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The effects of site conditions on ground motions

W.D. Liam Finn[I]

ABSTRACT

The more important contributions by seismologists and geotechnical engineers over the last 10 years to knowledge of effects of site conditions on ground motions are reviewed and the implications for seismic design are examined. The selection of material for review is based on a judgement of its importance to engineering practice.

INTRODUCTION

The estimation of site specific ground motion parameters for seismic design or microzonation studies is one of the more complex and challenging problems of earthquake engineering.

The effects of local site conditions on the incident wave field have been the focus of major studies by both seismologists and geotechnical engineers. Until the 1980's, these studies proceeded relatively independently with little interaction and with an apparent lack of agreement on some important issues. For example, following the pioneering studies of ground response during the Niigata earthquake of 1964 by Seed and Idriss (1969), geotechnical engineers have been convinced of the importance of nonlinear effects at most soil sites during strong shaking. Since the introduction of the SHAKE program by Schnabel et al. (1972), nonlinear site effects have been taken into account routinely in engineering practice. Yet in a study of the applicability of weak motion amplification factors to the strong motions recorded during the 1989 Loma Prieta earthquake Aki and Ta-Liang Teng (1991) concluded that their study had detected the "pervasive nonlinear effect at sediment sites for the first time seismologically".

Geotechnical engineers have always taken a rather restricted view of site effects, relying almost exclusively on 1-D analysis. They have routinely ignored the effects of surface and buried topography on ground motions which reviews by Aki (1988), Silva (1989) and Faccioli (1991) have shown can be significant from both the seismological and engineering points of view.

[I] Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada

On important projects geotechnical engineers rely on site specific response analyses to determine site effects. Computed surface motions or response spectra often show significant amplification over the corresponding input quantities. The geotechnical engineer's judgement about site-specific response tends to be based on his experience with a number of individual case histories.

Seismologists, on the other hand, determine the effects of local geology by averaging amplification factors over many soil and rock stations in a network. This process tends to smear out extremes. In addition, seismologists draw their conclusions about geological effects against the background of the standard error in the data. For some motion parameters the averaged effects of local soil conditions may be obscured by the standard error in the data. This may explain why peak ground acceleration has been reported to be independent of site conditions (Aki, 1988), despite obvious contrary findings in individual cases such as accelerations recorded in the lake-bed in Mexico City during the 1985 earthquake (Seed et al., 1988; Finn and Nichols, 1988).

This paper reviews the more important contributions by seismologists and geotechnical engineers over the last 10 years to the understanding of site effects on ground motions and the implications of these for seismic design. The selection of material for discussion is based on a judgement of its potential importance to engineering practice. The paper attempts to integrate both the seismological and geotechnical contributions to the problem of site effects on ground motions and provide a coherent summary of the field for geotechnical earthquake engineers.

The seismic response of ridges and sediment filled valleys will be reviewed first. A knowledge of the complex patterns of motion that can develop in these structures is an essential requirement for interpreting recorded motions and understanding the limitations of 1-D response analysis.

EFFECTS OF TOPOGRAPHY

Aki (1988) used the simple structure of a triangular wedge (Fig. 1a) to illustrate the effects of topography. This structure may be used to model approximately ridge-valley topography as shown in Fig. 1b by Faccioli (1991). An exact solution exists for the wedge for SH waves propagating normal to the ridge and polarized parallel to the ridge axis. Displacement amplification at the vertex is $2/\nu$ where the ridge angle is $\nu\pi$ $(0 < \nu < 2)$. In Fig. 1b the amplification of the crest relative to the base is ν_1/ν_2. Thus the simple solution provides a rough estimate of the relative amplification at the crest of the ridge or deamplification in a valley.

Geli et al. (1988) have provided amplification factors in the form of Fourier transfer functions for a smooth-ridge with a shape ratio, defined as height over half-width, $h/L = 0.4$, in terms of the non-dimensional frequency $n = 2L/\lambda$ where λ is the wave length. The factors are shown in Fig. 2 for selected locations along the ridge. Note the broad band amplification at the crest and the increasingly complex nature of the response with

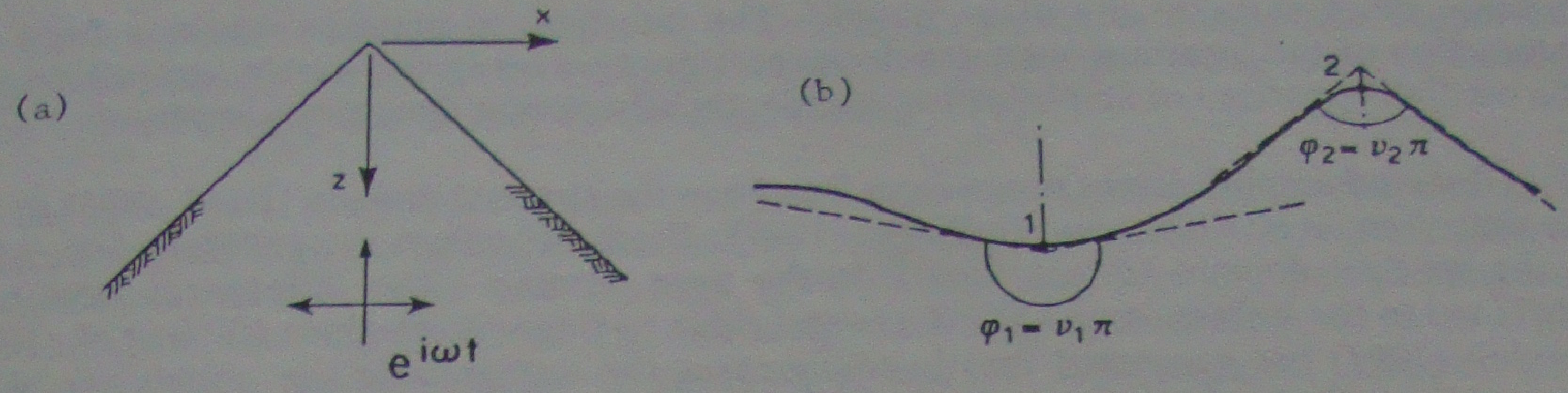

Fig. 1 (a) Approximating a ridge formation by a triangular wedge, (b) Infinite wedge excited by plane SH waves (after Faccioli, 1991).

