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Synopsis: The results of high quality in situ test results obtained at Hunter's Point Naval Station both before and after the Loma Prieta earthquake are presented. The interpretation of these tests and the results of subsequent numerical ground motion analyses are validated by the observed response at that site during the event. Data show that densification of the loose fill soils occurred as a result of the seismic activity and corroborate the observed surface deformations.

Introduction

Following the October 1989 Loma Prieta earthquake, a research study was conducted to evaluate the state of fill soils in San Francisco. A total of 10 sites were investigated using a range of in situ testing techniques including piezocone, seismic cone, pushed dilatometer, driven dilatometer and standard penetration testing. In addition, a number of samples were obtained from the various strata encountered for laboratory evaluation and testing. The rationale for selecting specific sites was based on one or more of the following criteria: (a) fill construction procedure, (b) well documented performance during Loma Prieta earthquake, (c) availability of pre-earthquake in situ test data and (d) importance of the facility.

The findings of part of the research study which looked at the change in condition of fills at several of these sites based on cone penetration resistance have already been documented (Chameau et al., 1991). Pre-earthquake predictions (Clough and Chameau, 1983) had indicated that poorly constructed fills in a loose to medium dense state would liquefy during a Loma Prieta type event. The post-earthquake study showed that the observed poor performance of these looser fill soils during the earthquake resulted in their densification. It was also shown that a number of locations would suffer severe damage during a postulated magnitude 7.5 event occurring near San Francisco. Even engineered fills could suffer some distress because of zones of looser material at shallow depths.

This paper presents the results of another phase of the research study which specifically focused on the performance of the fill soils at Hunter's Point Naval Station during the Loma Prieta earthquake. This site had been selected for extensive study because (a) significant damage including the collapse of a cellular cofferdam occurred at this site during the earthquake and (b) a range of high quality in situ tests including cone penetrometer, pressuremeter, dilatometer, Iowa stepped blade, cross-hole geophysical and rotary borings with standard penetration testing had been conducted in 1986, prior to the Loma Prieta event (Ng et al., 1988; Handy et al., 1990).

The post-earthquake investigation at the Hunter's Point site included piezocone, seismic cone, pushed dilatometer, driven dilatometer and standard penetration testing. Accordingly, comparison of pre and post-earthquake soil property profiles determined using a range of test devices was possible and is presented in the paper. In addition, the results of ground motion analyses at various locations within the Hunter's Point site (Reyna, 1991) that were used to evaluate the behavior during the earthquake are presented.

Site Description

The Hunter's Point Naval Station site is located on the West side of the San Francisco Bay (Figure 1). The site is a fill area that was built in the

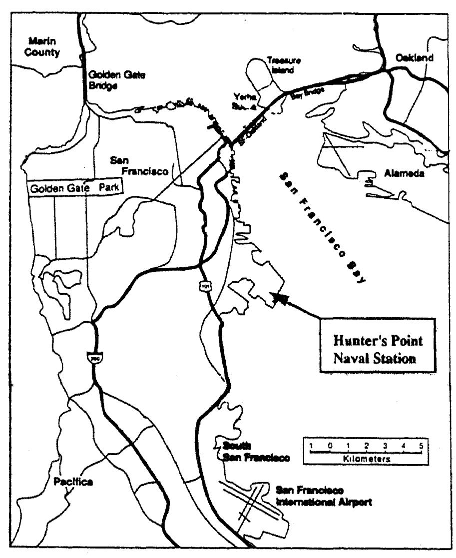
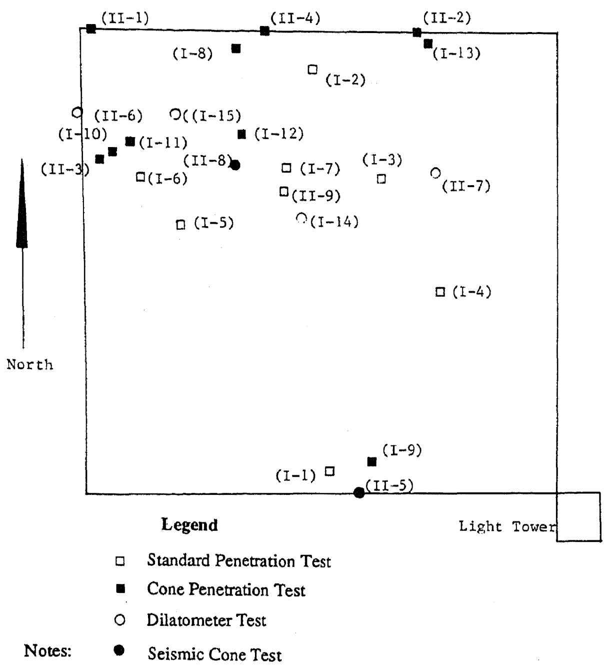


