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Soil Amplification at Treasure Island During the Loma Prieta Earthquake

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SYNOPSIS: The Loma Prieta Earthquake ground motions recorded on Treasure Island, a man-made fill in San Fransisco Bay were considerably greater than on the adjacent Yerba Buena rock outcrop. The Yerba Buena motions were used as input to the computer program SHAKE90 for computing soil amplification at Treasure Island. Shear wave propagation velocities were obtained by seismic cone penetration testing. Reasonable agreement was observed between the computed and recorded accelerations at the strong motion recording station. The maximum computed accelerations around the island ranged from 0.13 to 0.20 g's. The degree of damage at various locations on the island correlated somewhat with the maximum computed accelerations.

INTRODUCTION

The Mexico City Earthquake of 1985 and the 1989 Loma Prieta Earthquake both provide ample evidence of the effects of local geological conditions on the intensity of ground shaking. A notable example of soil amplification during the Loma Prieta earthquake was provided by the ground motions recorded at Yerba Buena and Treasure Islands. Yerba Buena is a rock outcrop located in the San Fransisco Bay. Treasure Island is a man-made hydraulic fill placed on the Yerba Buena shoals, a sandbar located immediately northwest of Yerba Buena Island. Both islands are located at essentially the same distance from the epicenter of the Loma Prieta earthquake, but had significantly different ground response. In this paper, results of analysis are presented which support the hypothesis that soil conditions can have a significant effect on the intensity of ground shaking.

A preliminary report on the geotechnical aspects of the Loma Prieta earthquake by the University of California (Seed et al., 1990) included an analysis of soil amplification at Treasure Island utilizing the best available estimates for shear wave propagation velocities (V_s) at Treasure Island. For the present study, seismic cone penetration tests (SCPT) were conducted at Treasure Island to accurately determine V_s. Tests were performed as deep as 29 m (95 ft.) immediately adjacent to the seismic recording station as well as at 5 other locations on the island. Analyses were performed using the equivalent linear program SHAKE90.

CONSTRUCTION HISTORY OF TREASURE ISLAND

Treasure Island is a 400 acre man-made island immediately northwest of the Yerba Buena rock outcrop in San Fransisco Bay (Figure 1). It was constructed in 1936-37 for activities celebrating the construction of the Golden Gate and San Fransisco-Oakland Bay Bridges. Subsequently, it was the site of an International Exposition. During the Second World War it was commissioned as a Naval Installation and serves as such today. The original surface soils included a shallow water sand bar or spit extending northwest from Yerba Buena and soft bay mud surrounding the sand bar to the north and east. Approximately 65% of the island was built on the sand bar, the remainder on bay muds (Lee, 1969).

Treasure Island was constructed by hydraulic and clamshell dredging. A perimeter rock dike was built in two to four stages on a bed of coarse sand placed over the Bay Mud. The dike acted as a retaining system for the sands that were pumped or placed inside. The structure is thus essentially an upstream constructed hydraulic fill.

SOIL STRATIGRAPHY

The soils at Treasure Island may be grouped into four broad categories: the fill material, native shoal sands, recent bay sediments and older bay sediments. Both the fill and the native shoal material is predominantly sand with varying degrees of gravel, silt and clay. However, the fill is somewhat looser and locally exhibits lower CPT tip resistance (q_c) than the native shoal material. Typical q_c's for the fill range from 10 to 50 kg/cm^2 The native shoal q_c typically ranges from 40 to 100 kg/cm^2. The recent bay sediment, also known locally as Bay Mud, is a relatively soft medium plastic silty clay with q_c increasing with depth and ranging from 8 to 14 kg/cm^2. The Bay Mud's cone friction ratio is about 1%. On the south-eastern end of the island, nearest to Yerba Buena, the recent deposits include a mixture of Bay Mud interbedded with sand. Much stiffer sandy or silty clays of pleistocene age underlie the Bay Mud.

Significant variation in the depths and thicknesses of the layers exists around the island. The thickness of fill and native shoal materials ranges from 35 ft. (10.7 m) at the southern end to 50 ft. (15.2 m) in the north. The recent bay sediments begin at 35 ft. (10.7 m) depth in the south and extend to only about 50 ft. (15.2 m) depth. However, in the southeastern corner of the island the recent bay sediments which

