1.4 – MICROZONING: MODELS AND REALITY

by

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INTRODUCTION

Nobody doubts that local conditions usually have a significant influence on the characteristics of earthquake ground motion. What is not agreed upon, however, is the manner in which that influence must be evaluated. When one talks about microzoning, attention is usually focused on shear-beam models of stratified soil formations and in unidimensional, vertically traveling shear waves. But strong-motion and seismological records have shown that those models can only be applied to a much narrower range of conditions than is usually believed, and that many other geologic or topographic features can have a more pronounced influence on ground motion than the presence of sediments. More general analytical models have been developed in order to account for two-dimensional and three-dimensional response and various types of arriving waves, but their validity and range of applicability have not been determined yet. Because of this, and because of the greater complexity of these models as compared with shear-beam amplification models, they have not gained wide acceptance in the solution of actual engineering problems.

Not only is the shear-beam amplification model the object of strong controversy with respect to the types of waves that significantly contribute to the earthquake motion at a site, but also with respect to the lack of consistent criteria intended to define base rock level, i.e., the level at which usual intensity-attenuation laws are supposed to be valid, and above which local soil contributes to modify intensity and frequency content of seismic motions. In other words, it cannot be uniquely defined what constitutes local conditions and what is a portion of the path. Those criteria can be objected also on the grounds that the influence of local soil conditions is often accounted for twice when making estimates of seismic risk: as a random factor associated with the path when establishing empirical attenuation laws and as a systematic correction associated with local conditions when studying amplification.

But microzoning is not only a matter of ground-motion amplification; it also implies formulation of consistent criteria to define design spectra at different sites, and evaluation of liquefaction potential. The former point requires consideration of the different laws that govern amplification of different types of waves and different directions of arrival, as well as their corresponding probabilities; the latter is not covered by this discussion, as it will be included in another panel session. Thus, the paper deals with the problems of ground motion characteristics, under the framework of conceptual models, analytic results and observed facts. The paper is not intended to be a state-of-the-art report although it is based on one

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(Ruiz, 1976). The intention of the author is mainly to point out some basic questions pertinent to the topic, aiming at the generation of vivid and fruitful discussion.

SEISMIC WAVES

The results of some analytical studies show that the influence of local soil on the ground motion is strongly dependent on the nature of the incoming seismic waves. Hence, analytical prediction of the amplitudes of ground motion at a site characterized by given local conditions as compared with those that would occur under standard conditions requires both the decomposition of the motion into various types of incoming waves, and the formulation of models adequate for the study of amplification and transformation of those types of waves. Despite the very significant effort devoted by seismologists to the formulation of analytical models for the study of wave amplification and transformation, very little of their contributions is either available or of use to engineers, as those models deal in general with the types of waves that are recorded at large epicentral distances (far field), or consider highly idealized topographical features. These results should not be overlooked, however, as they can provide a qualitative insight to many engineering problems.

If a reasonable degree of success is to be attained in the prediction of the influence of local conditions for a sufficiently wide range of cases, a lot of understanding has to be previously achieved about the decomposition of ground motion into different types of seismic waves in the near and intermediate fields. Obviously, the detailed source mechanism and the propagation path can be decisive in the directions and relative amplitudes of the most significant incoming waves, and hence on the laws governing ground motion amplification.

MECHANISM, PATH AND LOCAL CONDITIONS

The profusion of heterogeneities, irregularities and discontinuites in the earth's crust (Fig 1) is responsible for the complex patterns of reflection, refraction, and scattering that seismic waves suffer in their path from source to site. Hence, it is not surprising that the influence of mechanism and path on ground motion characteristics is in some instances more pronounced than that of local conditions. This influence stems both from the modification of the surface ground motion itself, independent of local conditions, and from the fact that the different types of seismic waves resulting from mechanism and path effects are modified by local soil in different manners.

Fig 2 shows the two main paths followed by seismic energy form the source to a site of interest: through the interior of the crust, in the form of body waves, and along the surface, in the form of surface waves. But this picture still displays an oversimplified conception of the process: the source is not a point, but a large volume, and the influence of path is much more pronounced and complex than is implied by Fig 2.

The general type of source mechanism, and not only the detailed history of relative displacement along a fault, has a strong influence on the types of seismic waves generated, and hence on the motion characteristics for standard ground conditions, and in the manner in which local conditions modify them. Thus, strike-slip motion tends to produce a relative higher proportion of SH and Love waves, while subduction faults tend to produce higher proportions of P, SV and Rayleigh waves. The fact that seismic waves are generated from a large volume that may extend as far as the ground surface or its close proximity means that a significant portion of the motion at the near field should be made up of the contribution of body waves that travel at very low angles with respect to the horizontal (Fig 3). These waves are probably guided along stratified formations and then modified by local conditions according to patterns similar to those affecting surface waves. Besides, it is likely that they give place to conventional surface waves that significantly contribute to ground motion at short epicentral distances and in the range of small and moderate frequencies. This pattern of energy travel seems plausible, and provides an explanation to the failure of conventional amplification theory to adequately predict the influence of local conditions.

The complexity of the path followed by ~~waves~~ is another reason for stating that surface ground motion at the near field is not the result of the superposition of a short number of wave trains: every wave impinging on a crust heterogeneity, subsurface discontinuity or topographic feature, gives place to a number of secondary trains of all types of waves (Fig 4).

Whatever the mechanism and the path of the waves for a given shock, it is of interest to assess the influence of local conditions; but, as Fig 5 shows, that influence cannot in general be made to depend only on the stratified soil formations underlying the site of interest: as an important portion of the energy may be traveling in the horizontal direction, the meaning of the term *local conditions* should be extended to include geologic and topographic features in the immediate vicinity of the site. Local amplification would hence be sensitive to the direction of wave arrival.

Even in the case that adequate tools were available for estimating the influence of local conditions on the amplification functions for the various significant types of seismic waves, the problem would remain of determining the trains of waves of different types that would arrive from a given direction. This is probably not feasible when dealing with near-field problems, first because of the possible occurrence of a large number of significant wave trains of different types incoming from different directions, and second because it is not always clear whether a given geologic or topographic accident should be taken as portion of the path –the influence of which would be included as a random factor in the experimental error of an *intensity attenuation expression* (expression relating intensity with magnitude and distance)– or of the local conditions –the influence of which should be included as a systematic correction– when trying to predict ground motion produced by seismic waves arriving from a given direction. For instance, coming back to Fig 5, a promontory such as *B* could be taken as a part of the path or of the local conditions for the purpose of assessing the contribution of surface waves coming from the left to ground motion at *A*, depending on whether the local zone is assumed to be bounded by line 1 or 2, respectively. Because the absence or presence of features such as these has not been explicity included in empirical attenuation expressions, a unique criterion cannot be easily established. For the purpose of microzoning, however, a great deal of information is provided by ratios of surface wave amplitudes at *A* and *B* –and not necessarily their absolute values– for earthquakes originated at the left of the figure.