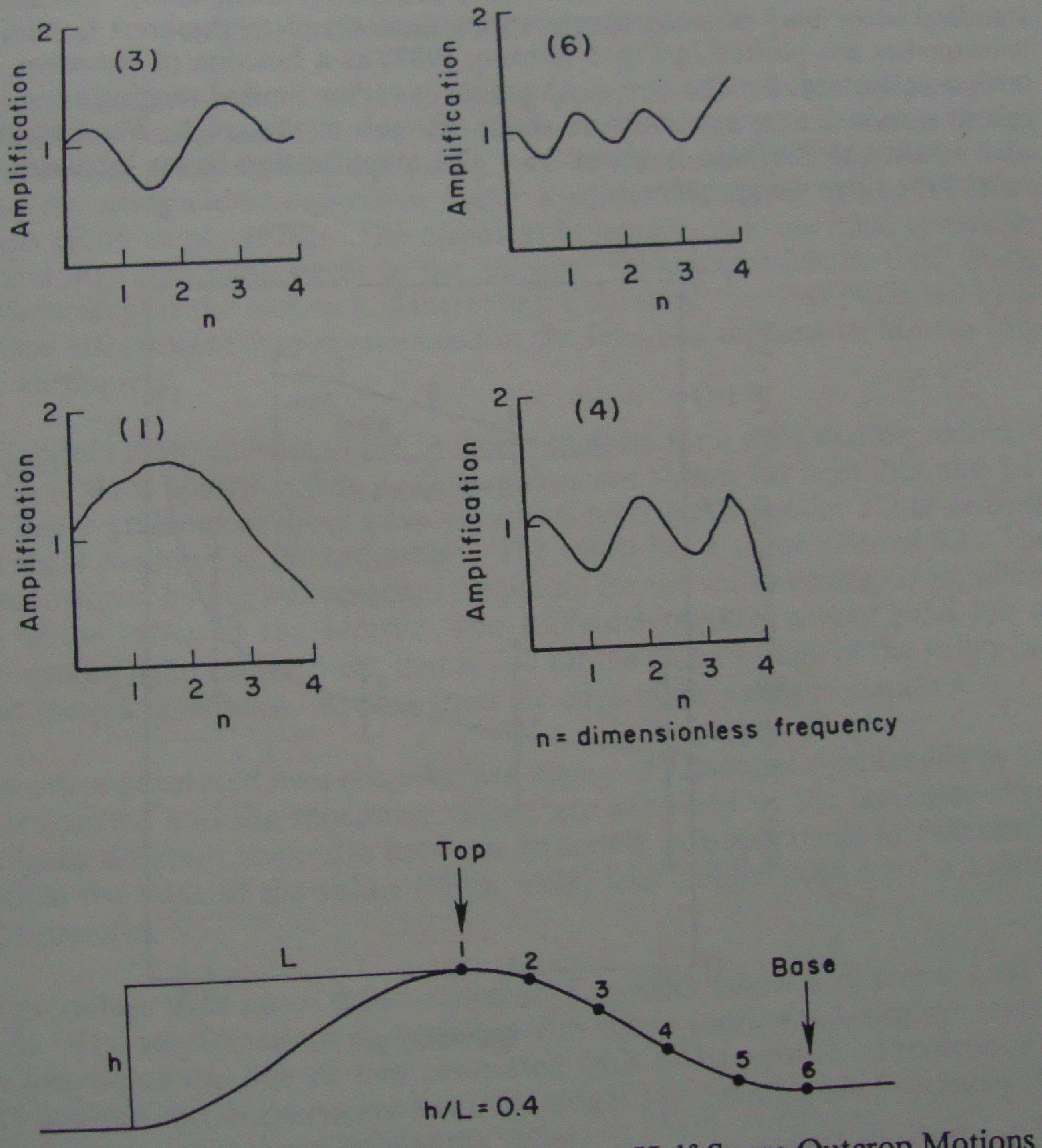

Fig. 2 SH Fourier Transfer Functions to Homogeneous Half-Space Outcrop Motions (after Geli et al., 1988).

distance down slope to the plane below. The interference patterns resulting from the interaction of the incoming waves with the scattered waves in the wedge are reflected in the oscillating pattern of amplification and deamplification at downslope locations.

Observed amplifications range from 2 to 20 in the spectral domain (Bard, 1983) to 5 in the time domain (Griffiths and Bollinger, 1979). Predicted values are generally less, 3 to 4 in the spectral domain to less than 2 in the time domain. The differences have been attributed to the influence of 3-D effects and ridge to ridge interactions (Geli et al., 1988). Faccioli (1991) has suggested that in many cases the topographic site effects are of the same order as the regional variability of motions on hard ground.

A case history illustrating the variation in amplification over a ridge structure is provided by data from the Matsuzaki array in Japan (PWRI, 1986). The mean values and standard error bars of peak accelerations normalized to the crest acceleration for five earthquakes are plotted in Fig. 3 (Jibson, 1987) as a function of elevation. The range in peak accelerations for the five earthquakes is rather limited ranging from a low of a few gals at station 5 to a maximum of about 100 gals at the crest. The amplification of the crest relative to the base is about 2.5. The amplification factor increases rapidly as the crest of the ridge is approached.

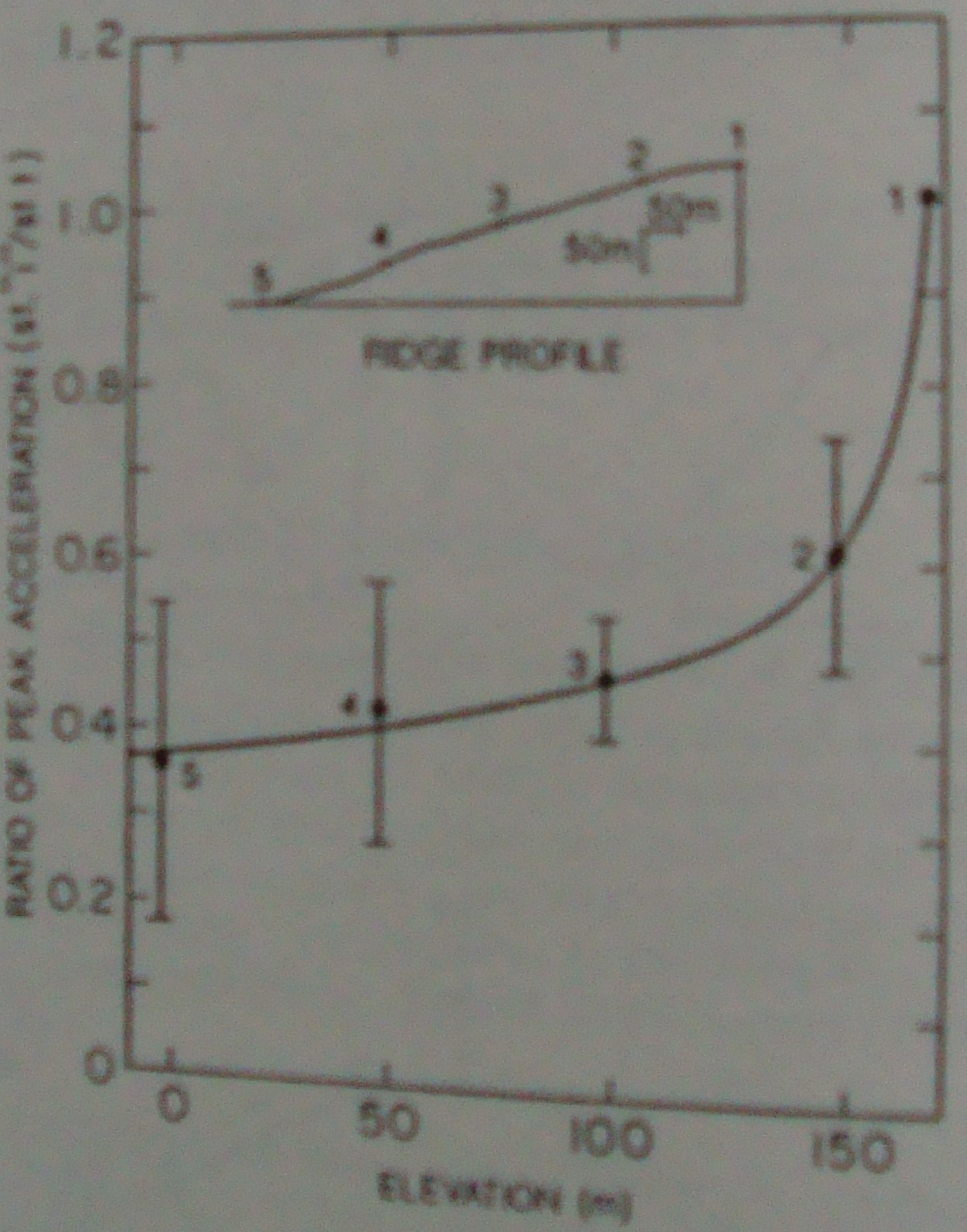

Fig. 3 Relative Distribution of Peak Accelerations Along a Ridge From Matsuzaki Array in Japan (after Jibson, 1987).

Amplification of motions at the crest of a ridge relative to the base is also supported by damage patterns during the 1980 Friuli earthquakes in Italy (Brambati et al., 1980) and in the Chilean earthquake of 1985 (Celebi and Hanks, 1986).

