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"THE PROPAGATION OF SEISMIC WAVES THROUGH NONLINEAR SOIL MEDIA"

A Thesis submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Civil Engineering

- at the -

School of Engineering
University of Auckland
New Zealand

- by -

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Synopsis

This study is concerned with a theoretical, laboratory and in situ investigation of the propagation of seismic stress waves through soil media.

Analyses are carried out to predict the surface response that results from earthquake motions being transmitted through the upper layers of the earth. The nature of the near surface geological layers affect to a marked degree the intensity of surface motion. The mathematical models presented are used in the evaluation of site response to earthquakes.

The theoretical methods used depart from the traditional viscoelastic approach and use a nonlinear hysteretic soil model to describe the complex dynamic stress-strain relationships evident in soil response. The dynamic soil model is based on previous laboratory work carried out at this university.

The theoretical solutions formulated are limited to one-dimensional situations. Three methods of analysis are presented for the propagation of seismic shear waves through nonlinear soil media and conclusions are drawn as to the best approach. The results of these analyses are generally significantly different from those obtained using a viscoelastic soil model. Seismic dilatational waves are also considered important and a method is presented to calculate the response of hysteretic soil media to these disturbances. The outcome from these dilatational and shear wave analyses is more accurate surface response spectra for use in aseismic structural design.

The nonlinear hysteretic soil model is generated from laboratory data. To this end an existing laboratory dynamic torsion test apparatus was modified and a series of tests carried out. The torsion equipment was coupled to an on-line computer which allowed accurate data recording and analysis over a wide range of strain ($2 \times 10^{-3}$ to $2 \times 10^{-6}$).

To provide a means of estimating sample disturbance, and to develop a method of in situ soil testing in the very low strain range, in situ shear wave measurements were undertaken. The downhole method of seismic wave testing was used to furnish values of the shear wave velocity of layers of silts, clays and sands down to a depth of 50m. Comparison of these wave velocities with those obtained from laboratory torsion tests on undisturbed samples revealed large differences and established the magnitude of sample breakdown.

A method of modifying the laboratory established shear modulus - strain relationship to obtain the correct (in situ) curve is presented. This allows more correct dynamic soil properties to be incorporated in the simulation of the in situ soil response to seismic shear waves.
Acknowledgements

The work presented in this thesis was carried out at the University of Auckland, Civil Engineering Department under the headship of Professor N.A. Mowbray.

During the course of the study the author was supervised by Associate Professor P.M. Taylor. The author wishes to express his great appreciation to Professor Taylor for the substantial knowledge, enthusiasm and vigour he imparted to the project, and the friendly manner in which this help has been given.

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k* initial elastoplastic element stiffness
k' final elastoplastic element stiffness
L length of torsion sample
M mass; applied moment
MIN minimum signal value in displayed points
M_i ith soil mass
MPY scaling parameter
m mass
P natural undamped frequency
R Coulomb resistance of elastoplastic element; spectral radius
R* initial Coulomb limit of elastoplastic element
R' final Coulomb limit of elastoplastic element
S_u undrained shear strength
T period of oscillation
T_N period of highest pseudo-mode of an N-mass system
T_n nth natural period of an n mass system
T_R relaxation time
T_1 pseudo natural period of nonlinear soil layer
t time
\hat{U}(\omega) Fourier transform of soil acceleration record
u displacement of soil particle in the x direction (horizontal)
\frac{\partial u}{\partial x}
u_x velocity of compressional wave through soil medium
V_c velocity of shear wave through soil medium
V_s
v displacement of soil particle in the z direction (vertical)
W maximum strain energy stored during a cycle of loading
\frac{\partial^2 u}{\partial z^2}w_z
X_s time value read off computer screen
x cartesian coordinate direction (horizontal)
x_i displacement of the ith mass relative to the base
Y_s rotational displacement read off computer screen
\hat{Y}(\omega) Fourier transform of bedrock acceleration record
y displacement of soil-rock interface
\hat{y}
y base acceleration
z cartesian coordinate direction (vertical)
\( \alpha_e \) effective tangent modulus
\( \alpha_m \) complex impedance ratio of the \( m \)th layer
\( \alpha_n \) tangent modulus of the \( n \)th hysteresis loop
\( \beta_n \) lateral stiffness of \( n \)th shear spring
\( \delta \) logarithmic decrement
\( \delta(t) \) unit impulse
\( \Delta D \) energy dissipated
\( \Delta t \) time increment
\( \Delta x \) space increment in \( x \) direction
\( \Delta z \) space increment in \( z \) direction
\( \varepsilon \) strain
\( \varepsilon_y \) yield strain of elastoplastic element
\( \tilde{\varepsilon} \) cubical dilation or volume expansion
\( \eta \) soil viscosity coefficient; parameter of Newmark's integration scheme
\( \gamma \) shear strain
\( \gamma_y \) yield shear strain of elastoplastic element
\( \lambda \) fraction of critical viscous damping; Lame's constant; stability parameter
\( \lambda_{eq} \) equivalent viscous damping factor
\( \lambda_n \) viscous damping ratio in the \( n \)th mode
\( \mu \) parameter of Newmark's integration scheme
\( \nu \) Poisson's ratio
\( \omega \) angular frequency, rad/sec; rotation of solid particles
\( \omega_n \) \( n \)th eigenvalue
\( \omega_{w} \) rotation of fluid particles
\( \psi \) specific damping capacity
\( \rho \) mass density
\( \rho_A \) mass density of fictitious mass representing coupling between the fluid and elastic structure
\( \rho_f \) mass density of pore fluid
\( \rho_s \) mass density of elastic structure
\( \sigma \) normal stress
\( \sigma_e' \) mean interparticle stress
\( \sigma_i' \) intrinsic stress
\( \sigma_m' \) mean effective principal stress
\( \sigma_v' \) vertical effective stress
\( \sigma_1 \) major principal stress
\( \tilde{\sigma} \) normal stress from simulated hysteresis loop
\( \theta \) angular displacement of soil sample; disturbance factor; tolerance level in moduli prediction
\( \tau \) shear stress; dummy variable