Earthquake Engineering, Tenth World Conference © 1994 Balkema, Rotterdam. ISBN 90 5410 060 5

Effect of foundation soils on seismic damage potential

W.D.Liam Finn
Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada

ABSTRACT: The effects of site conditions on ground motions and damage potential are critically reviewed using the results of site response analyses and case histories from past earthquakes. Topography and the rate of degradation in soil stiffness with strain have major effects on site response. Where topography is pronounced 1-D dynamic analyses do not give reliable estimates of response. The characterization of strong motion response by weak motion parameters is shown to be useful in indicating the relative damage potential of sites but may overestimate significantly ground motion amplification during strong shaking.

1 INTRODUCTION

Site conditions play a major role in establishing the damage potential of incoming seismic waves from major earthquakes. Site conditions in this context include the soil profile, soil properties and topographic structures. The major causes of damage to structures are ground shaking, liquefaction, and lateral spreading. The effects of liquefaction on stability of foundations in major earthquakes have been well documented (Kawasumi, 1964; Finn, 1979) and most recently, in the case of the Loma Prieta earthquake by Seed et al. (1990). Liquefaction continues to be a major research area in geotechnical earthquake engineering and major reviews of developments in research and practice are available (Finn, 1981,1990,1991; Seed and Harder, 1990; Mitchell and Wentz, 1991). Foundation failures due to liquefaction, therefore, will not be discussed in this paper. Lateral spreading is also a consequence of liquefaction. Although the damaging effects of lateral spreading have long been recognized, the first detailed quantitative study of the prevalence of lateral spreading and the factors controlling it was conducted by Hamada et al. (1986). This seminal report has sparked major research into the phenomenon of lateral spreading and its damage potential. Youd (1980) has established criteria relating the magnitude of lateral spreading to structural damage and has developed empirical equations for predicting the amount of lateral spreading (Bartlett and Youd, 1992). A succinct review of some of these developments has been made by Finn (1988a).

This report will focus on the estimation and characterization of strong seismic shaking. This is the most prevalent cause of damage to structures during earthquakes. It is also one of the more complex areas in geotechnical earthquake engineering.

Damage patterns in Mexico City after the 1985 Michoacan earthquake demonstrated conclusively the significant effects of local site conditions on seismic response of the ground. Peak accelerations of incoming motions in rock, generally less than 0.04 g were amplified about 5 times on the clay soils of the old lakebed on which the city is founded, with devastating effects for structures with periods close to site periods. In the 1989 Loma Prieta earthquake, major damage occurred on soft soil sites in the San Francisco-Oakland region where the spectral accelerations were amplified 2-4 times over adjacent rock sites (Housner, 1990). Clearly seismic design should incorporate the effects of local soil conditions.

2 FOUNDATION FACTORS

Most earthquake resistant structural design is based on the seismic design provisions of national buildings codes. In these codes, the effects of local soil conditions on seismic response are usually taken into account by the introduction of a foundation factor, F, or site factor, S, into the formula for computing the base shear in a building. Values of S are related to a number of broad categories of soil conditions. The Uniform Building Code (UBC, 1988) contains the four categories shown in Table 1 and the associated foundation factors range from 1.0 to 2.0. These factors are based on results of site specific analyses, recorded ground motions and assessments of damage to buildings on various soil profiles. The proper factor to use in a given case is based on the best available knowledge about the site under consideration and engineering judgement.

The fourth category S = 2.0 was added to the code in reaction to the damage sustained on the soft clay soils of Mexico City. There was concern that large amplifications might occur at other soft

TABLE 1. Site Coefficients

Type	Description	S Factor
S_1	A soil profile with either: a) A rock-like material characterized by a shear wave velocity greater than 2500 ft/sec, or by other suitable means of classification; or b) Stiff of dense soil conditions, where the soil depth is less than 200 ft.	1.0
S_2	A soil profile with dense or stiff soil conditions, where the soil depth exceeds 200 ft.	1.2
S_3	A soil profile 40 ft or more in depth and containing more than 20 ft of soft to medium stiff clay but not more than 40 ft of soft clay.	1.5
S_4	A soil profile containing more than 40 ft of soft clay.	2.0

sites such as sites in San Francisco underlain by Young Bay Mud. The S=2.0 category was also adopted in the National Building Code of Canada (NBCC, 1990) to provide additional protection for structures on deep soft sites.

The use of broad and distinctly different soil categories has the advantage that rather distinct patterns of ground response are associated with each type. An important example is provided by the different average spectral shapes associated with the first three soil categories (Table 1) shown in Fig. 1 (Seed and Idriss, 1983). Idealized forms

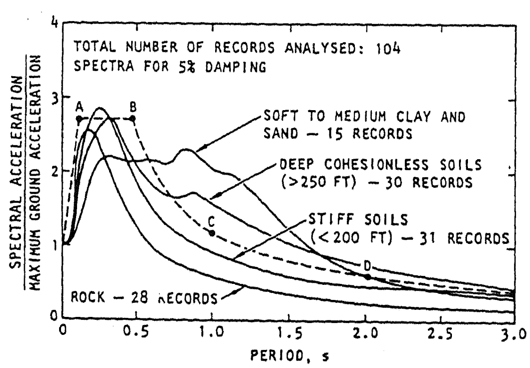

FIGURE 1. Average Acceleration spectra for different site conditions (after Seed and Idriss, 1983).

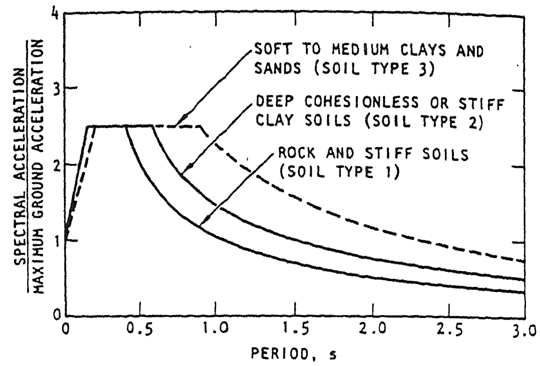

FIGURE 2. Normalized spectral curves suitable for use in building code (after Seed and Idriss, 1983).

of these spectra (Fig. 2) are suitable for adoption as design spectra in building codes (Seed and Idriss, 1983).

Hensolt and Brabb (1990) have published a microzonation map of San Mateo County, California, showing the distribution of the UBC soil factors. This map shows the relative hazard at various sites in terms of the factor S. The important feature of this microzonation map is that the parameter mapped, S, can be used directly in determining the seismic demand on a structure and the relative damageability of the site.

3 EVALUATION OF SITE FACTOR S=2

There is some concern in a number of building code jurisdictions regarding the appropriateness of the site factor S=2 for soft sites. A site amplification study was carried out to assess the level of protection offered by the site factor of 2 to buildings founded on deep soil deposits in the Fraser Delta near Vancouver, British Columbia (Lo et al., 1991). The delta is in one of the highest seismic regions of Canada. The study was based on site specific field and laboratory dynamic soil data and the most up to date assessment of the regional seismicity.

