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Damage Patterns/Response of Deep Stiff Clay in Oakland

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SYNOPSIS: The 1985 Mexico City earthquake and the 1989 Loma Prieta earthquake provided well-documented evidence of the effect of local ground conditions on site response and damage patterns. Deep soft clay deposits, in particular, were often cited as the "culprit" of amplified ground motions. However, during the 1989 Loma Prieta earthquake, ground accelerations in the downtown Oakland area were amplified by a factor of two to four and a significant number of structures were heavily damaged, despite the fact that much of the area is underlain by deposits of deep *stiff* clay. A preliminary review of damage patterns in the Oakland area and preliminary site response analyses were performed to investigate the influence of deep stiff clay deposits on the observed ground motions.

INTRODUCTION

The 1989 Loma Prieta earthquake provided well-documented evidence of the effect of local ground conditions on site response and damage patterns. The observed amplification of ground motions by thick layers of soft clay deposits was a repetition of previous earthquake experiences, such as the 1985 Mexico City earthquake (Seed and Sun, 1989). However, during the 1989 Loma Prieta earthquake, ground accelerations in the downtown Oakland area were amplified by a factor of two to four and a significant number of structures were heavily damaged, despite the fact that much of the area is underlain by deposits of deep "stiff" clay. In addition, the damage that Oakland suffered far exceeded the damage experienced by the metropolitan San Jose area, located about halfway between Oakland and the epicenter of the Loma Prieta earthquake. A preliminary review of damage patterns in the Oakland area and preliminary site response analyses were performed to investigate the influence of deep stiff clay deposits on the observed ground motions.

LOMA PRIETA EARTHQUAKE

The Loma Prieta earthquake occurred on 17 October 1989 and ruptured a 40 km (25 mi) long segment of the San Andreas Fault. The hypocenter (point of initial rupture) was located approximately 16 km (10 mi) northeast of Santa Cruz at a depth of 19 km (11.5 mi) and approximately 100 km (62 mi) south of the San Francisco/Oakland area. The earthquake has been assigned a Richter magnitude of $M_L=7.0$ and a surface wave magnitude of $M_s=7.1$; however, the duration of strong shaking (roughly 8 to 10 seconds) was much shorter than expected for events of this magnitude due to the bilateral propagation of the fault rupture.

LOCAL GEOLOGY AND SUBSURFACE CONDITIONS

The city of Oakland is located on the east side of San Francisco Bay. San Francisco Bay is a part of a larger structural geologic depression that has been filled to great depths with interfingering, relatively coarse-grained alluvial deposits and clays deposited in a subaqueous environment. Figure 1 shows a bedrock contour map of the Oakland area, prepared by Rogers and Figuers (1991). Along the east side of the Bay, the basement rock rises rapidly in the east and northeast directions from a depth of about 500 feet in the Oakland area to rock outcrops within a distance of no more than 2 to 3 miles. In addition, a small knoll of bedrock rising to approximately elevation -360(MSL) is located near the heart of downtown Oakland. The basement rock also rises gently toward the north and northwest. Thus, the downtown Oakland area is situated near a bedrock valley boundary.

The geologic profile of the Oakland area may generally be described as recent sediments (including artificial fill, Temescal Formation alluvium, and some Young Bay Mud along the bayshore) over the Pleistocene age San Antonio Formation, Pleistocene age Alameda Formation, and Jurassic-Cretaceous age bedrock of the Franciscan Assemblage. The San Antonio Formation includes varying thicknesses of wind and water deposited Merritt Sands overlying medium stiff to very stiff marine silty clay. The Alameda Formation consists of an upper unit of very stiff to hard marine clay and a lower unit of continental sandy oxidized clay. The marine silty clay deposits of the San Antonio and upper Alameda Formations are locally known as Old Bay Clay (Trask and Rolston, 1951).

DAMAGE PATTERNS

The common perception that areas of heavy damage were concentrated on deep soft clay sites overlooks the substantial damage that occurred on deep stiff clay sites such as the Oakland area. In fact, deep deposits of soft marine clay, locally known as Young Bay Mud, are noticeably absent throughout much of the Oakland area that experienced heavy damage.