Figure 1 Site Location Map

1940's using cellular cofferdams that were hydraulically filled with sand. The hydraulic fill is 13 to 15 m thick overlying a fractured serpentine bedrock. In the upper part of the fill (1 to 1.5 m) the sand is mixed with coarse particles up to 150 mm. Below this upper layer, the sand is classified as a clean, poorly graded, fine sand (D_{50} = 0.29 mm; Cu = 1.8). Several thin silty clay seams were encountered just above the bedrock. The water table is located at approximately 2.5 m below the ground surface. The pre and post-earthquake site investigation programs described herein were conducted in an area approximately 14 m by 14 m (Figure 2). A typical stratigraphic cross-section is shown in Figure 3.



Notes:

(1) Pre-earthquake testing performed by Ng et al., (1988) and Handy et al. (1987).

(2) Crosshole geophysical testing performed in holes I-2, I-3 and I-4.

Figure 2 Site Testhole Layout

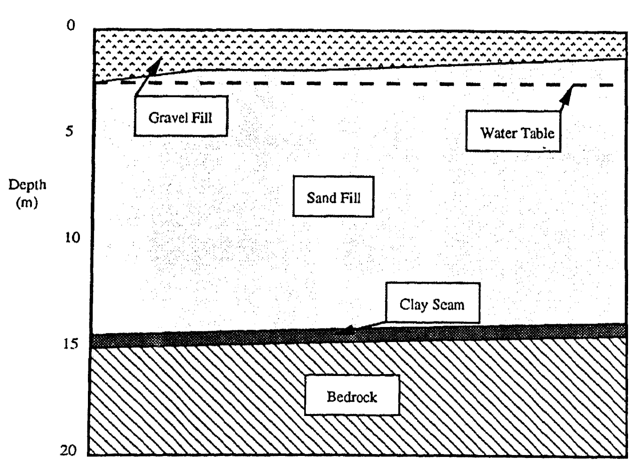


Figure 3 Typical Stratigraphic Section (modified after Karanikolas, 1990)

Pre-Earthquake Investigation Program

An extensive field investigation program was conducted in 1985 and 1986 as part of a Federal Highway Administration funded research project on pile group action (Ng et al., 1988; Handy et al., 1987 and 1990). The investigation used a range of in situ testing techniques including piezocone, pre-bored and self-boring pressuremeters, dilatometer, crosshole geophysical, stepped blade and standard penetration testing. A summary of relevant tests performed is given in Table 1 and locations are shown in Figure 2. It is noted that tests were performed before and after piling operations, thus the data are considered separately herein as appropriate in an effort to clearly isolate effects other than those resulting from the earthquake.