Three representative deep soil sites in the Fraser Delta (Sites A, B and C) were selected for ground response studies. The selection was influenced by the location of the sites relative to urban and industrial development and on the availability of site specific data. The dominant contributions to the ground motion specified in the NBCC come from earthquakes in the magnitude range 6.3-7.3 at epicentral distances ranging from 30-70 km with focal depths of about 20 km. A suite of 22 records with $0.8 < a/v < 1.2$ were selected to meet the above criteria and to minimize undue influence of any specific earthquake. The acceleration/velocity ratio, a/v, is in the range considered appropriate for the Delta. The impact of site conditions was examined for two types of structures; frame structures and shear wall structures.

The seismic elastic base shear, V_e, in a structure, according to the 1990 NBCC, is given by V_e = vSIFW, where v = zonal velocity ratio, S = a period dependent seismic response factor, I = importance factor, F = foundation factor, and W = dead load. For all NBCC earthquakes, the computed foundation factor, F_c, may be obtained for any structural period from the equation

$$F = V_e/vSIW \tag{1}$$

A comparison between the frequency dependent computed foundation factors, F_c, and the NBCC code factor, F, are shown in Fig. 3 for frame buildings, and in Fig. 4 for shear wall buildings. The code foundation factor, F, has a maximum value of 2, and below periods of 1 second it decreases to 1.

It appears that for these sites the foundation factor is adequate for the shear wall type of building, although at one site the response at the mean plus one SD level slightly exceeds the code factor for periods between 0.5 and 2 seconds. For frame buildings, judgement about the adequacy of the code foundation factor depends on whether the criterion for adequacy is based on mean response or the mean plus one SD. In the latter case, the code factor would seem to seriously underestimate response in the period range 0.5 to 2 seconds.

These preliminary results show the difficulties that can arise when using a single foundation factor for all kinds of structures.

The adequacy of the code foundation factor, F=2, is under review again for the 1995 code.

4 SITE CHARACTERIZATION

There are two other major approaches to characterizing the effects of site conditions on seismic response to strong shaking. The first involves the use of amplification factors or other ground motion parameters derived from weak ground motions or microtremors. The second involves site specific dynamic response analyses.

The first detailed field study of the applicability of weak motion characteristics such as amplification factors to the estimation of dynamic response under strong shaking was conducted by Hudson (1972). He made a detailed study of site response in the Pasadena area during the San Fernando earthquake of 1971 and attempted to correlate features of local geology with site response. Hudson concluded that local distribution of ground shaking, predicted on the basis of ground motions recorded during many small earthquakes, "may not correspond very well with the distribution occurring during a damaging earthquake".

Borcherdt and Glassmoyer (1991) and

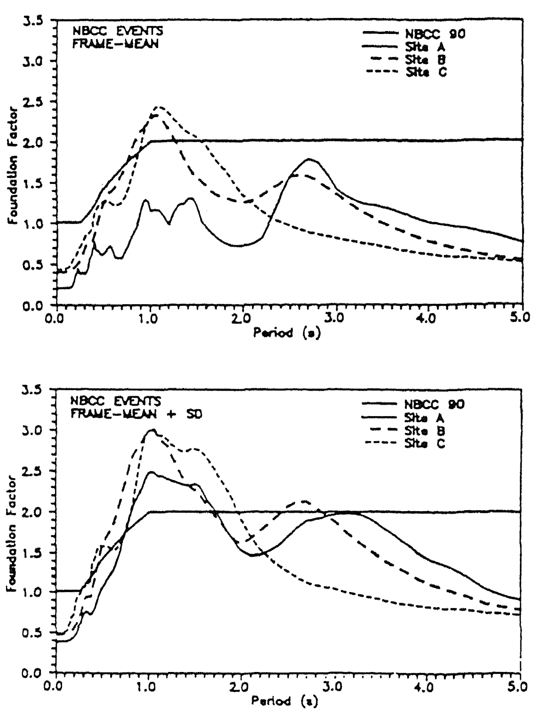

FIGURE 3. Comparison between computed and NBCC90 foundation factors for frame buildings on Sites A, B and C.

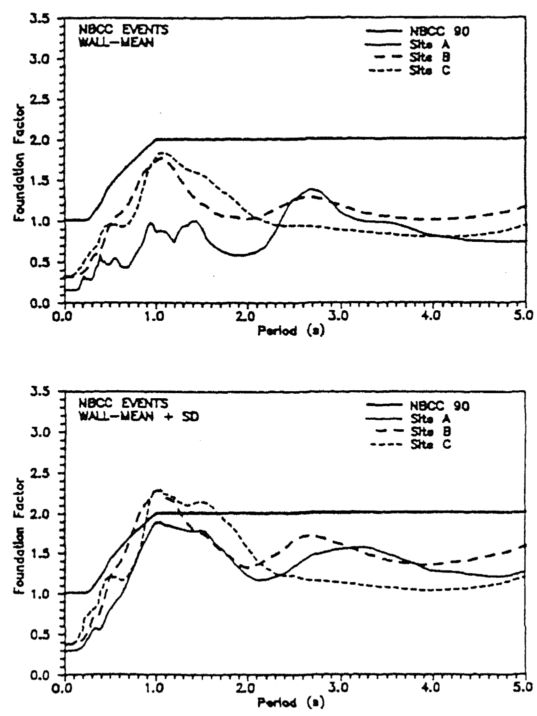

FIGURE 4. Comparison between computed and NBCC90 foundation factors for shear wall type structures on Sites A, B and C.

Borcherdt (1991) demonstrate that weak motion amplification factors on distinct geologic units were good indicators of the intensity of strong shaking during the Loma Prieta Earthquake of 1989. These differences in opinion result partly from the differences between site specific studies such as Hudson's from the global correlations with error bounds approach of Borcherdt (1991). Intrinsic differences between site specific and global studies have been explored at length from an engineering point of view by Finn (1990) and some key aspects of that study will be presented later.

The effects of local soil conditions are often evaluated by 1-D shear beam analyses which model the site as a layered half-space (Schnabel et al., 1972; Finn et al., 1977; Lee and Finn, 1978). The analyses are capable of modelling nonlinear effects and 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. These effects have been very clearly identified in ground motions recorded during earthquakes.

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, 1983, $M_{JMA} = 6.0$, were recorded at an epicentral distance of 18 km. The maximum acceleration at the ground surface was 435 gals and 135 gals at the base layer during the main shock. The transfer functions for 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. Similar data from other Japanese sites are given in Table 2 (after Okamoto, 1973). At these sites the predominant periods are increased by a factor of 5 as the shaking became stronger with increasing magnitudes. These shifts in predominant period entail modifications of the seismic response and damage potential. On this evidence, one should be cautious about using site periods of peak response deduced from low amplitude events such as microtremors and coda waves to characterize site response under strong shaking.