Based on the "Earthquake Damaged Buildings Summary" dated 18 June 1990 provided by the City of Oakland (Office of Planning & Building, Plan Check/Seismic Safety Division), 147 structures were designated "unsafe buildings" (red-tag) and 347 buildings were designated "limited entry" (yellow tag); in addition, 852 sites were listed as "unsafe areas," typically due to potential chimney hazards. Of the 147 red-tagged structures, 48 were classified as "immediate hazards." The summary list provided by the City includes buildings of all heights and types of construction including wood-frame, steel-frame, reinforced concrete, and unreinforced masonry. Although none of the

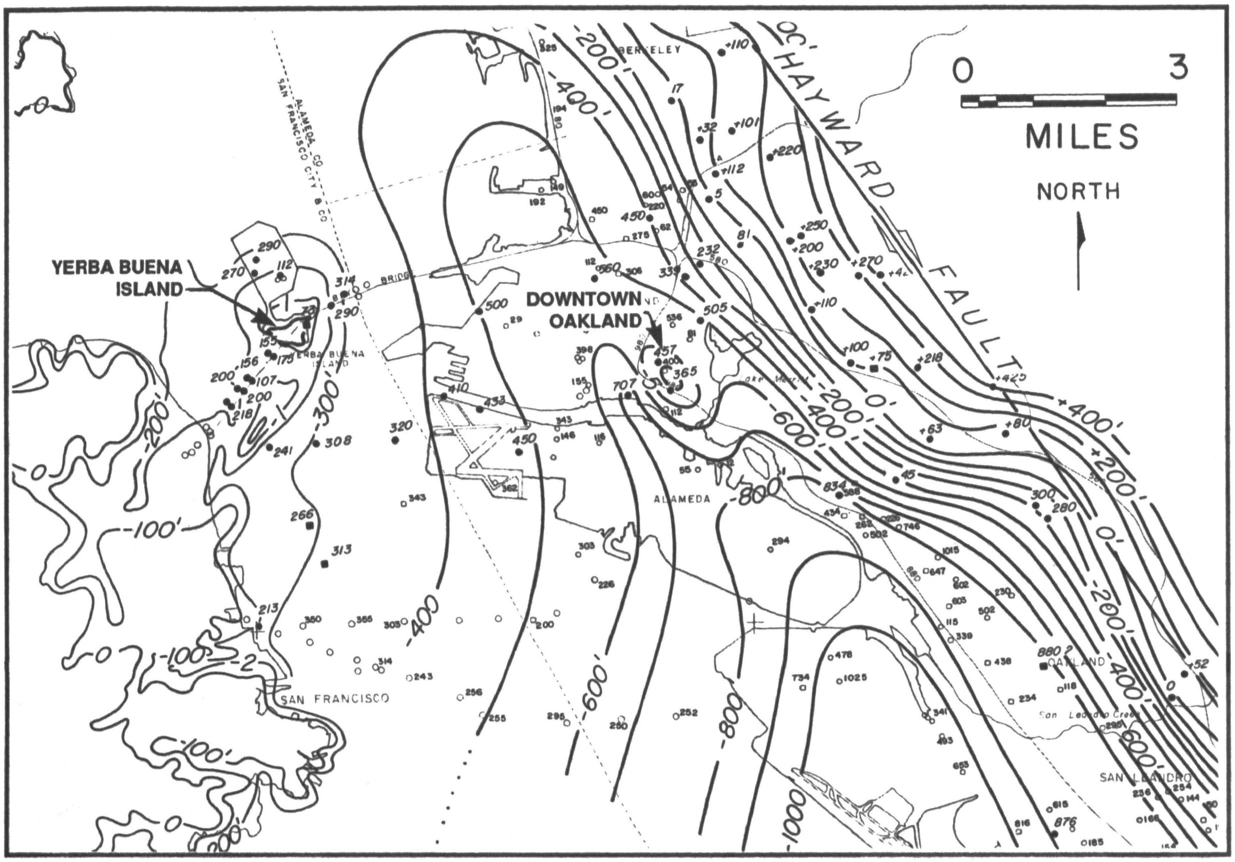

Figure 1: Bedrock Contour Map of the Oakland Area (Rogers and Figuers, 1991)