The effect of a topographic structure on ground motions depends on the shape ratio of the structure and how the lateral dimensions of the structure are related to wavelengths of the incident motions. Silva and Darragh (1989) show that over the period range of engineering interest, 0.2 Hz to 25 Hz, the range in wavelengths is from 40 m to 5 km assuming a shear wave velocity in rock of 1 km/s. Topographical features with characteristic dimensions in this range have the potential for a significant effect on ground motions depending on the shape ratios.

MOTIONS IN ALLUVIAL VALLEYS

Perhaps more interesting from an engineering point of view is the response of sediment filled valleys, usually the locations of greatest development. Ground motions on these sites generated by shear waves propagating vertically are usually estimated by 1-D shear beam models, using either equivalent linear methods (Schnabel et al., 1972) or nonlinear models (Finn et al., 1978). The sediment-basement rock interface generates surface waves and may trap body waves in the alluvium (Finn and Nichols, 1988; Silva, 1989). These waves amplify the motion and increase the duration over that predicted by 1-D analysis. These effects were very pronounced in the lake-bed motions in Mexico City during the 1985 earthquake.

Bard and Gabriel (1986) calculated the transfer functions for a wide shallow sediment filled valley ($h/L < 0.25$) shown in Fig. 4. The results are shown for both 2-D and 1-D analyses with a linear gradient in shear wave velocity S with depth and for a 2-D analysis with a constant shear modulus in the sediments. The valley has a shape ratio of 0.1. The frequency n is normalized by the 1-D resonant frequency for the valley centre, $S/4h$, where h is the depth of the valley at the centre. The 1-D analysis does a very good job of modelling the response from station 5 on, that is just off the sloping edge of the valley but tends to give too sharp a resonance response from the edge of the valley to station 3.

The surface waves generated near the edge are apparently damped significantly by the time station 5 is reached and the remaining effects are swamped by the incoming shear waves. The radically different responses between stations 1 to 5 may result in differential motions, normal to the edge of the valley (Silva, 1989) with implications for the seismic loading of long structures.

Deep narrow valleys with large shape ratios $h/L \geq 0.25$ show a different kind of response (Fig. 5). The amplifications for a valley with shape ratio of 0.4 displays several strong maxima instead of the one or two associated with 1-D response. Predictions of motions by 1-D analysis are conservative near the edges but underpredict seriously the response at high frequencies in the middle of the valley.

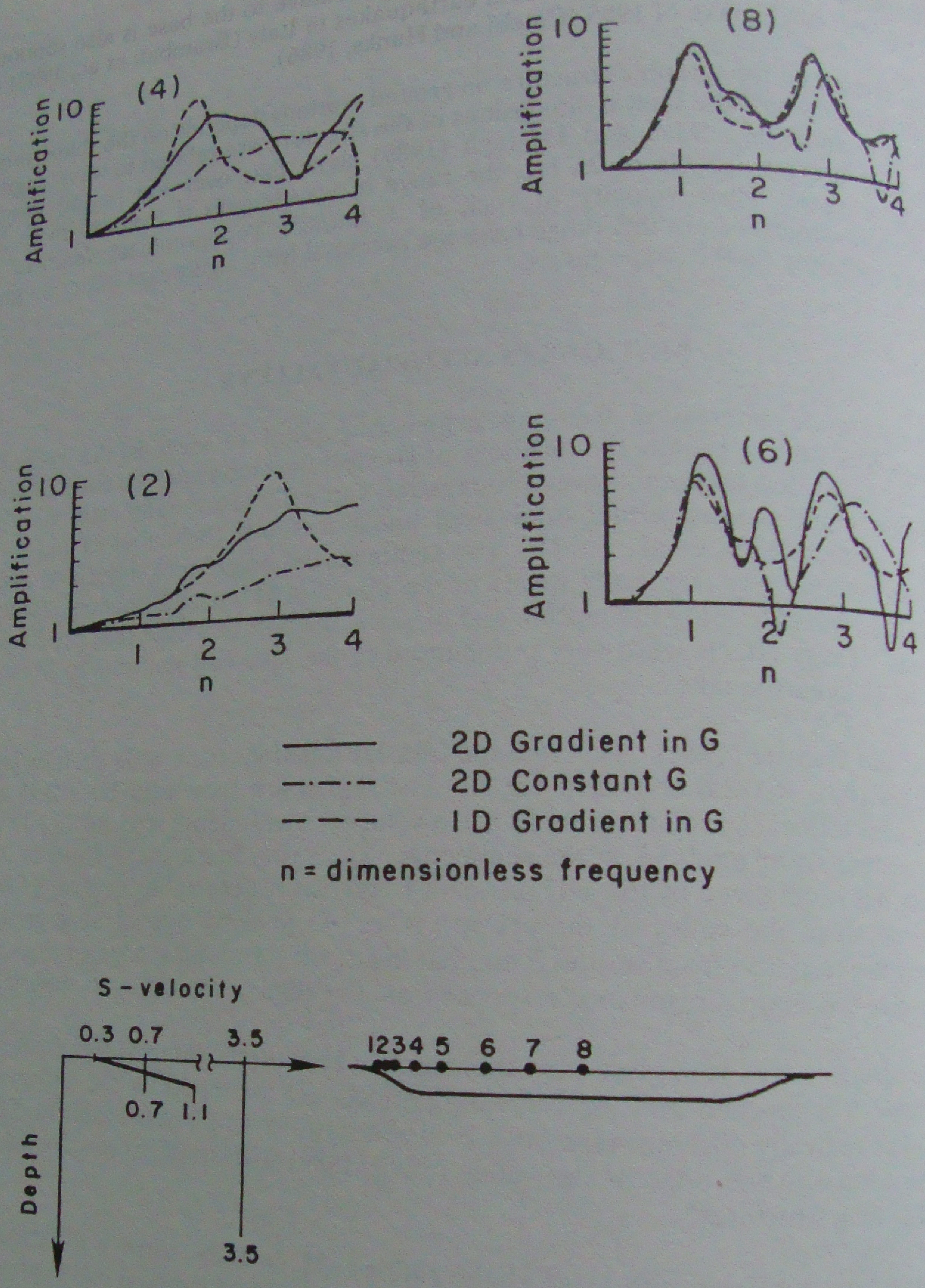

Fig. 4 Smoothed SH Transfer Functions to Homogeneous Half-Space Outcrop Motions for a Wide, Shallow Alluvial Valley with a Shape Ratio of 0.1 (after Bard and Gabriel, 1986).