Site specific studies are essential for understanding the role of geological profile, soil properties and topography on the seismic response of a site. Field data from two earthquakes, the 1985 Michoacan, Mexico earthquake, and the Loma Prieta earthquake of 1989, have been crucial to understanding the critical impact of site conditions on seismic response and in verifying the capability of current methods for site response analyses. These case histories will be reviewed in the next section.

TABLE 2. Dependence of Site Period on Intensity of Shaking (after Okamoto, 1973)

	Predominant Period	
Earthquake Scale	Koto	Arakawa
Large-scale earthquake	1.35 sec (Off-Tokachi earthquake, 1968, M=7.9)	0.77 sec (Niigata earthquake, 1964, M=7.5)
Medium-scale earthquake	0.46 sec (Higashi-Matsuyama earthquake, 1968, M=6.1)	0.77 sec (Higashi-Matsuyama earthquake, 1968, M=6.1)
Small earthquake	0.25 sec (Local earthquake)	0.17 sec (Local earthquake)

5. SEISMIC SITE RESPONSE: CASE HISTORIES

The state of knowledge on amplification and deamplification of ground motions in terms of peak acceleration has been summarized conveniently in Fig. 5 by Seed et al. (1976) and Seed and Idriss (1983). According to Fig. 5 deamplification of peak accelerations in rock at soft clay sites begins at about the 0.1 g level and becomes very significant at the 0.3 g level. The response of the soft clays in Mexico City during the 1985 Michoacan 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. 6, 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 amplifications are now attributed to soft soil sites

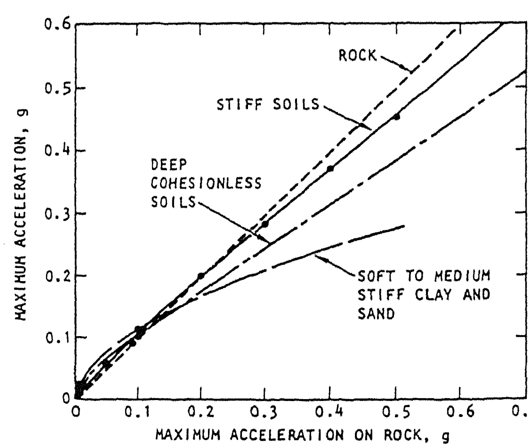

FIGURE 5. Approximate Relationships Between Maximum Accelerations on Rock and Local Site Conditions (after Seed and Idriss, 1983).

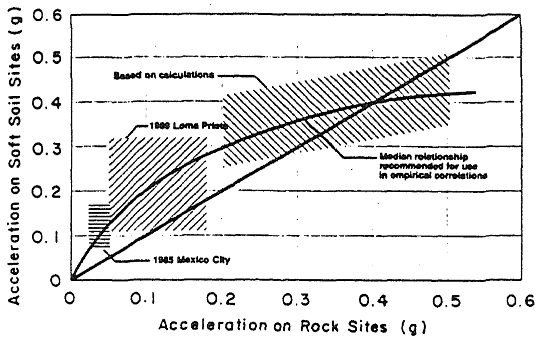

FIGURE 6. Variation of Accelerations on Soft Soil vs Rock Sites (after Idriss, 1990).

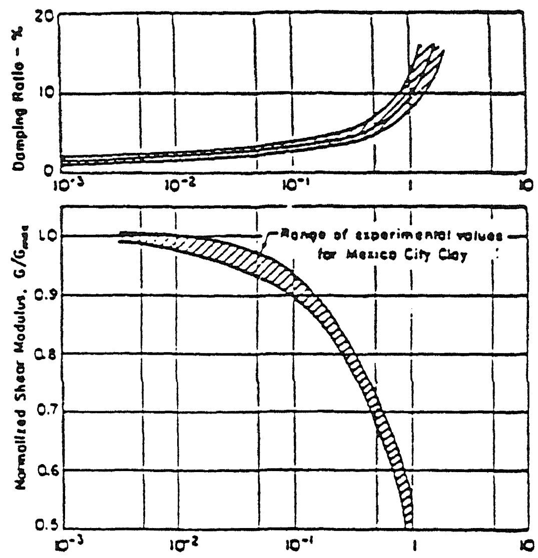

FIGURE 7. Strain Dependent Damping Ratios and Normalized Shear Moduli for Mexico City Clay (after Leon et al., 1974, and Romo and Jaime, 1986).

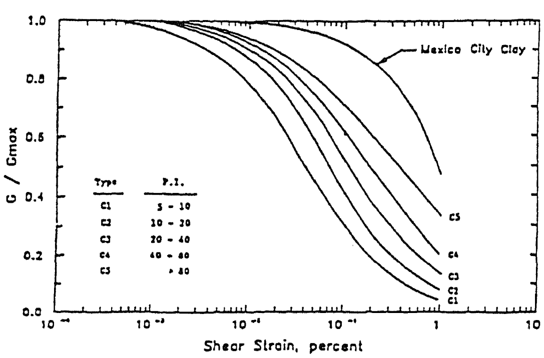

FIGURE 8. Normalized Modulus Reduction Curves for Clays with Different Plasticity Indices (after Sun et al., 1988).

and the peak acceleration range over which amplification may occur is raised from 0.1 g to about 0.4 g. Why did the assessment of seismic response of soft soil sites change so much from 1983 to 1990? The answer lies in a better understanding of the dynamic properties of soft high plasticity clays such as the Mexico City clays.

5.1 Motions in Mexico City

The response of the soft clay sites in Mexico City could be advanced as a strong argument in favour of the utility of weak motion amplification factors in defining site response to strong shaking. Here are sites at which ground accelerations were amplified 3-5 times relative to accelerations in the rocky, hilly parts of the city, and yet the response was essentially elastic even though the peak accelerations reached about 0.2 g.

The response of the Mexico City sites to shear waves propagating vertically is controlled by the strain dependent shear modulus and damping. Variations in damping and normalized shear modulus are shown in Fig. 7. The shear modulus does not show substantial degradation until strain levels of the order of 0.1% at which strain the shear modulus is still at 90% of its initial value. The response remains elastic because substantial modulus degradation did not occur at the strains developed during shaking.

Modulus degradation curves for a wide variety of clays are shown in Fig. 8 (Sun et al., 1988). Note that as the plasticity of the clay increases, the range of essentially elastic response also increases. The range for Mexico City clays represents a likely upper bound to elastic behaviour in clays. If the Mexico City clay had the modulus degradation properties of one of the lower plasticity clays such as clay C2, then the response would have shown strong nonlinear effects and the large amplification factors would not have been developed.

The role of damping is equally important. Because of the limited degradation in shear modulus, the hysteretic damping in the Mexico City clays was quite low. This allowed greater response at the resonant site periods and prolonged existence of significant reverberations in the valley after the period of direct excitation.

Some consideration should be given to the effects of great overburden pressures on effective damping ratios in the analysis of very deep sites. In the 1970's when soil damping first began to be studied experimentally in an extensive way, damping was considered to be pressure dependent, but this factor is no longer taken into account in conventional engineering analyses.