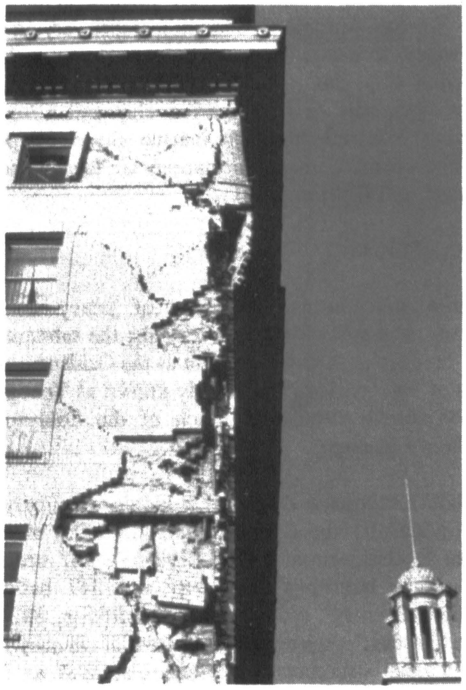

Figure 2: Damage to an Upper Corner of the Hotel Oakland (Photo courtesy of S. A. Mahin)

structures failed as dramatically as the collapse of the Cypress Viaduct double-deck freeway (Interstate 880), damage to structures was substantial and included severely cracked columns, shear walls and beams; collapsed roofs and walls, tilting or leaning; loosened parapets; shattered windows; and separation from foundations. The heavily damaged multi-story buildings appear to have been built between about 1930 and 1970. Figure 2 shows a photo of damage to the eight-story Hotel Oakland, a typical multi-story structure in the Oakland area. Multi-story structures constructed approximately within the last ten years generally performed satisfactorily during this distant event; however there were instances of severe architectural damage.

Although damage in the general Oakland area was widespread, the most heavily damaged buildings are located in the downtown Oakland area. Figure 3, prepared by the City of Oakland, shows the locations of red- and yellow-tagged buildings in the downtown area. The intensity of the shaking and the concentration of damage can easily be appreciated from this figure. The depth to bedrock in this general area is about 350 to 500 feet.

OBSERVED SEISMIC RESPONSE AND COMPARISON WITH THE 1991 UBC

Five strong-ground-motion stations in the Oakland area recorded the following peak horizontal ground accelerations:

