be useful to monitor dynamic compaction in construction sites with granular soil strata. The authors suggest that the method should first be validated in full scale field studies. Once field correlations are available the method may be used for quality control of dynamic compaction projects.

Investigation of Stress Waves Reflection Problems from a Free Surface by Means of Dynamic Photoelasticity Method

Kostin presents the well accepted relationships of stress amplitude of reflected and refracted waves in terms of the amplitude of the incident stress waves in the interface of two media with different acoustic impedance. In this context a free boundary can be represented as a medium with zero acoustic impedance. Theory of plane elastic waves can also predict stress waves reflected by the incidence of a plane wave on the free boundary of a half space, and longitudinal and shear wave reflection coefficients can be determined. These are dependent on the angle of incidence and acoustic impedance of the half space. Theoretically, under slide incidence of a P wave on a free boundary ($\phi=90^0$), there are no stress contours apparent. Nevertheless, there is extensive experimental evidence that close to, or at slide incidence of P waves, stress contour may occur at the free boundary.

In the cases involving longitudinal shear waves, stresses reflected from the boundary may be theoretically determined only if the incidence angle is smaller than a critical value. If the incidence angle approaches this critical value the stress contours on the boundary approach infinity. This theoretical conclusion also does not represent the physical phenomena.

Kostin conducted dynamic photoelasticity tests to determine coefficients of longitudinal wave reflection from a free boundary. These coefficients were determined for a range of incidence angles (from 0 to 90^0). He found that stress peculiarities result from interaction of three waves: incident longitudinal P waves, and reflected longitudinal (PP) and shear (PS) waves. This interaction is especially noticeable on the free surface boundary. The reflection coefficients were determined experimentally by measuring the amplitude changes of the different waves at a certain depth from the free surface where the stress impulses of the three waves are separated in time. With available damping relationships it is possible to back-calculate the stresses at the boundary where direct measurement is impossible. Comparison of the experimental reflection coefficients and stress contours with the corresponding theoretical values show that good correlation exist for the range $0<\phi<70^0$, while large differences are observed for incidence angles larger than 70 degrees ($\phi>70^0$). It was also observed that, close to the free boundary, several time dependent singularities exist in the stress field. These singularities are highly dependent on the incidence angle.

Tests for plane shear waves showed reflections even for incidence angles larger that the theoretical critical value. A longitudinal reflected wave could only be measured for incidence angles smaller then the critical value and, generally, its amplitude was very small. The form of reflected waves for incidence angles larger than the critical value is similar to the form of Rayleigh waves with the maximum stress magnitude corresponding to the critical incidence angle.

In conclusion, the paper shows that reflection and stress contours may be accurately estimated for a free surface boundary of a half space, for incidence angles smaller than 70^0 and that the effects of reflected waves can not be ignored. In addition, the experimental evidence of reflected plane shear waves at incidence angles larger than the critical angle is contradictory to the theory.

THEORETICAL ANALYSIS

Use of Rayleigh Modes in Interpretation of SASW Test

The spectral analysis of surface waves (SASW) is a seismic method to determine in-situ elastic moduli of layer systems. This in-situ surface measurement method has been found to be quite effective. However, its interpretation for irregular soil profiles (where a soft layer may exist between two hard layers) is usually difficult. The method is based on a dispersion curve obtained from the field data. Then, a theoretical dispersion curve for an assumed profile is compared to the experimental curve in an iterative process. The soil profile is modified during this process until the two curves are matched.

Gucunski and Woods conducted a theoretical study to investigate the influence of soil stratification on the level of participation of higher Rayleigh modes in surface wave propagation (for SASW testing). The paper presents a numerical model for the simulation of wave propagation due to oscillations of a circular plate on the surface of a media composed of a top hard layer overlaying a second softer layer over a half-space. The model accounts for higher order Rayleigh modes. The simulated dispersion curves are compared with the theoretical ones and results show that higher Rayleigh wave propagation modes may be dominant for most frequencies in media where soft layers exist between stiffer ones (with the exception of a narrow range of low frequencies).

The authors conclude that the first Rayleigh mode is dominant through the entire frequency range in profiles where the shear wave velocity increases with depth. The dispersion curves are well separated and, except for low frequencies, indicate that energy transmission occurs near the surface for all modes. Therefore, simulated (and field measurements) dispersion curves may be successfully matched with theoretical results. The authors also indicate that analyses of profiles where shear wave velocity pattern is irregular with depth indicate that higher Rayleigh modes may be dominant in surface propagation. The results presented for limited cases profiles where a softer layer exist between a stiffer surface layer and the half-space indicate that portions of the field evaluated dispersion curve may be strongly affected by higher modes of Rayleigh waves. Therefore, they recommend the inversion process should not be guided only by the first mode, and that the identification of a potential significant contribution of higher modes may be simply performed by observation of approaches of the measured dispersion curve between two modes. These conclusions are consistent with other researchers including Satoh (1989). The authors recommend further research to improve the inversion processes based on their initial findings.

