03 Jun 1993, 2:00 pm - 4:00 pm

Effects on High Plasticity Clay Deposits On Site Ground Amplification

John M. Ferritto
Naval Civil Engineering Laboratory, Port Hueneme, California

Recommended Citation

Ferritto, John M., "Effects on High Plasticity Clay Deposits On Site Ground Amplification" (1993). *International Conference on Case Histories in Geotechnical Engineering*. 19.
https://scholarsmine.mst.edu/icchge/3icchge/3icchge-session03/19

Proceedings: Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1-4, 1993, Paper No. 3.33

Effects on High Plasticity Clay Deposits On Site Ground Amplification

John M. Ferritto
Research Structural Engineer, Naval Civil Engineering Laboratory, Port Hueneme, California

SYNOPSIS This paper reviews the effects of the Loma Prieta earthquake on Treasure Island and discusses previous studies of site ground motion amplification. An independent study was performed in which it is shown that the site amplification is attributable to the presence of the Bay Mud deposits, a high plasticity silty clay that exhibits higher than normal shear modulus with cyclic strain. There is a similarity with the Mexico City clay deposits in both high plasticity and site amplification. Engineers should be alert to high plasticity clay deposits as a potential source of ground motion amplification.

INTRODUCTION

The Loma Prieta Earthquake of October 17, 1989 caused $125 million dollars of damage to U.S. Navy facilities. The predominant cause of damage was liquefaction of cohesionless waterfront deposits. This is a major continuing problem faced by the Navy which because of mission requirements must be situated at the waterfront often on marginal soils. This paper will analyze the response of soils at Naval Station, Treasure Island; of significance to this event was the fact that 80 percent of the loss of life occurred in a heavily concentrated damaged area approximately 50 miles from the fault rupture zone. The local site soil effects are the most striking feature of the Loma Prieta event. The references listed were used as part of this study.

The Earthquake

According to Lew (1990) and Seed, et al. (1991), the earthquake occurred when a segment of the San Andreas fault northeast of Santa Cruz, California ruptured over a length of 28 miles producing a Richter local magnitude, M_L, of 7.0 and an average surface wave magnitude, M_S, of 7.1. The epicenter was 10 miles northeast of Santa Cruz and 20 miles south of San Jose. The initial rupture length was estimated to be 24 miles. The main rupture began at a depth of 11 miles below the earth's surface and near the center of what would be the rupture plane. Over the next 7 to 10 seconds the rupture spread approximately 12 miles to the north and 12 miles to the south The unusual middle location of the hypocenter within the rupture location contributed to the unusually short duration of the event. Approximately 8 to 10 seconds of strong shaking was observed which is considerably less than would be expected from an event of this size. The rupture propagated towards the earth's surface but during the main event appears to have stopped at a depth of 3 to 4 miles.

NAVAL STATION TREASURE ISLAND

Geology

Treasure Island is a man-made island constructed in the 1930s and situated between San Francisco and Oakland and attached to Yerba Buena Island by a short causeway, Figure 1, Rollins, et al. Over 29 million cubic yards of mostly fine-to-medium grained sand was dredged from borrow areas in the San Francisco bay and used as fill material over the Yerba Buena Shoals north of Yerba Buena Island. The bottom of the shoals area varied in depth from -2 feet to -26 feet mean lower low water. About 65 percent of the bottom sediments in this area were composed of sand and the remainder was soft clay. A low mound of rock was placed along the perimeter of island to act as a retaining dike for the sand fill. The fill material was deposited hydraulically by using a pipeline, by hopper and by clam shell dredge. Where the depth of the shoals exceeded -6 feet a bed of hydraulic sand fill was placed. The dikes were constructed such that each succeeding level was placed inward of the lower dike and rested on previous levels of hydraulic fill. Fill was placed to a level of +13 feet. Photography of the construction shows that the dike was constructed segmentally starting at the southwest corner. A low weir was installed to allow water from the hydraulic dredges and soft mud displaced by the fill to escape. A small dredge was used to remove areas of entrapped mud.

