USE OF ANALYTICAL AND STATISTICAL TECHNIQUES TO ASSESS IN-SITU SOIL TEST PROCEDURES

by

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SYNOPSIS

A new field-testing procedure has been developed to measure strain-dependent in-situ shear moduli. Part of the development effort has used nonlinear finite element analyses to evaluate data-processing techniques for obtaining shear moduli and strains from the soil motions generated during the test. In addition, statistical techniques have been applied to results from special field tests to determine the sensitivity of the generated soil motions to various test parameters that may influence results from the in-situ soil test.

INTRODUCTION

The shear modulus of soil materials is of fundamental importance in the study of earthquake-induced ground responses. Existing field and laboratory procedures do not provide shear modulus measurements in strain ranges representative of strong earthquake motions (i.e., $10^{-3}\%$ to $10^{-1}\%$), and laboratory tests are further complicated by such factors as sample disturbance and imperfect duplication of in-situ stress conditions. As a result, a new field-testing procedure has recently been developed to measure in-situ shear moduli that are more nearly representative of earthquake-induced strain levels. The procedure (see Fig. 1) uses a cylindrical anchor bonded by radial pressures to the sides of a vertical borehole. An impact hammer, dropped through the borehole and onto a Belleville spring attached to the top surface of the anchor, generates shear waves in the soil that propagate radially away from the anchor. Sensors located in nearby boreholes measure vertical-velocity histories, from which strain-dependent shear moduli can be obtained using appropriate data-processing techniques (Ref. 1).

As part of the development of this testing approach, special field tests were conducted under carefully controlled conditions to measure in-situ soil responses and to estimate in-situ properties. By using a finite element simulation of these tests and statistical analyses of the test results, two key aspects of the in-situ test procedure have been investigated: (1) the data-processing techniques for obtaining shear moduli and strains from the sensor measurements; and (2) the sensitivity of the soil-response measurements to variations in certain test parameters. This paper describes results from these investigations.

DESCRIPTION OF SPECIAL TESTS

The special field tests were conducted in a large pit 20 ft (6.10m) in diameter and 10 ft (3.05m) deep that was filled with a clean, dry sand material. An anchor/Belleville-spring system was embedded in the sand, and sensors were hand-placed every few inches along the mid-depth of the pit (Fig. 2). The sensor spacing was selected to obtain the best possible definition of the spatial variation of the soil response, while at the same time avoiding interaction between adjacent sensors. Numerous in-situ tests were carried out to evaluate the repeatability of the data and the sensitivity of the soil-response measurements to effects of various test parameters.

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Data-processing techniques were applied to the measurements to estimate in-situ strain-dependent shear moduli, and cyclic-triaxial tests of the sand materials were carried out in the laboratory (Ref. 1).

FINITE ELEMENT SIMULATION OF SPECIAL TESTS

Basic Approach. A finite element analysis of the special tests was used to evaluate data-processing procedures for estimating strain-dependent shear moduli from the sensor measurements. This analysis used an axisymmetric model of the falling hammer, Belleville spring, anchor, and nonlinear soil medium. The node points of the finite element grid were treated as sensors in the field, and data-processing techniques were applied to the node-point velocity histories to estimate shear moduli and strains in the soil. These estimates were compared to the shear moduli actually used as input to the finite element model; and this comparison, in turn, provided a self-contained basis for evaluating the data-processing techniques.

Description of Model. The finite element grid consisted of 954 elements and 1020 node points, with the greatest mesh refinement in the vicinity of the anchor (Fig. 3). The left boundary of the grid corresponded to the anchor drill-hole, which was stress free in the region above and below the anchor. The remaining boundaries were located sufficiently far from the anchor to preclude boundary reflections from entering the region of interest (within about 10 ft, or 3.05m, of the anchor) until after the shear wave had propagated through.