It is reasonable to expect that deposits of high plasticity clays in other parts of the world would respond in a manner similar to the Mexico City clays.

5.2 Loma Prieta Earthquake

The Treasure Island site and the adjacent rock outcrop of Yerba Buena Island in San Francisco Bay are shown in Fig. 9. Depth to bedrock near the strong motion site UM10 is about 280 ft. Peak accelerations recorded at Yerba Buena on rock during the 1989 Loma Prieta earthquake were 0.06 g in the E-W direction and 0.03 g in the N-S direction. Corresponding peak accelerations at the Treasure Island site were 0.18g in the E-W direction and 0.11 g in the N-S direction. Duration of strong shaking was about 5 seconds. Liquefaction occurred at the UM10 site during the earthquake.

The soil profile at the Treasure Island site consists of about 12 m of fill followed by about 17 m of bay mud and 56 m of older bay sediments resting on bedrock. The normalized shear modulus and damping ratio are shown in Fig. 10 as functions of strain (Hryciw et al., 1991). Because of the presence of Young Bay Mud, this site is classified as a soft soil site (Housner et al., 1990).

The amplification factors for surface motions recorded at the Treasure Island Site during the Loma Prieta earthquake of 1989 relative to the rock motions at adjacent Yerba Buena Island are shown in Fig. 11. The solid line shows the variation in the 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 of engineering interest. The peak acceleration at the surface of 0.16 g shows an amplification of about 3. The reduction in amplification with increased shaking is due to the nonlinear stress-strain response of the soil.

Results from this site illustrate very well the advantages and disadvantages of using weak motion amplification factors or other small strain parameters such as shear wave velocity to characterize site response to strong motion. The weak motion factors would have correctly predicted enhanced ground motions during strong shaking but would have grossly overestimated the amplification factors. Therefore weak motion amplification factors may prove to be reliable indicators of relative response of different geologic units to strong shaking but in many cases cannot be used directly to quantify site response.

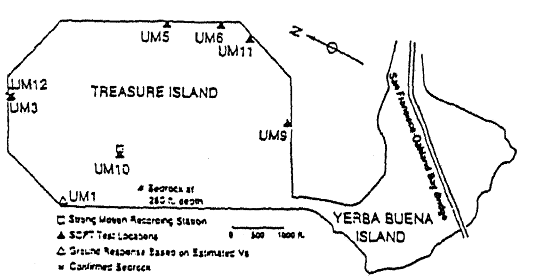

FIGURE 9. Treasure Island and Yerba Buena Sites (after Hryciw et al., 1991).

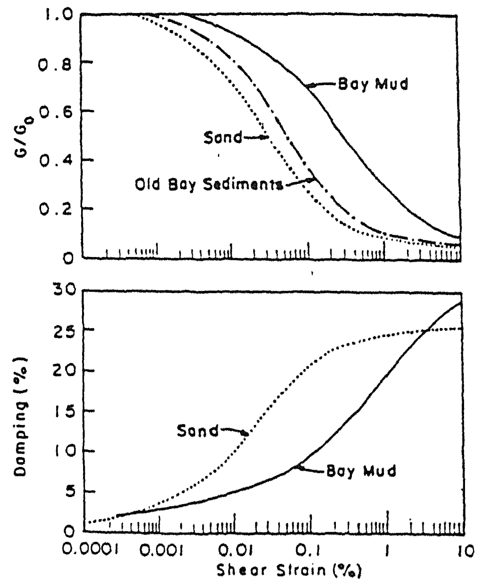

FIGURE 10. Strain Dependent Normalized Shear Moduli and Damping Ratios for Soils at Treasure Island Site (after Hryciw et al., 1991).

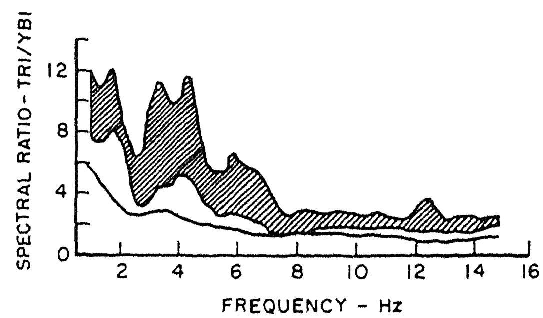

FIGURE 11. Amplification Factors for Strong and Weak Motions at Treasure Island Site (after Jarpe et al., 1990).

A major problem in determining site specific amplification factors or spectral ratios by site dynamic response analysis, even when soil properties are well defined, is the uncertainty about what the input motions ought to be. Since the response depends not only on the intensity of the motions but also on their frequency content, the determination of a representative input motion is a very difficult task. Rock outcrop motions "adjacent" to the site are usually considered to give the best definition of output motion. Finn and Nichols (1988) showed that the ground motions at the SCT strong motion site in the lakebed in

Mexico City during the 1985 Michoacan earthquake cannot be simulated by using the rock outcrop motions in the University district as input motions. The rock motions had no preferred direction (Fig. 12), whereas the motions at the SCT site on the lakebed had acquired a strong E-W orientation (Fig. 13). As a result of this, to match the spectra of the E-W motions, the rock input motions had to be increased about 2.5 times (Finn and Nichols, 1988). Rosenblueth (1991) made a similar observation about this site. The reason for the bias has not been established but is probably due to surface waves being propagated primarily in the E-W direction generated by either local subsurface topography or by lateral inhomogeneities in the properties and variations in the thickness of the clay layer.

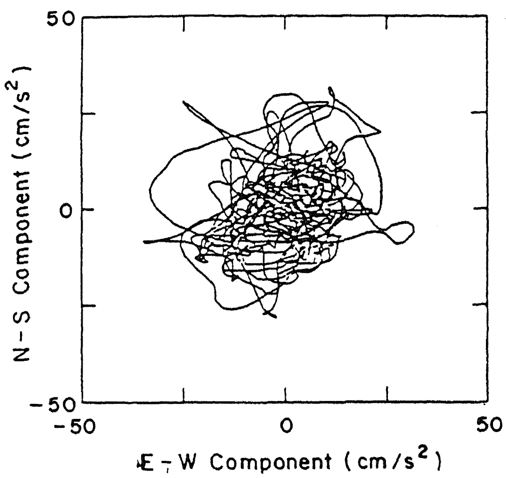

FIGURE 12. Accelerations at Rock Site in Mexico City Showing no Directional Bias (after Finn and Nichols, 1988).

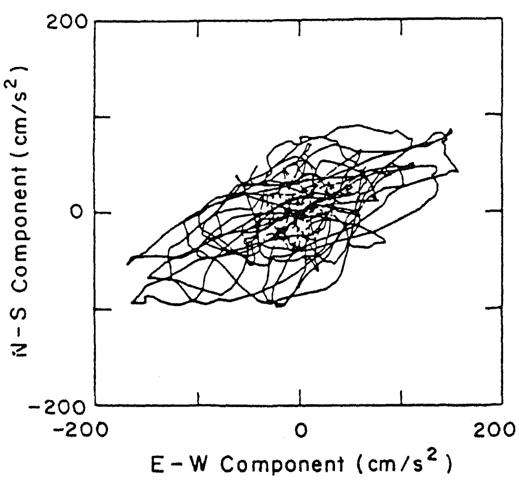

FIGURE 13. Accelerations at the SCT Site on the Lakebed in Mexico City Showing Strong Directional Bias (after Finn and Nichols, 1988).

