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SYNOPSIS: Strong motion records of the Loma Prieta Earthquake of October, 17, 1989 have been analyzed in comparison with epicentral distances and types of soil deposits, and site effects and attenuation relations have been studied. Site effects are significantly recognized in the earthquake, as usually found in Japanese earthquakes. And validity of the U.S. seismic intensity prediction method that Association of Bay Area Governments (ABAG) adopted to prepare some earthquake-preparedness maps has been examined on the basis of the Loma Prieta Earthquake data. Finally, soil damping of San Francisco Bay Area has been evaluated from the strong motion records.

INTRODUCTION

The Loma Prieta earthquake (M=7.1) struck San Francisco Bay Area on October 17, 1989, and caused a lot of damage, especially on the soft soils. They have had no major earthquake (M6.5-M7.5) and no great earthquake (M>7.5) in this region, since the Coyote earthquake of 1911 and the San Francisco earthquake of 1906.

Knowledge of the intensity and nature of ground motions is fundamental to sound earthquake engineering design. In Japan, it has been evident that local ground conditions can have significant effects on earthquake ground motions. In the U.S., not until the 1970's, however, were the phenomena understood well enough for relevant items to be incorporated into building codes and design procedures. From the above viewpoint, the Loma Prieta earthquake is a valuable earthquake to study them. Fortunately, some seismic intensity prediction projects have been performed to cope with major and great earthquakes in San Francisco Bay Area.

The objectives of this study are threefold: 1) to consider site effects of intensity and attenuation in the Loma Prieta Earthquake of October, 17, 1989; 2) to examine validity of the U.S. seismic intensity prediction method; 3) to consider soil damping characteristics in one-dimensional wave propagation analysis from the strong motion records.

A SEISMIC INTENSITY PREDICTION METHOD

Association of Bay Area Governments prepared maps of earthquake intensity and related damage in order to estimate earthquake intensity and cumulate damage potential from earthquake ground shaking, as one of earthquake preparedness programs. The intensity prediction method are summarized as follows:

Maximum Magnitude and Intensity on the Active Faults For strike-slip faults ; M = 0.597 + 1.351xlog L : For normal faults ; M = 1.845 + 1.151xlogL : For reverse and thrust faults ; M = 4.145 + 0.717xlogL, where L = fault rupture length in meters. The length of fault rupture typically chosen for use is one half the total mapped length. But, a second set of maximum magnitudes is calculated for comparison using the total mapped length, because the assumption is not universally accepted. Modified Mercali Intensity = 1.5 x M - 1.5, where M = Magnitude calculated assuming that 1/2 the total mapped fault length represents the maximum fault rupture length. Intensity-Distance Attenuation Predicted San Francisco intensity on a standard bed rock material = 2.69 - 1.9xlogD, where D = distance in km from the fault. In the formula, the SF intensity ranges of A-E are expressed numerically between 4 and 0. The attenuation relationship is based on data from the 1906 earthquake. Table 1 shows the relationship between the SF intensity and MM intensity. Correcting the General Formula for Geology Site effects are evaluated by adding an intensity increment, shown in Table 2, to the derived SF intensity on standard rock for any given distance.

Table 1 APPROXIMATE RELATIONSHIPS BETWEEN INTENSITY SCALE

(modified from Wood,1908, p.2-6 and Wood.and Newman. 1931, p.280-281)

San Francisco * scale	Modified Mercalli scale
A	XII
A / B	XI
B	X
B	IX
B / C	VIII
C / D	VII
D / E	VI

* San Francisco Intensity
A: Very Violent
B: Violent
C: Very Strong
D: Strong
E: Weak

Table 2 SEISMICALLY DISTINCT UNITS AND PREDICTED INTENSITY INCREMENTS

SEISMIC UNIT *	MATERIAL PROPERTIES	PREDICTED SAN FRANCISCO INTENSITY INCREMENT
SEDIMENTS		
I	Clay-silty clay, very soft to soft	2.9
II	Clay-silty clay, medium to hard	1.8
III	Sand, loose to dense	1.7
IV	Sandy clay-silt loam, interbedded coarse and fine sediment	1.4
V	Sand, dense to very dense	.9
VI	Gravel	.4

SEISMIC UNIT *	MATERIAL PROPERTIES			PREDICTED SAN FRANCISCO INTENSITY INCREMENT
BEDROCK	ROCK TYPE	HARDNESS	FRACTURE SPACING	
I	Sandstone	firm to soft	Moderate and wider	.7
II	Igneous, Sedimentary	Hard to soft	Close to very close	.3
III	Igenous, Sandstone, Shale	Hard to firm	Close	.0
IV	Igneous, Sandstone	Hard to firm	Close to moderate	-.3
V	Sandstone, Conglomerate	firm to hard	Moderate to wider	-.5
VI	Sandstone	Hard to quite firm	Moderate & wider	-.8
VII	Igneous	Hard	Close to moderate	-1.1

*Note that Roman numerals reoresenting seismic units for sediments are not underlined while numerals for bedrock units are underlined.