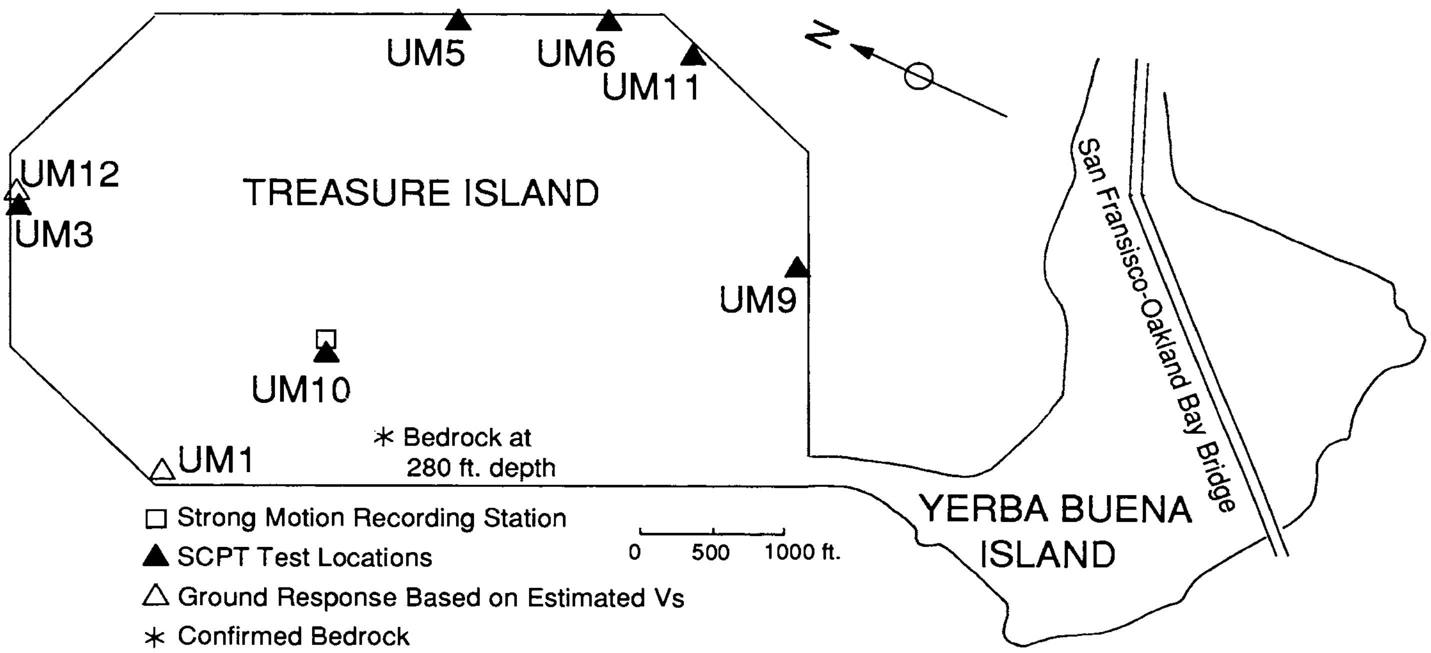

Fig. 1 Treasure Island and Yerba Buena Island

include both bay muds and interlayered sands are found to a depth of 120 ft. (36.6 m). In the north, the bay muds begin at depths of 45 ft. (13.7 m) to 55 ft. (16.8 m) and continue to anywhere between 70 ft. (21.3 m) depth in the northeastern corner to 160 ft. (48.8 m) in the western corner.

The bedrock elevation has been confirmed at a depth of 280 ft. (85 m) at the location shown in Figure 1. This is the only confirmed depth to bedrock at Treasure Island at this time. Nevertheless, from this point and the Yerba Buena rock outcrop, it is estimated that the bedrock dips at approximately 2° to the northwest.

RECORDED GROUND MOTIONS AT TREASURE ISLAND AND YERBA BUENA ISLAND

The seismographs at Yerba Buena and Treasure Islands were both located on the floors of small one story buildings and oriented to record motions in the N-S, E-W and Up-Down directions. The epicentral distances were 95 km at Yerba Buena and 98 km at Treasure Island. The strongest ground motions were in the E-W directions as shown in Figure 2. Peak accelerations in this direction were 0.16g at Treasure Island and 0.06g at Yerba Buena. In the N-S direction the peak accelerations were smaller (0.11g at Treasure Island and 0.03 at Yerba Buena). The duration of strong shaking lasted approximately 4 seconds.