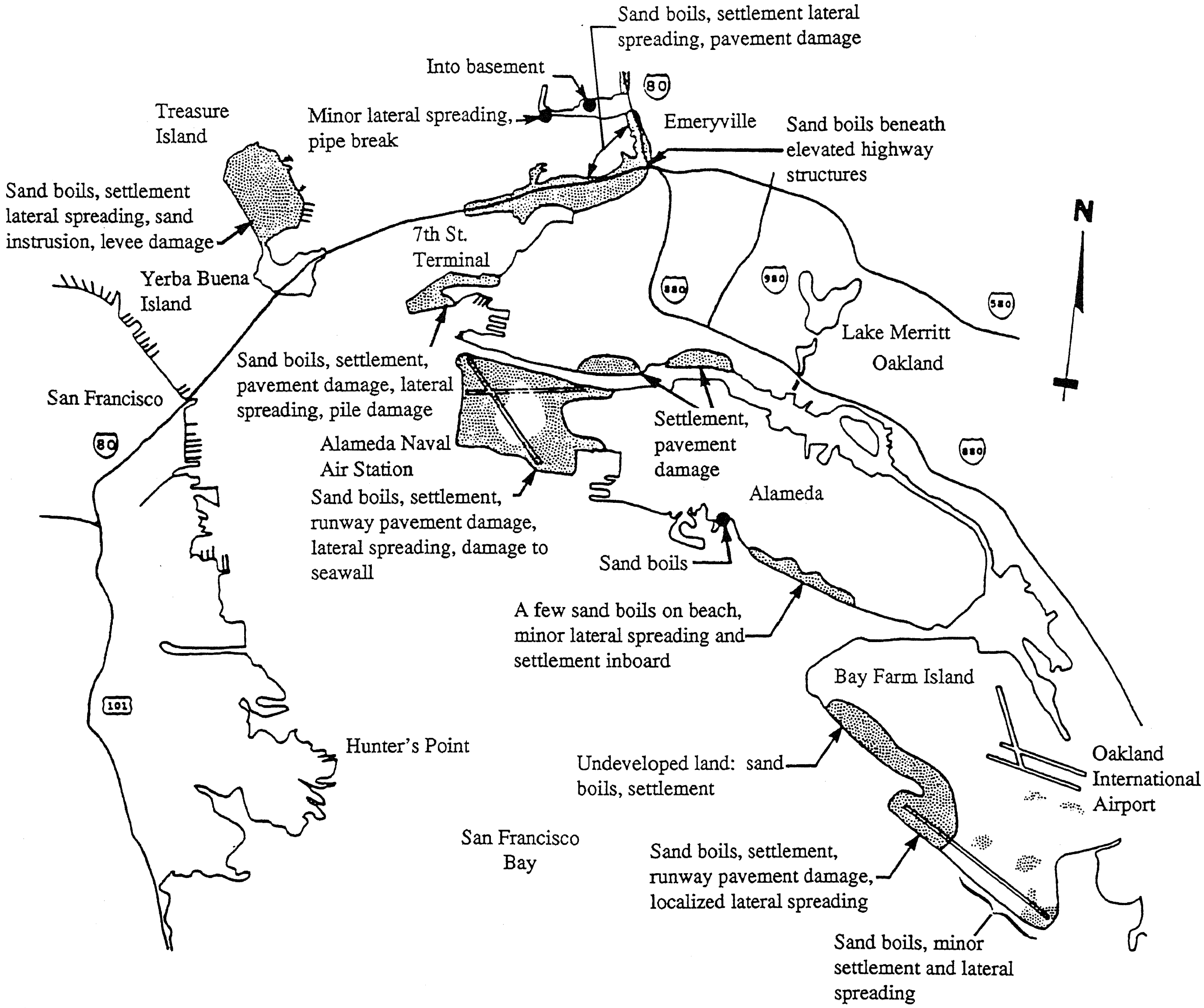

Fig. 1. San Francisco Bay showing Treasure Island and liquefaction (from Egan, et al., 1991).