Idriss (1990) and Hryciw et al. (1991) computed acceleration spectra for the Treasure Island site using the motions at Yerba Buena as input. The spectrum for the E-W component of the recorded motion is shown in Fig. 14, together with a range of calculated spectra (Idriss, 1990). The periods of peak response of the computed spectra agree well with those of the recorded motion. However, the spectral accelerations at periods of about 0.3 s and 0.7 s where the response is greatest are respectively 50% and 70% of the recorded values. The spectral accelerations in the long period range 1.75 s to 3 s are underestimated significantly. The recorded spectrum of calculated responses for the N-S component and the range in computed spectra are shown in Figs. 15 (Hryciw et al., 1991). In this case the computed periods of peak response do not match the periods of the recorded motion very well and response for periods greater than 1 second are badly underestimated, despite the fact that parametric studies were conducted to account for uncertainties in the soil properties.

A possible explanation for the substantial difference between the spectra of the recorded and computed motions is that the surface motions are not generated only by shear waves propagated

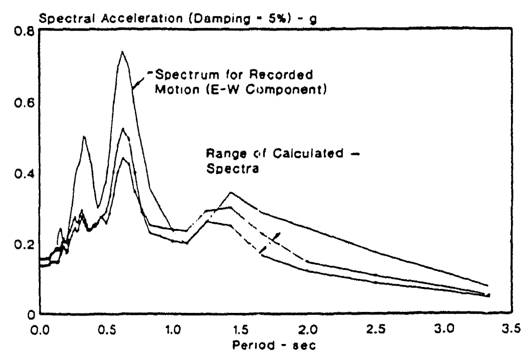

FIGURE 14. Spectra for Recorded and Calculated Motions at Treasure Island in the E-W Direction (after Idriss, 1990).

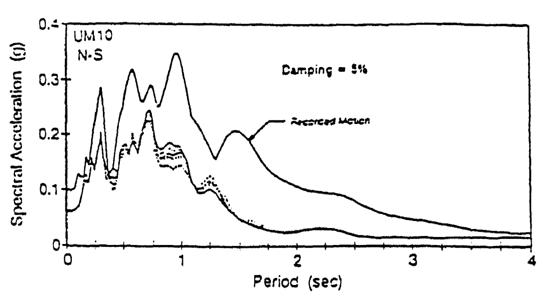

FIGURE 15. Spectra for Recorded and Calculated Motions at Treasure Island in the E-W Direction (after Hryciw et al., 1991).

from the bedrock underlying the site. Topographic effects due to the subsurface structure associated with the contact between the rock outcrop and the sediment can alter the motions significantly (Aki, 1988; Silva, 1989; Faccioli, 1991). The effects of surface topography and buried structures will be discussed briefly to complete the review of site effects on ground motion although topographic effects are rarely taken into account directly in site response analyses. Even a qualitative appreciation of potential topographic effects can be helpful in understanding deviations in seismic response from 1-D predictions in some cases.

6 EFFECTS OF TOPOGRAPHY

6.1 Motions on Surface Topography

Aki (1988) utilized the simple structure of a triangular wedge to illustrate the effects of topography. This structure may be used to model approximately ridge-valley topography as shown in Fig. 16 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. 16 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. 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. 17 (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.

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

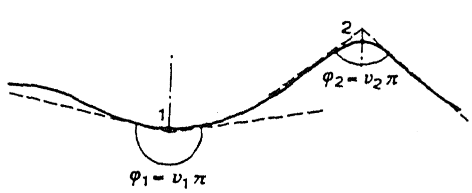

FIGURE 16. Infinite wedge excited by plane SH waves (after Faccioli, 1991).

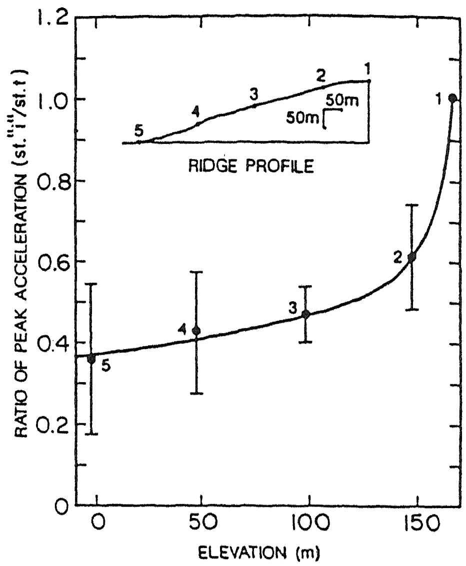

FIGURE 17. Relative Distribution of Peak Accelerations Along a Ridge From Matsuzaki Array in Japan (after Jibson, 1987).

(Brambati et al., 1980) and in the Chilean earthquake of 1985 (Celebi, 1987,1991).

6.2 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 1988b; Lee and Finn, 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. 18. 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 center, S/4h, where h is the depth of the valley at the center. 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 resonant response from the edge of the valley to station 3.