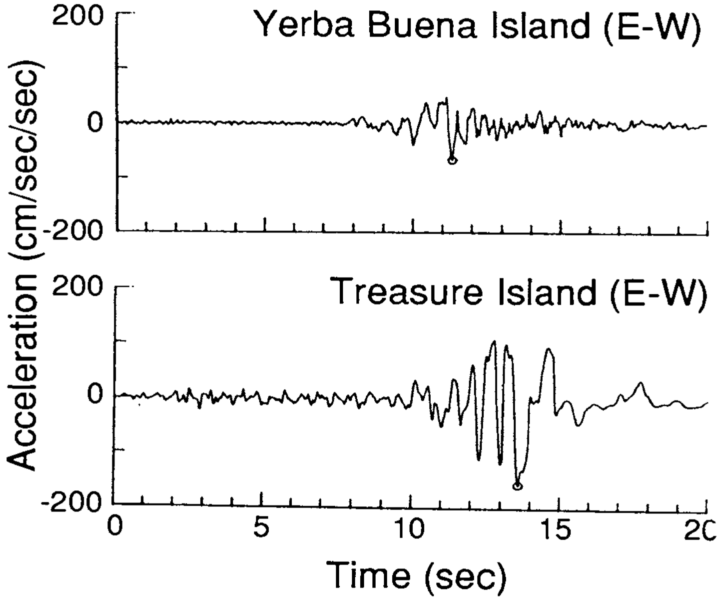

Fig. 2 Recorded Accelerations at Treasure Island and Yerba Buena Island (E-W)

EARTHQUAKE DAMAGE

An extensive post-earthquake assessment of damage to the perimeter retaining system at Treasure Island was performed by Shewbridge et al (1990). Seed et al. (1990) discussed damage to the interior of the island. Damage features to the levee system included lateral spreads, slope failures, pavement cracking and collapse and soil settlement. Evidence of soil liquefaction was pervasive on the interior of the island with numerous large sand boils observed. Settlements of up to 12 inches occurred and were accompanied by numerous pipe breaks and water ponding at the surface.

Since ground motion data will subsequently be presented for the eight select sites shown in Figure 1, the distress features observed at these locations are presented. The best performance was observed at UM1 where very little to no damage was evident. While damage immediately at UM3 was not evident, some liquefaction did occur in adjacent inland areas and a large slump of the retaining levee system was observed at UM12. UM12 is a particularly noteworthy location because during construction of the island a 400 ft. (120 m) wide trench was dug to a depth of 20 to 30 ft. (6 to 9 m) below the original bay bottom and backfilled with a heavy sand before placing the seawall here. The UM3 location was estimated to be at the inland fringe of this trench.

Up to 3.5 in. (9 cm) of vertical settlement was observed adjacent to a building approximately 200 ft. (60 m) inland from UM9. At UM5, some 3.5 in. (9 cm) of horizontal displacement of the soil was observed. In addition, 2 in. (5 cm) of vertical settlement was observed 100 ft. (30 m) away. At UM6, sand boils and 5 to 6 in. (12 to 15 cm) of horizontal movement of the levee was in evidence. Liquefaction was observed at UM11. However, soils in an area immediately south of UM11 had been improved by vibrofloatation and experienced no damage whatsoever.

SEISMIC CONE PENETRATION TESTING AND RESULTS

Shear wave propagation velocities for the fill materials and the newer bay sediments were obtained by seismic cone penetration testing utilizing the University of Michigan's 20 Ton Cone Penetration Rig. The Michigan SCPT system is based on a pseudo-interval concept whereby a single receiver in the cone records shear wave arrival times. The signals are generated at the surface by horizontally directed hammer blows to one of the CPT rig leveling pads. Reversed signal polarity traces and digital recordings provided a high degree of confidence in identification of shear wave arrivals.

Shear wave velocities for the older bay sediments could not be determined by the SCPT because tip resistances of the older sediments were much higher than those of bay mud. As a result, attempted penetration of the older bay sediments caused severe rod bending through the mud layer. It has become clear that a drilling program and downhole shear testing, possibly in conjunction with seismic refraction will be needed if the wave propagation characteristics of the older sediments are to be accurately determined.

At several locations SCPT soundings were terminated before reaching the older bay sediments. Thus, models of V_s versus depth needed to be developed for the bay muds and for the fill and shoal materials. The wave propagation profiles at other depths and locations could then be obtained from the developed models and from the known stratigraphy provided by Shewbridge et al. (1990).