During construction a 500-foot length of the north end of the east perimeter dike settled 10 to 14 feet. This failure area was stabilized by flattening the slope and placing a layer of sand beyond the dike toe. The north dike design was modified by first excavating a 400-foot trench 20 to 30 feet deep and backfilling with coarse sand as a foundation for the rock dike, Egan, et al. (1990).

Soil Conditions

The ground level of Treasure Island varies from +10.5 to +16 feet above mean lower low water level with a water table between +6 feet and +0 feet. Water levels are affected by the permeability of the sand fill and are not at the same levels as the bay. The ground water levels at the center of the island are less affected by the tide and vary from 5 to 8 feet below the ground surface. During the earthquake it is thought the water table was at +3 feet. Numerous explorations have been made by drill and sample or cone penetration testing, Egan and Wang (1991); Hrywic, et al. (1991); and Seed, Dickenson, and Mok (1992). Subsurface materials can be divided into four strata:

(1) Loose to medium dense hydraulically placed sand fill.

(2) Loose to medium dense native material, Yerba Buena Shoals sands and medium stiff native clays.

(3) Recent Bay sediments of medium stiff olive gray silty clay (Bay Mud) but containing some soft clay zones.

(4) Older Bay mud sediments consisting of brownish and greenish gray very stiff sandy, silty and/or peaty clays and dense sands.

The fill material is a fine to medium grained sand and has gradations ranging from well to poorly graded. It contains different amounts of gravel, silt and clay. In general the fill material is of lower density, looser, has a lower penetration resistance and lower shell content than the native shoals sands and clays. However from an engineering perspective the fill and native materials are thought sufficiently the same from an earthquake performance basis so as to be classified as a common strata. The blowcounts show the material to be loose to medium dense and susceptible to liquefaction under seismic shaking.

Post earthquake testing was performed by Hryciw, et al. (1991). Based on seismic cone penetration test shear wave propagation velocities for the fill materials and the recent Bay Muds were determined, Hryciw, et al. (1991). Equations of best fit were computed. Shear modulus and damping as functions of shear strain were determined for use in analysis, Figure 2 from Hryciw, et al. (1991).

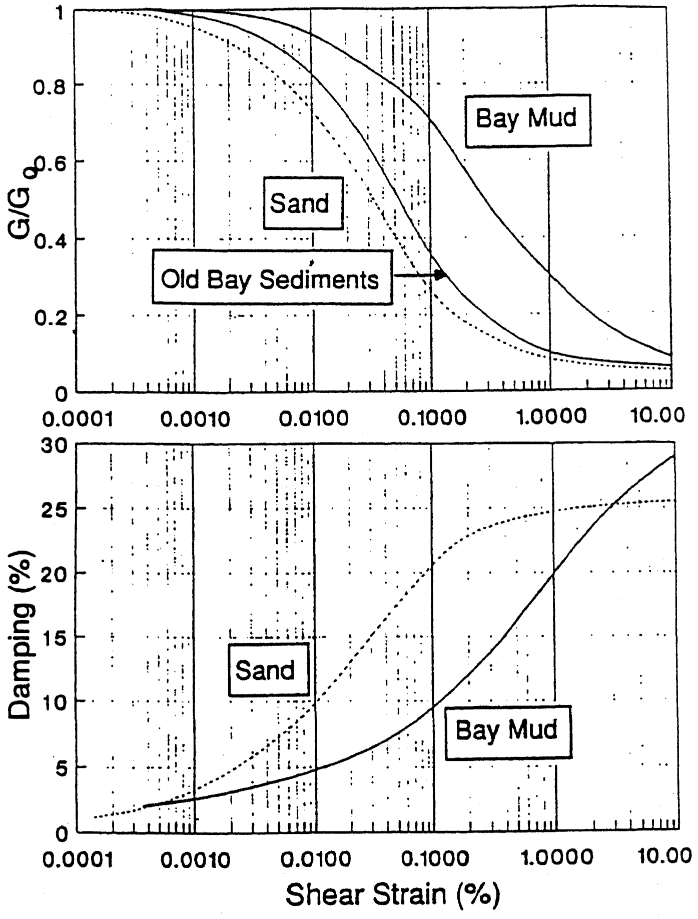

Fig. 2. Normalized shear modulus and damping with strain (from Hryciw, et al., 1991).