Table 1 Pre-Earthquake Investigation Program

Sounding	Type	Depth (m)	Remarks
I-1	SPT	15.5	Pre-piling
I-2	SPT	18.3	Pre-piling
I-3	SPT	15.4	Pre-piling
I-4	SPT	14.0	Pre-piling
I-5	SPT	22.1	Pre-piling
I-6	SPT	15.4	Post-piling
I-7	SPT	14.5	Post-piling
I-8	CPT	15.4	Pre-piling
I-9	CPT	14.1	Pre-piling
I-10	CPT	16.3	Pre-piling
I-11	CPT	15.7	Post-piling
I-12	CPT	14.7	Post-piling
I-13	CPT	14.6	Post-piling
I-14	DMT	14.8	Pre-piling
I-15	DMT	8.1	Pre-piling
I-16	CHGT	13.1	Pre-piling
I-17	CHGT	13.1	Post-piling

SPT - Standard Penetration Test
CPT - Cone Penetration Test
DMT - Dilatometer Test
CHGT - Crosshole Geophysical Test

Post-Earthquake Investigation Program

A field investigation program was conducted in 1990 following the Loma Prieta earthquake as part of the National Science Foundation - United States Geological Survey research initiative (Chameau et al., 1991; Reyna, 1991). The investigation also used a range of in situ testing techniques including piezocone, seismic cone, dilatometer and standard penetration testing. Tests performed are summarized in Table 2 and locations are shown in Figure 2.

Comparison of Pre and Post- Earthquake Conditions

The extensive investigation programs performed before and after the Loma Prieta event make the Hunter's Point site an ideal data set for assessing the effects of the earthquake with a range of different in situ tests devices.

Table 2 Post-Earthquake Investigation Program

Sounding	Type	Depth (m)	Remarks
II-1	CPTU	16.2	Post-earthquake
II-2	CPTU	14.6	Post-earthquake
II-3	CPTU	15.7	Post-earthquake
II-4	CPTU	15.5	Post-earthquake
II-5	SCPT	13.7	Post-earthquake
II-6	DMT	15.0	Post-earthquake
II-7	DMT	13.1	Post-earthquake
II-8	SCPT	14.9	Post-earthquake
II-9	SPT	13.7	Post-earthquake

SPT - Standard Penetration Test
CPTU - Piezocone Penetration Test
DMT - Dilatometer Test
SCPT - Crosshole Geophysical Test

Cone Penetration Testing

Cone penetration resistance values obtained at three different stages were considered (Chameau et al., 1991). These included after pile installation (1986) and after the Loma Prieta event (1990). A comparison of the cone tip resistance before the earthquake (after piling) and after the earthquake is shown in Figure 4.

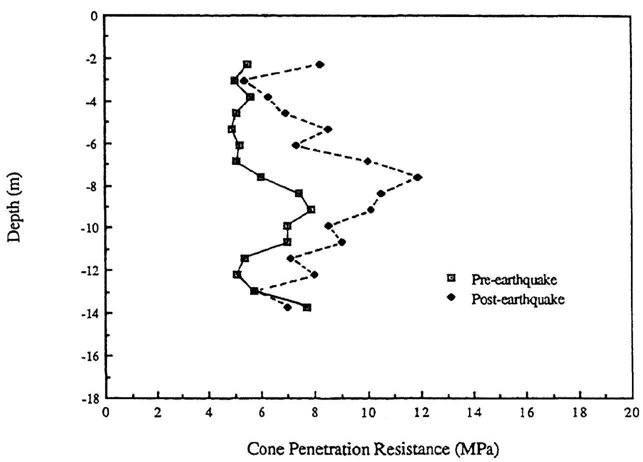


Figure 4 Comparison of CPT Resistance Data (modified after Chameau et al., 1991)

The 1990 curve is the average of four soundings while three soundings were used for the 1986 post-piling curve. The average cone penetration resistance measured in 1990 is significantly larger than the earlier measurement over a wide range of depths. These differences in penetration resistance obviously reflect in comparable changes in interpreted relative density (Figure 5). For depths between 5 to 11 m. the relative density ranged between 35 to 55 % based on the 1986 data, while it increased to a range of 60 to 75 % for the 1990 data.