OBSERVED FACTS

Before the San Fernando earthquake of 1971, conceptual models of soil-related intensity amplification had gained their main support from nearly qualitative comparisons of observed differences between intensities on firm ground and on sedimentary deposits at a number of sites, notably Tokyo, San Francisco, Mexico City and Caracas. A more quantitative support to models based on the concept of vertically traveling SV waves had been provided by the comparison of predicted and observed response of the soft clay deposits underlying Mexico City (Herrera I. *et al,* 1965); but conclusions valid for very peculiar conditions –existence of a very pronounced contrast between shear wave velocities of soil and underlying material– were being indiscriminately extrapolated, in spite of the fact that, in order to apply the same criterion, arbitrary decisions had often to be made concerning the portion of the ground profile that should be considered as a filter that would amplify standard-conditions-ground-motion. But records obtained during San Fernando earthquake disclosed the limitations of the mentioned criterion. Although a large portion of the area affected by that earthquake is known to be underlain by deep sedimentary formations (Fig 6), no pronounced contrast between shear wave velocities is apparent. Fig 7 (from Hudson, 1972) shows a sampling of peak accelerations measured at different sites. Included are all sites for which a clear distinction could be made between rock and alluvium as the basic site condition. It is evident that many factors other than distance and local site characteristics must be important.

Influence on ground motion of fault mechanism and propagation path has been disclosed by recordings obtained at a number of sites during several events. Thus, Udwadia and Trifunac (1973) analyzed a group of 15 events recorded at El Centro, California, characterized by short epicentral distances and magnitudes ranging from 3 to 6.8; the same authors (Trifunac and Udwadia, 1974) studied the records obtained at 6 stations located in the metropolitan area of Los Angeles during three different earthquakes, and Hudson (1972) analyzed the records of a number of seismoscopes and accelerographs obtained within an area of 40 square miles during San Fernando earthquake.

The 15 events recorded at El Centro were classified into four sub-groups, according to source azimuth with respect to the station, and Fourier spectra of records within each sub-group were compared. Group I included four events, three of them having the same epicenter, but different magnitudes. Spectral shapes of the components corresponding to the various events differ considerably among themselves. As propagation path and local conditions are the same, differences can only be ascribed to differences in fault mechanism and perhaps to nonlinear effects. Group II includes four events with different magnitudes and origins and, again, no similarity attributable to path or local conditions can be detected in the records. For one event in particular, predominant frequencies are very low, which can be explained in terms of predominance of surface waves. Group III includes the Imperial Valley earthquake of 1940, the record of which has been analyzed (Trifunac, 1971a) leading to the conclusion that it actually consisted of the superposition of several events, each starting a few seconds after the previous one. Horizontal components are similar, but the vertical component of the Imperial Valley earthquake shows significantly higher ordinates for high frequencies. This is probably a consequence of the short epicentral distance, that implies low attenuation of body waves, and of the peculiar source mechanism. Finally, the last group included events with large epicentral distances –about 150 km– and records were characterized by the low frequencies typical of surface waves. Despite very clear similarities between magnitude and origin of events in this group, their spectral shapes are significantly different, thus suggesting predominance of source effects over path and local conditions.

Similar conclusions are obtained from Trifunac and Udwadia's study concerning the records obtained at six stations during Borrego Mountain (1968), Lytle Creek (1970) and San Fernando (1971) earthquakes: source mechanism and epicentral distance significantly affected the records, while local conditions played only a secondary role. Of the six stations, four lie within Los Angeles Metropolitan area, two of them less than 1 km apart; two are located on base-rock and the other four –those within Los Angeles– on deep sediments of intermediate stiffness. In no case are dominant ground periods evident. An analysis of records obtained at the four sites on sediments makes apparent the influence of source mechanism. For the Borrego Mountain shock, for instance, transverse displacements are systematically larger than radial ones, thus suggesting significant contribution of Love waves; the shapes of the displacement and velocity records are the same at all four sites, but their amplitudes differ, probably as a consequence of variations in the depth of alluvium from station to station, within a distance of 12 km. Records and spectra corresponding to the San Fernando earthquake are also very similar among themselves, but they differ in shape and in relative frequency content from those obtained during the other shocks. Large amplitudes of radial and transverse displacements have been ascribed (Hanks, 1975) to Rayleigh and Love waves, respectively. Fourier spectra of Borrego Mountain records at the four Los Angeles stations shown are very similar in the range of frequencies smaller than 1 hz; the similarity should not be ascribed to dominant group periods, but to the predominance of surface waves, given the long epicentral distance –about 200 km. For San Fernando earthquake, instead, the contribution of high frequencies is rather important, as could be expected, given the proximity of the source–40 km.

Hudson's observations during San Fernando earthquake covered a wide range of ground conditions, from crystalline rock to alluvial deposits 300 m deep. Notorious discrepancies were observed in seismoscope traces even for sites with very similar ground conditions, stressing the importance of other factors, such as topography or subsurface irregularities, pointed out, for instance, by Jackson (1971) and Boore (1972). A comparison of response spectra corresponding to rock and alluvium sites fails to show any systematic influence of local soil. The author concludes that the properties of response spectra at the same sites during another earthquake would probably show quite different relative variations. This implies that formulation of microzoning maps must be based on the analysis of records obtained during a sufficiently large number of intense earthquakes.

Some interesting cases have been presented in the literature, describing the overall response of some soil formations during strong earthquakes. Although the influence of local conditions was shown to be clear in those cases, it was also clear that it may not suffice to study the influence of the soil directly underneath the structure of interest, but that an analysis of the response of a wider area can explain observed facts. Two instances will be described in this respect: one corresponds to the Skopje earthquake of 1963, and the other to two records obtained at Hutt Valley, New Zealand.

Poceski (1969) describes the geological setting of Skopje: the city is located in a long valley along which flows the Vardar river. A cross section of the valley shows a large discontinuity of the sediment thickness along a line that follows the river course (Fig 8). The greatest intensity of damage on constructions was observed directly above the discontinuity, and was ascribed to the hypothetical occurrence of large rotational components of the ground motion with respect to a vertical axis, motivated by the also hypothetical difference in the horizontal response of the alluvial deposits at each side of the discontinuity.

The rotational response of a large volume of alluvium was actually detected by Stephenson (1974), when he analyzed the records obtained at two sites near Hutt Valley. The sites are 900 m apart, and are underlain by saturated recent alluvial deposits with shear wave velocities of about 100 m/sec. Spectral densities of acceleration at both sites show each a predominant direction of response, with a high statistical correlation between the corresponding predominant components, thus suggesting the torsional oscillation of a large mass of alluvium.

How should microzoning be influenced by effects such as those described in this section? .