Below the fill and native material layer is a layer of Bay Mud composed of a medium plastic silty clay with interbedded regions of sand and silt. These recent Bay sediments vary in thickness between 10 and 120 feet. The layers were deposited in a marine environment and are normally consolidated.

The older Bay sediments of Pleistocene age are generally stiff to sandy, silty and or peaty clays that extend down to the Franciscan bedrock. The layer is lightly to moderately overconsolidated. Bedrock is at a depth of about 280 feet below ground surface. Thickness of the older Bay sediments is estimated to be range from 20 to 170 feet.

Ground Motion

Strong motion recordings were obtained from an instrument on Treasure Island, Lew (1991); Seed, et al. (1990); and Hryciw, et al. (1991). The peak horizontal ground acceleration components from the main shock were 0.16 g and 0.10 g. A significant factor in the Loma Prieta earthquake was the amplification of ground motion in areas underlain be thick deposits of Bay sediments. Treasure Island falls within this observation especially in comparison with recordings on nearby Yerba Buena where the peak horizontal acceleration recorded on a rock site were about three times less than those on Treasure Island. This will be discussed in the following section. Observation of the Treasure Island record shows that at about 15 seconds after the start of recording, the ground motion was subdued; this was probably caused by the occurrence of subsurface liquefaction. Liquefaction occurred after about 4 or 5 "cycles" of shaking after about 5 seconds of strong motion. Sand boils were observed at numerous location and bayward lateral spreading occurred with associated settlements. Ground cracking was visible with individual cracks as wide as 6 inches. Overall lateral spreading of 1 foot was estimated. Ground survey measurements indicate that settlements of 2 to 6 inches occurred variably across the island and that some areas had as much as 10 to 12 inches of settlement. The liquefaction related deformations resulted in damage to several structures and numerous broken underground utility lines.

Yerba Buena Island, a large rocky outcrop, had horizontal components of motion from this event equal to 0.068 g and 0.031 g, both significantly less than those on Treasure Island.

PREVIOUS STUDIES

Treasure Island Site Parameters

Hryciw, et al. (1991), performed post-earthquake cone penetration tests to determine shear wave velocities. They estimate that the shear wave velocity in the sand fill upper layer was defined by a best fit of the data as:

$$V_s = 150 + 4z$$

where z is depth in meters and V_s is in meters per second.

They estimate the shear wave velocity for the Bay Mud layer to be:

$$V_s = 30\,z^{0.55}$$

For the alternating layers of stiff clay and dense sands the following is estimated:

$$V_s = 250 + 2z$$

For the purposes of constructing a site model the following additional information can be used.

Soil	Depth	Shear Wave Velocity
Silty sand	100 to 141 ft	1100 ft/sec
Stiff to hard clay	141 ft	1100 ft/sec
Stiff to hard clay	285 ft	1400/ft sec

Hryciw, et al. (1991), used the computer program SHAKE to analyze the soil profiles at Treasure Island. SHAKE is a frequency domain analysis using strain dependent elastic material parameters. They ran a parameter analysis to consider the uncertainty in specification of the older bay deposits using the measured rock accelerogram recorded on Yerba Buena as the basis for bedrock motion. Their results which would be classed as typical response of this category of analysis are shown in Figure 3. They compute a peak surface acceleration of 0.18 g in comparison with the recorded value of 0.16 g. The recorded spectra exceeds the computed spectra which is explained by Hryciw that the SHAKE analysis does not take into account the softening of the upper layers with the onset of liquefaction.