For practical geotechnical applications, an average value of tip resistance, q_c, over some depth interval or layer of interest is usually more relevant than discrete values. Hence, to fully appreciate the importance of the findings in Figures 4 and 5, average values of q_c are summarized in Table 3 for depth intervals of 1.0 m. For instance, 6.5 MPa in the first row of the table is the average tip resistance for all CPT data between 3.0 and 4.0 m that were measured at the site in 1986. The increase in resistance resulting from the earthquake is also given as a percentage. These statistical summaries show that the increase in q_c between 1986 and 1990 was negligible from 3 to 5 m, however it increased between 30 and 80 % at depths of 5 to 11 m.

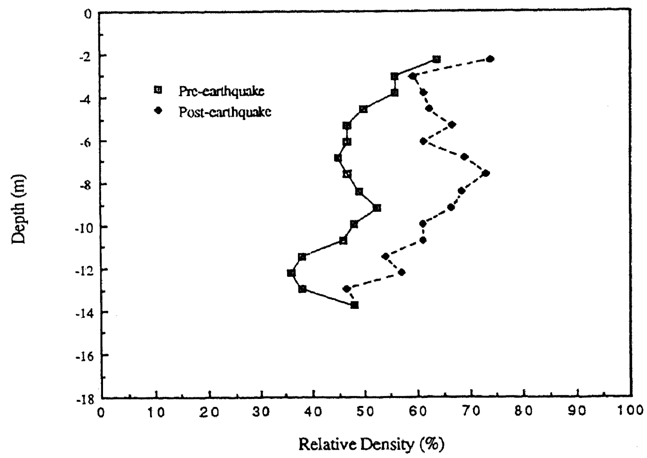


Figure 5 Comparison of CPT Based Relative Density (modified after Chameau et al., 1991)

Table 3 Average Values of CPT Resistance

Depth Interval (m)	Pre-earthquake q_c (avg.) (MPa)	Post-earthquake q_c (avg.) (MPa)	Percent Increase (%)
3-4	6.5	6.8	5
4-5	5.7	5.9	4
5-6	5.2	7.2	38
6-7	4.9	7.7	57
7-8	5.1	9.2	80
8-9	6.3	11.4	81
9-10	6.9	10.4	51
10-11	7.6	9.2	21

Standard Penetration Testing

As with the cone penetration testing, standard penetration resistance values obtained before piling (1985), after piling (1986) and after the Loma Prieta event (1990) were compared. A comparison of the N values before the earthquake (after piling) and after the earthquake is shown in Figure 6. The 1986 curve represents the average of 2 soundings while the 1990 curve is for a single testhole. All N values were corrected to an equivalent 60 % energy ratio to account for differences in hammer type as proposed by Skempton (1986). No corrections were made for rod length, liner usage and borehole diameter since the standard procedure was followed in all cases. It can be seen that, in general, the N values measured in 1990 reflect a similar increase in density observed with the CPT data when compared to the pre-earthquake N

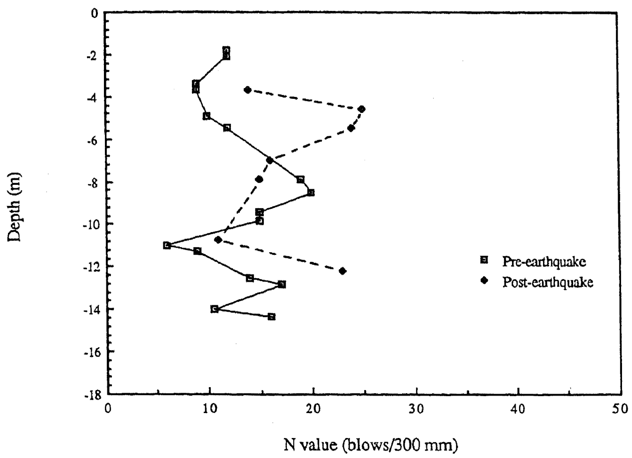


Figure 6 Comparison of SPT Data

values, particularly between 3 and 7.5 m. At other elevations the increase is less evident. Whether this is due to the limited database of N values or minor changes in soil gradation causing significant changes in induced pore pressures or other procedural effects, it appears that the standard penetration test is less sensitive to the changes in density resulting from the earthquake than the other tests reported herein. This lack of sensitivity of particularly the standard penetration test has been previously noted by Leonards and Frost (1988).