EXAMINATION BASED ON DATA OF LOMA PRIETA EARTHQUAKE

A maximum magnitude 6.8 calculated for strike-slip fault and 7.4 for reverse and thrust fault by substituting 40000 m, the fault rupture length of the Loma Prieta Earthquake to the formulas. The values agree with magnitude 7.1 of the earthquake. Seismic MM intensity on the fault was calculated IX (9.15) for M=7.1 and X (9.6) for M=7.4. Maximum horizontal acceleration of 0.64g at Corralitos, 7.2 km far from the epicenter, corresponds to the lower of MM intensity X. The prediction method is excellent at this stage.

Figure 1 presents maximum horizontal accelerations of the earthquake on and around Sky Londa - Coyote Hill line, parallel to Dumburton Bridge, with geological cross-section. The section is almost perpendicular to the San Andreas Fault, the rupture fault of Loma Prieta earthquake. An average of max. acc. on alluvium soils is 2.4 times larger than that on rocks. A ratio of maximum and minimum of max. acc. is 4.2. In spite of almost the same epicentral distances, site effects on seismic intensity are profoundly noticeable.

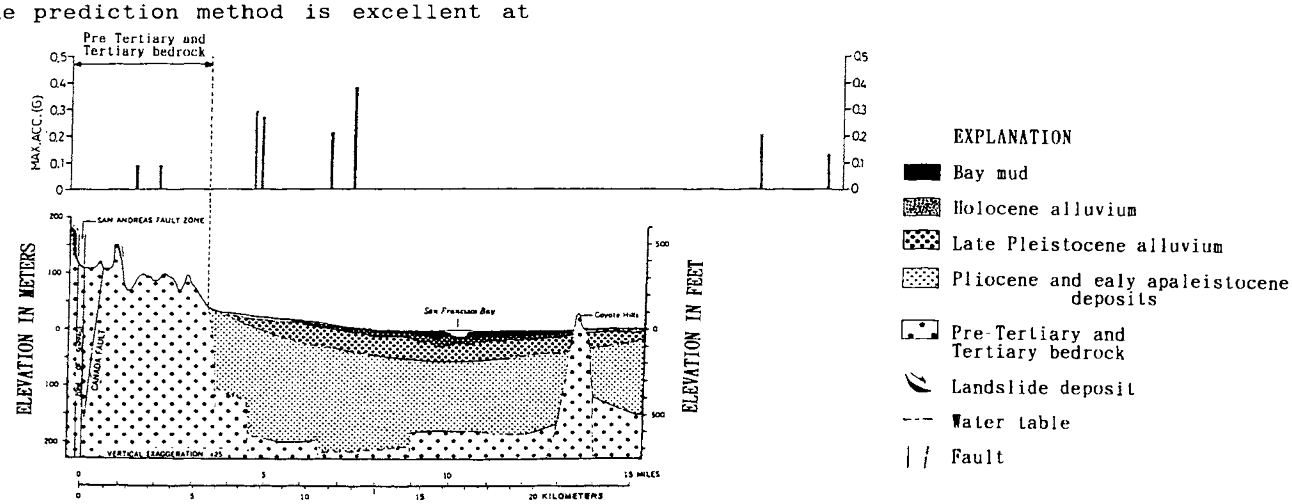

Fig. 1 MAX. ACCELERATIONS AND GEOLOGICAL CONDITIONS (SKYLONDA - COYOTE HILL PROFILE)

Figure 2 shows max. acceleration - epicentral distance relationships at stations with maximum and minimum values by using ABAG prediction method. Figures 3 and 4 present the relationships on stiff soils & rocks and on soft soils, respectively. ABAG evaluation gives extremely small values, compared with strong motion data both on stiff soils & rocks and on soft soils. Both attenuation and site effects are underestimated in ABAG seismic intensity prediction method.