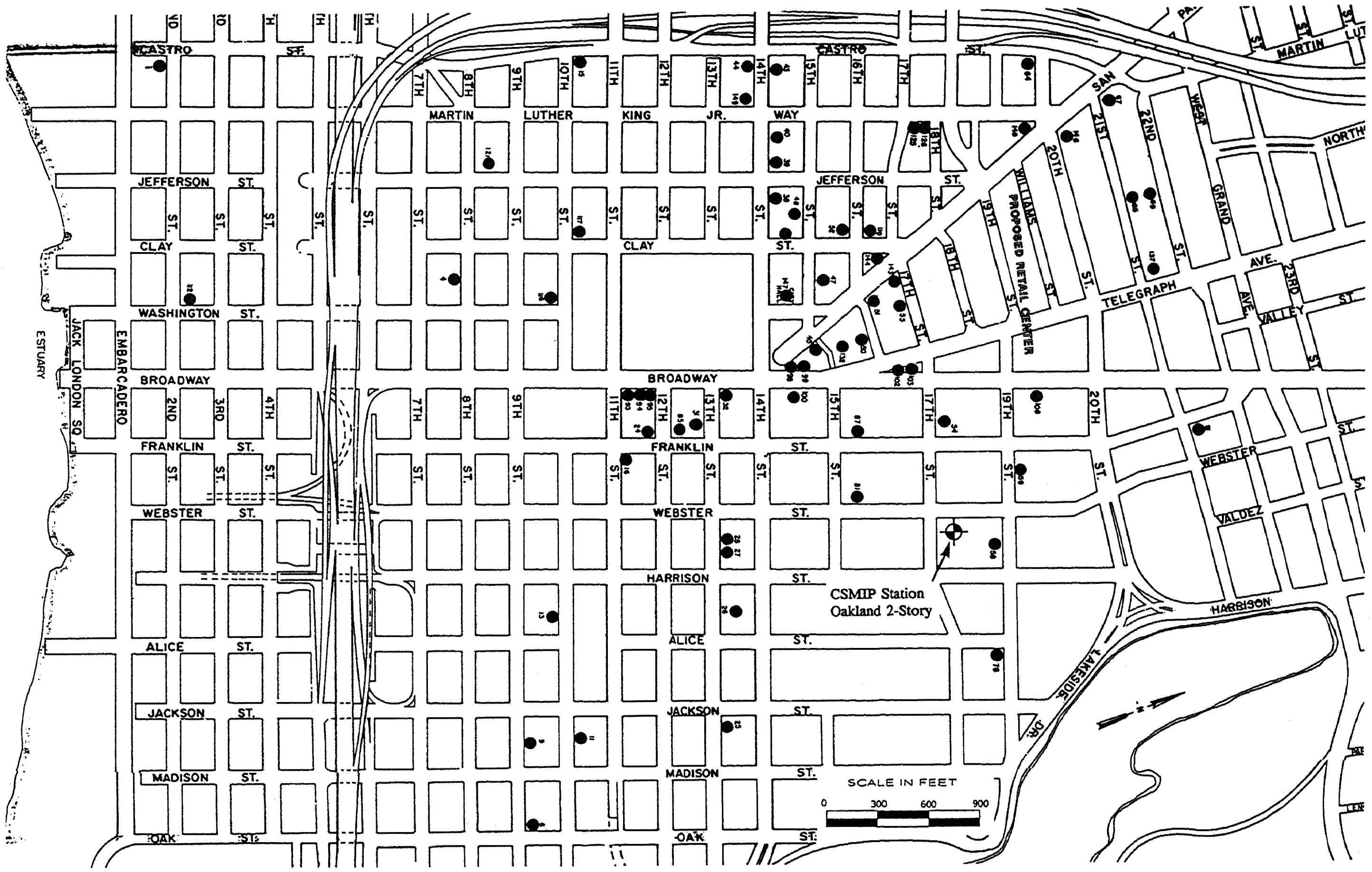

Figure 3: Areas of Substantial Damage in the Oakland Area (Courtesy of the City of Oakland)

Station	Peak Horizontal Ground Acceleration(g)
Oakland 2-story (ground floor)	0.26
Oakland 24-story(ground floor)	0.18
Oakland Outer Harbor Wharf	0.29
Emeryville	0.27
Alameda Naval Air Station	0.26

The logs of recent borings and geophysical investigations conducted at these sites indicate that the stations are not situated over significant thickness of Young Bay Mud, with the exception of Alameda Naval Air Station. Young Bay Mud is completely absent at the Oakland two-story site (Bray, et al., 1992, USGS, 1992, Woodward-Clyde Consultants, 1993).

In comparison, several nearby rock stations recorded the following accelerations:

Station	Peak Horizontal Acceleration (g)
Oakland Piedmont Jr. High	0.08 (45 deg comp)
Yerba Buena Island	0.06 (90 deg comp)
Oakland Caldecott Tunnel	0.06 (both comp)
UC Berkeley Haviland Hall	0.06 (45 deg comp)
UC Berkeley Strawberry Canyon	0.08 (45 deg comp)
Lawrence Berkeley Laboratory	0.12 (90 deg comp)
UC Berkeley Memorial Stadium	0.13 (135 deg comp)

It can be clearly seen that the peak ground accelerations (PGA) in the Oakland area have been amplified three to four times with respect to those recorded at nearby rock sites. To put this in perspective, the 1985 Mexico City earthquake amplified the average rock motions of 0.035g at three UNAM sites to 0.17g and 0.10g at the SCT site located in the heavily damaged zone in Mexico City, an amplification factor of about three to five. The amplification of the deep stiff clay sites in the general Oakland area exceed those recommended for soft clay sites by Idriss (1991). When compared to a much larger database as shown in Figure 4, the mean recorded peak accelerations from these five stations plot over two standard deviations greater in magnitude than the mean values predicted by the Joyner and Boore (1988) attenuation relationship, which provides an estimate of peak horizontal ground acceleration versus distance from the zone of energy release. It is also interesting to note that most of the above mentioned rock stations recorded a higher acceleration in the direction perpendicular to the Bay or the bedrock valley boundaries.

The response spectra of the ground motions recorded at three of the deep stiff clay sites in the Oakland area show considerable spectral amplification of long period motions (Figure 5). At deep stiff clay sites where the thickness (H) of the deposit may range from 100 to 300 feet and the average shear wave velocity (V_s) ranges from 600 to 1600 feet per second, the fundamental period of the site (T_{site}) is estimated to range from 0.25 to 1.5 seconds, where $T_{site} \sim 4H/V_s$. Thus, these sites have the potential for significant amplification of structural response in a wide range of building heights from about 2 to 15 stories.