The wave propagation velocities in the fill and shoal materials shown in Figure 3 exhibited considerable scatter as would be expected of a man-made deposit. Nevertheless, the best fit equation:

$$V_s = 150 + 4z \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where: z = depth (meters)

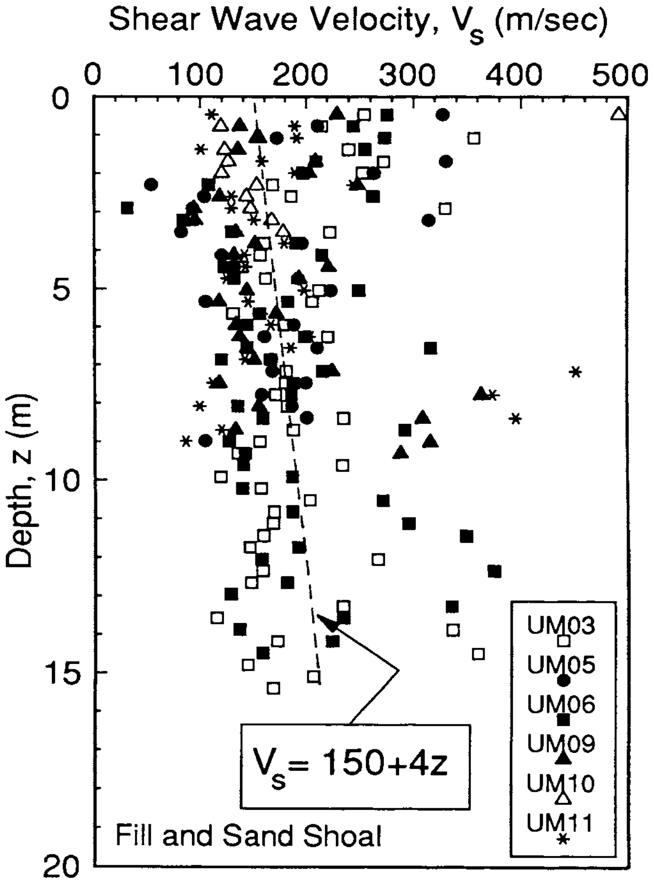

Fig. 3 Shear Wave Propagation Velocities in Fill and Shoal Sands

V_s = shear wave propagation velocity (meters/second)

was used for estimation of V_s at UM1 and UM12.

The wave propagation velocities for Bay Muds is shown in Figure 4. To supplement the data from Treasure Island with V_s for Bay Muds at shallower depths, an additional SCPT was performed at the Alameda Naval Air Station (ANAS) which lies approximately three miles southeast of Yerba Buena Island. A best fit equation which includes some degree of subjective interpretation based on the authors' degree of confidence in the data is given by:

$$V_s = 30z^{0.55} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

This model agrees very well with the propagation velocities for Bay Muds collected by Seed and Sun (1989) from seven previously published sources.

For the analysis of ground motions at the recording station (UM10) Seed et al. (1990) used V_s= 335 m/s for a dense silty sand between depths of 30 m (100 ft.) and 43 m (141 ft.). They also assumed that V_s in the underlying stiff to hard clay increased from 335 m/s (1100 ft./s) at a depth of 43 m (141 ft.) to 425 m/s (1400 ft./s) at a depth of 87 m (285 ft.). It will subsequently be shown that the analysis is rather insensitive to the assumed values of V_s

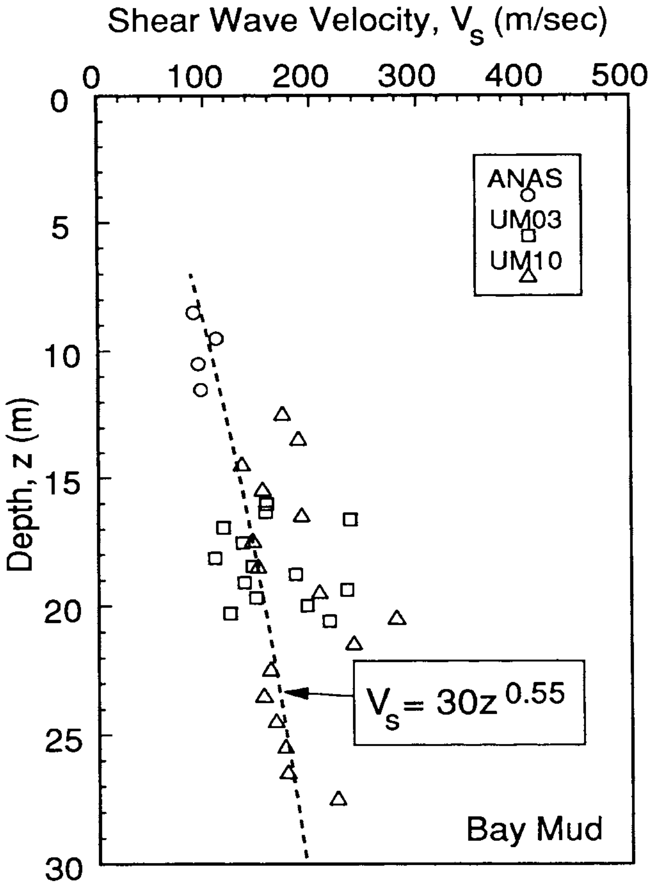

Fig. 4 Shear Wave Propagation Velocities in Bay Mud

for the older bay sediments. Nevertheless, since SCPT V_s's for these layer were not available, Seed's assumed relationship for V_s versus depth for the stiff clay was adopted for the full thickness of the old bay sediments. The expression is given by:

$$V_s = 250 + 2z \quad \text{.............................} \quad (3)$$

A summary of layer depths at the test locations and the depths of SCPT testing is presented in Table 1. Below the maximum SCPT test depths, equations (1)-(3) were used to compute V_s. The propagation velocities at UM1 and UM12 are based entirely on equations (1)-(3).

SHAKE90

At each of the sites shown in Figure 1, the ground response was determined using the computer program SHAKE90, an updated version of SHAKE (Schnabel et al., 1972). SHAKE90 assumes equivalent linear soil response. Dynamic soil properties are iteratively adjusted until they are compatible with the computed cyclic strain. The variations of normalized shear modulus and damping as a function of shear strain are shown in Figure 5. The data for sand fill was obtained from Seed et al. (1982) while the information for Bay Mud and older bay sediments is from Lodde (1982). The recorded time histories at Yerba Buena Island were used as the rock input motions in all cases.

TABLE 1. Layer Thicknesses and SCPT Test Depths

	Depth to Top of Layers (m)			
Location	Bay Mud	Older Bay Sediments	Bedrock	SCPT Depth
UM01	13.5	48.5	97	NA
UM03	15.5	33.9	110	21.0
UM05	11.9	15.6	79	8.3
UM06	14.6	17.0	64	14.6
UM09	9.3	28.0	46	9.3
UM10	11.7	28.9	85	29.0
UM11	14.0	28.0	59	9.0
UM12	21.0	33.0	107	NA

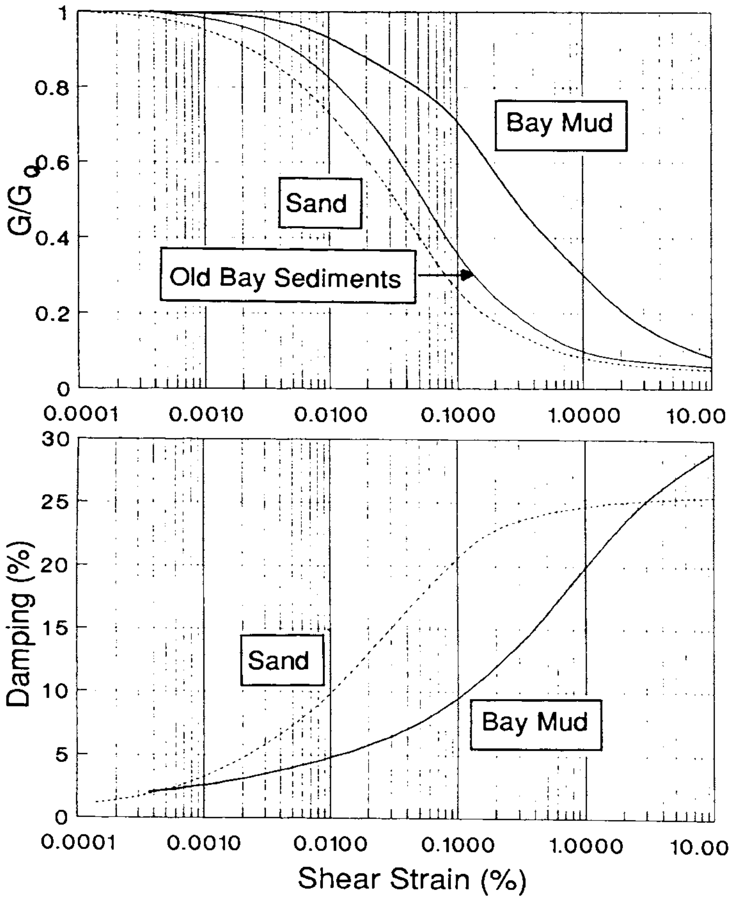

Fig. 5 Normalized Shear Modulus and Damping versus Shear Strain

GROUND MOTIONS AND RESPONSE SPECTRA

A typical acceleration time history computed by SHAKE90 for location UM10 is shown in Figure 6. Comparison with the recorded ground motions shown in Figure 2 indicates reasonable agreement.