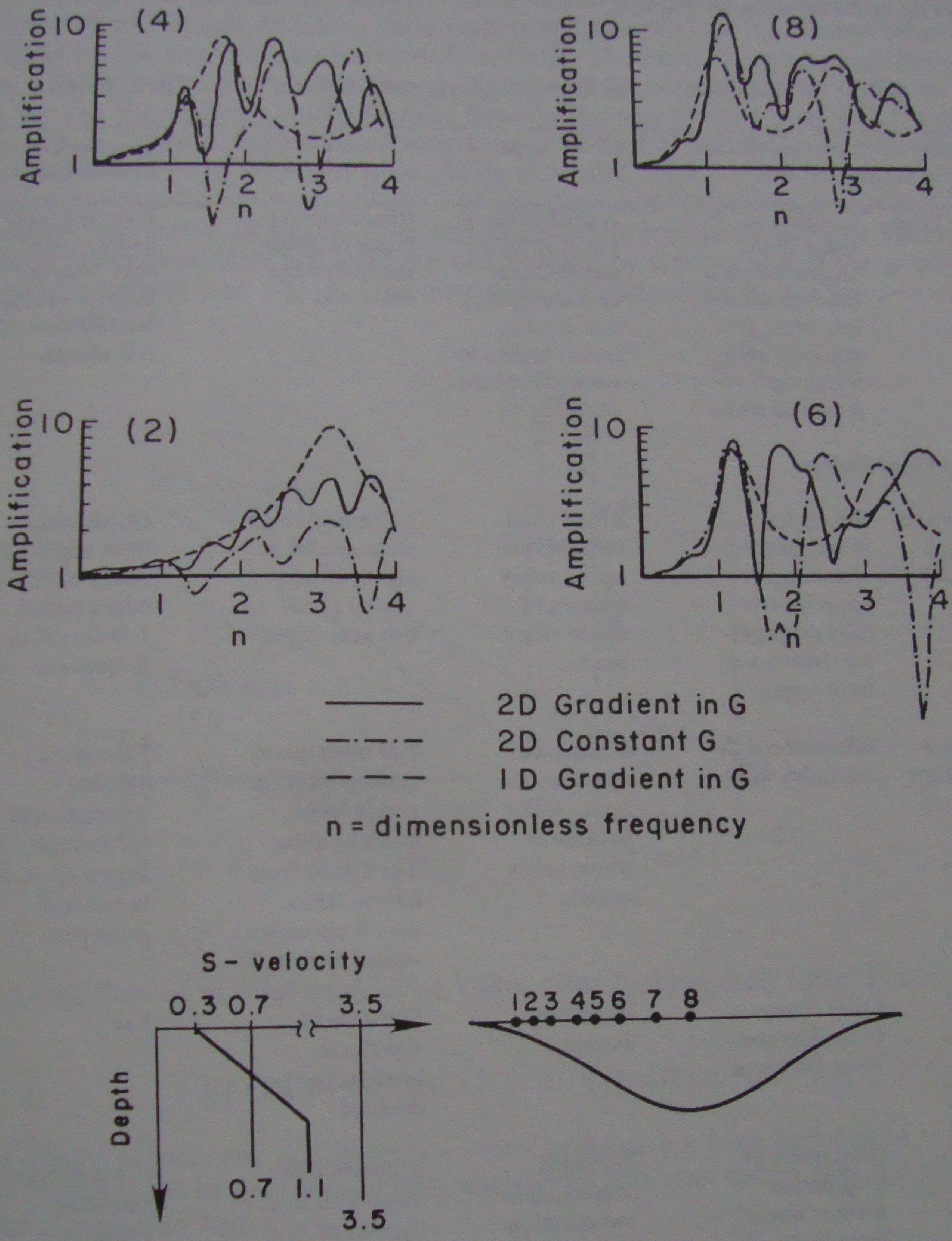

Fig. 5 Smoothed SH Transfer Functions to Homogeneous Half-Space Outcrop Motions for a Valley with a Shape Ratio of 0.4 (after Bard and Gabriel, 1986).

Silva (1989) has summarized the effects of surface topography and sediment-filled valleys on site response in Table 1.

Table 1. 2-Dimensional Geologic Structural Effects (after Silva, 1990)

Structure	**Conditions**	**Type**	**Size**	**Quantitative Predictability**[a]
Surface Topography	Sensitive to shape ratio, largest for ratio between 0.2 to 0.6. Most pronounced when wavelength $\simeq$ mountain width	Amplification at top of structure amplification and deamplification at base, rapid changes in amplitude phase along slopes	Ranges up to a factor of 30 but generally from about 2 to 10	Poor: generally underpredict size. May be because of ridge interaction and 3-D effects
Sediment-Filled Valleys				
1) Shallow and wide (shape ratio <0.25)	Effects most pronounced near edges. Largely vertically propagating shear wave from edges.	Broad band amplification across valley because of whole valley modes	1-D models may underpredict at higher frequencies by about two near edges	Good: away from edges 1-D works well, near edges extend 1-D amplifica- frequencies
2) Deep and narrow (shape ratio $\geq$ 0.25)	Effects throughout valley width	Broad band amplification across valley because of whole valley modes	1-D models may underpredict for a wide bandwidth by about 2 to 4 away from edges. Resonant frequencies shifted from 1-D.	Fair: given detailed description of vertical and lateral changes in material properties
3) General	Local changes in shallow sediment thickness	Increased duration	Duration of significant motions can be doubled	Fair
4) General	Generation of long period surface waves from body waves at shallow incidence angles	Increased amplification and duration because of trapped surface waves	Duration and amplification of significant motions may be increased over 1-D predictions	Good at periods exceeding 1 second

[a] Good: generally within a factor of two
Fair: generally within a factor of two to four
Poor: qualitative only, can easily be off by an order of magnitude

An interesting case history which shows the engineering implications of valley effects has been presented by Faccioli (1991). The problem is the estimation of seismic soil displacements to be used as a kinematic loading function for the foundation piles of an expressway bridge near Belluno in North East Italy. The expressway runs parallel to the edge of a broad valley. A cross-section of the edge of the valley is shown in Fig. 6. Also shown are the shear wave velocity profiles close to the axis of the bridge and the design accelerogram. The soil deformations were calculated by 1-D and 2-D methods assuming the design motions were SH waves propagating vertically. The 2-D analysis used an exact solution by Sanchez-Sesma et al. (1989). The soil displacement profiles from the 1-D and 2-D analyses are shown in Fig. 7. The displacements predicted by the 2-D analysis are much larger than those obtained from the 1-D analysis, by a factor of 2 at the ground line. These results suggest that 1-D analysis may seriously underestimate the seismic demand on pile capacity.