EFFECTS OF TOPOGRAPHY

The largest acceleration ever recorded occurred at one of the abutments of Pacoima dam during the San Fernando earthquake and implied, according to Reimer *et al* (1973) a three-fold amplification of its peak value. Ratios of up to 30 between the peak ordinates of the Fourier spectrum of the velocity record obtained at the top and at the base of Kagel mountain were computed for several aftershocks of the mentioned event, while the corresponding ratios of peak ground velocities "only" reached 3.95. This implies a resonant effect of the mountain, which was explained by Davis and West (1973) in terms of the ratio of its average width and the length of shear waves. The values indicated are not necessarily amplifications with respect to standard conditions (whatever they are), as analytical studies show (see Fig. 9) that at some frequencies wave amplitudes tend to be amplified at the top of promontories and reduced at their base (Bouchon, 1973; Aki & Larner, 1970; Boore, 1972), but the fact remains that the effects of surface topography cannot be overlooked. Similar considerations can be made regarding the significance of subsurface topography: the distribution of structural damage in Skopje in 1963 was ascribed to excessive torsional oscillations in the region directly above a sharp discontinuity of soft layer thickness (Fig. 8) for incident waves that possessed significant horizontal components parallel to the discontinuity; and analytical studies predict focusing of waves in the vicinity of subsurface irregularities (Jackson, 1971). The interaction of subsurface topography and direction of wave arrival is illustrated in Fig 10 (Trifunac, 1971b), which shows relative amplitudes of the motion produced at the surface by SH waves arriving at a semicylindrical valley. Amplitudes vary with site location and with incidence angle at a fast rate, thus suggesting that detailed knowledge of subsurface topography and of directions and types of incoming waves would be required for the deterministic prediction of the influence of topographic features. As this knowledge is not easy to achieve at present, careful judgement must be exercised when trying to employ analytical results as those shown here in the predictions of seismic risk.

A further question stemming from the significance of surface and subsurface irregularities is that related to the homogeneity of the data set that has been used by different investigators in the derivations of empirical attenuation expressions: unless those sites for which the topographic conditions are suspected to have a significant systematic influence on ground motion are eliminated from the data set used to derive those attenuation expressions, we face the danger of accounting for the mentioned conditions twice: as random effects in one step and as systematic effects in another.

MODELS AND REALITY

Theoretical considerations and observed facts concerning mechanism, path and local conditions, point at the complexities involved in the formulation of mathematical models intended to predict the influence of local conditions on ground motion.

Hence, the question arises of whether the role of those models is too limited to be of practical significance. This is probably too pessimistic an outlook although detailed simulations of near-field motions based on physical models that account for source, path and local conditions are probably beyond reach of present engineering practice, the writer believes that a fair degree of understanding of the parameters and mechanisms that affect ground motion amplification and attenuation can be gained by means of simplified analytical models that consider alternate patterns of energy liberation and propagation.

The significance of models as related to reality and to decision making in engineering is dramatically illustrated by the applicability of the vertically-traveling-shear wave model to the study of ground motion amplification in the valley of Mexico: this is the site on earth where that model has been most beautifully supported by instrumental evidence, and however, the shallow depths and large epicentral distances of earthquakes usually observed there imply that practically all energy must arrive in the form of surface waves. It is easy to understand that the apparent confirmation of the unidimensional-shear-wave model in this case stems from the fact that the large lengths of the incoming surface waves lead to the response of the soft soil formation far away from the borders of the valley according to a pattern very similar to that of the shear beam model. The agreement is accentuated because very little energy is radiated back to the base, and because a significant portion of it is radiated in accordance with the shear beam model. This form of soil response and the small ratio of energy radiation are responsible for the occurrence of dominant ground periods. For the same reasons, dominant ground periods determined by means of excitation applied at the surface coincide with those resulting from earthquake excitation. But the conditions that favor the practical applicability of the mentioned model in the case where a pronounced contrast exists between the soft formations and the base do not appear in the absence of that contrast, and conditions other than sediment properties may dominate the local pattern of intensity variations.

In an attempt at developing a unified approach to the combined intensity-attenuation and local-amplification effects for site underlain by stratified soil formations, Sanchez and Esteva (1977) made use of available data for the derivation of attenuation expressions that directly account for the systematic influence of local soil, while random deviations were dealt with as equation errors. Data of earthquakes recently recorded at sites where detailed information was available about local soil conditions (this means 50 horizontal components at 10 different sites) provided the basis for semiempirical attenuation expressions for Fourier spectra at the ground surface. These expressions are of the form $F(\omega) = G(\omega; R, M)\, g(\omega; s)$, where $F(\omega)$ is the ordinate of Fourier spectrum for frequency ω, G accounts for source (M) and path (R) effects, and g is a function that accounts for amplification effects in terms of local soil properties (s). G was assumed of the form $b_1(R + c)^{-b_3} \exp(b_2 M)$, and g was taken as the amplification function of an equivalent single-degree-of-freedom model of a linear shear beam assumed to represent the soil layers above firm ground. A number of expressions were derived for seven values of ω, in accordance with three alternate definitions of firm ground: the surface material itself, or those with shear wave velocities of 400 and 800 m/sec, respectively. The results were disappointing: the ratio of observed to predicted ordinates of Fourier spectra was systematically greater than unity for the components recorded at the particular site where the computed values of g were highest (i.e., where a thick layer of very soft materials existed), and the standard deviation of that ratio for the whole ensemble of sites and records was very high and independent of the definition of firm ground. But Mohraz (1976) obtained significantly different intensity attenuation expressions for different alluvium thickness. A similar study was carried out by Faccioli (1976), who classified ground properties into four categories: crystalline rock, sedimentary rock (including stiff conglomerates and very compact sands), typical alluvial deposits with intermediate stiffness and soft deposits (loose sands and soft clays). He succeeded in obtaining empirical attenuation expressions for each of these categories, for which the standard deviation of error is lower than that associated with previous expressions that neglected the influence of local conditions (Esteva and Villaverde, 1973; Mc Guire, 1974). The systematic influence of such conditions is thus confirmed, as well as the inadequacy of the shear beam model to predict them.

Two-dimensional models as shown in Fig 11 can perhaps suffice for the qualitative study of the overall patterns of wave generation and transformation. They should also prove useful for the understanding of the possible influence of irregularities and discontinuites found by different types of waves along their path, and for the assessment of local variability of intensities in the neighborhood of some geological or topographical accidents. Probably, they can even help at gaining some insight into the general patterns of waves arriving at a site, thus permitting the formulation of adequate amplification models. There are instances, however, where three-dimensional models may be required. One such case is the study of the amplified motion recorded at one of the abutments of Pacoima Dam during San Fernando earthquake; another would be the study of the response of an alluvial formation where torsional oscillations might be of importance.

Given a train of incoming waves, predictions of the resulting motion at a site with heterogeneous properties or irregular topography can be dealt with as a diffraction problem. However, standard analytical formulation (Morse & Feshbach, 1953) can only be applied in practice to simplified idealizations of actual conditions (see, for instance, Aki and Larner, 1970; Bouchon, 1973; Trifunac, 1971b). For more general applications, finite difference solutions of the wave equation (Boore, 1972), finite element wave-propagation investigations (Smith, 1974) and dynamic response studies of finite-element models of small local regions (Lysmer & Drake, 1971; Ayala & Aranda, 1977) have been undertaken. The latter formulation is very attractive to engineers, because it permits direct application of standard programs of frequency-domain or time-response dynamic analysis. But adequate boundary conditions have to be defined at the edges of the region under study in order to allow transmittal of incoming and outgoing waves without excessive energy losses or reflections. When incoming and outgoing waves are of the same type and have the same direction, theoretically exact boundary conditions can be established, expressed in terms of equivalent damping units (Lysmer & Drake, 1971; Tsai, 1969). Aproximate solutions have also been formulated for the case of outgoing body waves of known type and unknown direction (Lysmer & Kuhlenmeyer, 1969) and these solutions have been extended to the combination of incoming and outgoing waves (Ayala & Aranda, 1977), but the general case of known incoming waves and unknown outgoing wave types and directions has not been sufficiently studied.