The finite element calculation simulated special test conditions for a 58 lb (258N) hammer falling 0.5 ft (0.15m) onto the Belleville spring and anchor. The hammer was represented as a rigid mass initially attached to the top of the Belleville spring. To simulate the desired excitation, the spring was assumed to be undeformed at time-zero, and the rigid mass was assigned an initial velocity that corresponded to the free-fall velocity due to a drop height of 0.5 ft (0.15m).

The mechanical properties of the soil medium were modeled using a variable-modulus formulation in which, for each integration step of the calculation, the instantaneous tangent shear- and bulk-moduli were computed as functions of the current state of stress and the stress history of each element in the grid. Hysteresis was incorporated in the shear modulus by distinguishing, on the basis of stress history, between the conditions of virgin loading and unloading/reloading. Values were selected for the parameters of the soil model such that the model behavior closely agreed with cyclic-triaxial test results for the sand used in the special tests.

Comparisons Between Calculation Results and Measurements. To verify the adequacy of the finite element calculations for evaluating data-processing techniques, the calculation results were compared with special-test measurements corresponding to the hammer weight and drop height used in the calculations. Measured vs. computed velocity and displacement histories were compared at numerous sensor locations; such comparisons are typified by the results shown in Fig. 4. This figure indicates that, when the finite element results were adjusted to account for the frequency-response characteristics of the sensors, excellent agreement between measured and computed soil responses was achieved.

Evaluation of Data-Reduction Procedures. Numerous procedures for estimating strain-dependent shear moduli were evaluated using the finite element calculations. From these evaluations, the following procedure was judged to produce the closest overall agreement with calculation results: (1) for each sensor, plot the time of occurrence of the peak displacement of the measured signal as a function of the distance from that sensor to the axis of the anchor; (2) obtain the shear wave velocity at that sensor, V_s, from the slope of this distance-vs.-time curve; (3) compute the shear modulus, G, from the relationship

$$G = \rho V_s^2$$

where ρ is the mass density of the soil medium; (4) select the peak shear strain from the time-dependent shear strain at the sensor, γ, computed from the equation

$$\gamma = \frac{\alpha}{r} u - \frac{\dot{u}}{V_s}$$

where r is the distance from the anchor axis, u and $\dot{u}$ are the time-dependent displacement and velocity, respectively, at the sensor, and α is a parameter used to quantify the rate of decay of peak displacement with distance from the anchor axis (Ref. 2). Modulus-strain relationships obtained by applying this method to node-point velocity histories resulted in excellent agreement with the actual modulus-strain relationship of the soil material model used in the finite element calculations (Fig. 5).

STATISTICAL EVALUATION OF SPECIAL-TEST RESULTS

Basic Approach. To evaluate the repeatability of the in-situ soil-response measurements and the sensitivity of the measurements to various test parameters, the special-test program included numerous sets of tests which were repeated 10 times; in each set, one of the selected parameters was varied. Velocity-time histories measured at each sensor and for each set of test conditions were analyzed statistically to determine mean time histories and velocity history bands that represent mean ± one standard deviation (MSD) bounds. Results of this type were developed for a large number of sensors and differing test conditions. Trends pertaining to data repeatability, effects of prior load history, sensor placement, and radial pressures are summarized below.

Repeatability of Data. The repeatability of the data was evaluated using tests with a wide range of hammer weights, drop heights, and radial pressures. For nearly all cases, the data were shown to be repeatable, as typified by overlaid velocity histories (not shown) and by the relatively narrow width of the velocity history bands corresponding to MSD bounds (Fig. 6 to 8). Only the near-anchor soil motions generated by the heaviest hammer (150 lb, or 668N) exhibited significant variability – possibly owing to difficulties in manually controlling the precise drop height and orientation of the hammer as it struck the Belleville springs, and the sensitivity of the near-anchor soil motions to these load details (Ref. 1).