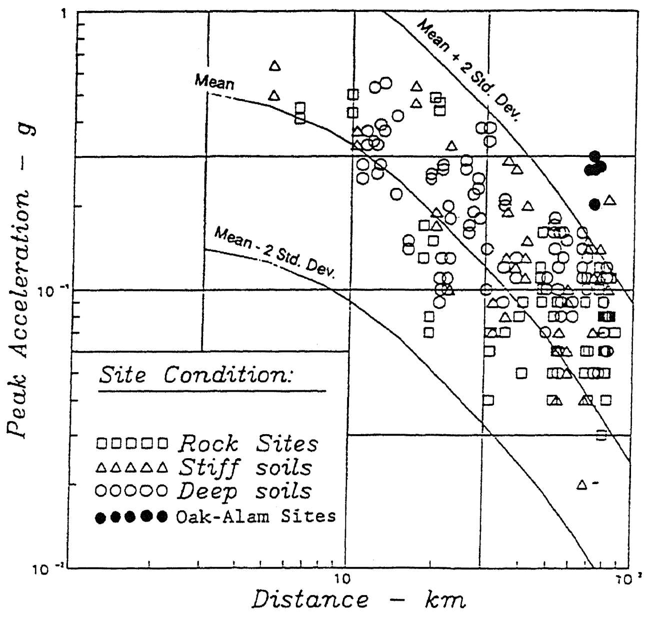

Figure 4: Peak Ground Accelerations Recorded During the 1989 Loma Prieta Earthquake and the 1988 Joyner and Boore Attenuation Relationship

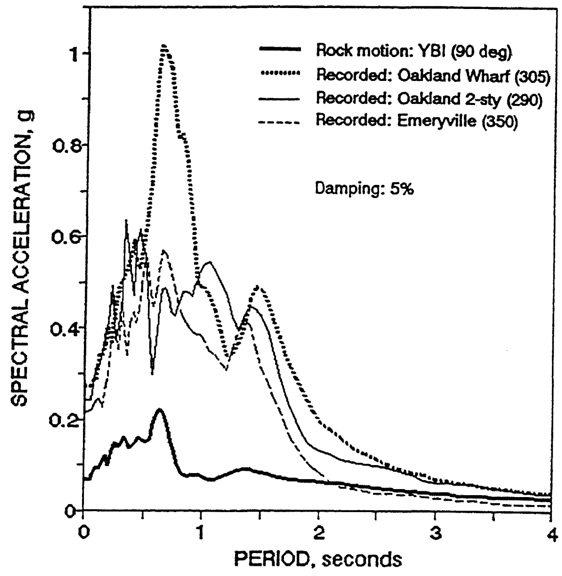

Figure 5: Response Spectra for Three Deep Stiff Clay Sites in the Oakland Area

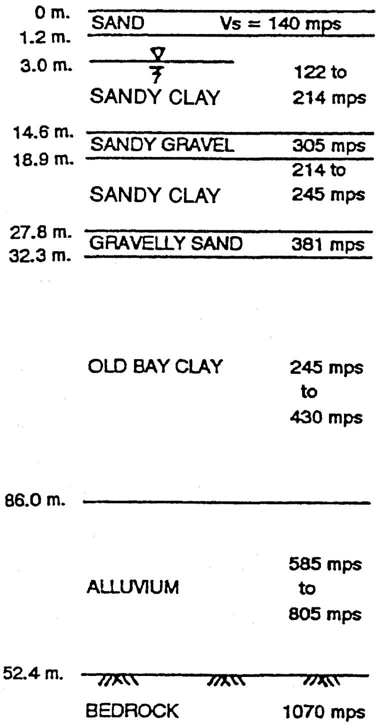

Figure 6: Idealized Soil Profile Used in Dynamic Response Analyses of the Oakland 2-Story Site