Despite these problems, criteria based on the time-history analysis of finite element models will probably gain wide acceptance in view of their ability to account for nonlinear soil behavior. But despite the importance usually ascribed to nonlinearities when trying to explain discrepancies between observed and predicted local amplification effects, it must be recognized that their influence is often overshadowed by the overall patterns of shock generation and propagation. It is this consideration that supports the usefulness of frequency-domain studies as advocated above.

CONCLUDING REMARKS

Microzonation implies much more than influence of stratified soil formations. It implies a better knowledge of the fault mechanisms of earthquakes that significantly contribute to seismic risk at a site, study of the possible influence of path characteristics on the types of arriving seismic waves and hence on the manner in which local conditions will affect them. More general analytical models for the study of all factors affecting seismic waves from their source will have to be developed, adapted and implemented by engineers. But, as a consequence of the complexities inherent in the phenomena under study, those models should only play a role complementary to instrumental observations. Because path and mechanism effects have been shown to affect local variations of ground motion, a large number of events will have to be recorded at every site of interest and its neighborhood before reliable conclusions can be drawn concerning those variations. Hence, small magnitude shocks should be given increased attention, as they will probably constitute the main source of information at some sites, in spite of their inability to provide information about the influence of nonlinear soil behavior associated with severe shocks. Deployment, operation and interpretation of the records of local instrumental networks should aim at the description of earthquake motion variability throughout small regions, and at the understanding of the patterns of seismic waves giving place to that variability.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to S. E. Ruiz for her assistance in the revision and interpretation of the literature, through the preparation of a state-of-the-art report. Critical reading of the manuscript by G. Ayala and J. Bielak is also gratefully acknowledged.

REFERENCES

Aki, K. & Larner K., 1970, "Surface motion of a layered medium having an irregular interface due to incident plane SH waves", J. Geophys Res., 75,pp. 933-954

Ayala, G. & Aranda R., 1977 "Boundary conditions in soil amplification studies", 6WCEE, Delhi

Boore D. M., 1972, "A note on the effect of simple topography on seismic SH waves", Bull, Seism. Soc. Am., Vol 62, No. 1, pp. 275-284

Bouchon, M., 1973, "Effect of topography on surface motion", Bull. Seism. Soc. Am., Vol 63, No. 3, pp.615-632

Davis, L. L. & West, L. R., 1973, "Observed effects of topography on ground motion", Bull. Seism. Soc. Am., Vol 63, No. 1, pp. 283-298

Duke, C. M., Johnson, J. A., Kharraz, Y., Campbell, K. W. and Malpiede, N. A., 1971, "Subsurface site conditions and geology in the San Fernando earthquake area", Report UCLA-ENG-7206, University of California, Los Angeles

Esteva, L. & Villaverde, L., 1973, "Seismic risk, design spectra and structural reliability", Proc. 5WCEE, Rome

Faccioli, 1976, personal communication

Hanks, T. C., 1975, "Strong ground motion following the San Fernando, California, earthquake. 1. Ground displacements", mentioned by Trifunac and Udwadia, 1974

Herrera, I., Rosenblueth, E. & Rascón, O. A., 1965, "Earthquake spectrum prediction for the valley of Mexico", Proc. 3WCEE, Vol 1, pp 161-174

Hudson, D. E., 1972, "Local distribution of strong earthquake ground motions", Bull of the Seismological Soc. of America, Vol 62, No. 6, pp. 1765-1786

Jackson, P. S., 1971, "The focusing of earthquakes", Bull. Seism. Soc. Am., Vol 61, No. 3, pp. 685-695

Lysmer, J. & Drake, L. A., 1971, "A finite element method for seismology", Methods in Computational Physics, Cap. VI, University of California, Berkeley

Lysmer, J. & Kuhlemeyer, R. L., 1969, "Finite dynamic model for infinite media", Journ. Eng. Mech. Div. ASCE, Vol 95, No. EM4, pp. 859-877

Mohraz, B., "A study of earthquake response spectra for different geologic conditions", Bull. Seism. Soc. Am., Vol 66, No. 3, pp. 915-936

Morse, & Feshbach, 1953, "Methods of Theoretical Physics", McGraw-Hill, Kogakusha, Tokyo

Poceski, A., 1969, "The ground effects of the Skopje July 26, 1963 earthquake", Bull. Seism. Soc. Am., Vol 59, No. 1, pp. 1-29

Reimer, R. B., Clough, R. W. and Raphael, J. M., 1974, "Evaluation of the Pacoima Dam accelerogram", 5WCEE, Vol 2, pp. 2328-2337

Ruiz, S. E., 1976, "Influencia de las condiciones locales en las características de los sismos", M S Thesis, Faculty of Engineering, National University of Mexico

Sánchez-Sesma, F. J. & Esteva, L., 1977, "Intensity attenuation and local amplification: a unified approach", Institute of Engineering, National University of Mexico

Smith, W. D., 1974, "A non reflecting plane boundary for wave propagation problems", Journal of Computational Physics, Vol 15, No. 4, pp. 492-503

Stephenson, W. R., 1974, "Earthquake induced resonant motion of alluvium", Bull. New Zealand Nat. Soc. for Earthquake Engng, Vol 7, No. 3

Trifunac, M. D., 1971a, "Response envelope spectrum and interpretation of strong earthquake ground motion", Bull. Seism. Soc. Am., Vol 61, No. 2, pp. 343-356

Trifunac, M. D., 1971b, "Surface motion of a semi-cylindrical alluvial valley for incident plane SH waves", Bull. Seism. Soc. Am., Vol 61, pp. 1755-1770

Trifunac, M. D. & Udwadia, F. E., 1974, "Variations of strong earthquake ground shaking in the Los Angeles area", Bull. Seism. Soc. Am., Vol. 64, No. 5, pp. 1429-1454

Tsai, N., 1969, "Influence of local geology on earthquake motion", Ph. D. Thesis, California Institute of Technology, Pasadena, Calif

Udwadia, F. E. & Trifunac, M. D., 1973, "Comparison of earthquake and microtremor ground motions in El Centro California", Bull. of the Seismological Soc. of America, Vol 63, No. 4, pp. 1227-1253

