GEOGRAPHIC VARIATION IN GROUND SHAKING AS A FUNCTION OF CHANGES IN NEAR-SURFACE PROPERTIES AND GEOLOGIC STRUCTURE NEAR LOS ANGELES, CALIFORNIA

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SUMMARY

An empirical technique is developed to predict relative spectral site response in three period bands, as a function of the underlying site properties and geologic structure. A set of three-component recordings of Nevada Test Site nuclear tests and a collection of geotechnical site attributes form the basis of the technique. A suite of site types or clusters is defined having common geotechnical attributes. The clustering attributes are those most strongly affecting site response in a given period band. These clusters, which display usefully stable site factors, and maps of the controlling attributes, permit the construction of maps showing relative site response for Los Angeles.

INTRODUCTION

Although the importance of local geologic conditions has long been recognized (Ref. 1; Ref. 2; Ref. 3) the quantitative prediction of the influence of geologic conditions on ground shaking using either empirical or theoretical models is still in the developmental stage. In this study we extend the technique developed by Ref. 4 to the Los Angeles region and recast the technique to include the effects of geologic structure and near-surface site properties. In order to determine relations between local geologic factors and shaking amplification, 19 nuclear explosions were recorded at 98 sites throughout the Los Angeles region (Ref. 5). Sites for the study were chosen to obtain as complete a sample of underlying geologic conditions and as broad a geographic coverage as possible. Because the seismic source lies between 400 and 450 km from the recording sites, effects of azimuthal variations in the energy radiated by the nuclear source and major portions of the crustal propagation paths are similar for all sites. Estimation of each site's response characteristics over the period band 0.2 to 10 seconds was accomplished by computing Fourier spectra and alluvium-to-crystalline rock spectral ratios (Ref. 5). The site CIT, underlain by crystalline rock, was occupied for every recorded nuclear explosion and served as the base rock site.

In the case of ground motions from distant nuclear explosions, the effects of site conditions predominate on the recorded time histories. For example, Fig. 1A shows time histories recorded simultaneously at eight sites from a single Nevada Test Site nuclear explosion. The example illustrates several effects local site conditions commonly have on the recorded time histories from distant sources of shaking. For instance, maximum amplitudes

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of motion recorded on the alluvial sites are several times larger than those recorded on the sedimentary or the crystalline rock sites. The degree of amplification occurring in the long-period peak amplitudes visible in these records is greatest at sites underlain by the thickest sediments (HOI: 300 m; MIL; 372 m: ATH: 372 m; GMB: 120 m; FS4: 15 m).

The amplitude spectral ratios computed for the simultaneous recordings shown in Fig. 1A are presented in Fig. 1B. The ratios show that the effects of site conditions relative to those at CIT are strongly frequency-dependent, with amplification occurring for many of the sites over most of the frequency band for which a good signal-to-noise ratio exists (Ref. 5). Horizontal amplification factors in the range 2-7 are apparent for the lower-frequency ground motions (<1 Hz) for those sites on thick sections of alluvium, with lower amplifications being apparent at these frequencies for the site underlain by a thin section of alluvium. Considerable amplification at intermediate frequencies (1-2 Hz) and at higher frequencies (2-5 Hz) is readily apparent at several of the sites, especially FS4, where a predominant ground resonant frequency is observed. Note that resonance is not a factor for the thick alluvium sites, which display relatively flat spectra across the entire observed frequency range. The spectral ratios for the GOC site suggest that the response of the two crystalline rock sites (GOC and CIT) is similar for the lower frequencies, but the intermediate and higher frequency motions recorded at GOC are larger than those recorded at CIT. Site 3838, located on sedimentary rock, shows a uniformly higher response compared with CIT over most of the frequency band.