Dilatometer Testing

Dilatometer testing was performed before piling (1986) and after the Loma Prieta event (1990). A comparison of the average of 2 soundings performed at each of these stages in terms of the horizontal stress index, K_D, is shown in Figure 7. The K_D values measured following the

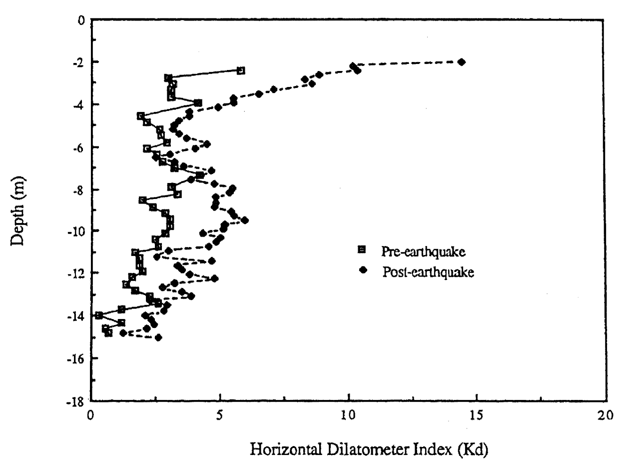


Figure 7 Comparison of Dilatometer Data

earthquake show a clear increase when compared with the pre-earthquake data. Average values are summarized in Table 4 for 1 m intervals. These statistical summaries show that the increase in K_D from 1986 to 1990 ranged from 30 to in excess of 100 % over the entire depth of soil tested. This increase reflects not only the effects of the earthquake but also the pile driving operations. Nevertheless, given the relative influence of these effects on the cone penetration resistance (Chameau et al., 1991), it is clear that (a) the earthquake resulted in significant increases in K_D and (b) the dilatometer is well suited to sense the effects of prestressing from both natural and man-induced densification processes.

Table 4 Average Values of Horizontal Stress Index

Depth Interval (m)	Pre-earthquake K_D (avg.)	Post-earthquake K_D (avg.)	Percent Increase (%)
2-3	4.4	10.5	139
3-4	3.4	6.7	97
4-5	2.1	4.0	90
5-6	2.8	3.6	29
6-7	2.5	3.3	32
7-8	3.5	4.6	31
8-9	2.6	5.0	92
9-10	3.0	5.5	83
10-11	2.7	4.4	63
11-12	1.9	3.5	84
12-13	1.6	3.7	131
13-14	2.0	2.8	40

Geophysical Testing

Pre-earthquake geophysical testing consisted of two crosshole surveys performed in 1986 after pile installation. The crosshole tests were performed in a linear borehole array (Ng et al., 1988). A shear wave hammer was placed in one of the end holes of the array and vertical geophones were placed in the other two boreholes. The hammer and geophones were located at the same elevations in the holes and the hammer was used to create vertically polarized shear waves. The post-earthquake geophysical testing was performed using a seismic cone with a surface hammer. The different test procedures used before and after the earthquake should be expected to give comparable results since travel times for vertical shear waves are being measured in both cases (Stokoe et al., 1985). A comparison of the average of 2 soundings performed before and after the earthquake is shown in Figure 8. Average

