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General Report —Session X: Wave Propagation in Soils

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General Report - Session X
Wave Propagation in Soils

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This session consists of thirteen papers. Six are directly concerned with the soil amplification of seismic waves, covering a variety of topics which range from nonlinear soil effects on the one-dimensional amplification of vertically propagating shear waves to the effects of two-dimensional geometries on the amplification of different types of waves, and an evaluation of a suggested procedure to derive site amplification parameters from microtremor records. The other seven papers deal with more general wave propagation topics: the response of soil deposits to moving surface loads and shock loading, a study of the effect of cross anisotropy on the propagation of Rayleigh waves, the derivation of an analytical formulation to study the propagation of longitudinal waves along a rod of infinite length embedded in a full space, the presentation of a model to analyze the propagation of Love (SH) waves in a layered medium overlying an elastic half space, a study of the effect of the degree of saturation on the energy needed for the compaction of sands, and an investigation of the effect of random variations in material properties on the rod wave propagation velocity.

The importance of nonlinear soil behavior and its effects on soil amplification were soon recognized by geotechnical earthquake engineers. The method most commonly used to obtain site specific earthquake motions (direct analysis or convolution) or to obtain compatible motions at bedrock for a specified earthquake at the free surface (deconvolution) is the one implemented in the computer program SHAKE. The soil is assumed to consist of horizontal layers with constant properties and the earthquake is represented by a plane train of vertically propagating shear waves. To simulate nonlinear soil behavior an iterative procedure is used. Initial values of shear modulus and damping are assumed for each layer. A linear elastic analysis is performed with these properties and the time histories of the horizontal shear stresses at mid-depth of each layer are obtained. From these time histories, a characteristic value, typically two thirds of the maximum, is selected and soil properties consistent with this level of shear strain are obtained from experimental curves relating shear modulus and damping to shear strain. The analysis is repeated with these new properties and the procedure continues until the results from two sequential analyses differ by less than a specified tolerance. In each analysis the damping is assumed to be of a linear hysteretic type, independent of frequency. The approximations involved in this procedure were already pointed out by Constantopoulos in 1973. A consequence of the assumption of a damping which is the same for all frequency components irrespective of their amplitudes is that high frequencies are filtered out excessively in direct analyses; in deconvolution studies, on the other hand, the high frequency components would have amplitudes increasing with depth and after a certain point the results would blow up. To avoid this in practice, the input motion at the free surface is often modified, filtering out all frequencies above 15, 10, or in some extreme cases 5 Hz. This is, of course, unrealistic. The problem is most severe when dealing with soft and deep soil deposits. The paper by Roesset, Huerta and Stokoe discusses again these facts and compares the results of true nonlinear analyses with those of the iterative scheme assuming that the damping is proportional to frequency, independent of frequency or inversely proportional to frequency. The study shows that the nonlinear solution lies between the last two: frequency independent damping filters out excessively the high frequency components but inversely proportional damping exaggerates their importance. The paper by Yamada, Miura and Kobori illustrates again the limitations and inaccuracies of the iterative linear analyses as performed in SHAKE and proposes the use of a nonlinear analysis in the time domain with the method of characteristics (as suggested by Papadakis in 1973 and Streeter et al in 1974 for the linear case). Of particular interest is the formulation and application of the procedure for deconvolution analyses. This problem is normally ill-conditioned. If the scheme recommended by Yamada, Miura and Kobori eliminates this ill-conditioning of the solution and provides realistic results, it would be a significant contribution which might help to eliminate the errors committed at present.