Since the wave propagation velocities of the older bay sediments could not be determined by SCPT, a sensitivity analysis was performed to gauge the possible errors due to misestimation of V_s. The response spectra for UM10 was therefore computed using six different assumptions including V_s varying with depth as suggested by

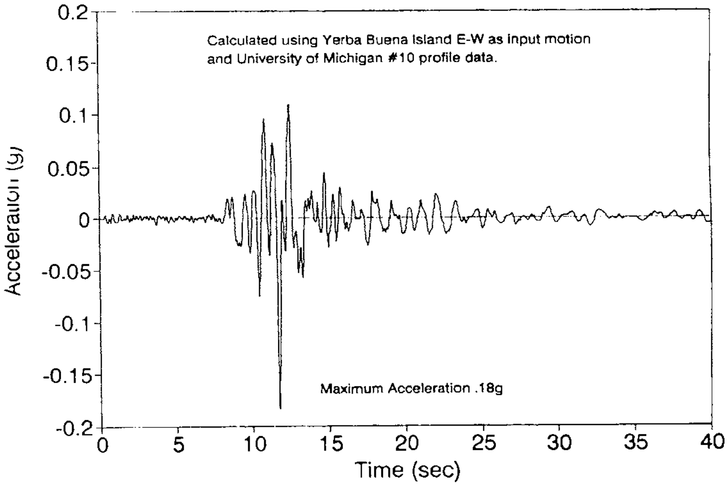

Fig. 6 Acceleration Time History Computed by SHAKE90 for UM10 (E-W)

Seed et al. (1990), V_s varying with depth as suggested by Joyner et al. (1976) and V_s equal to four different constant values as shown in Figure 7. The results clearly indicate that the computed ground motions are not sensitive to the assumed V_s for the older bay deposits and therefore any reasonable assumptions for V_s could be made.

The response spectra for the computed ground motions have the same basic shape as the response spectra for the recorded ground motions. However, the computed accelerations are generally 10 to 30% below the recorded values. The periods of the peaks for the recorded and computed ground motions match well. The poorest agreement is for periods greater than 1 second on the N-S component where the computed response is only about 50% of the measured. This may result from the fact that SHAKE90 does not account for the softening of the soil due to liquefaction which apparently occurred after about 13 seconds of strong ground motion.