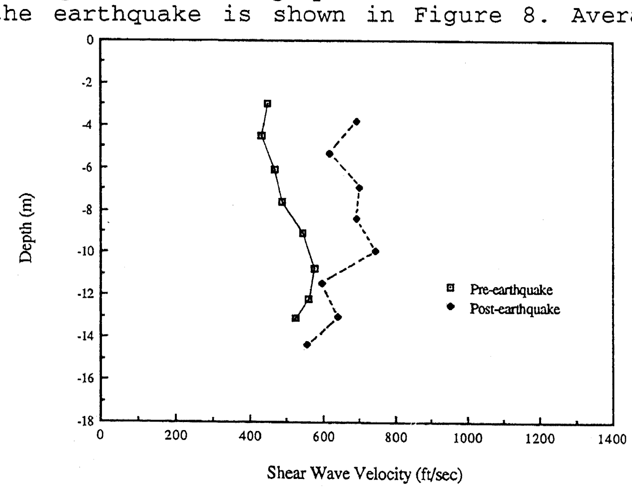


Figure 8 Comparison of Geophysical Data

values for 1 m intervals are summarized in Table 5. The shear wave velocity increased by 30 to 50 % over a depth range of 3 to 10 m. Based on a review of laboratory test results, it is clear that an increase in the measured shear wave velocity values of this magnitude reflects not only the increase in density (void ratio) but also the change in mean confining stress reflected in the dilatometer tests and resulting from the seismic activity.

Table 5 Average Values of Shear Wave Velocity

Depth Interval (m)	Pre-earthquake V_S (avg.) (ft/sec)	Post-earthquake V_S (avg.) (ft/sec)	Percent Increase (%)
3-4	445	690	55
4-5	435	655	51
5-6	455	625	37
6-7	475	675	42
7-8	485	695	43
8-9	520	695	34
9-10	550	725	32
10-11	570	700	19
11-12	565	610	8
12-13	550	625	14

Ground Motion Analyses

Ground motion analyses using the soil test data obtained before and after the earthquake was performed for the Hunter's Point site. The soil profile was idealized as shown in Figure 9 using appropriate shear wave velocity data depending on whether a pre or post-earthquake condition was being analyzed. A summary of the cases analyzed is given in Table 6. A typical response spectra is shown in Figure 10. Using pre-earthquake shear wave velocity data (Ng et al., 1988), peak ground acceleration values of 0.12 g were calculated using the Rincon record scaled to 0.114 g as outcrop motion. This is considered to be a reasonable representation of the response at the site during the Loma Prieta event based on the observed post-earthquake conditions and the in situ test results. Peak ground acceleration values of 0.19 g could be expected in a future event based on ground motion analyses using the same outcrop motion and the post-earthquake shear wave velocity data.

Table 6 Summary of Ground Motion Analyses

Case	Record	Scaled Motion (g's)	Initial Period (sec)	Final Period (sec)	PGA (g's)	Profile
1	Diamond	0.114	0.26	0.37	0.191	Post
2	Telegraph	0.114	0.26	0.35	0.186	Post
3	Rincon	0.114	0.26	0.36	0.190	Post
4	Telegraph	0.093	0.26	0.33	0.133	Post
5	Rincon	0.093	0.26	0.37	0.141	Post
6	Rincon	0.114	0.37	0.52	0.119	Pre
7	Rincon	0.114	0.31	0.41	0.125	Pre
8	Rincon	0.200	0.26	0.41	0.303	Post
9	Rincon	0.300	0.26	0.45	0.376	Post
10	Rincon	0.400	0.26	0.47	0.417	Post
11	Rincon	0.500	0.26	0.50	0.464	Post
12	Rincon	0.600	0.26	0.51	0.514	Post
13	Diamond	0.200	0.26	0.41	0.300	Post
14	Diamond	0.300	0.26	0.49	0.408	Post
15	Diamond	0.400	0.26	0.50	0.518	Post
16	Diamond	0.500	0.26	0.51	0.593	Post