The effects of two- and even three-dimensional geometries on the amplification, or modulation, of seismic waves have been topics of a considerable amount of research in recent years. In 1970, Aki and Larner suggested a method, based on collocation, to account for two-dimensional geometries which is still extensively used today, although most recent formulations rely on the boundary element method. Additional work was conducted in the 70's by Trifunac (1971, 1973), Wong and Trifunac (1974, 1977), Wong and Jennings (1975), Bouchon and Aki (1977), Sanchez Sesma and Rosenblueth (1979), and Sanchez Sesma and Esquivel (1979). In the 80's important research results were published by Bard and Bouchon (1980, 1985), Bouchon, Aki and Bard (1982), Bard and Gariel (1986), Wong (1982), Dravinski (1982, 1983), Lee (1984), Sanchez Sesma (1983, 1985), and Dominguez and Abascal (1987), and in the 90's by Papageorgiou and Kim (1992). An excellent summary of the work done up to 1988 was presented by Aki (1988) at the Earthquake Engineering and Soil Dynamics II Conference of the Geotechnical Division of ASCE in Park City, Utah. For an elastic half space with a canyon or a homogeneous sediment-filled valley and SH waves, the solution using the boundary element method is particularly simple because an explicit analytical expression for the Green's function is available in closed form. In the paper, "Scattering of SH Waves by Arbitrary Surface Topography," Manoogian and Lee address again the problem of SH waves and a 2D geometry using weighted residuals. The solution procedure could be considered an extension of the original Aki-Larner method since collocation is a weighted residual with Dirac delta functions as weights. The authors indicate that they can match with their method the results published by others and conclude primarily that the method is a viable alternative, which would appear to be true. The basic question would seem to be whether the method is more efficient than any of the available ones.

Ahmad, Fishman and Xue use the normal boundary element formulation in their paper, "Response of Alluvial Valleys to Incident SH, SV, and P Waves," and apply it to the study of alluvial valleys of elliptical shape under different types of waves, variable angles of incidence of the waves, different aspect ratios of the valley (from shallow to deep), different impedance ratios between the materials of the valley and the surrounding medium and different frequencies or wavelengths. The extensive parametric studies show some important and interesting effects. It is interesting to notice, for instance, that the maximum amplification does not always occur at the middle of the valley but its location is a function of the frequency, and that for waves with inclined incidence the amplification will not be symmetric. Some of the conclusions, however, would appear to be misleading. Such for instance the statement that "shallow valleys have little effect on ground motion."

A particularly simple case is that where the soil consists of horizontal layers with vertical planes of separation between different regions. For the case of only 2 regions extending to infinity towards the left and the right of the separation plane it would be sufficient to combine the left and right hand consistent boundaries developed by Waas (1972) to reproduce the complete problem. When dealing with more than 2 regions one can use the hyperelements described by Kausel and Roesset (1977) and by Tassoulas (1981). In fact, this approach was used by Tassoulas and Roesset (1991) to study the wave propagation in rectangular valleys with special emphasis on Rayleigh waves. In the paper, "Analysis of Inclined Shear Waves in Vertical Bluffs," Ashford and Sitar use a "generalized transmitting element" and a "generalized hyperelement" which are not described but which seem very similar in concept to the work described above. The fact that there are no references to any previous work except for a 1991 Ph.D. Dissertation makes it very hard to assess exactly what method was used. In their study, these authors find that for this simple geometry the angle of propagation of the SH waves, traveling into or away from the scarp, makes a substantial difference in the amplification while this does not seem to be true for SV waves. The amplification values reported for SH waves are, however, smaller than those for SV waves.

The application of microtremor measurements to experimentally determine soil amplification effects at a given site has been a subject of some controversy over the past 30 years. The controversy has centered primarily around the amount of information obtained from microtremors which can be directly extrapolated to the study of soil amplification effects for strong earthquake motions. Recently Nakamura (1989) has suggested that the spectral ratio of the horizontal to the vertical component of motion, function of frequency, has a peak at the natural frequency of the soil deposit in shear and that the amplitude of this peak allows the determination of the amount of soil amplification. In the paper, "Theoretical Investigations on the Nakamura's Technique," Lachet and Bard assess the validity of these suggestions. Simulating a number of different sources of noise and considering different soil profiles the authors conclude that the frequency of the peak of the H/V ratio is indeed very close to the natural frequency in shear of the soil, and is essentially independent of the source. The amplitude is, however, strongly affected by a number of factors and cannot provide an easy and reliable estimate of the amplification. In addition to these important conclusions, the procedure used for the simulation of noise will be of interest to many readers.