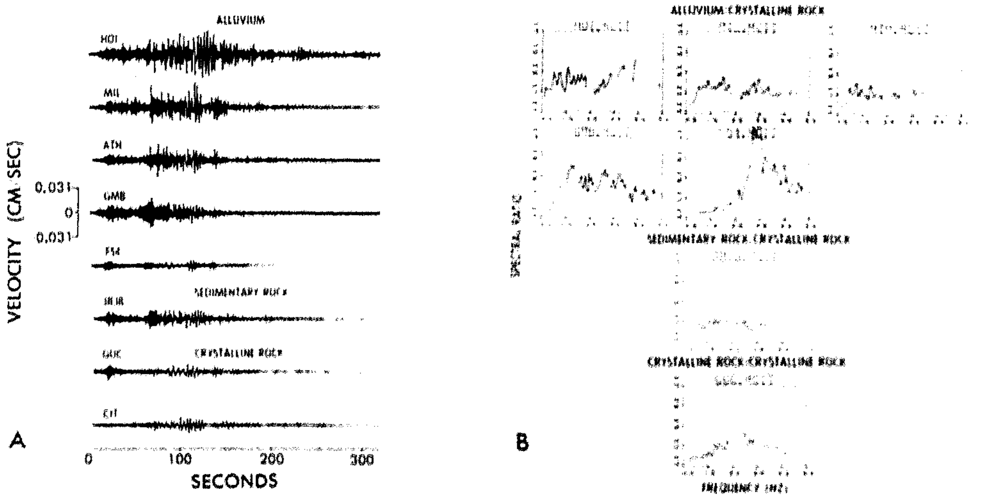


Fig. 1A.--Radial component time histories recorded simultaneously at 8 sites grouped according to type of geologic materials immediately beneath each recording station. 1B.--Spectral ratios of these radial components of ground motion relative to the crystalline rock site (CIT).

COMPARISON OF GROUND RESPONSE WITH GEOLOGIC FACTORS

Geotechnical data describing underlying site conditions and spectral ratios, reduced to mean spectral response values over several period bands, were assembled into a data matrix to facilitate study of the relations between response and the geotechnical attributes (Table 1). These parameters were chosen to characterize the recording sites because either the parameters have some direct application in a theoretical model of site response or the parameters have been reported to have some influence on ground shaking in past studies. Thus, parameters such as percent silt-clay, percent saturation, and depth-to-water table have been reported to influence site response, whereas shear velocity (or void ratio, which strongly influences the shear modulus), Holocene thickness, Quaternary thickness, and and depth-to-basement are all parameters that might be used directly in a model of site response. Most of these data are obtainable from geologic maps, well logs, and city files containing engineering borehole data for construction projects. The data would be of great value if related to site response in some quantifiable manner.

Table I
STATION DATA LIST

Spectral Response Data	Geologic Data	
Frequency Band	*Type*	*Per cent Reported*
Short-Period Band		
0.2 - 0.3 s	Mean Void Ratio (0-8m)	[illegible]
0.3 - 0.5	Mean % Silt-Clay (9 depth ranges)	37.9*
0.2 - 0.5	% Saturation	15
Intermediate-Period Band	Quaternary Deposit Thickness	100
0.5 - 1.0 s	Age	100
0.5 - 3.33	Holocene Deposit Thickness	99
Long-Period Band	Depth to Water Table	97
1.0 - 10.0 s	Sediment Type (very coarse to fine)	99
1.0 - 3.33	Depth to Crystalline Basement	100
3.33 - 10.0	Depth to Cementation	91
Total-Period Band	Mean Bore Hole Shear Velocity (4 intervals)	51
0.2 - 10.0 s		
0.3 - 10.0		

Table 1--List of geotechnical parameters compiled for each station.

To examine the relation between site response and the geological parameters, the most straightforward approach is to group the sites according to variations in one of the geologic factors and to compute mean response for each group. Table 2 indicates the following ground response characteristics: 1.) Sites underlain by Holocene and Pleistocene sedimentary deposits undergo levels of shaking 2.6 to 3.4 times greater than those underlain by crystalline rock for all period bands; 2.) The void ratio has a strong influence on short-period response, with void ratios in the 0.8-0.9 range indicating a mean response on soil 6 times greater than on crystalline rock and 3 times greater than on low-void-ratio soils; 3.) Amplitudes in the long-period band generally increase with increasing thickness of Quaternary deposits and/or depth to basement.