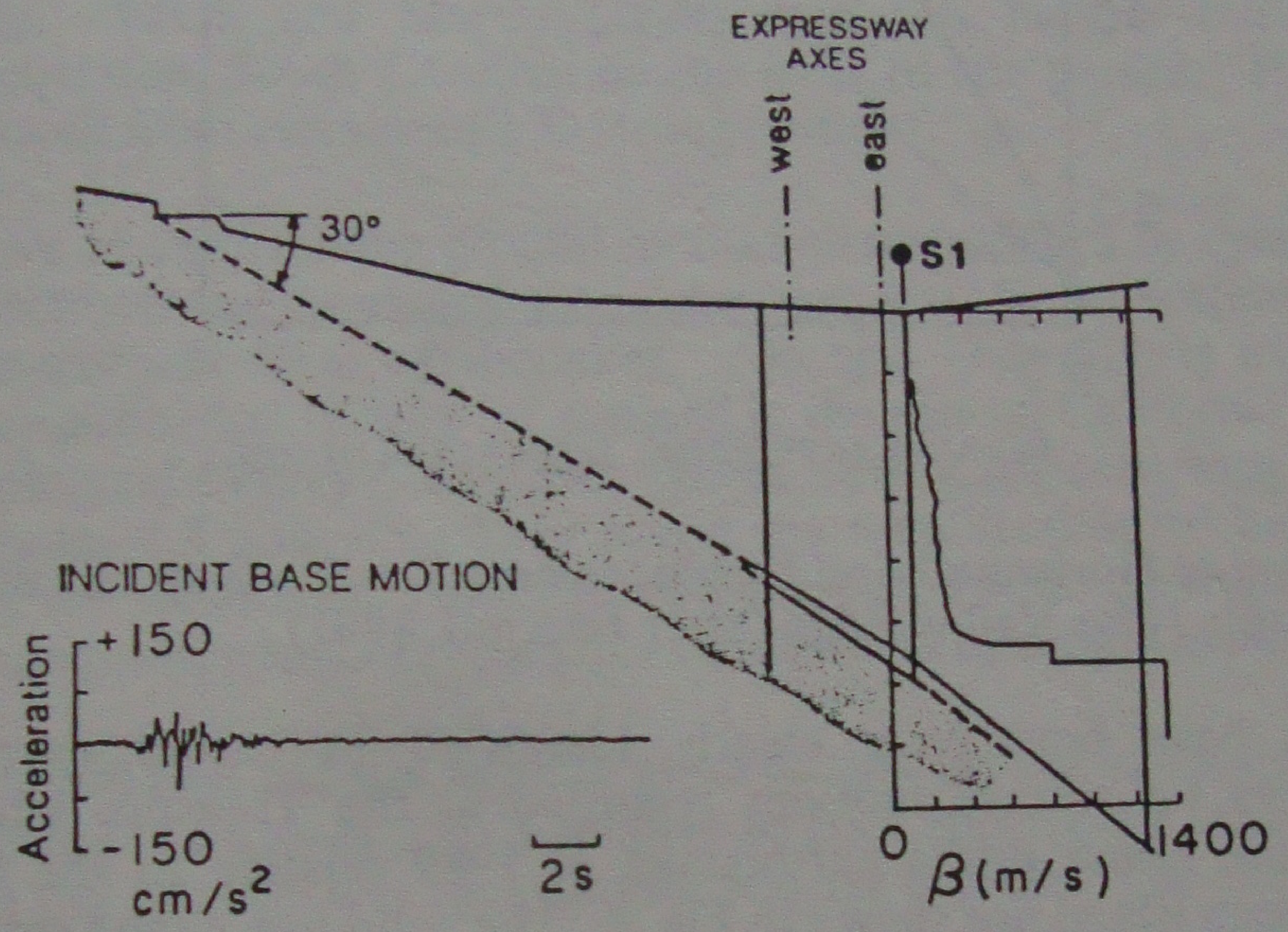

Fig. 6 Cross-Section at Edge of Alluvial Valley Near Belluno, Italy (after Faccioli, 1991).

EFFECTS OF LOCAL SOIL CONDITIONS

The effects of local soil conditions on waves propagating from bedrock to the surface are usually evaluated by 1-D shear beam analysis on the assumption that the site can be modelled as a layered half-space.

The analyses are capable of identifying the more important characteristics of the surface motions; the resonant period of the site, the lengthening of the period with increasing intensity of shaking and the amplification or deamplification of motions at various frequencies.

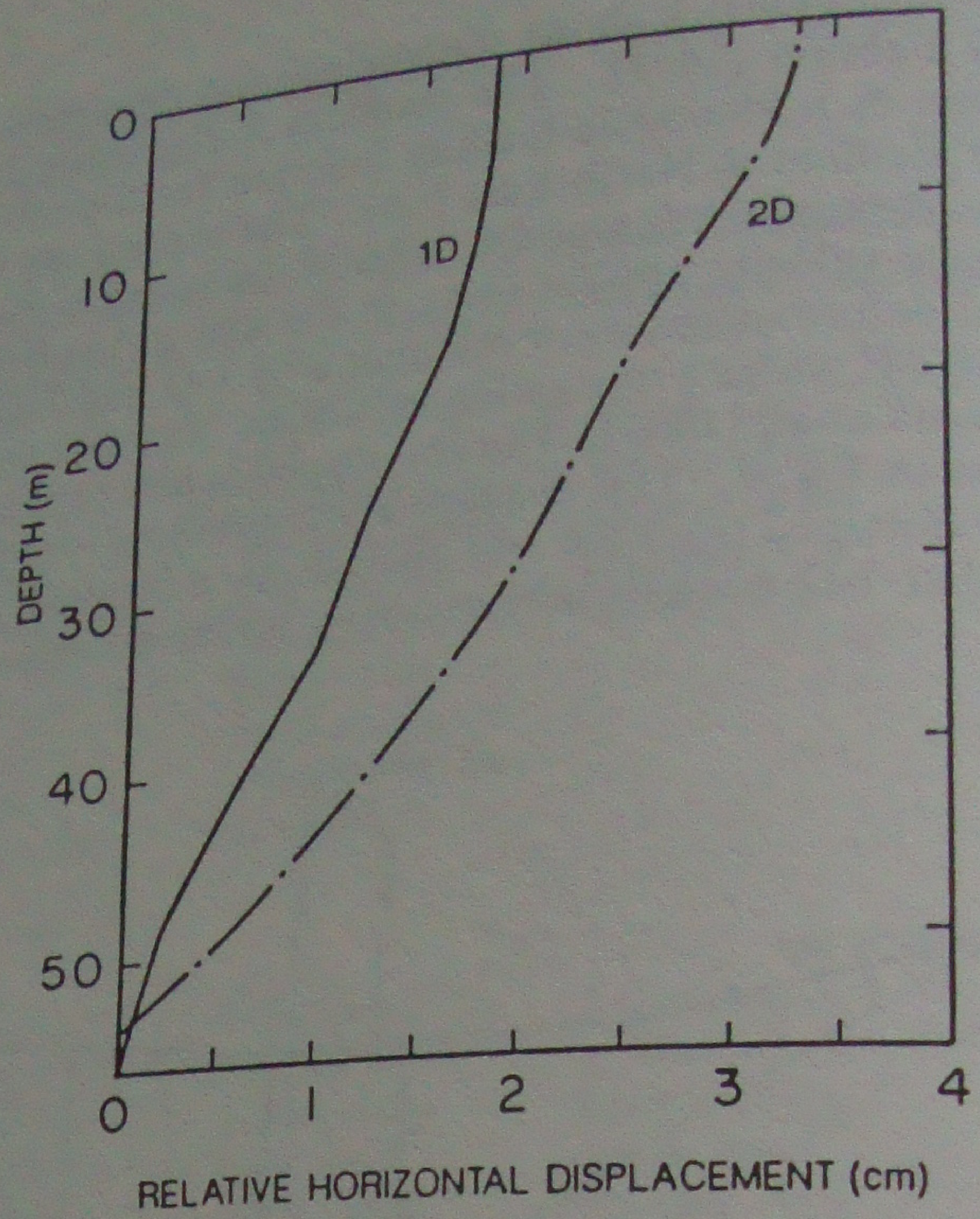

Fig. 7 Comparison of Horizontal Soil Displacements Predicted by 1-D and 2-D Analyses in Soil Profile Near Valley Edge (after Faccioli, 1991).

These effects have been very clearly identified in recent earthquakes. The amplification factors for surface motions recorded at the Treasure Island Site in San Francisco during the Loma Prieta earthquake of 1989 relative to the rock motions at adjacent Yerba Buena Island are shown in Fig. 8. The solid line shows the variation in the