A number of different models and formulations have been developed to study wave propagation in layered media. In some cases the medium is discretized in the horizontal and vertical directions using standard finite difference or finite element techniques. In others the solution is discretized in the vertical direction with a piece-wise linear variation of the displacements with depth while using the exact continuous expressions in the horizontal directions. This is the approach used for instance by Waas (1972). A different approach is to use the exact expressions in the vertical direction but a Fourier series expansion in the horizontal direction (transformation from the space to the wave number domain), as done by Gazetas (1975). More recently a "finite strip" method has been developed using a piecewise linear variation of the displacements in the vertical direction (as done by Waas) and a Fourier series expansion in the horizontal direction (as done by Gazetas). While the advantages of this double discretization over any of the other two approaches are very unclear, this method has been the subject of a substantial number of studies. Finally, discrete Green's functions as derived by Kausel (1981), are now available for solutions with the boundary element method. In the paper "Dynamic Modeling of Layered Systems to Moving Surface Loads - Application," Siddharthan, Norris and El-Gamal use a "recently developed moving load model," which "uses an efficient semi-analytical finite layer formulation" to study the response to moving loads. The basic assumptions and details of the formulation are not presented (the reader is referred to two other papers) so it is not clear whether the "finite layer" method is closer to the finite strip or Waas' approach. The additional and main assumption is that all results can be expressed as functions of $x\text{-}ct$ where c is the velocity of the moving load. The formulation is two-dimensional for plane strain problems and corresponds therefore to a line load. The authors claim, without proof or details, that a finite width load can be simulated using lateral viscous dashpots. This would seem to be similar to the approach used in the program FLUSH to simulate a pseudo 3D situation but again no reference is made to this program so the reader is unclear about the validity of the claim. The authors indicate resilient behavior of the asphalt concrete and linear behavior of the soil. Two applications are presented, one for a plane strain line load moving on the surface of a soil deposit, the second, more debatable, for simulated tandem axle loading.

The paper "Elastic Wave Propagation in Inhomogeneous Media," by D.S. Shridhar and V.S. Chandrasekaran uses standard finite elements in cylindrical coordinates and a transmitting boundary based on an extrapolation scheme suggested by Liao and Wang (1984) and Liao and Liu (1992). The actual values of the soil properties are not provided but it seems that the lateral boundary is placed at a sufficient distance to avoid any reflections from reaching the zone of interest within the time span considered, in which case the characteristics of the boundary would be irrelevant. The bottom boundary seems to be placed, according to fig. 1, at a distance where reflections would reach the receivers without appropriate boundary conditions but along the axis of symmetry a simple viscous dashpot should provide very good results and it is hard to see from the results in figure 3 whether there are any reflections in the response. The authors indicate that the problem considered might correspond to practical applications ranging from bomb blast to hammer foundations. Since they assume small deformations and linear elastic soil behavior this would not seem to be so. The formulation could be, however, of interest for other applications. The basic conclusions offer no surprise. The authors find that the response oscillates around the static displacement and tends to it as time goes by, that the amplitudes decay with horizontal distance and with depth and that the same type of behavior takes place when the soil properties increase proportionally to the square root of the depth.

The effect of cross-anisotropy on the dispersion curve of Rayleigh waves is studied by Wu and Wang in their paper, "R-wave Dispersion Analysis in Transversely Isotropic Stratum." The formulation used is an extension of Kausel's (1986, 1991) work for isotropic and anisotropic media. The authors refer to this formulation as the "finite layer" approach and it is not clear whether this is what was meant in the paper by Siddharthan et al discussed above. The authors conclude that the effects of cross-anisotropy are very important and must be taken into account, in particular in the interpretation of SASW dispersion curves. They do not indicate, however, how this can be accomplished. More importantly it is not clear what is considered "very important." The results presented do not seem to show very large variations. To reach a valid conclusion it would be necessary to see how much the estimated soil properties may change if one assumes isotropic behavior when dealing with a realistic anisotropic soil. It appears, therefore, that more work is needed to fully assess the importance of cross-anisotropy effects.

Xia and Wu in their paper, "Finite Element Method for Love Wave Dispersion in Soils," suggested an approximation to extend Waas' (1972) formulation for a layered medium on a rigid base to the case of an underlying elastic half space. The approximation suggested seems to be the same proposed in 1984 by Hull and Kausel, who considered both Love (antiplane conditions) and in-plane Rayleigh waves. These solutions have been used extensively for a number of years now. The paper shows results for three specific examples but provides little detail on the discretization used.