More detailed examination of the influence of all the geologic parameters using the methods of exploratory data analysis (Ref. 6) indicate that the strongest changes in site response were correlated with changes in void ratio, thickness of Holocene deposits, depth to basement, and thickness of Quaternary deposits. Applying the smoothing techniques of exploratory data analysis, it is frequently possible to extract the influence of one factor on the response variable given a body of data in which several factors are changing simultaneously. Fig. 2, for instance, shows the smoothed short-period ratio plotted against Holocene deposit thickness (A) and void ratio (B). The peak in short-period response for Holocene bed thicknesses of about 15 m is due to the shift through this period band of the fundamental resonance period of the Holocene layer. The general increase in the short-period response as void ratio increases is due principally to the increasing shear-wave velocity contrast at the Holocene-Pleistocene boundary. For comparative purposes, theoretical spectral ratios were computed using a horizontally layered SH-body-wave model and assuming constant Q. The physical properties of the geologic column used in this modelling were generated by computer from the geologic data matrix with variable surface layer velocities, fixed lower layer velocities, and depths to velocity contrasts determined by Holocene deposit thickness, Quaternary deposit thickness, and depth

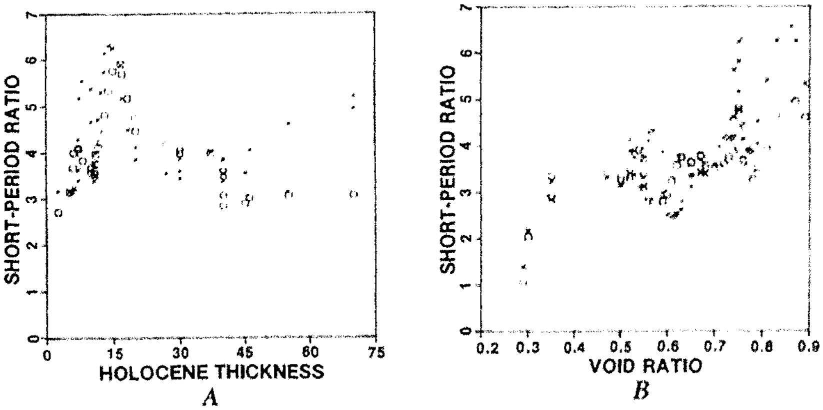


Fig. 2.--Smoothed short-period response at sites on Holocene deposits in comparison with Holocene deposit thickness (A) and void ratio (B). In order to minimize the influence of void ratio in (A), only sites with void ratios greater than 0.65 were included. A circle or X indicates theoretical or observed values, respectively.

Table II
MEAN RESPONSE

A				B	
Age	Short Period (0.3 - 0.5s)	Intermediate Period (0.5 - 3.3s)	Long Period (3.3 - 10.0s)	Void Ratio	Short Period Mean Response (0.3 - 0.5s)
Holocene	3.4	3.3	2.8	0.2 - 0.4	2.3
Pleistocene	3.2	3.1	2.6	0.4 - 0.6	3.1
Pliocene	1.4	1.6	2.0	0.6 - 0.7	3.9
Miocene	[1.9] 2.5	[1.6] 2.2	[1.3] 1.4	0.7 - 0.8	4.3
Mesozoic	1.7	1.1	0.8	0.8 - 0.9	6.2

C			D		
Quaternary Deposit Thickness (m)	Intermediate Period Mean Response (0.5 - 3.3s)	Long Period Mean Response (3.3 - 10.0s)	Depth to Basement (km)	Intermediate Period Mean Response (0.5 - 3.3s)	Long Period Mean Response (3.3 - 10.0s)
0	1.6	1.3	0	1.1	0.6
0-75	2.3	1.4	0-2	2.6	1.3
75-200	3.8	2.9	2-4	2.6	2.5
200-500	3.6	3.1	4-6	3.9	4.1
500-1000	4.1	5.9	>6	3.9	7.9
>1000	3.4	3.1			

Table 2.--Mean site response factors as function of site parameters and period band.