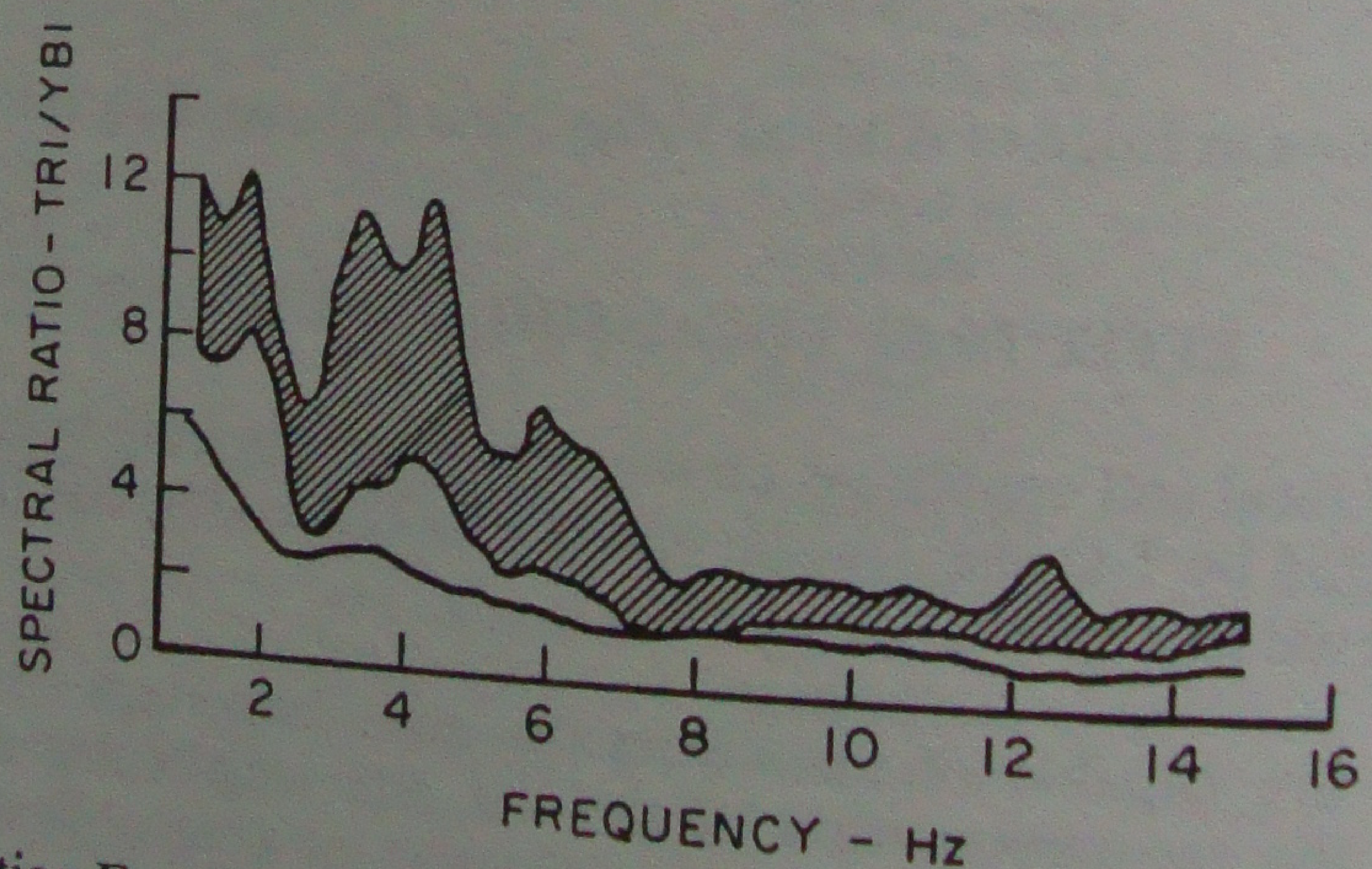

Fig. 8. Amplification Factors for Strong and Weak Motions at Treasure Island Site (after Jarpe et al., 1990).

NS spectral ratio for the first 5 seconds of the shear wave in the main shock in the period before liquefaction took place at the site. The shaded area is the 95% confidence region for the NS spectral ratios of 7 aftershocks (Jarpe et al, 1990). The amplification factors are drastically reduced in the strong motion phase although still 2 or greater over a wide frequency band.

Evidence of a significant shift in site period during strong shaking is provided by data from a Japanese site (Tazoh et al., 1988). Ground motions from the Kanagawa-Yamanashi earthquake of August 8, 1988, $M_{JMA} = 6.0$, were recorded at an epicentral distance of 18 km. The maximum acceleration at the ground surface was 435 gals and 134 gals at the base layer during the main shock. The transfer functions for both weak motions and the main shock between base and surface showed a period shift from 0.33 s for the weak motions to 0.5 s for the main shock. On this evidence, one should be cautious about site periods of peak response deduced from low amplitude events such as microtremors and coda waves. Elton and Martin (1989) took this period shift into account in microzoning Charleston, South Carolina on the basis of site period. They used dynamic site periods deduced from calculated 1-D strong motions.

An alternative to determining ground motion characteristics by dynamic analysis is to establish the parameters empirically from site response to microtremors or frequently occurring low magnitude local earthquakes. Aki and Teng (1991) used coda waves to determine site amplification factors for stations in the central California network operated by the U.S. Geological Survey. The coda waves were associated with local earthquakes between magnitudes 1.8 and 3.5. They found the amplification to be controlled by the geological age of the sediments. Amplification decreased with age from young Quaternary to Tertiary Pliocene sediments. Presumably the stiffness of sediments increased with age.

Aki (1988) found that the site amplification factors for strong motion response spectra showed amplification factors of 2 to 3 relative to rock spectra for periods longer than 0.2 seconds and that the relation was reversed for shorter periods. The site dependent spectra proposed by Seed et al. (1976) showed a similar cross-over near the period of 0.2 seconds.

The amplification factors for weak motions based on coda waves did not show such a cross-over. The data showed consistent amplification at all frequencies up to 12 Hz.

Aki and Teng (1991) applied the weak motion amplification factors derived from coda waves in fundamental studies of strong ground motions recorded during the Loma Prieta earthquake in 1989. For distances less than 50 km, they found a systematic overprediction of peak acceleration. They concluded that, depending on site and level of motion that nonlinear effects became significant in the acceleration range 0.1g - 0.3g. The lower limit agrees with the acceleration level proposed by Seed et al. (1976) as roughly the boundary between amplification and deamplification of rock motions by surface sediments (Fig. 9).