The paper, "Longitudinal Waves in a Rod in an Elastic Medium," by Bodare, Eriksson and Samuelsson is an interesting contribution which could have been more valuable if the different parameters used (such as the constant Σ) had been properly defined and if the differences between figures with the same titles and variables (such as figures 2 and 4 or 3 and 5) had been more clearly explained. Assuming a full space and a cylindrical rod of infinite length the authors derive an exact analytical solution for the axial vibrations of the combined system and compare the results with those obtained considering frequency independent springs and dashpots. A comparison with the results that would be obtained using instead the expressions for frequency dependent springs and dashpots based on Baranov's work and used by Novak would have been even more interesting.

The paper, "Stress Wave Propagation in Unsaturated Sands," by Veyera and Ross addresses primarily the effect of the degree of saturation on the energy needed for compaction of two sands and the resulting properties (P wave velocities) of these compacted sands. The results indicate that the compaction energy increases as the degree of saturation increases from 0 to 20%, remains almost constant from 20 to 90% and decreases above 90%. The P wave velocity increases also, but once the sample is compacted the variation in results testing the sample moist or dry is erratic and no conclusions can be reached.

Finally, J. Naprstek in his paper, "Dispersion of Longitudinal Waves Propagating in a Continuum with Randomly Perturbated Parameters," studies the effect of stochastic imperfections on the propagation of compressional waves in an ideal bar (one-dimensional model). The formulation is based on the use of Markov models to solve the diffusion or random walk problem (Fokkes - Plank - Kolmogorov equation). The paper will be of particular interest to readers familiar with random vibrations but may be hard to understand for those who do not have sufficient familiarity with the subject. Some language problems contribute to the difficulty in following the presentation.

REFERENCES

Aki, K. (1988), "Local Site Effects on Ground Motion - State of the Art Report," Recent Advances in Ground Motion Evaluation, Geotechnical Special Publication, No. 20, ASCE.

Aki, K. and K.L. Larner (1970), "Surface Motion of a Layered Medium Having an Irregular Interface due to Incident Plane SH Waves," Journal of Geophysical Research, No. 75.

Bard, P.Y. and M.A. Bouchon (1980), "The Seismic Response of Sediment-Filled Valleys - Parts I and II," Bulletin, Seismological Society of America, No. 70.

Bard, P.Y. and M.A. Bouchon (1985), "The Two-Dimensional Resonance of Sediment-Filled Valleys," Bulletin, Seismological Society of America, No. 75.

Bard, P.Y. and J.C. Gariel (1986), "A Numerical Study of the Variations of Ground Motion Parameters Across Two-dimensional Sediment-Filled Valleys," Proceedings of the 8th European Conference on Earthquake Engineering, Lisbon, Vol. 2.

Bard, P.Y. and J.C. Gariel (1986), "The Seismic Response of Two-Dimensional Sedimentary Deposits with Large Vertical Velocity Gradients," Bulletin, Seismological Society of America, No. 76.

Bouchon, M.A. and K. Aki (1977), "Near Field of Seismic Source in a Layered Medium with Irregular Interfaces," Geophys. J. R. Astr. Soc., No. 50.

Bouchon, M.A., Aki, K. and P.Y. Bard (1982), "Theoretical Evaluation of Differential Ground Motions Produced by Earthquakes," Proceedings of the 3rd Microzonation Conference, G2-G12, Seattle, Washington.

Constantopoulos, I.V. (1973), "Amplification Studies for a Nonlinear Hysteretic Soil Model," Report R73-46, Civil Engineering Department, MIT.

Dominguez, J. and R. Abascal (1987), "Effects of Irregular Soil Profile on Soil Amplification," Developments in Geotechnical Engineering, Vol. 43, Elsevier.

Dravinski, M. (1982), "Scattering of Elastic Waves by an Alluvial Valley," Journal of the Engineering Mechanics Division, ASCE, No. 108.

Dravinski, M. (1983), "Amplification of P, SV and Rayleigh Waves by Two Alluvial Valleys," Soil Dynamics and Earthquake Engineering, No. 2.

Gazetas, G. (1975), "Dynamic Stiffness Functions of Strip and Rectangular Footings on Layered Soils," M.S. Thesis, Civil Engineering Department, MIT.

Hull, S.W. and G. Kausel (1984), "Dynamic Loads in Layered Halfspace," Engineering Mechanics in Civil Engineering, ASCE, Engineering Mechanics Division Specialty Conference, Laramie, Wyoming.