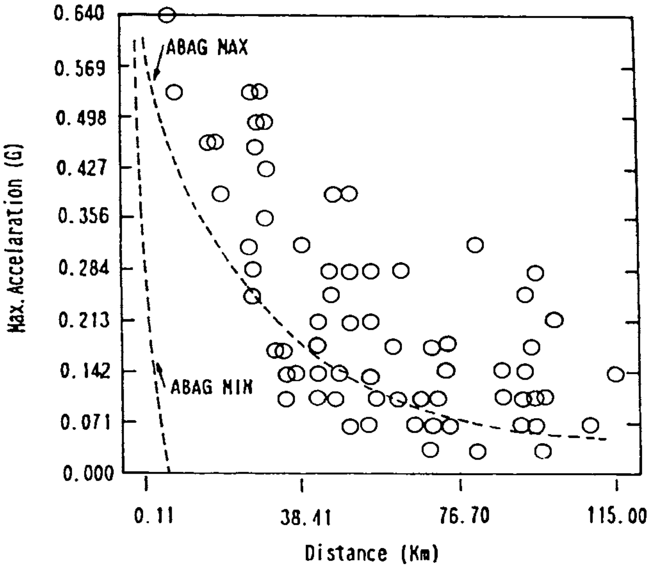

Fig. 2 MAX. ACCELERATIONS AND EPICENTRAL DISTANCES (ALL DATA)

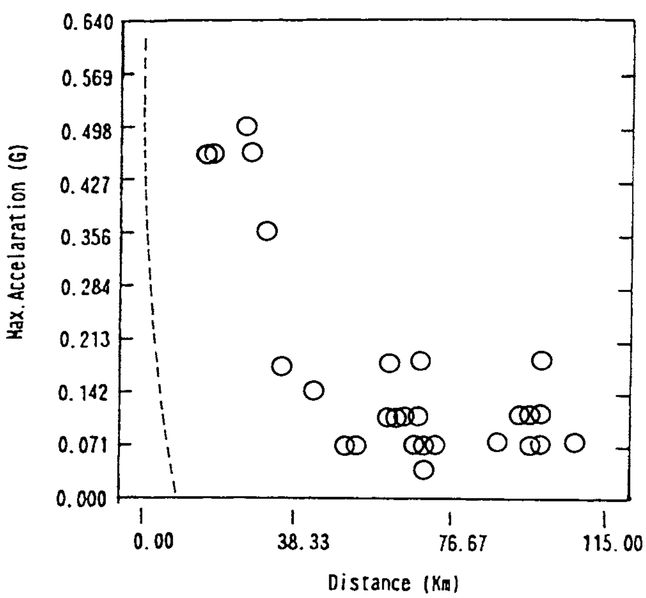

Fig. 3 MAX. ACCELERATIONS AND EPICENTRAL DISTANCES (ON ROCKS)

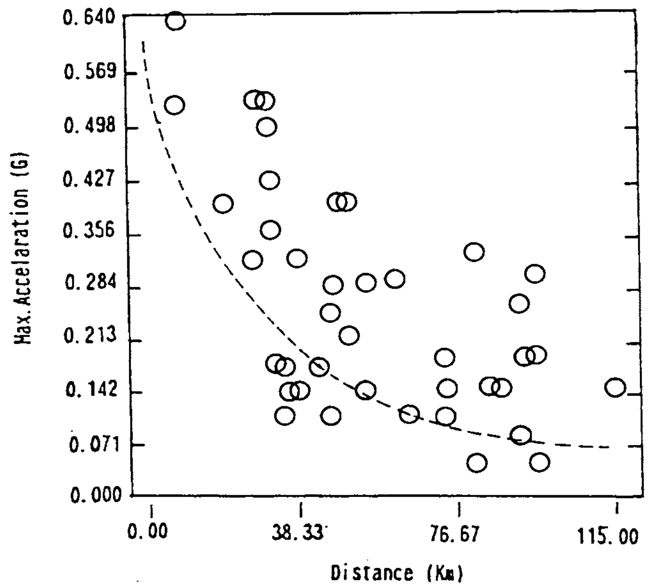

Fig. 4 MAX. ACCELERATIONS AND EPICENTRAL DISTANCES (ON SOFT SOILS)

DAMPING EVALUATED FROM STRONG MOTION RECORD

Damping of soil was examined by using two CDMG strong motion records digitized from the analogue date. Foster City - Redwood Shore site is covered with alluvium of 210 meter depth on serpentine bed rock. Wood Side - Fire Station site, which is about 13 kilometers away from the Redwood Shore site, is located on sandstone. EW accelerogram (Max. Acc. 80 gals) of the Wood Side site was assumed to be an outcropped record of the Foster City EW accelerogram (Max. Acc. 290 gals). Figure 5 shows spectra of the two records. Ramberg-Osgood relation was used as backbone curve of soil nonlinearity in 1-D linearized wave propagation analysis with equivalent shear modulus and damping ratio, and formulas was derived from R-O relation as G-γ and h-γ relations of soil. Appropriate parameter values were searched by changing parameter values of R-O relation, and comparing amplitudes and spectra of accelerations with those of EW strong motion record at Redwood shore..