Prior Load History Effects. During the in-situ test, the soil at a particular depth can be subjected to repeated load applications at different energy levels (i.e., the product of the anchor weight and drop height) to obtain a wide range of shear modulus vs. strain measurements. However, for some soil materials, prior loadings may affect the measured responses in a subsequent test. To investigate this potential effect for the sand materials used in the special tests, a series of initial tests was conducted during which a 58 lb (258N) hammer was dropped 0.5 ft (0.15m) onto the Belleville springs. Several tests were then conducted at higher energy levels followed by a series of tests corresponding to the initial load conditions. Comparisons of the measured velocity histories corresponding to the initial and final sets of the 58 lb x 0.5 ft (258N x 0.15m) loadings were used as a basis for assessing prior load history effects. These comparisons indicated that, for the particular soil materials and loadings represented by these special tests, prior load history effects were generally slight and were noticeable only after the initial positive velocity pulse had occurred (Fig. 6).

Sensor Placement Effects. To guide the planning of sensor placement in future site investigations, comparisons were made between measured velocity histories for sensors at equal radial distances from the anchor but at different circumferential locations. These variations in circumferential position produced only small differences in the measured soil velocities (Fig. 7); these differences may possibly be due to such factors as inhomogeneities in the soil and slight nonuniformities in the bearing of the various anchor plates against the sides of the borehole.

Radial Pressure Effects. In the anchor configuration used in the special tests, radial pressures are developed by a vertically-oriented hydraulic piston within the anchor that expands and thereby forces the curved anchor-bearing plates to be pressed tightly against the sides of the borehole. The pressures so developed must be sufficient to prevent slippage along the anchor/soil interface, but should not be so large as to cause localized soil failures or distort the dynamic properties of the soil medium near the anchor. To determine the sensitivity of soil-response measurement to variations in these radial pressures, three sets of tests were conducted corresponding to the three sets of pressures and the applied loading shown in Fig. 8. Comparisons of the MSD-bound time histories from the ensemble of results for each set of tests indicated only slight effects on soil motions; these effects were most noticeable when the lowest radial pressure (11.4 psi or 78.7 kN/m^2) was applied (Fig. 8).

CONCLUSIONS

These investigations have represented an important step in the development of a technique for measuring in-situ strain-dependent shear moduli. The data-processing procedures developed for use with in-situ tests were successful, as evaluated by their application to finite element results. Furthermore, soil motions measured during the special tests were found to be not strongly sensitive to the range of variations in test parameters. Interpretation and assessment of these investigations should consider that they were based on a single soil type and an idealized set of test conditions. Nevertheless, the results indicate that the in-situ test method shows promise for application at actual soil sites.

ACKNOWLEDGMENTS

This investigation was carried out as part of a joint-venture effort by Shannon & Wilson Inc. and Agbabian Associates directed toward evaluating the earthquake-induced behavior of soil materials. Test-hardware development and field work associated with the special tests were carried out by Shannon & Wilson Inc.; the finite element calculations and statistical analyses of test results described herein were performed by Agbabian Associates. Additional contributions were made by L.S. Jacobsen, special consultant. J. Harbour of the U.S. Nuclear Regulatory Commission is technical monitor to the joint venture.

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2. Shannon & Wilson-Agbabian Associates. *Progress Report — Evaluation of In-Situ Soil Damping Characteristics*, Washington, D.C.: U.S. Nuclear Regulatory Commission, Jun. 1976.