The surface waves generated near the edge are

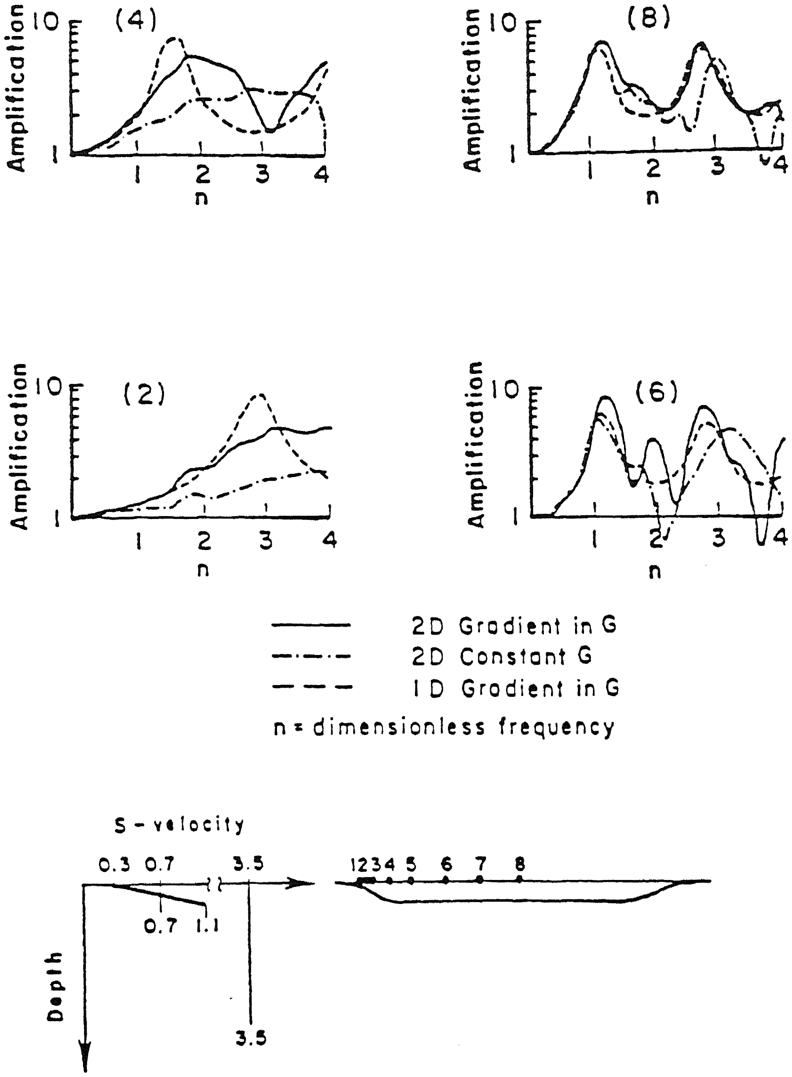

FIGURE 18. Smoothed SH Transfer Functions to Homogeneous Half-Space Outcrop Motions for a Wide, Shallow Alluvial Valley with a Shape Ratio of 0.1 (after Bard and Gabriel, 1986).

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.

The effects of surface topography and sediment-filled valleys on site response have been summarized by Silva (1989) in Table 3.

7 WEAK MOTION CHARACTERIZATION

Many attempts have been made to characterize site response to strong seismic input using parameters based on weak motion response because of the greater data base and wider prevalence of weak seismic motion data and the ease of obtaining weak motion response from microtremor measurements. In this context weak motions are defined as motions which elicit mainly elastic response from the site. Strong motions have sufficient intensity that nonlinear effects become important enough to invalidate conclusions about site response based on weak motion data.

In areas which have experienced strong shaking in the past such as California or Japan it may be possible to establish the upper limit of weak motions for typical geological units before nonlinear effects becomes important.

The definitive studies on characterization of

TABLE 3. 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 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 ≥ 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

sites for weak motion response have been conducted by Borcherdt (1970) and Borcherdt and Gibbs (1976). They analyzed data from 19 nuclear explosions in Nevada recorded at 99 sites in the San Francisco Bay region. The sources were all at distances exceeding 400 km, so variations in distance to each recording site was small compared to the source distances. Because of the great distances the energy of the incoming wave was concentrated in the period band of considerable engineering interest around 1 Hz. This work established some important results.

* ground motion characteristics showed strong correlation with the type of geological deposit.
* existence of resonant site periods for <u>some</u> of the softer Bay Mud and alluvial sites.

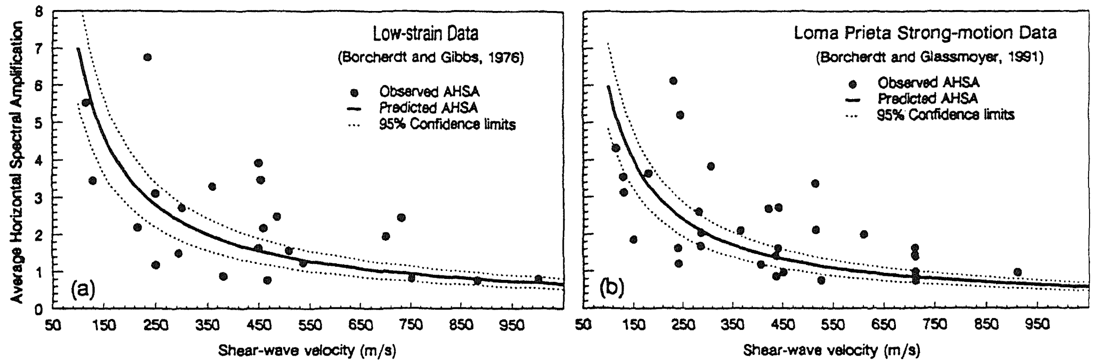

FIGURE 19. Relationship between average horizontal spectral acceleration (AHSA) and shear wave velocity, V_S for (a) low-strain (nuclear) data, and (b) Loma Prieta strong motion data, (AHSA - $701/V_S$ and $598/V_S$, respectively).

* quantitative estimates of ratios of peak ground velocity and spectral ratios over the period range 0.3 s - 2.0 s.

* statistical estimates of ground response and its variability for various geological units.

* a relationship between average horizontal spectral amplification (AHSA) determined from weak motion recordings and intensity increments inferred from to the 1906 San Francisco earthquake (Borcherdt et al., 1975), given by

$$dI = 0.27 + 2.70 \log (AHSA) \quad (2)$$

* a correlation between local shear wave velocity and intensity increments for the various geological units.

Recent correlations based on all available data show a strong correlation between shear wave velocity and the average horizontal spectral amplifications from recorded weak motion data (Borcherdt, 1991),

$$AHSA = 701/V_s \quad (3)$$

where V_S is the local shear wave velocity in m/s averaged over the top 30m of the sediments (Fig. 19a). This relation together with Eqn. (2) above have been shown to provide robust estimates for intensity increments (Borcherdt et al., 1991).

Of major interest for estimating the intensity of strong shaking is how well the response patterns based on these weak motions are applicable to the strong motions recorded during the Loma Prieta earthquake in the same area.

Borcherdt (1990,1991) and Borcherdt et al. (1991) report that, in general, the spectral amplifications were consistent with the weak motion data. The mean vertical and horizontal amplifications on San Francisco Bay Mud sites were within one standard deviation of the weak motion data except for motions at Foster City and Treasure Island sites. For alluvial sites, the amplifications are within two standard deviations. The relationship between mean horizontal spectral amplifications and shear wave velocity for strong ground motions was found to be (Borcherdt, 1991)

$$AHSA = 598/V_s \quad (4)$$

which does not differ significantly from the relationship for weak motions. However, there is great scatter in the data (Fig. 19b).

The explanation of these differences from the geotechnical engineering point of view is the nonlinear response of the soil sites during strong shaking. Nonlinear effects were clearly shown by the dynamic analyses of the Treasure Island site (Idriss, 1990, Hryciw et al., 1991). From the seismological point of view, the much greater proximity of the source to the sites (33 km - 101 km) during the Loma Prieta earthquake introduces factors not present in the weak motion data from sources at distances greater than 400 km. Some of these factors are the increased effects of geometrical spreading, the different types of travel paths for sites in the southern and northern Bay regions and the reflection of energy from the Moho (Borcherdt, 1990). However the amplification data at the Treasure Island site by Jarpe (1990) for the main shock and aftershocks, for which these seismological distinctions should not be very significant did show major differences in amplification consistent with the results of the site specific analyses.