Soil at Redwood shore is mainly composed of very soft silty clay and shear wave velocities in the analysis are assumed to be 80 m/sec (G.L.-11m), 114 m/sec (-11m-18m), 233m/sec (-18m-40m), 380 m/sec (-40m-210m) and 700m/sec (-210m-), derived from measurements and soil profile data of USGS and Study of E. W. Warrick(1974). In the analysis, G_0 and reference stress of R-O relation are assumed to be the shear modulus at the strain of 1×10^{-6} and the stress at the strain of 5×10^{-4}, respectively. An exponent b of the relation is a variable. Two types of damping were examined; viscous damping and linear hysteretic damping.

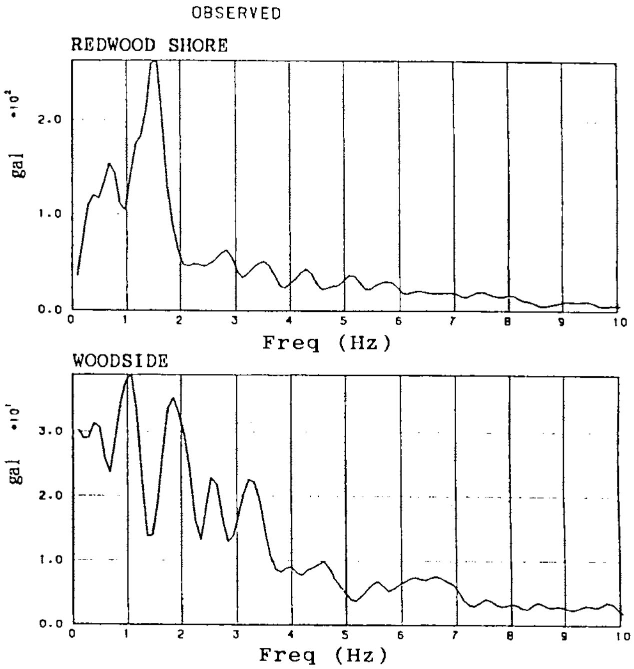

Fig. 5 ACCELEROGRAMS SPECTRUM AT REDWOOD SHORE AND INPUT SPECTRUM FROM WOODSIDE

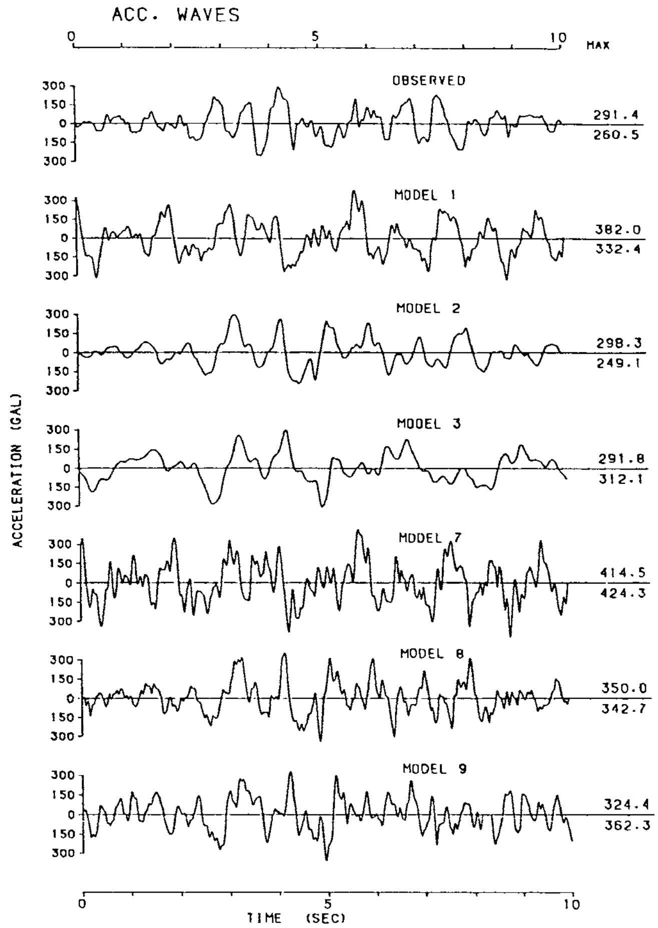

Fig. 6 RESULTS OF MODELS (MODEL 1-3, MODEL 7=9)