Seed, et al. (1990), analyzed the same site using the following:

Soil Type	Depth (ft)	Shear Wave Velocity
Loose sandy fill	0 to 30	500 to 600 ft/sec
Loose silty sand	30 to 45	550 to 650 ft/sec
Silty clay bay mud	45 to 100	500 to 700 ft/sec
Dense sand & silty sand	100 to 140	1100 ft/sec
Stiff to hard clay	285	1100 to 1400 ft/sec

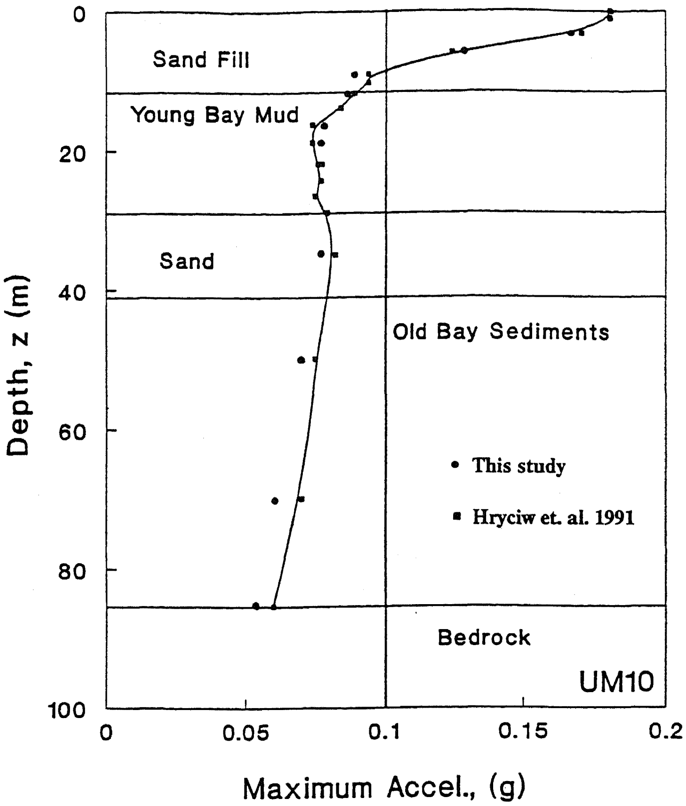

Fig. 3. Computer results in comparison with results (from Hryciw, et al., 1991).

Their calculated peak ground acceleration of 0.18 g agrees with the measured value of 0.16 g. The results show a spectral amplification of 4 to 5 although the computed spectral content is lower than observed. Seed, et al. (1990) explain the underestimation of the computed spectra as caused by surface waves generated by the dipping of the Yerba Buena rock outcrop beneath the alluvium and fill of Treasure Island. The late occurrence of liquefaction would not explain the underestimation of long period spectral response (> 0.15 sec). They note that peak spectral response occurs at a period of 0.6 seconds and a has a secondary response at 1.3 seconds. The 0.6 seconds does not represent the predominant period of this deep soft site but rather would be at the 1.3 seconds. The 0.6-second peak result from the site being strongly excited by the input rock motion having an energy concentration at this period.

One should conclude that the soil column analysis using SHAKE is an effective tool for predicting approximate levels of response. It is a simple expedient tool to use requiring data that is usually easily available. It can reliably indicate amplification when the site is properly modeled.

DETAILED ANALYSIS OF SITE

Site Analysis

It was of interest to examine the Treasure Island site to explore reasons for the site amplification. The data reported by Hryciw, et al. (1991) were used as the starting point for this investigation. Additional information on the site was obtained from DeAlba, et al.

SHAKE Analysis

Using the same soil profile defined by Hryciw, et al. (1991), the soil column was analyzed for the Loma Prieta earthquake using the SHAKE85 computer program. The Yerba Buena Island record was used as the rock input motion and average cyclic shear strain was taken as 0.65 times the maximum shear strain. Hryciw, et al. used SHAKE90, a more recent version of the same program. SHAKE90 uses strain dependent properties based on the ratio of shear modulus as a function of strain to the maximum shear modulus which occurs at low strain; multiple functions can be used for representation of sands and clays. SHAKE85 uses a function which is defined by equation; the user is limited to only one function for clay. These differences caused slight differences in the computed results. Figure 3 shows the computed data of this study which agrees very closely with that of Hryciw, et al. (1991). This establishes a benchmark control point from which a detailed analysis can be undertaken.

