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TWO DIMENSIONAL NONLINEAR SEISMIC GROUND RESPONSE STUDIES

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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July, 1992
ABSTRACT

The work in this thesis investigates the nature of the two dimensional nonlinear seismic ground response of alluvial basins. Computer programs are developed to analyse both the out-of-plane (SH) and in-plane (PSV) two dimensional solution spaces. A finite difference approach is utilised. The seismic input motion may originate from either below or from within the two dimensional mesh modelled. The analyses are performed in terms of total stresses and strains, and pore water pressures are not taken into account. A transmitting boundary allows energy to radiate from the solution space. The computations are performed with a nonlinear soil model which incorporates hysteretic material damping. The shape of the initial loading curve of the soil model may be arbitrary, but the majority of the analyses presented utilise a hyperbolic initial loading curve.

Alluvial basins of constant L/H ratio are analysed subject to both vertically propagating seismic waves and seismic waves inclined at angles to the vertical. Both simple displacement pulse and complex transient earthquake acceleration input forms are utilised. Varying levels of excitation are employed to study the effect of strain level on the basin response. Two dimensional basins of varying L/H ratios are analysed subject to vertically propagating waves, and the results compared to a one dimensional nonlinear formulation. The results obtained using a hyperbolic initial loading curve are compared to those produced using initial loading curves derived from empirical relationships for dynamic soil properties. Results from the two dimensional nonlinear analysis are compared to those obtained from a two dimensional linear visco-elastic solution. A detailed case study is investigated with the two dimensional nonlinear analysis forming part of the Ashigara Blind Prediction Test. Elastic closed form solutions for simple two dimensional configurations are calculated, and time domain results compared to the nonlinear analysis. In-plane Rayleigh wave and out-of-plane Love wave characteristics in the nonlinear medium are investigated. A study of soil-structure interaction in the nonlinear medium is made. The feasibility of including discrete fault source models in the two dimensional analysis is investigated, with both dislocation and stress drop methods of input.

The two dimensional nonlinear site response analysis method presented in this thesis is found to be a very flexible tool in calculating the ground response of alluvial basins to seismic waves. The method is relatively inexpensive computationally in the light of present computer capabilities. The method is therefore preferred to one dimensional and linear visco-elastic analyses in calculating the response of alluvial basins, given sufficient site data.
ACKNOWLEDGEMENTS

The work in this thesis was carried out in the Civil Engineering Department at the University of Auckland under the supervision of Dr. Tam Larkin.

I wish to thank Tam Larkin for his advice, guidance, support and encouragement throughout this thesis. His friendship and humour are always appreciated.

I would also like to thank the following:

Members of staff of the Civil Engineering Department for their advice and criticism, especially Professor Michael Pender and Dr. Barry Davidson. Special thanks to Dr. Tony Bryant and Dr. Richard Hunt for the use of their laser printer and computers.

Members of my PhD committee not already mentioned, Professor Peter Lowe, Professor Ian Collins and Associate Professor Peter Hunter.

Dr. John Haines and Dr. Rafael Benites from DSIR Wellington for their assistance.

Fellow postgraduate members of the Civil Engineering Department for their friendship, especially the "3rd floor boys" and longest serving in-mates James Burr and Steve Marks. Also friends outside the department for their encouragement, especially John Soo Ping Chow and Stuart Kay.

Graham Duske and Neil Crystal for supplying my developing lifeline in computers.

My family in the UK for their long distance support and encouragement.

Heather for her patience and encouragement during the tenser moments of this write up.

The Commonwealth Scholarship Commission and the New Zealand Vice Chancellors Committee for their financial support.
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SYMBOL NOTATION

The units of all the quantities expressed in this thesis are standard S.I. units.