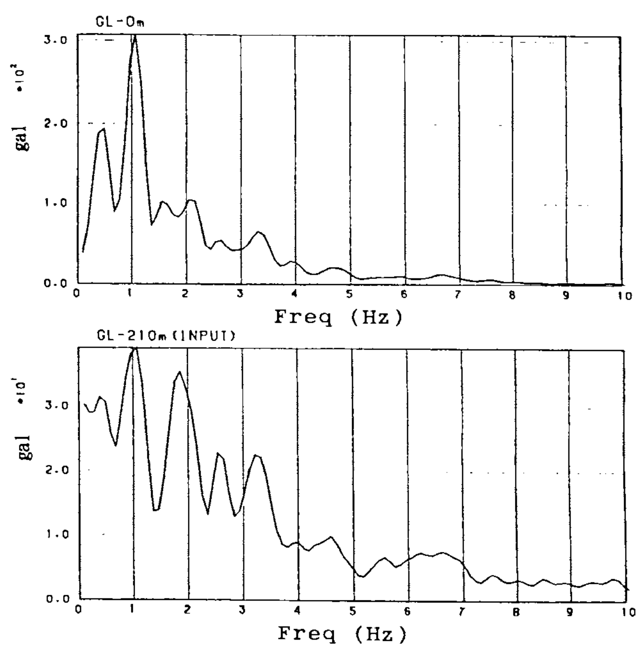

Fig. 7 OUTPUT AND INPUT SPECTRA OF MODEL 2

Figure 5 shows accelerogram spectrum at Redwood shore and input spectrum derived from Woodside. The observed data are compared with calculation results of some models in Fig. 6. Models 1-3 are assumed to be viscous damping type. An R-O relation parameter b is assumed 3.0 for model 1, 2.0 for model 2, and 1.0 for model 3. Models 7-9 are assumed to be hysteretic damping type, and damping is determined at 5 Hz and frequency-independent. The parameter b is 3.0 for model 7, 2.0 for model 3 and 1.0 for model 9. Model 2 (b=2, viscous damping) is most appropriate one, and output and input spectra are shown in Fig. 7.

Through the analysis, G-γ relation does not much affect the response. On the other hand, h-γ relation affects significantly the response, as shown in Fig. 6. As shown in Fig. 7, the relation of h-γ derived from strong motion records is smaller than that generally used induced from laboratory soil tests more than ten years ago.

Figure 8 shows comparison between the observed accelerogram and the result of model 2. The numerical result shown by broken line agrees with the observed of solid line, though the numerical result of the linearized 1-D method includes inevitable discrepancies of phase. Figure 9 presents accelerations and shear stresses in soil profile at Redwood shore by using model 2. Figure 10 shows calculated accelerations and shear stresses at Redwood Shore.