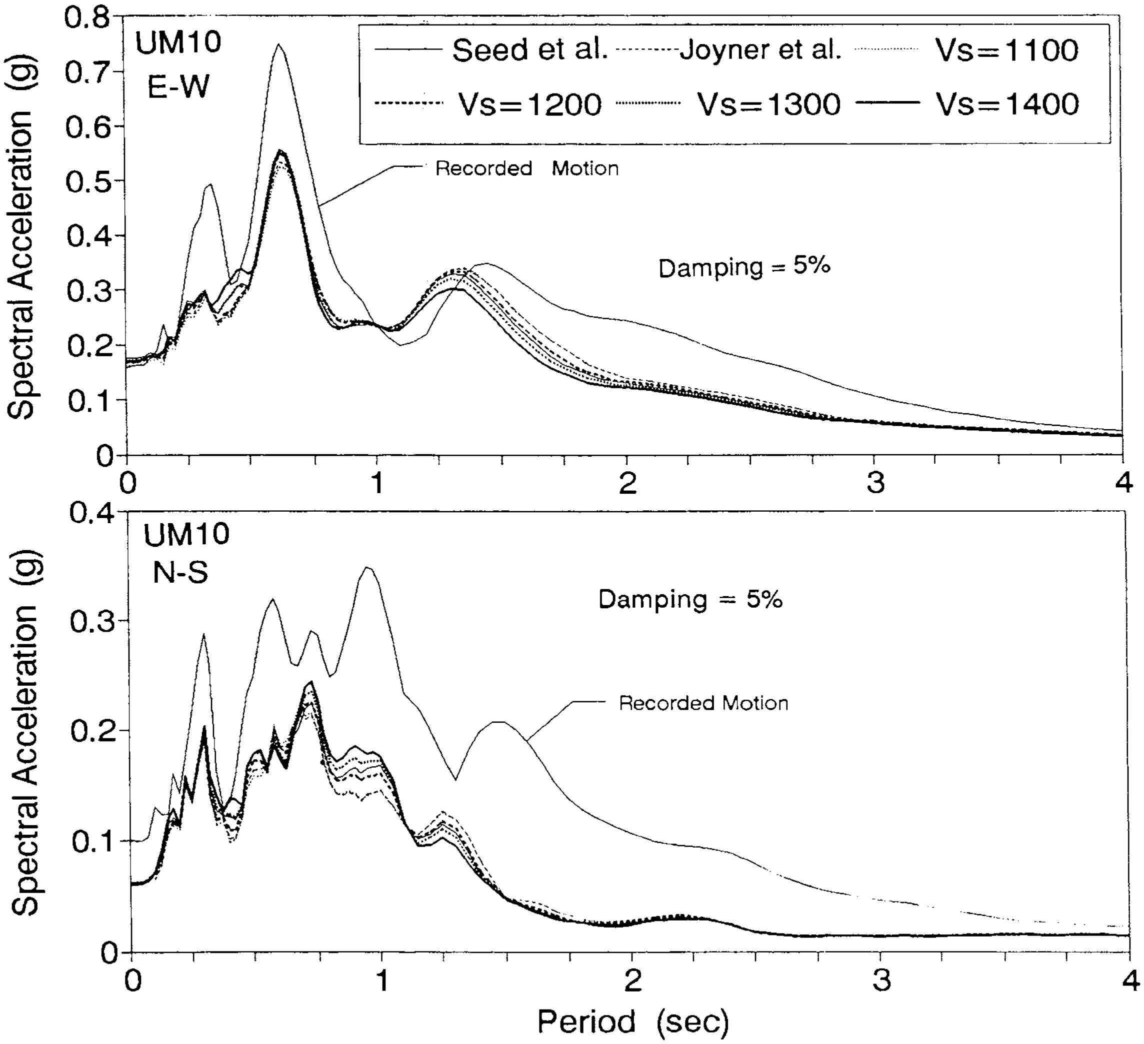

Fig. 7 Spectral Accelerations at UM10 using Various Assumptions for Propagation Velocity of Old Bay Sediments

The range of computed response spectra for all eight locations is shown in Figure 8 along with the spectra of the recorded motions at Treasure Island and Yerba Buena. A summary of the computed peak ground accelerations in the E-W and N-S directions at all locations is given in Table 2. The differences in stratigraphy around the island clearly resulted in different computed ground motions. The peak accelerations in the E-W direction ranged form a low of 0.13 at UM03 to a high of 0.20 at UM09.

The variation in maximum acceleration may be related to the natural period at each location. Higher surface accelerations develop in cases where the site period corresponded to peaks in the spectral acceleration of the input rock motion and lower accelerations correspond to troughs. It appears that overburden thicknesses were too large to be in resonance with the predominant input accelerations at a period of 0.7 seconds, but some amplification due to the peaks at 1.3 seconds was observed.

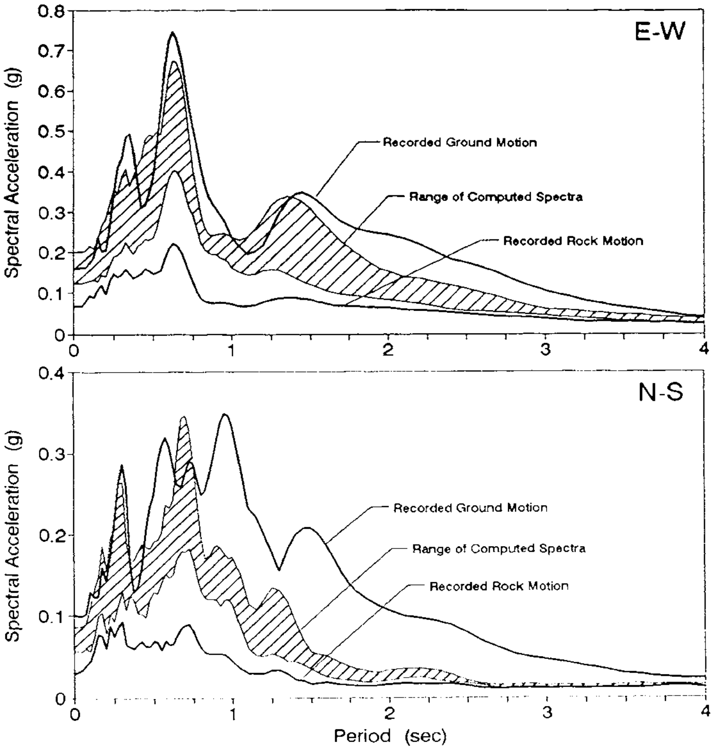

Fig. 8. Ranges of Computed Spectral Accelerations at Treasure Island

TABLE 2. Maximum Ground Accelerations

Location	Maximum Ground Accelerations (g's) E-W Component	N-S Component
UM01	0.16	0.06
UM03	0.13	0.06
UM05	0.19	0.07
UM06	0.17	0.08
UM09	0.20	0.09
UM10	0.18	0.06
UM11	0.16	0.07
UM12	0.16	0.06

It also appears that the maximum accelerations correlated somewhat with the fill thickness, or depth to Bay Mud. However, it is unclear whether this was a factor in soil amplification or just a coincidental trend which paralleled the effects of site period.