Kausel, E. and J.M. Roesset (1977), "Semi Analytic-Hyperelement for Layered Strata," Journal of the Engineering Mechanics Division, ASCE, No. 103.

Kausel, E. (1981), "An Explicit Solution for the Green Functions for Dynamic Loads in Layered Media," Report R81-13, Civil Engineering Department, MIT.

Kausel, E. (1986), "Wave Propagation in Anisotropic Layered Media," International Journal of Numerical Methods in Engineering, No. 23.

Kausel, E. (1991), "Dynamic and Static Impedances of Cross Anisotropic Half Spaces," Soil Dynamics and Earthquake Engineering, No. 9.

Lee, V.W. (1984), "Three-Dimensional Diffraction of Plane P, SV and SH Waves by a Hemispherical Alluvial Valley," Soil Dynamics and Earthquake Engineering, No. 3.

Liao, Z.P. and H.L. Wong (1984), "A Transmitting Boundary for Numerical Simulation of Elastic Wave Propagation," Soil Dynamics and Earthquake Engineering, No. 3.

Liao, Z.P. and J.B. Liu (1992), "Numerical Instabilities of a Local Transmitting Boundary," Journal of Earthquake Engineering and Structural Dynamics, No. 26.

Nakamura, Y (1989), "A Method for Dynamic Characteristics Estimations of Subsurface Using Microtremors on the Ground Surface," QR of RTRI, No. 30.

Papadakis, C.N. (1973), "Soil Transients by Characteristics Method," Ph.D. Dissertation, The University of Michigan.

Papageorgiou, A. and J. Kim (1992), "Propagation and Amplification of Seismic Waves in 2D Valleys Excited by Obliquely Incident P and SV Waves," Journal of Earthquake Engineering and Structural Dynamics, No. 22.

Sanchez Sesma, F.J. and E. Rosenblueth (1979), "Ground Motion at Canyons of Arbitrary Shapes Under Incident SH Waves," International Journal of Earthquake Engineering and Structural Dynamcs, No. 7.

Sanchez Sesma, F.J. and J.A. Esquivel (1979), "Ground Motion on Alluvial Valleys Under Incident Plane SH Waves," Bulletin, Seismological Society of America, No. 69.

Sanchez Sesma, F.J. (1983), "Diffraction of Elastic Waves by Three-Dimensional Surface Irregularities," Bulletin, Seismological Society of America, No. 73.

Sanchez Sesma, F.J. (1985), "Diffraction of Elastic Waves by Wedges," Bulletin, Seismological Society of America, No. 75.

Streeter, V.L., Wylie, E.B. and F.E. Richart (1974), "Soil Motion Computation Method," Journal of Geotechnical Engineering Division, ASCE, GT3.

Tassoulas, J.L. (1981), "Elements for the Numerical Analysis of Wave Motion in Layered Media," Report R81-2, Civil Engineering Department, MIT.

Tassoulas, J.L. and J.M. Roesset (1991), "Wave Propagation in a Rectangular Valley," Structural Safety, No. 10.

Trifunac, M.D. (1971), "Surface Motion of a Semi-Cylindrical Alluvial Valley for Incident Plane SH Waves," Bulletin, Seismological Society of America, No. 61.

Trifunac, M.D. (1973), "Scattering of Plane SH Waves by a Semi-Cylindrical Canyon," International Journal of Earthquake Engineering and Structural Dynamics, No. 1.

Waas, G. (1972), "Linear Two-Dimensional Analysis of Soil Dynamics Problems in Semi-Infinite Layered Media," Ph.D. Dissertation, University of California, Berkeley.

Wong, H.L. (1982), "Effect of Surface Topography on the Diffraction of P, SV and Rayleigh Waves," Bulletin, Seismological Society of America, No. 72.

Wong, H.L. and M.D. Trifunac (1974), "Surface Motion of a Semi-Elliptical Alluvial Valley for Incident Plane Waves," Bulletin, Seismological Society of America, No. 64.

Wong, H.L. and P.C. Jennings (1975), "Effect of Canyon Topography on Strong Ground Motion," Bulletin, Seismological Society of America, No. 65.

Wong, H.L., Trifunac, M.D., and B. Westermo (1979), "Effects of Surface and Subsurface Irregularities on the Amplitude of Monochromatic Waves," Bulletin, Seismological Society of America, No. 67.