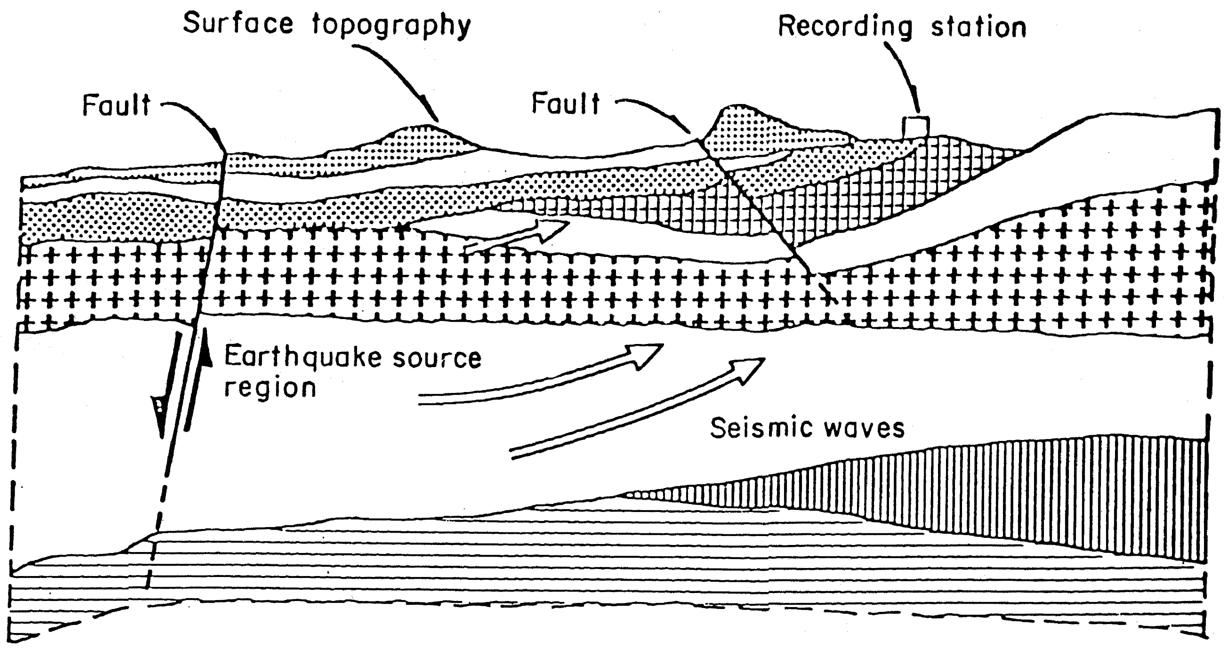

Fig. 1 Source, path and local conditions (Hudson, 1972)

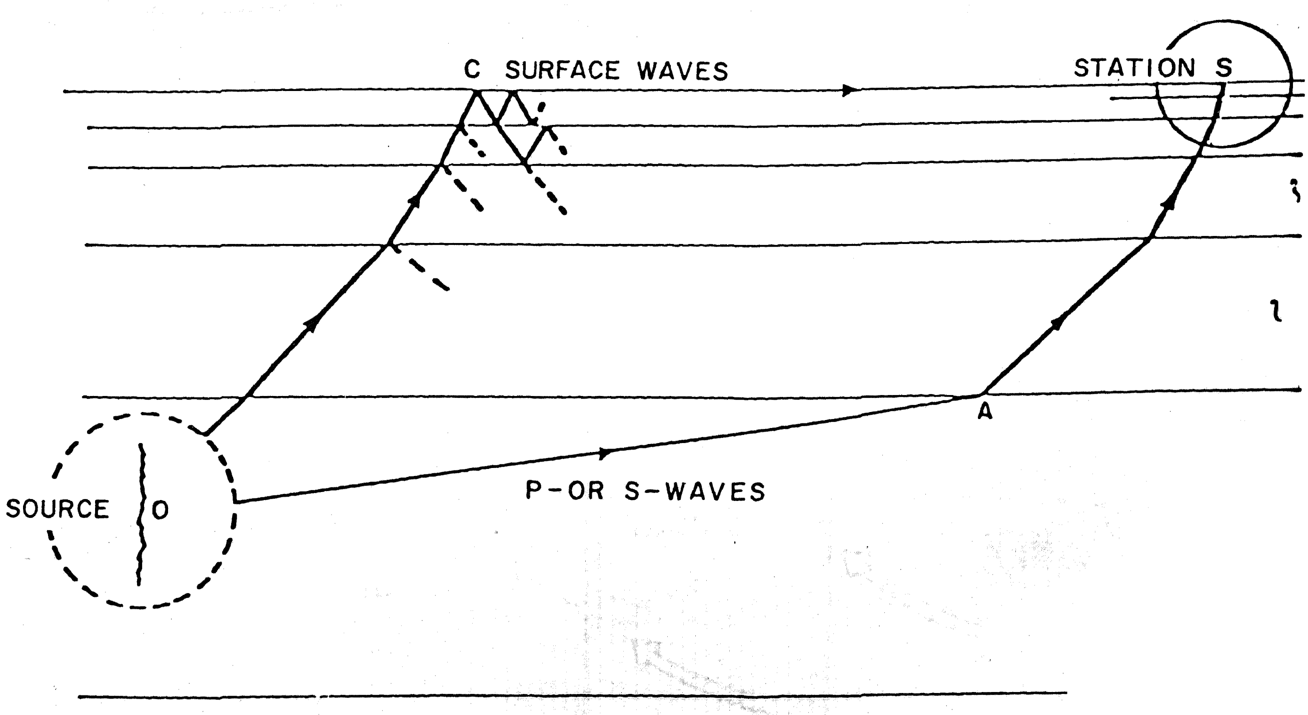

Fig. 2 Seismic waves (Tsai, 1969)