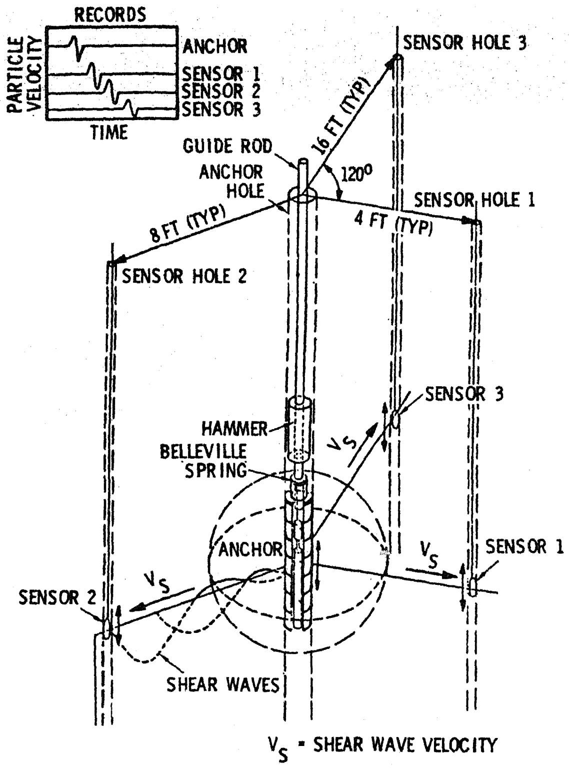


FIGURE 1. SCHEMATIC OF IN-SITU SOIL TEST

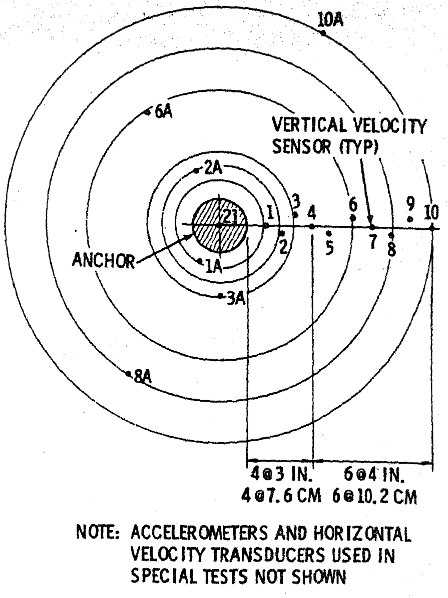
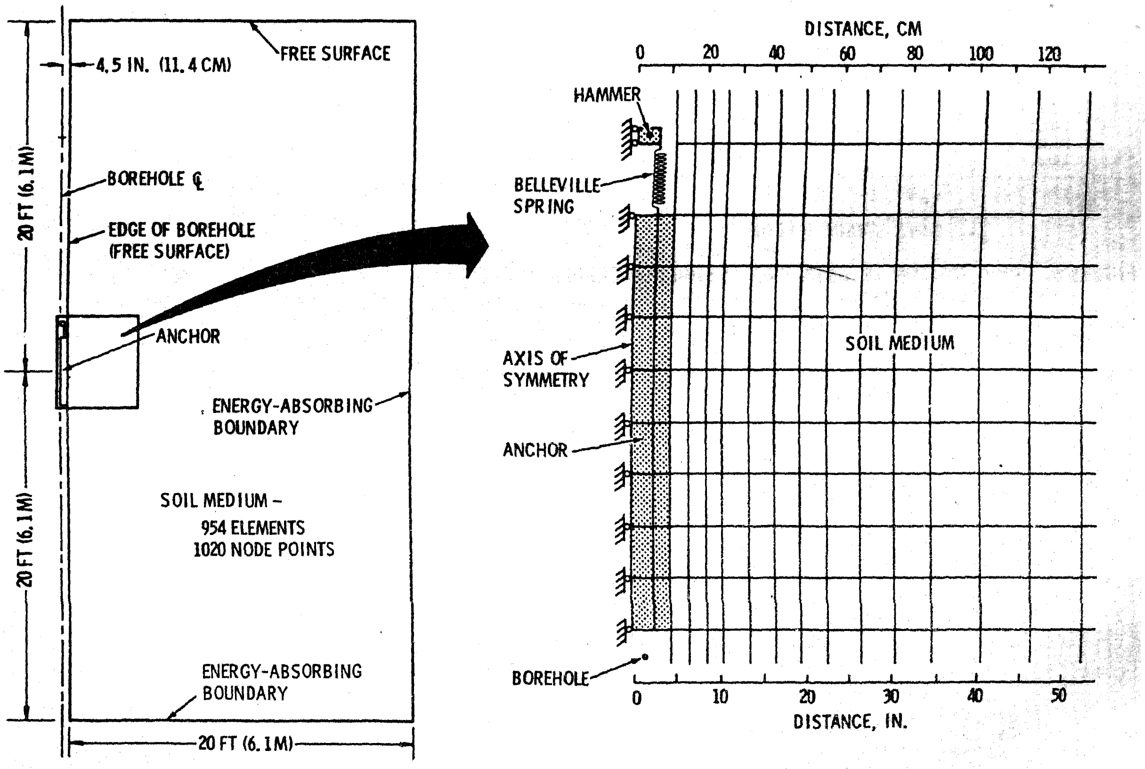