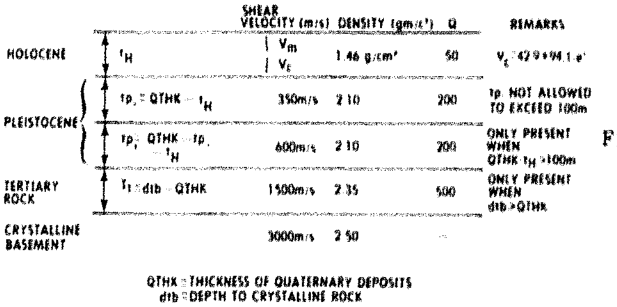


Fig. 3--Shear-wave velocity model used to compute theoretical damped SH-wave response.

to basement (Fig. 3). Surface layer velocities were either measured borehole shear velocities (Ref. 7) or were computed from void ratios. The theoretical spectral ratios and mean spectral values were processed in exactly the same fashion as the observed quantities. The concordance between the observed data and the theory supports our interpretation of the observed behavior. Although similar analysis of other factors indicates that variables such as depth to basement and Quaternary deposit thickness have an effect on the short-period response, these and other variables are secondary in importance to Holocene deposit thickness and near-surface void ratio.

CLUSTERING OF SITES BY GEOLOGIC ATTRIBUTES TO REFLECT SHAKING RESPONSE VARIABILITY

Sites with similar response characteristics can be clustered by computing an analytical measure of similarity between a list of items based on their attributes. In our analysis, the items are recording sites and the attributes are the geotechnical properties of each site. (Note that we do not use the response factor as an attribute because we are attempting to predict response as a function of the geologic properties of the site). The clustering algorithm (Ref. 8) uses a computing rule to establish those items most nearly alike and the similarity level at which clusters of similar items are alike. The results can be plotted as an inverted hierarchical tree of similarity nodes. The choice of a similarity level below which clusters form is a subjective judgment and in practice may change across the cluster diagram.

Once a set of clusters is formed by this procedure on a chosen set of factors, the degree to which these factors define unique groups can be analyzed using discriminant analysis (Ref. 9), which determines the significance of each factor's discriminating power using the statistics of factors within and between clusters. A set of discriminant functions are computed that enable one to calculate the probability that a single member of a cluster belongs to that cluster or to any other cluster. Given a table of these probabilities, the percentage of sites that have been correctly classified can be calculated.

In our application, this procedure was a trial and error process, during which some of the data analysis described was done concurrently with the cluster and discriminant analysis. At the start, the site response data were first divided into rock and alluvium groups, and then clusters were examined in which many or all of the measured factors were part of the clustering model. This approach, however, produces too many clusters, with too few station members. The number of factors in the clustering process was reduced iteratively by gradually discarding factors having low statistical significance in the discriminant analysis.

Comparison of the mean response values in each cluster set for the three period bands revealed that some clustering parameters reduced the response variance in each cluster better than others, in accord with the results of the preliminary data analysis showing that the most important factors in each period band should be different. Ultimately, the cluster sets selected were chosen because they had the lowest dispersion in the defining variables while using those factors having the strongest effect in a given period band; in addition, the probability of misclassification was low, and each cluster in the set had a sufficient amount of data to estimate the mean cluster properties. The final sets of clusters are a compromise between the many clusters required to preserve the complexity in the site response as a function of geology, and the requirement that each cluster contain enough cases to estimate its average response.