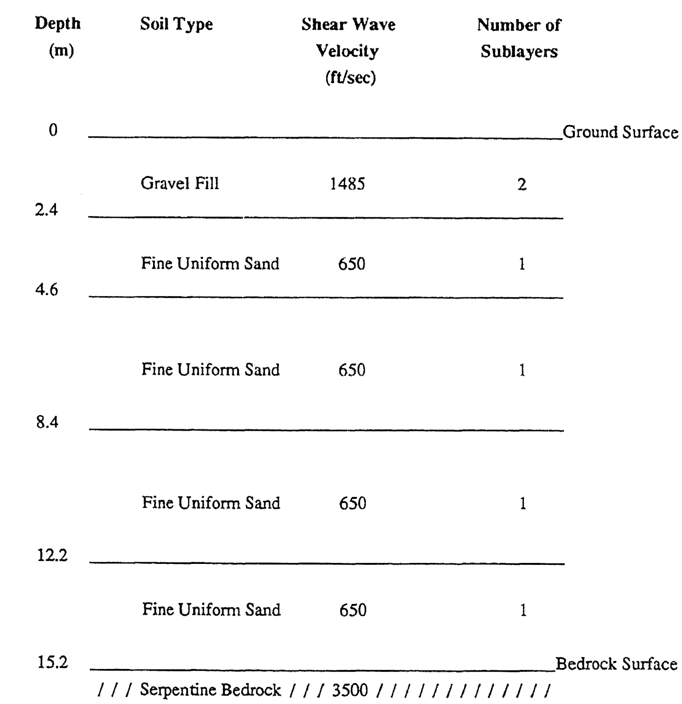


Figure 9 Idealized Soil Profile (modified after Reyna, 1991)

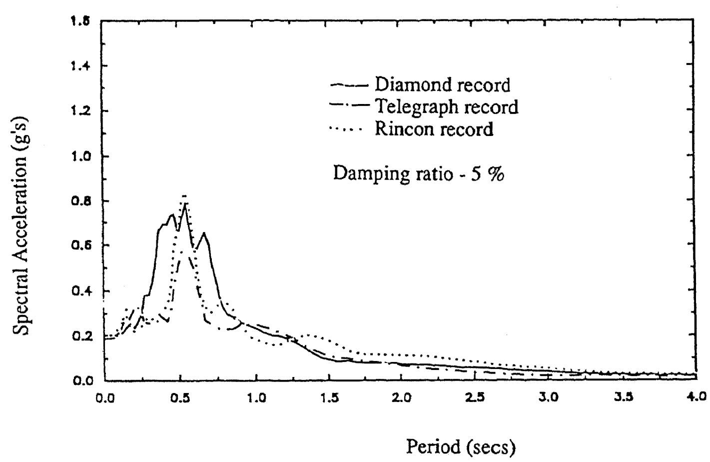


Figure 10 Typical Response Spectra (after Reyna, 1991)

Summary

The extensive database of high quality pre and post-earthquake in situ test data at Hunter's Point Naval Station makes it one of the best natural test sites available. It has enabled the effects of seismic activity on fill soils to be assessed using a range of test devices and hence

the relative predictive capabilities of these devices to be compared. The main conclusions are:
(a) Based on the field tests summarized above, loose fill sands at the Hunter's Point Naval Station densified as a result of the Loma Prieta event. The change in state was observed in the results of cone penetration, standard penetration, dilatometer and geophysical tests.
(b) The relative abilities of the various test devices was evaluated and showed that the standard penetration test was least sensitive to the change in state. It is considered that this lack of sensitivity is related to the dynamic nature of the test itself wherein a large portion of the soil being sensed at a given time is significantly altered by the test procedure itself.
(c) The magnitude of the changes in the dilatometer readings confirms that the test is sensitive not only to changes in density but also changes in stress that resulted from the earthquake. The relatively lesser amount of insertion disturbance associated with this test when compared to penetration tests such as the cone and standard penetration tests facilitates this sensitivity.
(d) The geophysical testing reflected the change in density and stress state resulting from the seismic activity. Ground motion analyses showed that peak ground acceleration values of about 0.12 g would have been measured at the Hunter's Point site during the Loma Prieta event and that values of about 0.19 g could be anticipated in a repeat event.

Acknowledgments

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