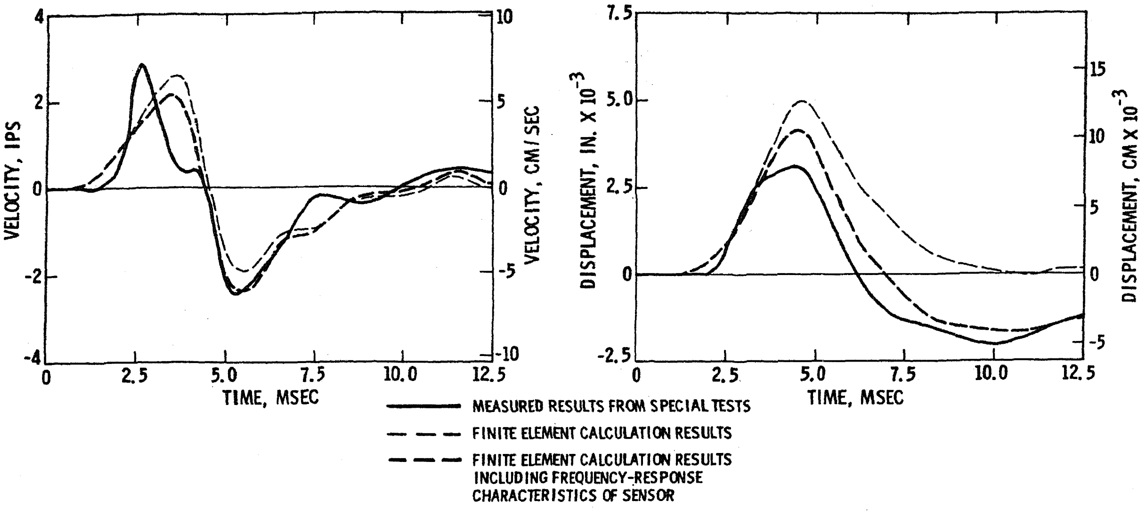
FIGURE 2. PARTIAL PLAN OF VERTICAL VELOCITY SENSOR LOCATIONS FOR SPECIAL TESTS (Only sensors within 3 ft [0.9 m] of anchor edge are shown)



(a) Overall grid layout

(b) Near-anchor region

FIGURE 3. FINITE ELEMENT SIMULATION OF SPECIAL TESTS



(a) Vertical velocity (positive downward) (b) Vertical displacement (positive downward)