One point of considerable interest is the strain dependent properties for the Bay Mud. Rollins, et al., used data by Lodde (1982), to define the strain dependent shear modulus ratio. Figure 4 shows a plot of the Bay Mud curve compared with the more normal values based on data provided by Schnabel, et al. (1972). It can be seen that the Bay Mud has a significantly stiffer modulus with strain. Figure 4 also contains data from Mexico City, Seed, et al. (1987), which is very similar to the Bay Mud behavior. The Mexico City clays were noted to be rather stiff at low strain. Note that distant earthquakes are low strain events. The SHAKE analysis was repeated using the less stiff values normally associated with clays as a substitute for the Bay Muds. Figure 5 shows that amplification does not occur. Strains in the analysis using the Bay Mud properties are in the range of 0.03 to 0.08 percent in the Bay Mud layers; this results in an effective shear modulus of about 60 percent of maximum with damping in the range of 0.06 to 0.12 of critical. However when typical clay data is used the shear modulus drops to about 10 percent of maximum and damping increases to 0.08 to 0.15 of critical. This explains why the stiffer Bay Mud properties do not attenuate the motion as does typical clay. Rollins, et al. evaluate the significance of shear wave velocity over a wide range and concludes that this is not a factor of high sensitivity. They also conclude that:

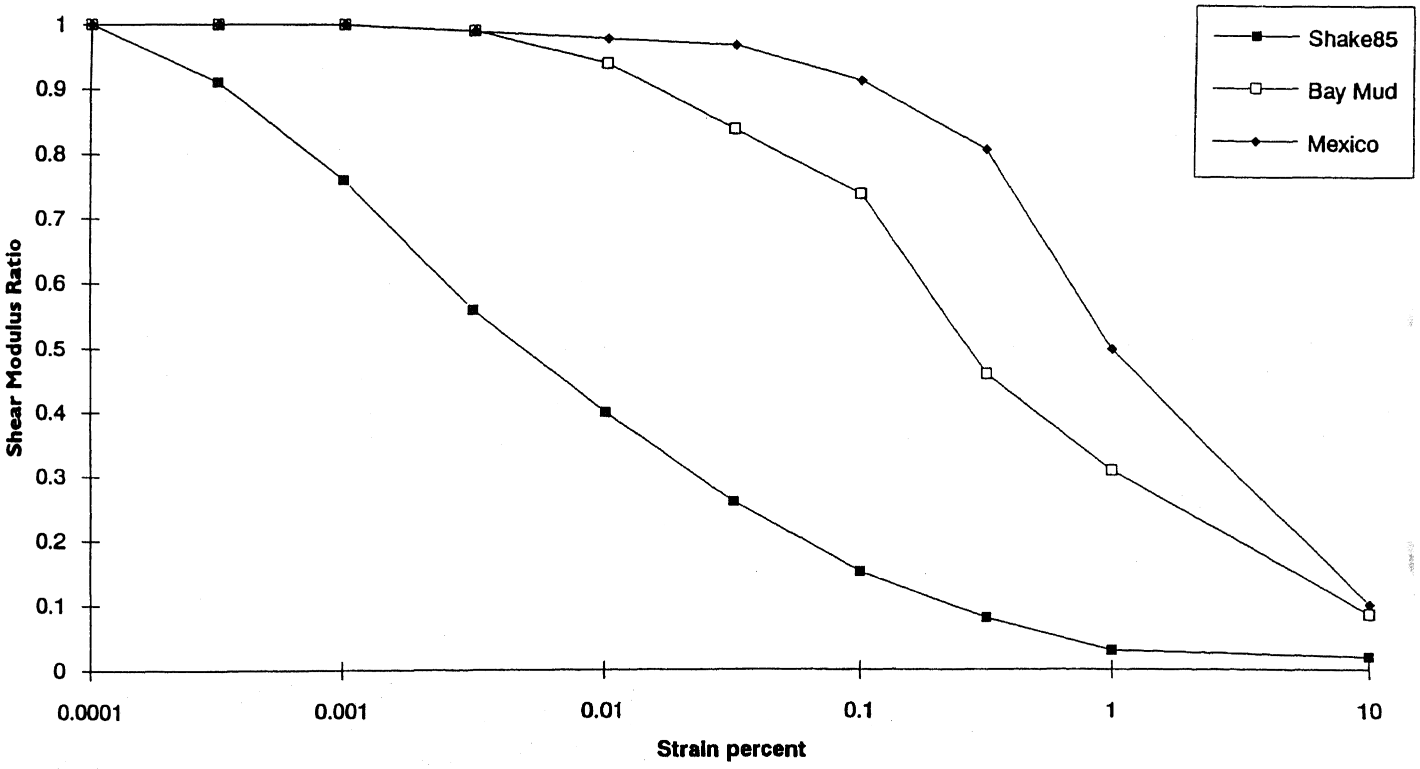