Reference: Satoh, T. " On Controlled Source Spectral Rayleigh Wave Excitation and Measurement System," VIC, Tokyo, 1989.

Dispersion Characteristics of Elastic Waves in Saturated Soils

Wu and Chen present a theoretical formulation for the dispersion of P and S waves in saturated soils. Theoretical results are verified with laboratory tests and field survey data. The results are used to obtain theoretical relationships between wave velocities and mechanical parameters of saturated soils. The most important assumption used in the formulation is that the pore size is smaller than the wave length.

Two models are proposed for pore water motion equations. The first considers that one third of the pore water moves in the direction of one axis with the same microscopic acceleration of the pore water, and the other two thirds move with the microscopic acceleration of the solids. In the second model, water and solids are considered as two different continuous media with independent accelerations, and the permeability is considered as a body force.

Similar dispersion curves for S waves are obtained by using the two models. The velocity varies between two limiting values. This variation is the result of the change in participating mass of pore water added to the soil skeleton. The differences in the results between the two models are slight and appear only in the range between these limiting values.

The dispersion curve for the P wave is highly dependent on the model, especially for high frequencies. The degree of dispersion of the P wave for the first model is much more significant than the second model.

The authors present a relationship between the effective Poisson's ratio and the wave velocities for certain conditions. The proposed equation is a generalization of the theory of elasticity equation. Generally, the effective Poisson's ratio is smaller than the total one.

The depth to full saturation is determined by using the sensitivity of the P-waves to soil voids with air. Even if only a small portion of the voids are unsaturated the P wave velocity, V_p, are always lower than velocities measures in saturated soils where $V_p \geq 1450$ m/sec (the P wave velocity in water). The authors show that the water table can easily be determined based on this observation. This is contrary to previous findings of Hardin (1978) and others.

The authors also conclude that a relationship between the porosity and the P wave velocity exist at low frequencies. In that case, if the specific gravity of the soil is known, the unit weight can be determined.

Generalized Rayleigh Waves in Layered Solid-Fluid Media.

Tan presents a finite element method formulation to solve Rayleigh wave propagation in layered solid-fluid media. The method uses displacement as the only parameter describing solid and fluid motions. The main advantage of this approach is that the displacement compatibility and force equilibrium along the solid-fluid interface are easily satisfied and thus, no special coupling is required.

The fluid is treated as an elastic solid with negligible shear modulus. The boundary conditions include null normal stresses at the free surface, continuity of vertical displacements, zero shear stresses at the fluid-solid interface, and zero displacements at the rigid base. A penalty function is included using the constraint of irrotational flow. The proposed method can compute both horizontal and vertical distributions of particle motion and stress in the normal modes.

A semi-discretization technique is introduced to discretize the layered solid-fluid system. with this technique, the horizontal direction of the medium is treated as a continuum. In the vertical direction, one dimensional, two node, linear solid or fluid elements are used. The node at the solid-fluid interface has three degrees of freedom to be able to model a slip between the solid and the fluid.

In integration of matrices, different techniques are used for fluid and solid elements. For a system containing both a solid and a fluid, the selective integration method is used for the fluid elements. The mass matrix represents the average of the lumped and consistent mass matrices.

A numerical example was used to compare results from the finite element method and Biot's analytical method. The finite element results improved with mesh refinement and show good agreement with the analytical solution. The method should be further investigated to study Rayleigh wave propagation in two-dimensional, irregular solid-fluid medium, and to derive the dynamic stiffness matrix of such layered medium.

SOIL EXPLORATION

Leak Detection in Large Storage Tanks Using Seismic Boundary Waves

Kashi et al. report on a method of leak detection from storage tanks based on the transmission anomalies in seismic boundary waves due to soil saturation. The waves are generated using a hammer and their behavior is similar to that of surface (Rayleigh) waves. Wave transmission paths that encounter leaking tank products in the soil have different arrival characteristics than those which do not. The boundary waves are generated at various locations and received by an array of geophones. Using tomography a two dimensional picture of the bottom of the tank is produced.

Boundary Stoneley waves have minimum energy loss into the surrounding media. If they travel in the boundary of two homogeneous half spaces, they are non dispersive, otherwise they are. Stoneley waves depend on the shear wave velocity and, to a lesser extent, on longitudinal wave velocity. If the soil is saturated, the Stoneley wave velocity changes according to the soil type. In granular soils it increases and in cohesive soils it decreases.