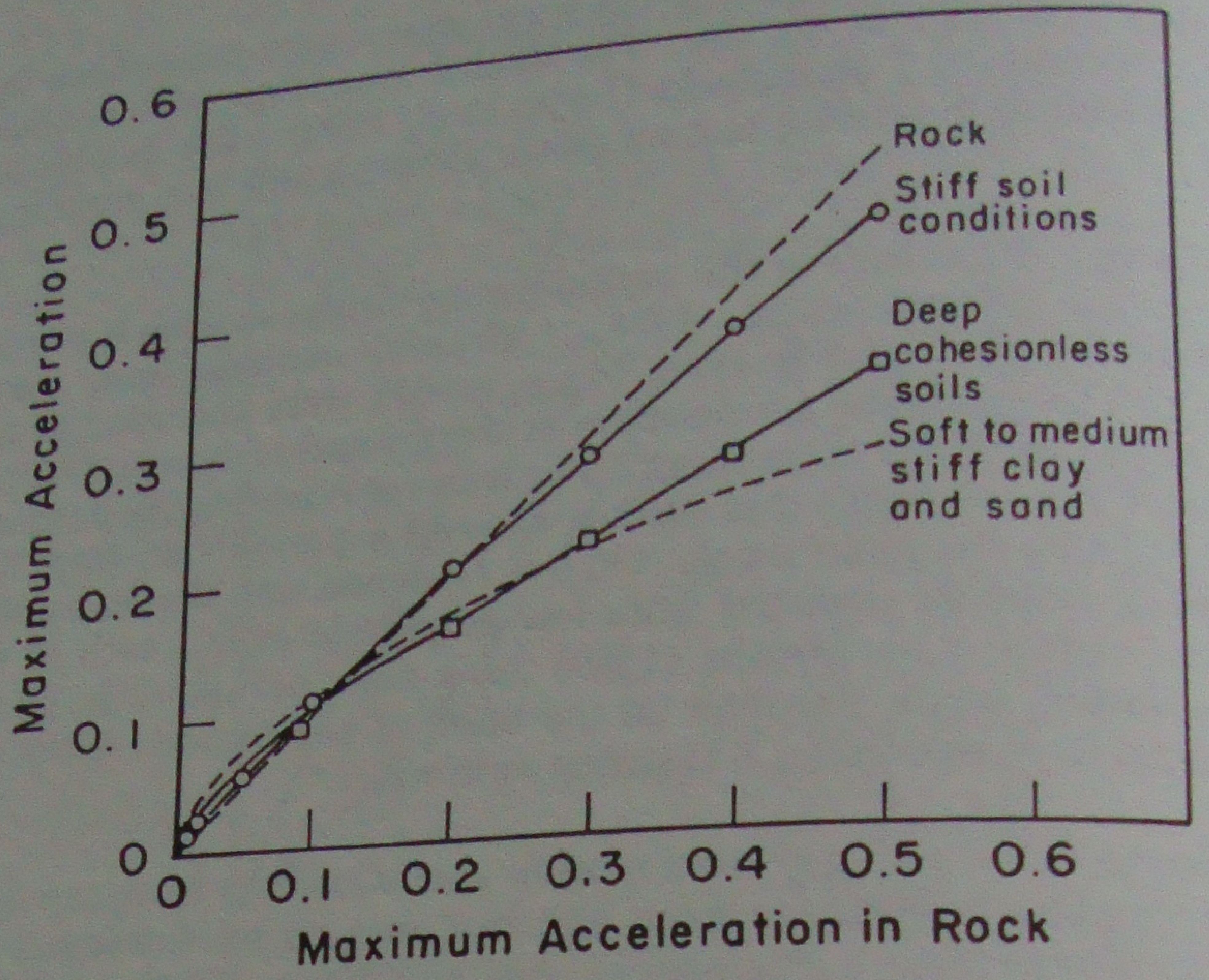

Fig. 9. The Effects of Site Conditions on Ground Accelerations (after Seed et al., 1976).

Data in Fig. 9 suggest massive deamplification on soft soil sites during strong ground motion. The response of the soft clays in Mexico City during the 1985 Mexican earthquake and of the soft soil sites in California during the Loma Prieta earthquake in 1989 changed that view dramatically. Idriss (1990) gives an updated picture of the response of soft soil sites in Fig. 10, based on the Mexico City and Loma Prieta data and on 1-D response analyses using the SHAKE program (Schnabel et al., 1972). Much greater amplification is now attributed to soft soil sites and the acceleration range over which amplification may occur is raised from 0.1g to 0.4g. Why did the predictions by 1-D dynamic analysis in 1990 change so much from those in 1983 when the same program was used in analysis. The answer lies in a better understanding of the dynamic properties of soft high plasticity clays.

Dynamic response analyses of clay sites in the past were conducted using generalized curves giving the damping ratio and the degradation in shear modulus as functions of shear strain developed by Seed and Idriss (1970). The degradation in stiffness became significant at very low strains. Consequently, response analyses using strong motion inputs showed high deamplification of soft clay sites. Studies of the Mexico City clay showed that it remained essentially elastic over a much larger range in strain than the generalized curve would suggest. It was thus elastic behaviour that allowed resonance to develop large

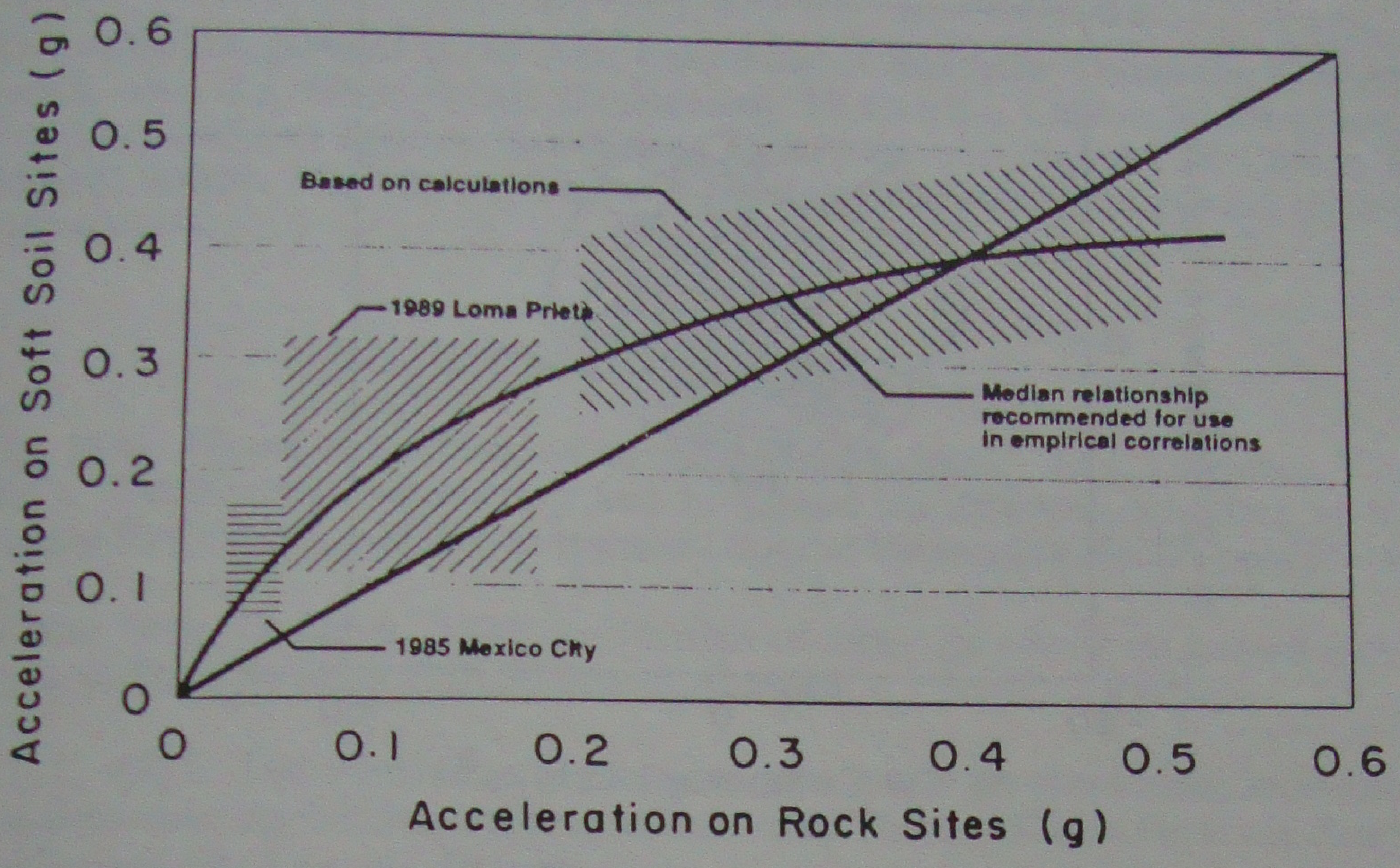

Fig. 10 Comparison of Peak Accelerations in Rock and Soft Clay Sites (after Idriss 1990).

amplifications (Finn and Nichols, 1988). Studies of dynamic soil properties since 1985 shows that the rate of modulus degradation at a given strain level decreases with increasing plasticity. The important lesson to be learned from the ground response in Mexico City is that site specific properties should be used in site response analyses.

But a major problem still remains for dynamic analysis despite all the improvements in the constitutive modelling and methods of analysis, uncertainty in the input motions. This problem cannot be evaded by calculating average motion parameters such as average spectra. The ground motions in Mexico City could not be simulated by following the usual practice of inputting outcrop motions. The rock motions had no preferred direction (Fig. 11), whereas the motions at the SCT site on the lakebed has acquired a strong E-W orientation (Fig. 12). As a result of this, to match the spectra of the E-W motions, the rock input motions had to be increased 2.5 times (Finn and Nichols, 1988).

Idriss (1990) had similar difficulties in simulating the response spectra at the Treasure Island site when using the rock outcrop motions from the nearby Yerba Buena site as input. It would seem that the motions emanating from the rock-sediment interface acquired a directional bias that resulted in substantially underestimating the response spectral ordinates as happened in Mexico City (Finn and Nichols, 1988).