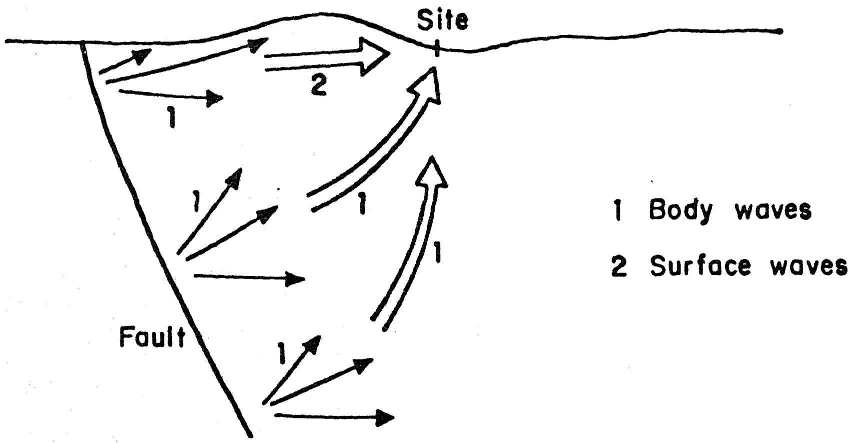

Fig. 3 Seismic waves in the near field

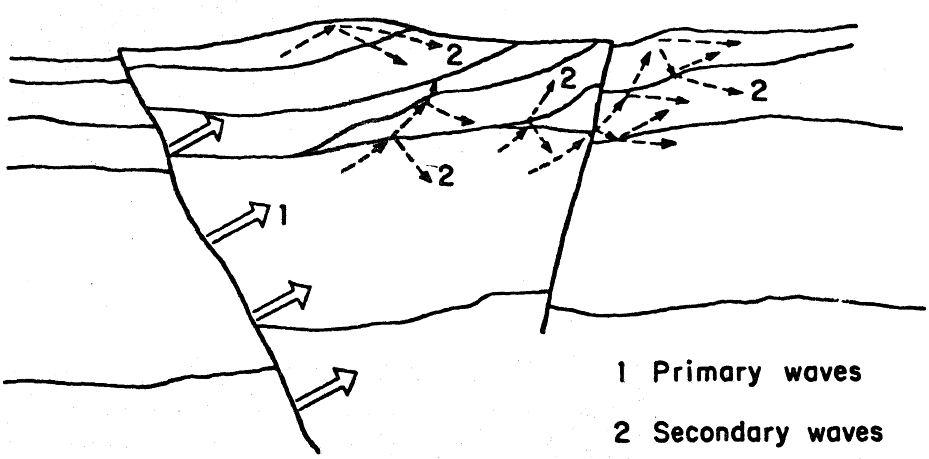

Fig. 4 Secondary wave trains

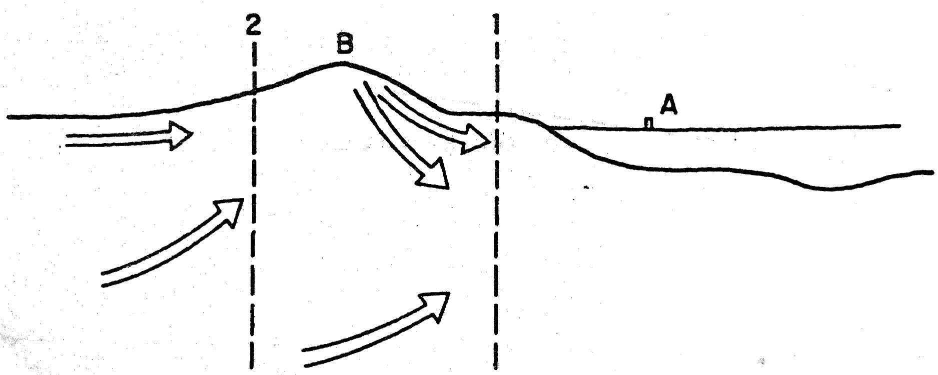

Fig. 5 Path and local conditions

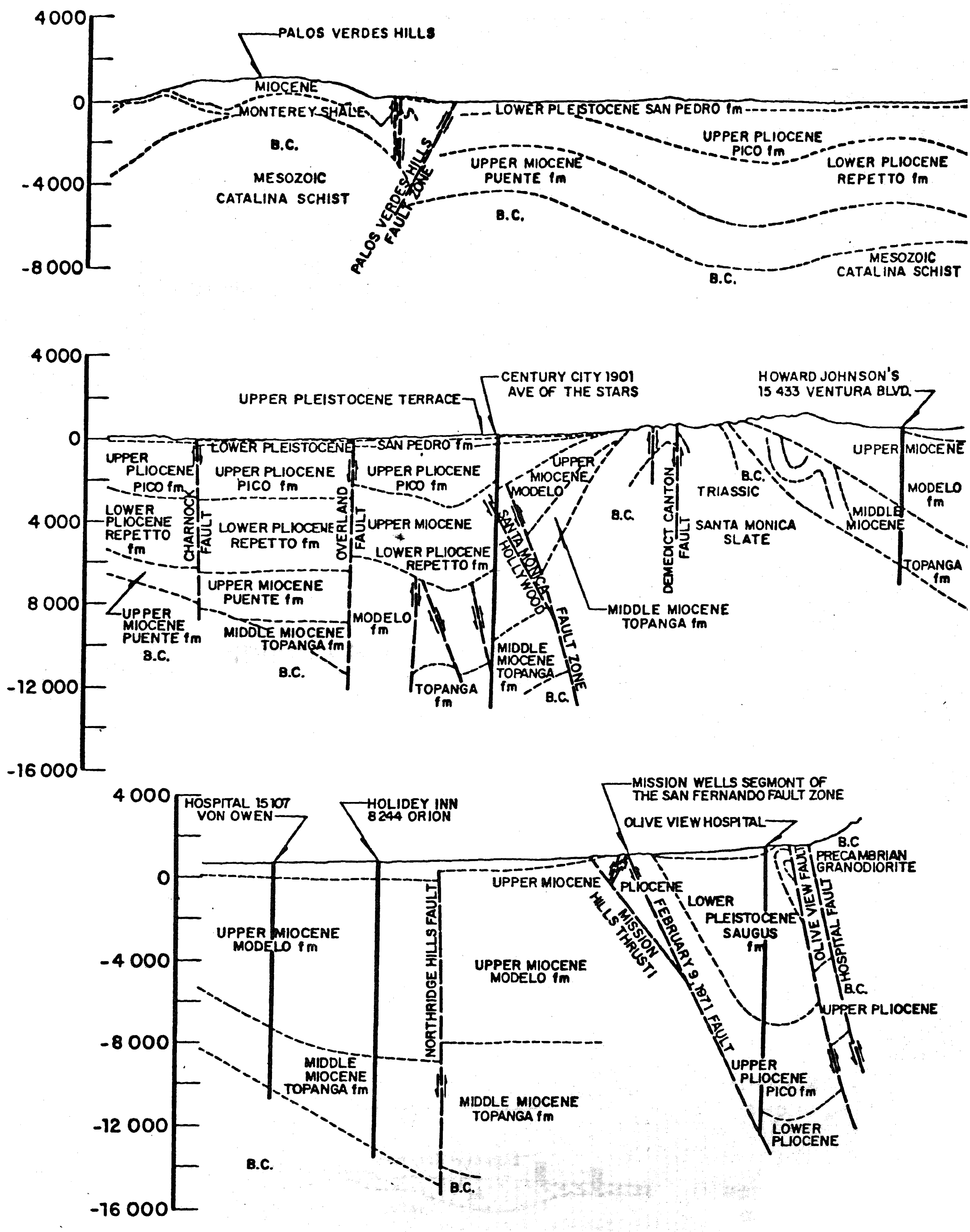

Fig. 6 Geologic cross section, Los Angeles area (Duke et al, 1971)