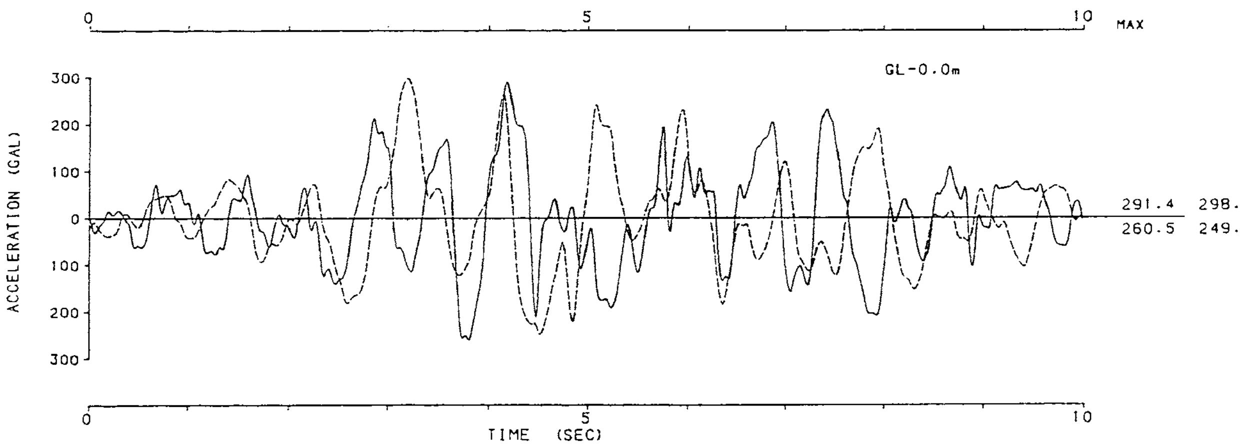

Fig. 8 COMPARISON BETWEEN OBSERVED ACCELEROGRAM AND MODEL 2 RESULT

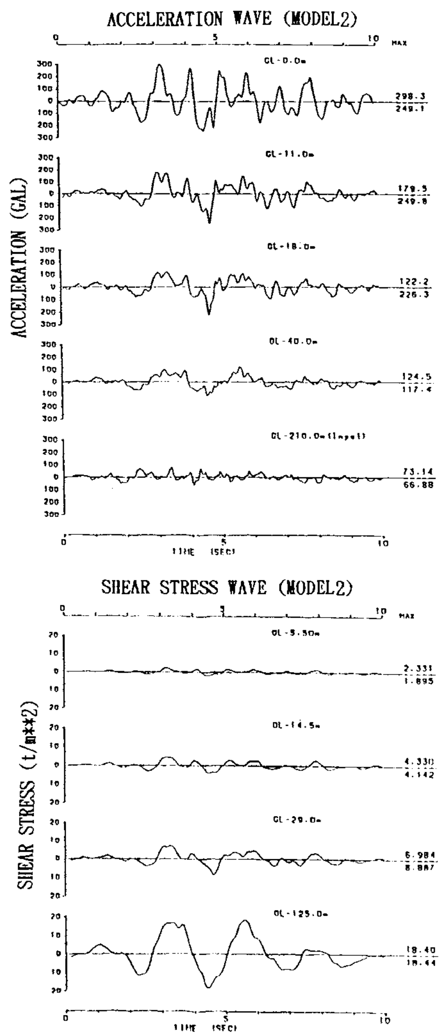

Fig. 9 accelerations and shear stresses in soil profile at Redwood shore (MODEL 2)

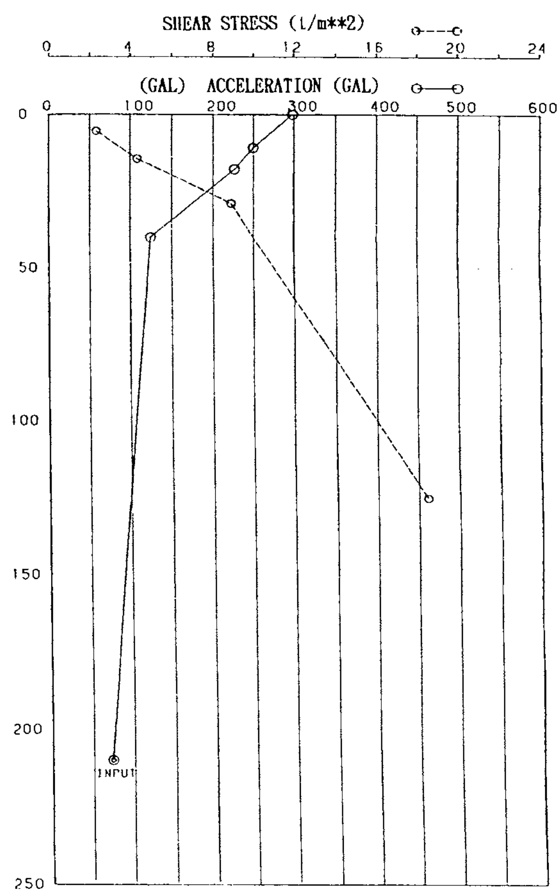

Fig. 10 ACCELERATIONS AND SHEAR STRESSES AT REDWOOD SHORE (MODEL 2)

CONCLUSIONS

From the results of analysis the following conclusions may be drawn:
1) Site effects during the Loma Prieta earthquake are significantly. The effects should be more adequately considered in the US earthquake preparedness programs, and attenuation evaluation should be adjusted in ABAG seismic intensity prediction method on the basis of the Loma Prieta earthquake data.
2) Damping determined from Redwood shore strong motion accelerogram is smaller than that generally used. In the 1-D linearized wave propagation analysis, more attention should be paid to damping determination for evaluating adequate site effects.

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