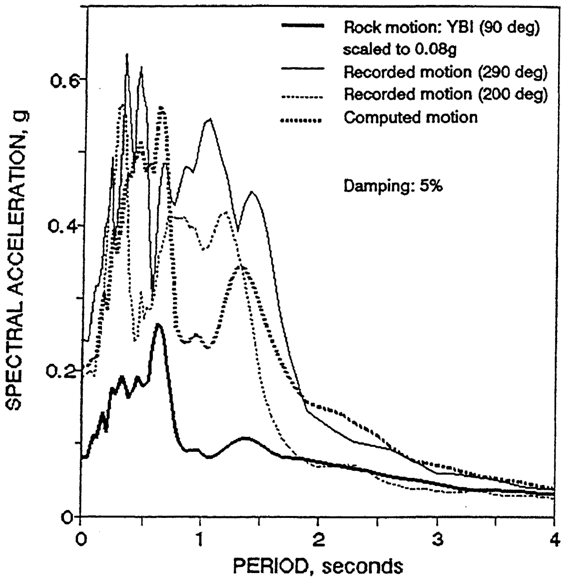

Figure 7: Oakland 2-story Building - Computed Response Spectra from SHAKE

According to the 1991 Uniform Building Code (UBC), these deep stiff clay sites would typically be characterized as an S_2 soil profile and assigned a Site Coefficient of $S=1.2$, implying that for the deep stiff clay sites, the anticipated increase in base shear is only 20 percent higher than that for rock or shallow stiff soil sites. However, the seismic response of the deep stiff clay deposits in the Oakland area during the Loma Prieta earthquake show spectral acceleration amplification factors of about 3 to 8 (in comparison with the recorded Yerba Buena Island rock motion, Figure 5), suggesting that the current seismic codes may underestimate the potential site response hazard at these sites.

WAVE PROPAGATION ANALYSES

Preliminary one-dimensional site response analyses were performed for the Oakland 2-story building site based on subsurface soil information obtained from a recent field investigation program (Bray et al., 1992). Two boreholes were drilled within 50 feet of the strong-motion instrument, and one of the boreholes was drilled into Franciscan claystone/sandstone bedrock at a depth of 390 feet. Shear wave velocity measurements were made using the suspension P-S logging technique. The P-S logger produced clear wave forms for determining shear wave velocities. Measurements were taken every two meters throughout the depth of the boring and thus provided a high resolution velocity profile for the site (Agbabian, 1993). Samples were taken from these two boreholes for static, cyclic, and index property testing (Bray et al., 1992).

An idealized soil profile of the Oakland 2-story site and the corresponding shear wave velocities used in the analyses are shown in Figure 6. The nonlinear, strain-dependent moduli and damping relationships for the cohesive materials were selected based on their Plasticity Index (Sun et al., 1988, Vucetic and Dobry, 1991). For the sandy materials, the relationships proposed by Seed et al. (1984) were used. It should be noted that the computed strains within the soil profile were relatively small. Thus the computed ground response was more dependent upon the insitu measured shear wave velocities than on the nonlinear soil properties.

The program SHAKE91 (Idriss and Sun, 1991) was used to perform the site response analyses at this site. SHAKE calculates seismic response based on the vertical propagation of shear waves through a one-dimensional column of soil and uses the equivalent linear method to model the nonlinear dynamic soil moduli and damping as a function of strain. As shown in Figure 7, the one-dimensional analyses were able to capture the tendency of this deep stiff clay site to amplify motions, and the computed response is in fair agreement with the recorded motions, except at periods in the range of about one second. In this range, the computed motion greatly underpredicts the recorded motions at the site. Further analyses are necessary to determine whether this discrepancy is the result of the selection of input rock motions, limitations of the one-dimensional model (two- and three-dimensional effects), dynamic properties of the soil (particularly at small strains), soil-structure interaction, or other factors.

CONCLUSION

The 1989 Loma Prieta earthquake again emphasized the importance of local site conditions on ground response; however, the areas of heavy damage were not confined to deep soft clay or liquefiable sites as is commonly believed. Deep stiff clay sites in the Oakland area were also found to amplify peak ground accelerations and contributed to high spectral amplification of long period motions. This finding is particularly significant since deep stiff clay deposits are present in many seismically active areas around the world.

The response at these sites also appear to be underestimated by the Uniform Building Code. Portions of the amplified response can be predicted with some certainty by conventional one-dimensional analysis techniques; however, there may be other influencing factors such as two- and three-dimensional valley boundary effects, reflection off the Mono layer, soil-structure interaction effects, and other factors.

In the event of the occurrence of the design magnitude 7 event on the Hayward Fault (located less than four miles from the city of Oakland), damage in the Oakland area will probably far exceed that caused by the Loma Prieta earthquake. In such an event, a bedrock peak horizontal acceleration of 0.5g may be expected. Due to the proximity of the city to the Hayward Fault, the directivity effect, which also increases response at long period motions, may be much more severe than that experienced during Loma Prieta. In light of the damage in Oakland caused by rock motions with peak accelerations on the order of 0.08 to 0.10g, it would be prudent to re-evaluate the seismic design criteria used in the Oakland area, the general East Bay region, and at other deep stiff clay sites located in seismically active areas. For these areas, continued use of the UBC site factor appears to result in significant underestimation of the seismic hazard.

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