- \( a \)  
  Radius of semi-circular basin  
- \( a \)  
  Focal length of ellipse  
- \( a_n \ldots d_n \)  
  Complex constants
- \( A \)  
  Surface displacement amplification  
- \( c \)  
  Phase velocity of surface waves  
- \( c e_{2n}(\eta,q) \)  
  Even Mathieu Function  
- \( C_n \)  
  Hardening constant of the \( n^{th} \) yield surface  
- \( e_{ij} \)  
  Components of deviatoric tensorial strain  
- \( e_m \)  
  Mean tensorial strain  
- \( e_{m,n}k_n \)  
  Normalised deviatoric stress-strain pairs defining initial loading curve  
- \( e_{Eij} \)  
  Elastic component of deviatoric strain  
- \( e_{Pij} \)  
  Plastic component of deviatoric strain  
- \( e_{Puij} \)  
  Component of plastic deviatoric strain associated with the \( n^{th} \) yield surface  
- \( E \)  
  Young's modulus  
- \( E_{ij} \)  
  Components of total strain  
- \( f \)  
  Frequency  
- \( F_i \)  
  Nodal forces  
- \( F_n \)  
  Yield function of the \( n^{th} \) yield surface  
- \( F_t \)  
  Yield function of outermost yield surface  
- \( G \)  
  Shear modulus  
- \( G_i \)  
  Stiffness of spring in units of nonlinear soil model  
- \( G_o \)  
  Low strain maximum shear modulus of soil  
- \( h_n \)  
  Constant of proportionality of \( n^{th} \) yield surface  
- \( h_t \)  
  Constant of proportionality of outermost yield surface  
- \( H \)  
  Thickness of soil layer  
- \( H_p^{(2)}(x) \)  
  Hankel Function of the 2\(^{nd}\) kind of order \( p \) and argument \( x \)  
- \( H_t \)  
  Modified hardening constant  
- \( I \)  
  Moment of inertia  
- \( J_n(x) \)  
  Bessel Function of order \( p \) and argument \( x \)  
- \( k \)  
  Wavenumber  
- \( k_a \)  
  Characteristic constant of the \( n^{th} \) yield surface  
- \( K \)  
  Bulk modulus of soil  
- \( L \)  
  Height of building
L Width of two dimensional basin
L(c,k) Love's Function
L_n Variable defining whether n_th yield surface is yielding
m Mass per unit length per metre run of building
m_i Mass acting at nodes
Mc_{2m}^{(1)} Modified Mathieu Function of the 1st kind
Mc_{2m}^{(3)} Modified Mathieu Function of the 3rd kind
Q Viscous damping factor
R Ratio of minor to major axes of ellipse
R(c) Rayleigh's Function
r Radial cylindrical coordinate
se_{2m}(\eta,q) Odd Mathieu Function
S_{ij} Components of total stress
S_u Maximum undrained shear strength of soil
T_1 Fundamental period of building
u Out-of-plane displacement
v_p Compression wave velocity
v_s Shear wave velocity
V Shear wave velocity
V_F Forcing input velocity at boundary nodes
V_i Nodal velocities
V_i' Nodal velocities in rotated coordinate system
x_1...x_3 Coordinate system of mesh
Y_i Yield stress of units in nonlinear soil model
<table>
<thead>
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<tr>
<td>$\alpha$</td>
<td>Compression wave velocity</td>
</tr>
<tr>
<td>$\sigma_{ui}$</td>
<td>Origin of $n$th yield surface in stress space</td>
</tr>
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<tr>
<td>$\beta_{ij}$</td>
<td>Components of rotation matrix</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Angle of incidence of seismic waves to the vertical</td>
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<tr>
<td>$\gamma$</td>
<td>Shear strain</td>
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<tr>
<td>$\gamma_{xy}$</td>
<td>Components of deviatoric engineering strain</td>
</tr>
<tr>
<td>$\delta_{ij}$</td>
<td>Kronecker delta</td>
</tr>
<tr>
<td>$\Delta s$</td>
<td>Segment length of boundary element</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Time step of analysis</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Angular elliptical coordinate</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Dimensionless frequency</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of incidence of seismic waves to the vertical</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of rotation of coordinate system</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Wavenumber</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Lame’s constant</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
</tr>
<tr>
<td>$\lambda_{eq}$</td>
<td>Equivalent viscous damping</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Radial elliptical coordinate</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Mass density</td>
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<tr>
<td>$\sigma_{ij}$</td>
<td>Components of deviatoric stress</td>
</tr>
<tr>
<td>$\sigma_m$</td>
<td>Mean stress</td>
</tr>
<tr>
<td>$\sigma_n$</td>
<td>Contributing terms to each $\sigma_{ij}$</td>
</tr>
<tr>
<td>$\sigma_{kl}$</td>
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<tr>
<td>$\tau$</td>
<td>Shear stress</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency</td>
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