FIGURE 4. COMPARISON BETWEEN MEASURED AND COMPUTED SOIL RESPONSE 9 IN. (22.9 CM) FROM EDGE OF ANCHOR

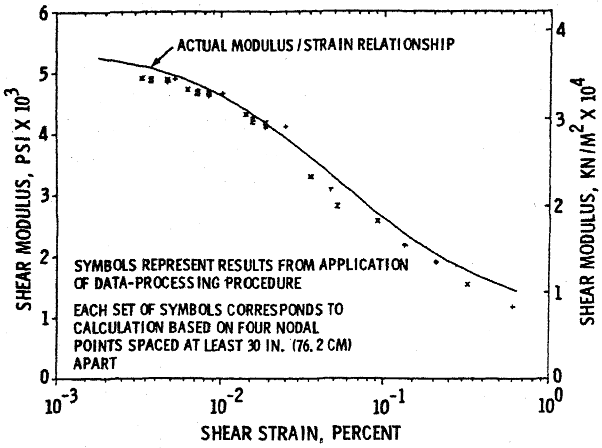
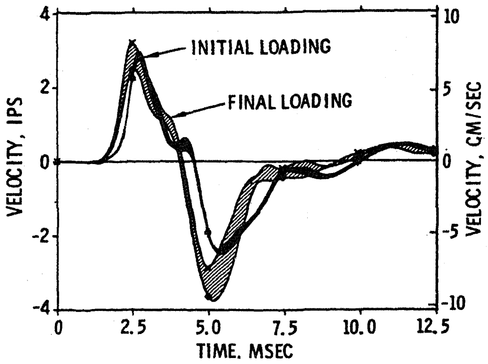
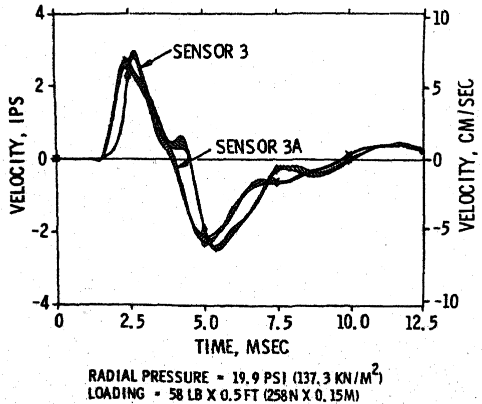


FIGURE 5. APPLICATION OF DATA-PROCESSING PROCEDURE TO FINITE ELEMENT CALCULATIONS



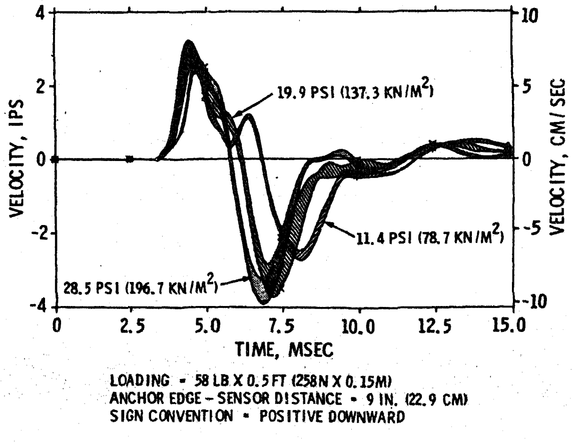
RADIAL PRESSURE = 19.9 PSI (137.3 KN/M^2)
LOADING = 58 LB X 0.5 FT (258N X 0.15M)
ANCHOR EDGE – SENSOR DISTANCE = 9 IN. (22.9 CM)
SIGN CONVENTION = POSITIVE DOWNWARD

FIGURE 6. EFFECT OF PRIOR LOAD HISTORY ON MSD VELOCITY BOUNDS



RADIAL PRESSURE = 19.9 PSI (137.3 KN/M^2)
LOADING = 58 LB X 0.5 FT (258N X 0.15M)
ANCHOR EDGE – SENSOR DISTANCE = 9 IN. (22.9 CM)
SIGN CONVENTION = POSITIVE DOWNWARD

FIGURE 7. EFFECT OF CIRCUMFERENTIAL POSITION OF SENSOR ON MSD VELOCITY BOUNDS



LOADING = 58 LB X 0.5 FT (258N X 0.15M)
ANCHOR EDGE – SENSOR DISTANCE = 9 IN. (22.9 CM)
SIGN CONVENTION = POSITIVE DOWNWARD

FIGURE 8. EFFECT OF RADIAL PRESSURE ON MSD VELOCITY BOUNDS