Fig. 4 shows the set of two rock and eight alluvium clusters that were derived for the short-period band. This figure can be understood by using cluster 4A as an example; that cluster includes sites that have a depth to basement rocks of greater than 0.5 km, a Holocene deposit thickness greater than 20 m, void ratios in the range 0.6–0.7, and a geometric mean response of about 3.6. Using these clusters to predict response preserves the important features of site behavior. For instance, for a fixed Holocene deposit thickness, response increases as void ratio increases (compare clusters 1A, 3A, and 6A, for example). Response also increases, for a constant void ratio, as the Holocene deposit thickness increases to the critical range (compare clusters 6A, 7A, and 8A, for example). Note that the clusters with thin Holocene cover also contain most of the Pleistocene sites; those Pleistocene sites in the thickness range 11 to 20 m, however, are grouped with the Holocene sites in this range. The rock sites 1R and 2R indicate a geometric mean response that typically is lower than that of the alluvium clusters, as might be predicted on the basis of surface velocities. A comparison of clusters 1A and 2A shows that sites underlain by shallow alluvium over crystalline rock (2A) have a response two times higher than does the same type of site overlying a deep sedimentary basin, further emphasizing the role of high impedance contrasts at shallow depths. Even though we were able to divide the sites into only ten clusters, resulting in a moderate range in the geologic and response factors in each cluster, a useful result can be demonstrated by comparing average spectral level with shaking intensity. A reasonable assumption is that a factor of two in mean spectral level corresponds to a change of one Modified Mercalli intensity unit (Ref. 10); we infer, then, from the data of Fig. 4 that these clusters predict the true site-response more closely than one intensity unit increment for 90% of the cases, because the geometric 90% confidence interval is less than a factor of two (1.45). Clusters were derived for the intermediate- and long-period bands on the basis of Quaternary thickness and depth-to-basement rock. These clusters will not be discussed here.

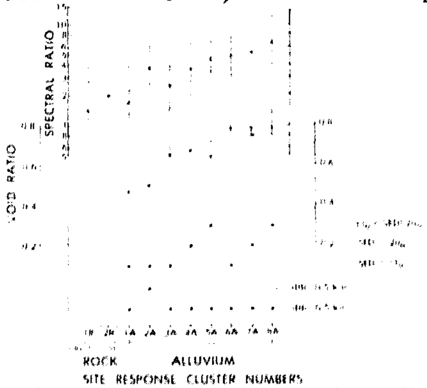
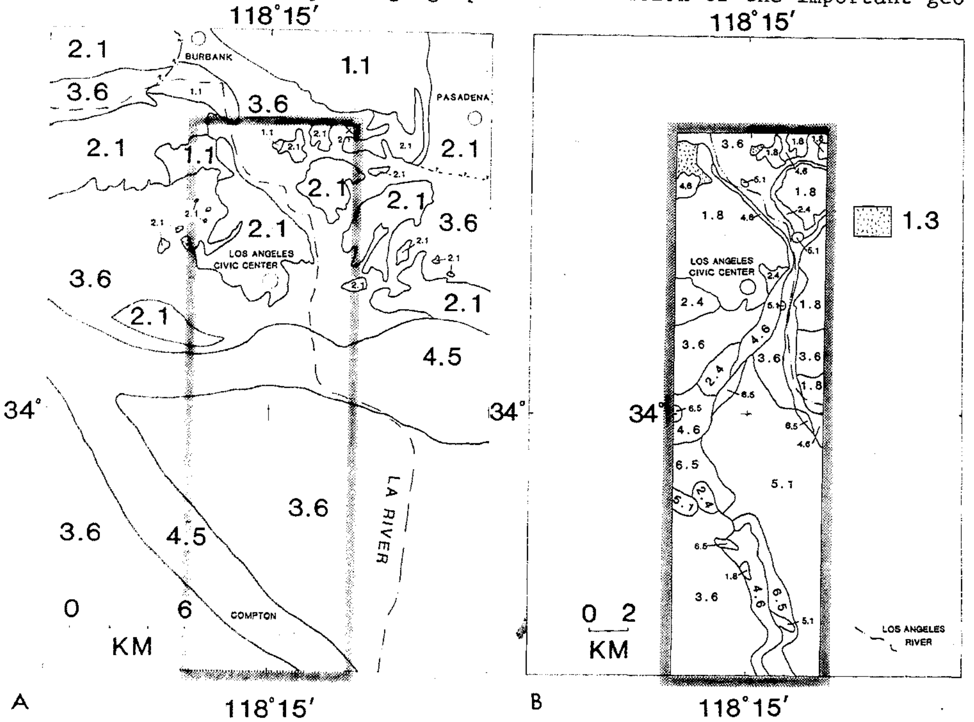