What then may be said about the effectiveness of the shear wave velocity, V_S (small strain) as a parameter for defining relative intensity or damage potential? It is clear that increasing amplification is associated with decreasing shear wave velocity although there is considerable scatter in the data. Therefore, V_S seems to be a very useful parameter in microzoning for damage potential. This is confirmed by the recent studies of Borcherdt et al., (1991). However, the scatter in the data would seem to preclude using zonation to provide any very accurate predictions of ground motion at a specific site. Instead zonation may be useful for delineating areas for which further investigation may be required regarding ground response.

8 CONCLUSIONS

It is clear that there are many uncertainties associated with the estimation of strong ground shaking and damage potential. The reliability of estimates by 1-D nonlinear dynamic response analysis is affected by uncertainty in the input motions and the effects of local topography. Despite these problems, these 1-D site response analyses are likely to give the best estimates for engineering purposes.

Global parameters such as weak motion amplification factors linked to site conditions by site parameters such as average shear wave velocity are especially useful for establishing the relative damage potential or the relative intensity of strong shaking of different geologic units. This kind of data is particularly useful for land use planning to minimize earthquake damage.

9 ACKNOWLEDGEMENTS

The author wishes to thank the following for helpful discussions and constructive criticisms: K. Aki, University of Southern California; R.D. Borcherdt and M. Celebi, U.S. Geological Survey, Menlo Park, California; C.B. Crouse, Dames and Moore, Seattle, Washington, W.J. Silva, Pacific Engineering, El Cerrito, California. The financial support of the National Science and Engineering Council, Canada under grant No. 1498 is gratefully acknowledged.

10 REFERENCES

Aki, K. 1988. "Local site effects on strong ground motion." in J. Lawrence Van Thun (Ed.), "Earthquake Engineering and Soil Dynamic (Recent Advances in Ground-Motion Evaluation", ASCE Geotechnical Special Publication No. 20, pp. 103-155.

Bard, P.Y. and Gabriel, J.C. 1986. "The seismic response of two-dimensional sedimentary deposits with large vertical velocity gradients." Bulletin of the Seismol. Soc. of America, No. 76, pp. 343-346.

Bartlett, S.F. and Youd, T.L. 1992. "Empirical Analysis of Horizontal Ground Displacement Generated by Liquefaction-Induced Lateral Spreads." Technical Report CEG-92-01, Dept. of Civil Engineering, Brigham Young University, Provo, Utah.

Borcherdt, R.D. 1970. "Effects of local geology on ground motion near San Francisco Bay." Bull. Seis. Soc. Am., 60, 29-61.

Borcherdt, R.D., Gibbs, J.F. and Lajoie, K.R. 1975. "Prediction of maximum earthquake intensities in the San Francisco Bay region for large earthquakes on the San Andreas and Hayward faults." U.S. Geol. Survey, Misc. Field Studies Map 709.

Borcherdt, R.D. and Gibbs, J.F. 1976. "Effects of local geology conditions in the San Francisco Bay region on ground motions and the intensities of the 1906 earthquake." Bull. Seis. Soc. Am., 66, 467-500.

Borcherdt, R.D. 1990. "Influence of local geology in the San Francisco Bay region, California, on ground motion generated by the Loma Prieta earthquake of October 17, 1989." Proc., Int. Symp. on Safety and Urban Life and Facilities, Tokyo Inst. Tech., Tokyo, Japan.

Borcherdt, R.D. 1991. "On the observation, characterization and predictive GIS mapping of strong ground shaking for seismic zonation." Proceedings, Pacific Conference on Earthquake Engineering, Auckland, New Zealand, November 20-24, 1991.

Borcherdt, R.D. and Glassmoyer, G. 1991. "On the characteristics of local geology and its influence on ground motions generated by the Loma Prieta earthquake in the San Francisco Bay Region, California." Submitted to Bulletin of the Seismological Society of America.

Borcherdt, R.D., Weatworth, C.M., Janssen, A., Fumal, T. and Gibbs, J. 1991. "Methodology for predictive GIS mapping of special study zones for strong ground shaking in the San Francisco Bay region, California." Proc., 4th Int. Conf. on Seismic Zonation, Palo Alto, California, Vol. III, ppp. 545-552.

Brambati, E. Faccioli, E., Carulli, E., Culchi, F., Onofri, R., Stefanini, R. and Uloigrai, F. 1980. Studio de microzonizzacione sismica dell'are do Tarento (Friuli), Edito da Regione Autonoma Friuli-Venezia, Giulia.

Celebi, M. 1987. "Topographical and geological amplifications determined from strong motion and aftershock records of the 3 March 1985 Chile earthquake." Bulletin of the Seismological Society of America, Vol. 77, No. 4, pp. 1147-1167.

Celebi, M. 1991. "Topographical and geological amplification case studies and engineering implications." Proceedings, International Workshop on Spatial Variation of Earthquake Ground Motion, Elsevier Science Publishers, B.V. Amsterdam.

Faccioli, E. 1991. Seismic amplification in the presence of geological and topographic irregularities, Proceedings, 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, Vol. II, pp. 1779-1797.

Finn, W.D. Liam, Lee, W.K. and Martin, G.R. 1977. An effective stress model for liquefaction. J. Geotech. Eng. Div., ASCE, Vol. 103, No. GT6, pp. 517-533.

Finn, W.D. Liam. 1979. "Role of foundation soils in seismic damage potential." Proc., 3rd Canadian Earth. Eng. Conf., Montreal, Vol.I, pp. 77-116.

Finn, W.D. Liam. 1981. "Liquefaction potential: development since 1976." State-of-the-art paper, Int. Conf. on Recent Advances in Geotech. Earth. Eng. and Soil Dynamics, St. Louis, Missouri, April 26 - May 2, Vol. Ii, pp. 655-681.

Finn, W.D. Liam and Nichols, A.M. 1988.