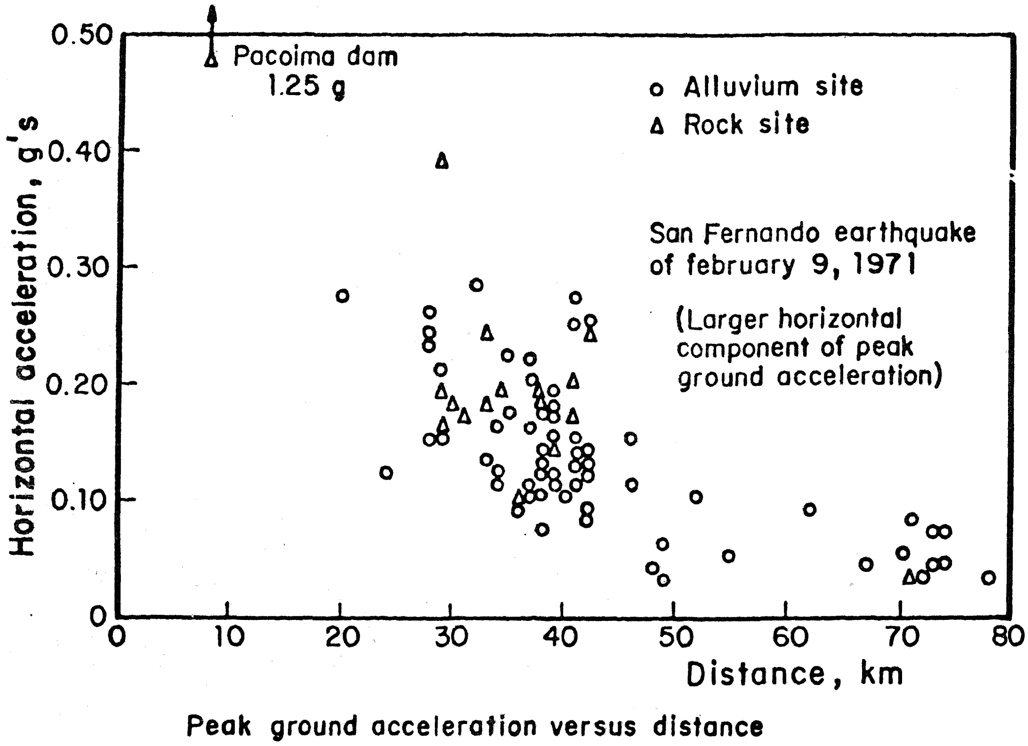

Fig. 7 Peak accelerations and ground conditions (Hudson, 1972)

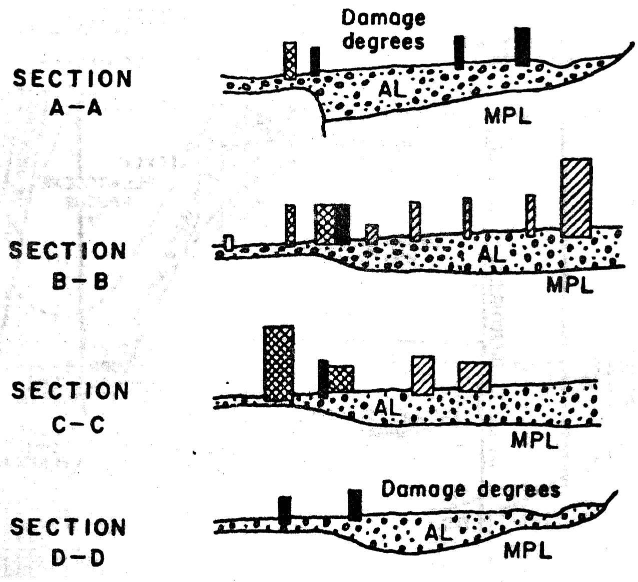

Fig. 8 Geologic cross section at Skopje (Poceski, 1969)

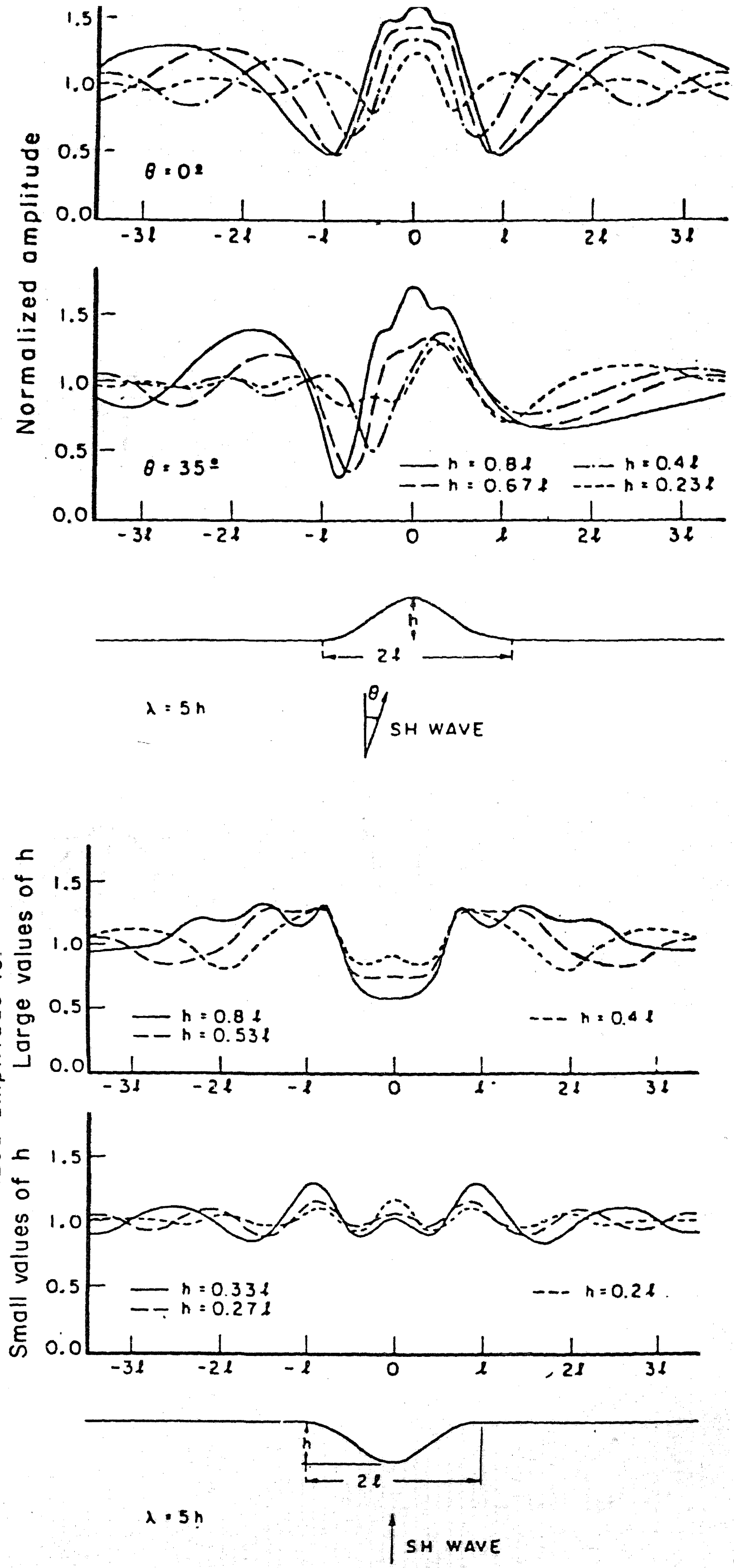

Fig. 9 Normalized amplitudes of motion produced by SH waves (Bouchon, 1973)