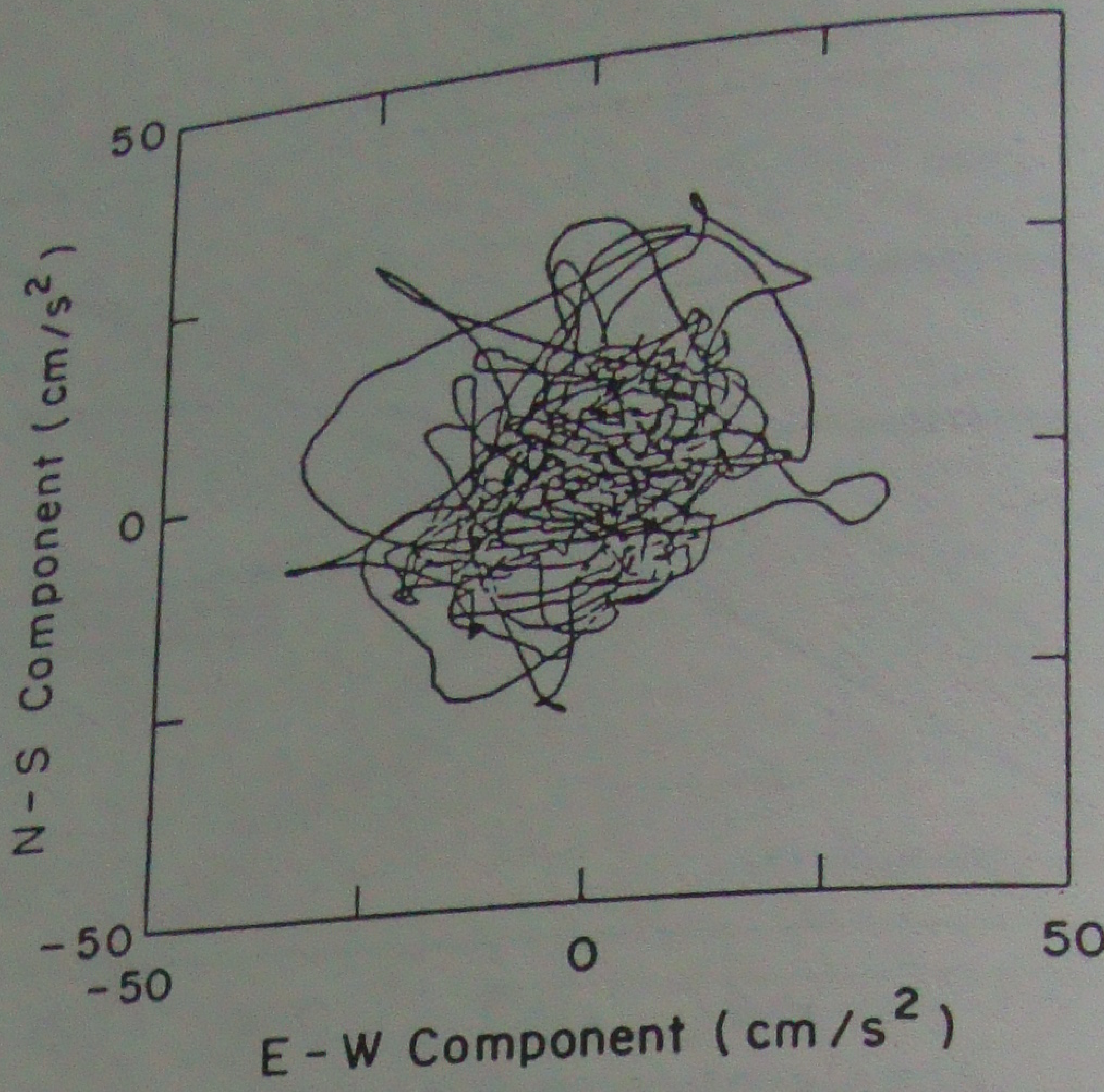

Fig. 11 Accelerations at Rock Site in Mexico City Showing no Directional Bias (after Finn and Nichols, 1988).

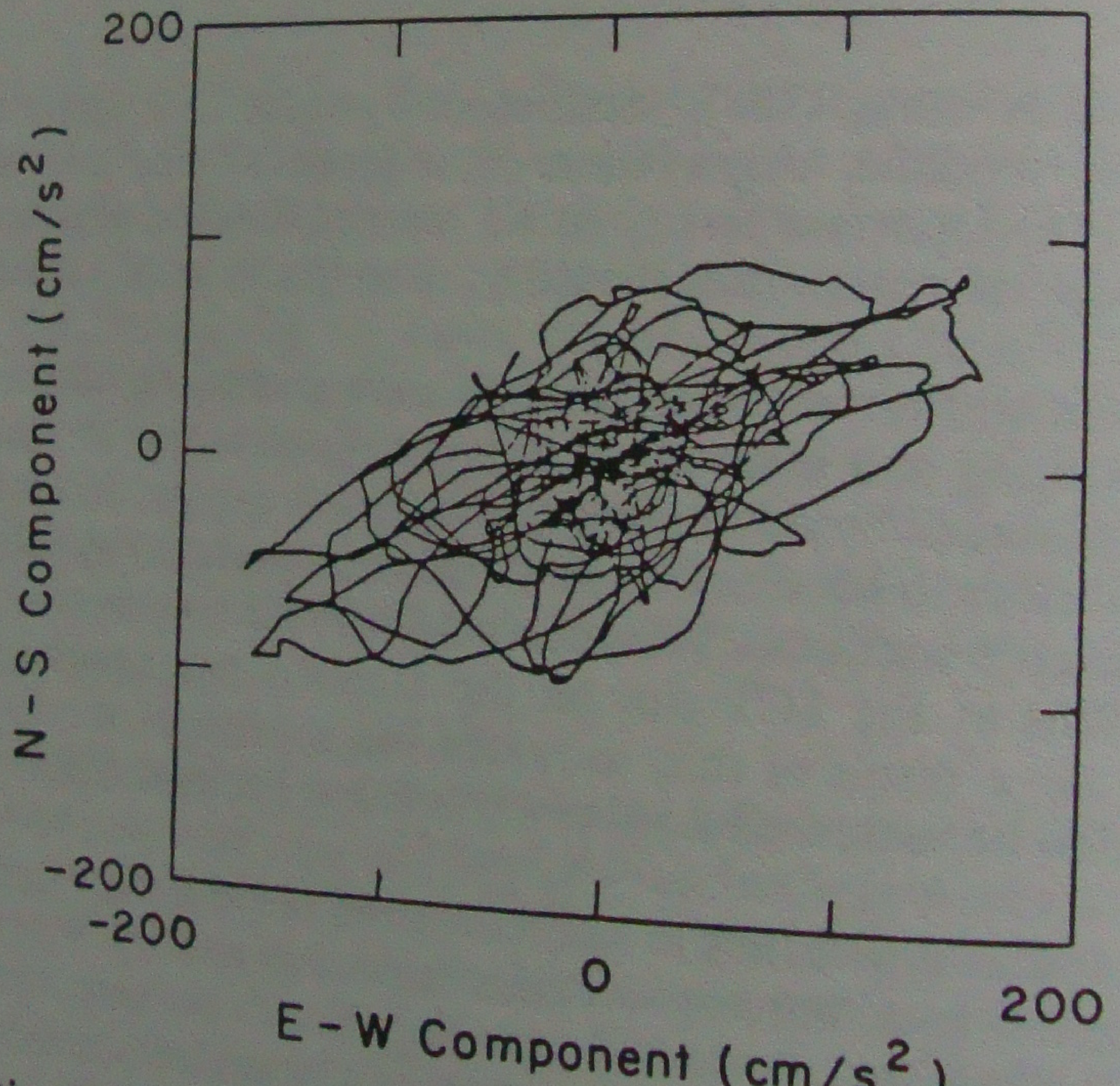

Fig. 12 Accelerations at the SCT Site on the Lakebed in Mexico City Showing Strong Directional Bias (after Finn and Nichols, 1988).

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