Seismic response of long period sites: Lessons from the September 19, 1985 Mexican earthquake. Canadian Geotech. J., Feb. 1988, pp. 128-137.
Finn, W.D. Liam. 1988a. "Permanent deformations in ground and earth structures during earthquakes." Proc., 9th World Conf. on Earth. Eng., Tokyo, Japan, August 2-9, Vol. 8, pp. 201-212.
Finn, W.D. Liam. 1988b. "Dynamic analysis in Geotechnical Engineering." Earth. Eng. and Soil Dynamics II - Recent Advances in Ground Motion Evaluation, Geotech. Special Publication No. 20, ASCE, August 1988, pp. 523-591.
Finn, W.D. Liam. 1990a. "Analysis of post-liquefaction deformations in soil structures." Proc., H. Bolton Seed Memorial Symp., Univ. of California, Berkeley. J.M. Duncan (Ed.), Bi-Tech Publishers, Vancouver, Canada, Vol. 2, May 9-11, pp. 291-311.
Finn, W.D. Liam. 1990b. "Geotechnical aspect of microzonation." Proc., Fourth Inter. Conf. on Seismic Zonation, Vol. I, pp. 199-259.
Finn, W.D. Liam. 1991. "Assessment of liquefaction potential and post-liquefaction behaviour of earth structures." Proc., 2nd Intl. Conf. of Recent Advances in Geotech. Earthquake Eng. and Soil Dynamics, March 11-15, Vol. II, pp. 1833-1851.
Griffiths, D.W. and Bollinger, G.A. 1979. "The effect of Appalachian mountain topography on seismic waves." Bulletin of the Seismol. Soc. of America, No. 69, pp. 1081-1105.
Hamada, M., Yasuda, S., Isoyama, R. and Emoto, K. 1986. "Study of Liquefaction Induced Permanent Ground Displacements." Assoc. for the Development of Earth. Prediction, Tokyo, Japan, pp. 1-87, November.
Hensolt, W.J. and Brabb, E.E. 1990. "Maps showing elevation of bedrock and implications for design of engineered structures to withstand earthquake shaking in San Mateo County, California." USGS Open File Report 90-496.
Housner, George W. 1990. Competing Against Time. Report to Governor Deukmejian of California, Governor's Board of Inquiry on the 1989 Loma Prieta Earthquake, George W. Housner, Chairman.
Hryciw, R.D., Rollins, K.M., Homolka, M., Shewbridge, S.E. and McHood, M. 1991. "Soil amplification at Treasure Island during the Loma Prieta earthquake." Proc., 2nd Inter. Conf. on Recent Advances in Geotech. Earth. Eng. and Soil Dynamics, St. Louis, Missouri, Vol. II, pp. 1679-1685.
Hudson, D.E. 1972. "Local distribution of strong earthquake ground motions." Bulletin of the Seismological Society of America, Vol. 62, No. 6, pp. 1765-1786.
Idriss, I.M. 1990. Response of soft soil sites during earthquakes. Proc., H. Bolton Seed Memorial Symp., Berkeley, California, Vol. II.
Jarpe, S., Hutchings, L., Hauk, T. and Shakal, A. 1989. "Selected strong- and weak-motion data from the Loma Prieta earthquake sequence." Seismol. Res. Letters, 60, pp. 167-176.
Jibson, R. 1987. "Summary of research on the effects of topographic amplification of earthquake shaking on slope stability." U.S. Geol. Survey, Open-File Rpt 87-268, Manlo Park, California, USA.
Kawasumi, H., Editor-in-Chief. 1968. "General Report on the Niigata Earthquake of 1964." Tokyo Electrical Engineering College Press, March.
Lee, M.K.W. and Finn, W.D.L. 1978. "DESRA-2, dynamic effective stress response analysis of soil deposits with energy transmitting boundary including assessment of liquefaction potential." Soil Mech. Series No. 38, Dept. of Civil Eng., Univ. of British Columbia, Vancouver, B.C.
Leon, J.L., Jaime, A., and Rabago, A. 1974. "Dynamic properties of soils - preliminary study." Institute of Eng., UNAM (in Spanish).
Lo, R.C., Sy, A., Henderson, P.W., Siu, D.Y., Finn, W.D.Liam and Heidebrecht, A.C. 1991. "Seismic site amplification study for Fraser Delta, British Columbia." 6th Canadian Conf. on Earth. Eng., Toronto, pp. 509-516.
NBCC. 1990. National Building Code of Canada. National Research Council of Canada, Ottawa.
Mitchell, J.K. and Wentz Jr., F.J. 1991. "Performance of improved ground during the Loma Prieta earthquake." Report No. UCB/EERC-91-12, College of Eng., Univ. of California, Berkeley.
Okamoto, S. 1973. Introduction to Earthquake Engineering. University of Tokyo Press, Tokyo.
PWRI (Public Works Research Institute). 1986. "Dense instrument array observation of strong earthquake motion." Ministry of Construction, Tsukubo, Japan.
Romo, M.P. and Jaime, A. 1986. "Dynamic characteristics of some clays of the Mexico Valley and seismic response of the ground." Technical Report, DDF, April, (in Spanish).
Rosenblueth, E. 1991. "Geotechnical lessons learned from Mexico and other recent earthquakes." Proc., 2nd Inter. Conf. on Recent Advances in Geotech. Earth. Eng. and Soil Dynamics, St. Louis, Missouri, Vol. II, pp. 1799-1819.
Sanchez-Sesma, F., Chavez Garcia, F. and Bravo, M. 1988. "Seismic response of a class of alluvial valleys for incident SH waves." B.S.S.A., 78, pp. 83-95.
Schnabel, P.B., Lysmer, J. and Seed, H.B. 1972. "SHAKE: a computer program for earthquake response analysis of horizontally layered sites." Report No. EERC 72-12, University of California, Berkeley, December.
Seed, H.B., Murarka, R., Lysmer, J, and Idriss, I.M. 1976. "Relationships of maximum acceleration, maximum velocity, distance from source, and local site conditions for moderately strong earthquakes". Bulletin of Seismological Society of America, Vol. 66, No. 4, pp. 1323-1342.
Seed, H.B. and Idriss, I.M. 1983. Ground Motions and Soil Liquefaction During Earthquakes. Earthquake Engineering Research Institute, El Cerrito, California.

Seed, R.B. and Harder Jr., L.F. 1990. "SPT-based analysis of cyclic pore pressure generation and undrained residual strength." Proc., H. Bolton Seed Memorial Symp., Univ. of California, Berkeley. J.M. Duncan (Ed.), Bi-Tech Publishers, Vancouver, Canada, Vol. 2, May 9-11, pp. 351-376.

Seed, R.B., Dickenson, S.E., Riemer, M.F., Bray, J.D., Sitar, N., Mitchell, J.K., Idriss, I.M., Kayen, R.E., Kropp, A., Harder Jr., L.F. and Power, M.S. 1990. "Preliminary report on the principal geotechnical aspects of the October 17, 1989 Loma Prieta earthquake." Rpt. No. UCB/EERC-90/05, College of Eng., Univ. of California, Berkeley.

Silva, W.J. 1989. Site geometry and global characteristics, state of the art report, Proceedings of Workshop on Dynamic Soil Properties and Site Characterization, National Science Foundation and Electric Power Research Institute, Palo Alto, California, November.

Sun, J.I., Golesorkhi, R. and Seed, H.B. 1988. "Dynamic moduli and damping ratios for cohesive soils." Report No. UCB/EERC-88/15, Dept. of Civil Eng., Univ. of California, Berkeley.

Tazoh, T., Sato, K., Shimizu, K. and Hatakeyama, A. 1988. Nonlinear seismic response analysis of soil deposit using strong seismic records. Proc., 9th World Conf. on Earth. Eng., Tokyo, pp. 507-512.

Uniform Building Code. 1988. International Conference of Building Officials, 5360 South Workman Mill Road, Whittier, California, U.S.A.

Youd, T.L. 1980. "Ground Failure Displacement and Earthquake Damage to Buildings." Proceedings, Conf. on Civil Eng. and Nuclear Power, Knoxville, Tenn., ASCE, 2, 7-6-1 to 7-6-26.