Some correlation between maximum ground accelerations and damage was observed. Lower ground motions were computed for the northwest section of the island where damage was least noticeable. The excavation performed during island construction at UM12 resulted in larger ground motions than at the adjacent UM3 locale. Large ground settlement was observed near UM9, where the largest accelerations were computed. On the eastern side of the island, where damage was also significant, accelerations ranged from 0.16 to 0.19 g's. These correlations, however, are somewhat incomplete without consideration given to the soil properties. Future work will include such analysis.

The SHAKE90 analyses revealed several additional interesting features of ground amplification at Treasure Island. In Figure 9, the maximum peak accelerations at UM10 are shown versus depth. Apparently, the older bay sediments contributed very little to ground amplification, the Bay Muds contributed somewhat, but by far the greatest contribution came from the fill material. However, this observation should not be under-

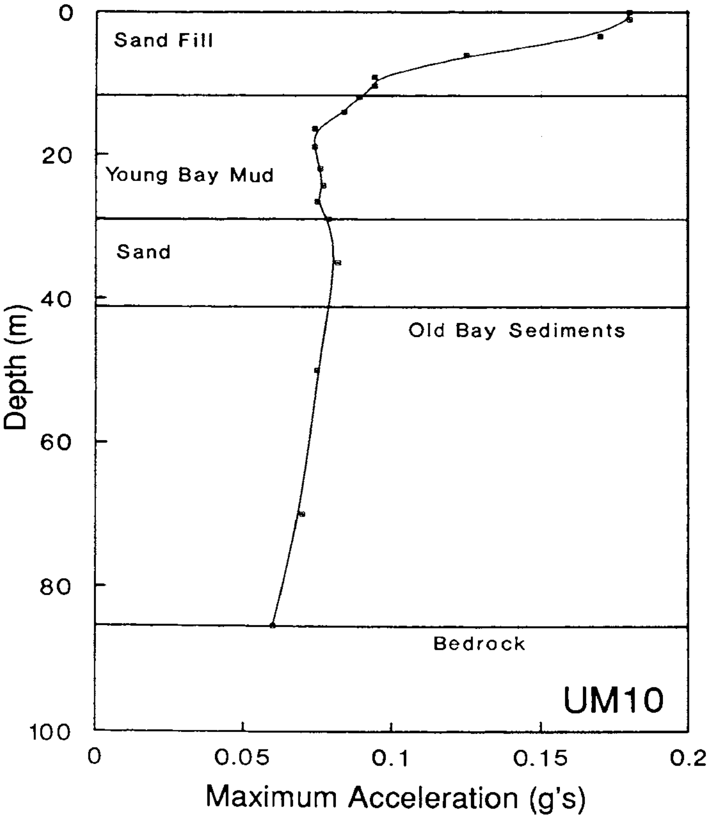

Fig. 9 Maximum Computed Acceleration versus Depth at UM10

stood to mean that the fill sand is inherently more prone to amplification than the Bay Mud, but rather that the fill is under lower confining pressure and, by its surcharging effect, provides the Bay Mud with higher shear stiffness. To support this hypothesis, an additional SHAKE90 run was performed for the UM10 location with the assumption that the fill and shoal materials were replaced by Bay Mud. The mud's wave propagation velocity was modelled by equation (2). The result was a peak acceleration of 0.18g's (E-W) which is equivalent to the peak acceleration for the actual stratigraphy shown in Figure 9.

SUMMARY

1. Seismic Cone Penetration Testing was conducted at Treasure Island to determine shear wave propagation velocities of the fill materials and Bay Mud. Models for wave propagation in these materials were developed for use at other locations where SCPT data was not available.

2. The ground motions and response spectra computed by SHAKE90 showed reasonable agreement with those recorded at Treasure Island, except for periods greater than 1 sec. The disagreement may be due to SHAKE90's inability to model softening of the soil after the onset of liquefaction.

3. The analyses at other locations revealed that variation in response spectra and maximum accelerations probably occurred on Treasure Island during the Loma Prieta Earthquake. Maximum computed acceleration values in the east-west direction ranged from 0.13 to 0.20 g's.

4. Some correlation could be made between the maximum ground accelerations and observed earthquake damage. The greatest damage was observed on the southeast side of the island where the largest ground motions are believed to have occurred. The least damage was observed in the northwest corresponding to the area in which the smallest ground motions occurred.

5. While older bay sediments contributed very little to ground amplification and younger Bay Mud contributed only somewhat, the majority of the amplification occurred in the shallower fill.

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