It was confirmed experimentally that soil saturation affects the arrival properties of the waves. However, there was evidence of a healing process at distances of 25 ft beyond the saturated spot where no changes could be observed.

The field procedure described in the paper is quite rigorous. The tank perimeter is divided into 36 stations. A measurement set includes an array of 12 geophones, placed along successive stations. Seven sources are used for each set with the center one being on the opposite end of the diameter to the center of the geophone array, with three sources to each side. The procedure is repeated for different geophone locations to completely cover the tank bottom.

Based on the measurements a simulated tank bottom is analyzed. Tank bottom surface is divided into cells which are analyzed with a personal computer by using a tomography algorithm. The algorithm is based on the arrival time of the waves, and a set of linear equations is developed to determine the slowness (inverse of velocity) of each cell under the tank.

The paper presents field results where the method proved to be successful for leakage detection in an actual, 36' diameter tank. Stoneley waves were induced under the tank and successfully measured by the geophones set. The tomography algorithm proved to be suitable for the leak detection in the simulated tank bottom.

The authors acknowledge that the method needs further research. The measurement resolution loss issue is especially important due to the large size of most actual tanks.

Array Processing of Rayleigh Waves for Shear Structure

In recent years there has been an increase in application of surface measurements of Rayleigh waves to obtain shear wave velocity profiles in order to determine soil properties. One of the most important sources of errors in Rayleigh waves measurements is the difficulty in identifying the fundamental mode. This is a result of certain circumstances and stratification where higher modes may become dominant. This shortcoming is especially critical in shallow shear wave velocity profiles needed for evaluating site response to earthquake motions.

In their paper, Barker and Stevens present a technique where measurement data form a linear array of geophones is used to identify the fundamental Rayleigh waves mode. The measured data is processed as an array.

The inference of shallow shear wave velocity profile from Rayleigh waves has two primary steps: extraction of dispersion information, and inversion of dispersion data for shear wave velocity profile.

In the case of arrays two curves are obtained: group velocity curve, and phase velocity curve. A joint inversion process of both yields a better result of the shear wave velocity profile.

The authors' procedure to obtain group velocity is based on using narrow band filtering of a seismogram at a sequence of center frequencies and combining them with their Hilbert transforms to obtain the envelope functions. The peak of the envelope occurs at the group arrival time, and the delay can be obtained. With the group velocity (found from the envelope functions), the phase velocity is calculated. The array calculation minimizes errors of any single station. Additionally, the phase consistency is easily checked. By using both group and phase velocities, the ambiguities in the inversion process may be reduced substantially.

The paper compares results of the Rayleigh wave array method with down-hole S-P measurement data at several sites. The shear wave velocity profile obtained from the Rayleigh wave array is a smooth version of the S-P measurement data. An additional advantage with respect to the P-S measurements is that the array method can be automated.

Soil Profiling by Spectral Analysis of Surface Waves

Shear wave velocity profiles provide useful information about geotechnical properties of soil deposits. The controlled source spectral analysis of surface waves (CSSASW) is a combination of the steady state Rayleigh wave (SSRW) and the spectral analysis of surface waves (SASW) methods. In the paper, Satoh et al. describe the CSSASW method. It offers the advantages of both SSRW and SASW methods without their disadvantages.

To obtain a "raw" (apparent) Rayleigh wave velocity profile with depth, a wide range of surface wave frequencies is used in a sequential automated process. The raw dispersion curve is then automatically processed to yield a raw velocity profile. The layered profile is then computed in an automatic process based on a simplified conversion algorithm.

A controlled electromagnetic vibrator generates amplitude modulated surface waves which are measured by two vertically oriented accelerometers positioned at a known distance from the vibrator. For each frequency the apparent wave velocity and affected depth are calculated and the process is automatically repeated for the next frequency, at preselected frequency intervals. The apparent velocity versus depth profile is displayed and processed. After conversion, the layered velocity profile is displayed and may be printed.

For field measurements it is necessary to select the appropriate vibrator size according to the sampling depth. Unlike other Rayleigh wave measurement methods the CSSASW has been used successfully to a depth reaching 100 m. Field set-up is rapid and the receivers are placed in a straight line with the vibrator. The range of frequencies and decrements are selected and the automated system is activated. In the latest development of the method, the vibrator applies random vibration pulses with preselected frequency ranges. The automated spectral analysis of these measurements provides consistent data resolution throughout the survey depth.

The relationship between Rayleigh and shear wave velocities is used to produce a layered shear wave velocity soil profile. Widely accepted correlations may then be used to obtain other geotechnical parameters of the soil profile, such as shear strength and elastic properties.

The paper presents results from recent case studies where CSSASW results show good correlation to data obtained from SPT borings used for verification. As shown in the paper, the method is also used for detection of cavities and buried objects.