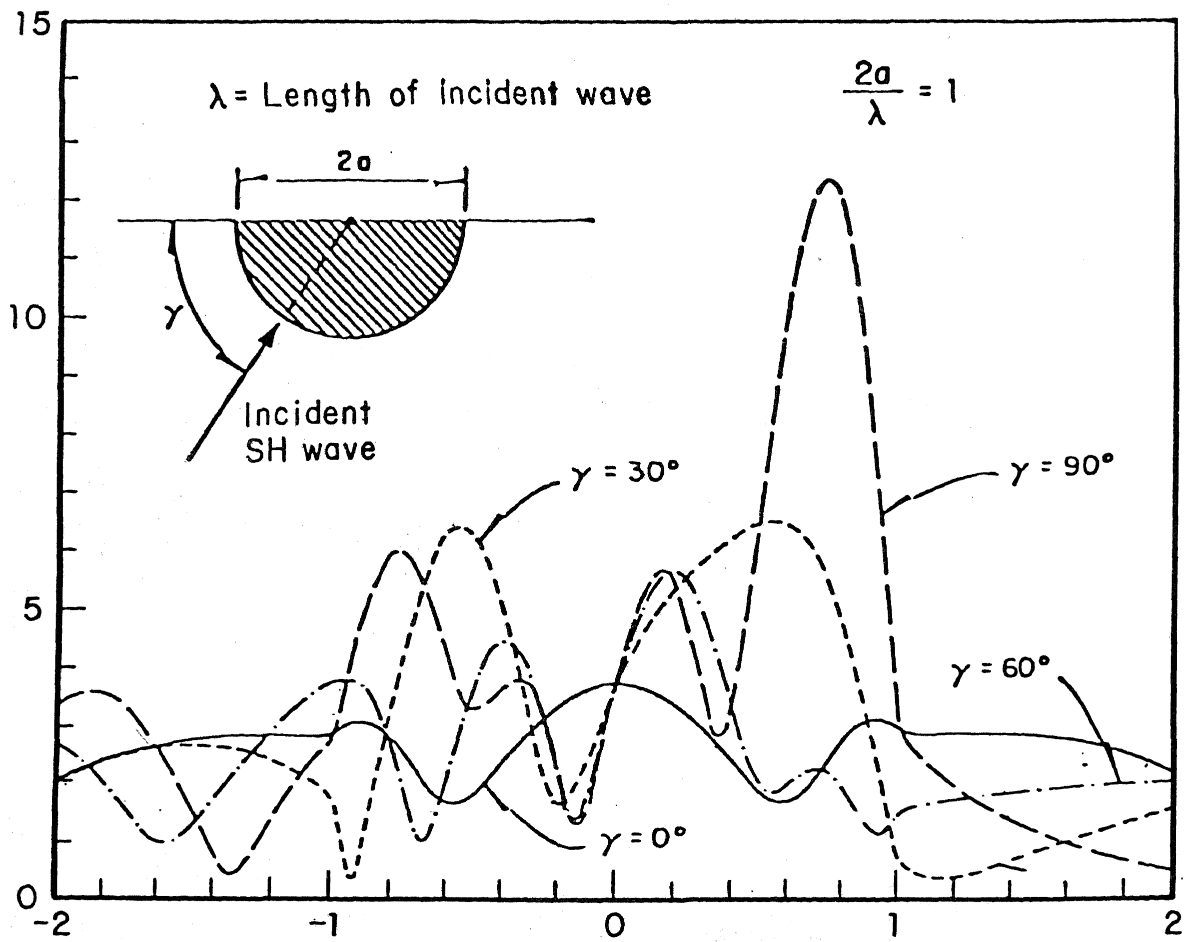

Fig. 10 Displacement amplitudes at the surface of a semicylindrical valley (Trifunac, 1971b)

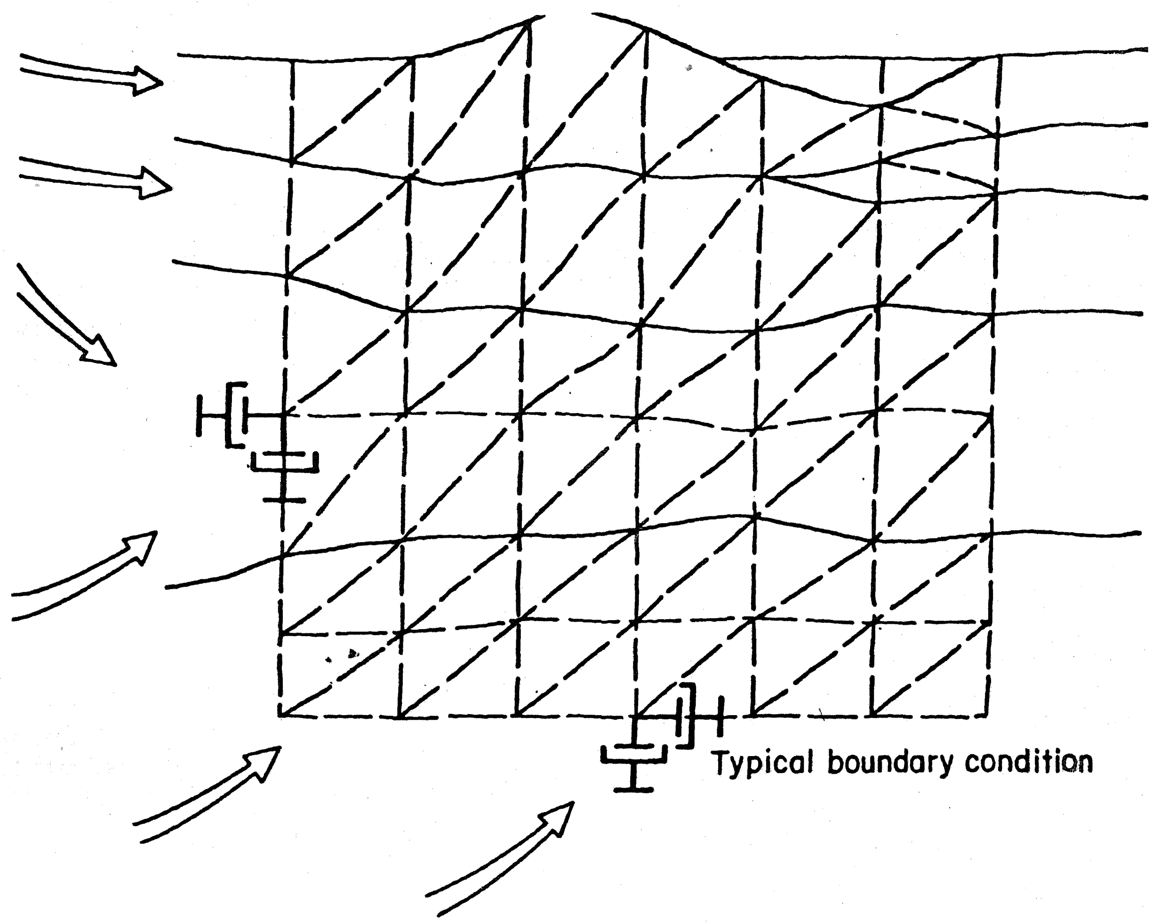

Fig. 11 Two-dimensional finite element models