Fig. 4.--Site clusters for short-period ground motions in the Los Angeles region. Solid dots indicate the mean of the short-period spectral ratios for a given cluster, mean void ratio, Holocene deposit thickness, and depth to basement rock groups, as appropriate. Vertical bars indicate the range in the variable for a given cluster, and side ticks indicate the 90% confidence intervals.

SITE-RESPONSE PREDICTION MAPS FOR A PORTION OF THE LOS ANGELES REGION

Response maps for the intermediate- and short-period bands for a small area approximately centered on the Los Angeles Civic Center are shown in Figs. 5A and 5B, which are based on the clusters just discussed and on a set of maps delineating the geographic distribution of the important geotechnical factors. The intermediate-period map (Fig. 5A) of significance to structures between 5 and 30 stories high, predicts that low response will characterize areas underlain by rock and alluvium thicknesses of less than about 150 m; intermediate levels of response will be observed where alluvial thickness is greater than 150 m and/or depth to basement rocks is in the 0.15 to 4 km range; highest levels of response will be observed in areas where the depth to basement rocks ranges between 4 and 6 km. Slightly lower levels of response are predicted in the deepest parts of Los Angeles basin. The lowest response will be in the areas where crystalline basement is at or near the surface in the Santa Monica Mountains and the Verdugo Mountains. South of Burbank and west of Pasadena, the relatively thin alluvium in the intermontaine basin areas and along the Los Angeles River valley near the eastern end of the Santa Monica Mountains and north of the Los Angeles Civic Center also will exhibit a low to intermediate response. Response is expected to increase to the northwest (San Fernando Valley) and southern Los



Figs. 5A & 5B.—Maps of predicted relative shaking response for part of the Los Angeles basin. Numbers are mean amplification factors, comparing levels of shaking to sites on crystalline basement rock. A. Map for intermediate-periods (0.5-3.3 seconds). Stippling outlines area of Fig. 5B. B. Map for short-periods (0.2-0.5 seconds).

Angeles basin. In the area shown in the southwestern part of the map, the response will be relatively low where crystalline basement rock is about 3 km deep along the Newport-Inglewood structural zone. The long-period map is similar to this map except that the long-period map predicts low response in regions where alluvium thicknesses are less than 300 m and/or depth to basement rock is less than 3 km.

The short-period map (Fig. 5B), which is most relevant to buildings in the 2-5 story class, has been prepared for the central third of the area shown in the long-period map. The lowest response is predicted for areas underlain by crystalline and sedimentary rock, and the highest response is observed in regions where thicknesses of near-surface alluvium (11-20 m) and high void ratios (greater than or equal to 0.7) produce significant resonant response in this period band. In some respects, this map closely resembles a surficial geologic map; thus, details of the alluviated valleys, including that of the Los Angeles River, are delineated. The southwest part of the map depicts an area where silt (characterized by high void ratios) deposited by the Los Angeles River thin to the west and wedge out along the east flank of the Newport-Inglewood zone where deformed Pleistocene deposits characterized by low void ratios are exposed. Note that high short-period response may occur at sites underlain by rock if these sites are near the crest of a ridge or other pronounced topography, as shown by the range of high response for clusters 1R and 2R (Fig. 4).

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