Figure 4. Shear modulus as function of strain.

"the older bay sediments contributed very little to the ground amplification, the Bay Muds contributed somewhat, but by far the greatest contribution came from the fill material. However, this observation should not be understood 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."

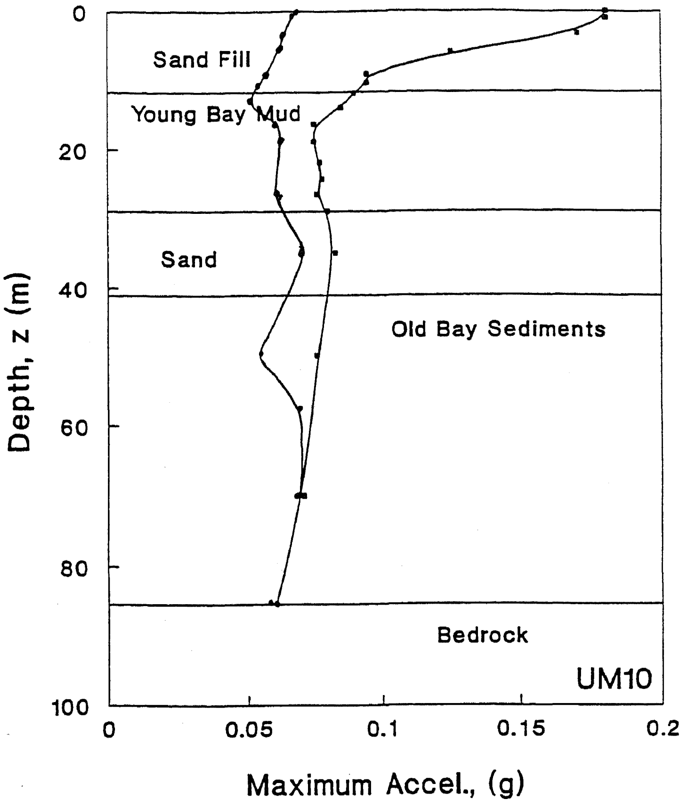

Figure 5. Results without amplification compared to results with amplification.

This author disagrees at least in part with this conclusion. It would appear from looking at Figure 3 that the amplification is occurring in the upper sand layer; however as shown above it is the stiff Bay Mud characterization which was shown to cause amplification. It is true that the confinement of the Bay Mud by the upper sand layer contributes to the stiffness of the Bay Mud. However, the Bay Mud as characterized by Lodde (1982), shows it to be stiffer with straining than would be expected. This is thought to be very significant. The San Francisco site and the Mexico City site both have clays that are substantially stiffer than would be expected. Sharma (1991) shows that the Plasticity Index for Bay Muds is in the range of 20 to 40 between 38 and 75 feet. The Plasticity Index for Mexico City clays was 30. Vucetic, et al. (1991) show data documenting that the shear modulus is stiffer with shear strain as the Plasticity Index increases. This little publicized data indicates that the stiffness of clay under cyclic loading should be increased to account for the Plasticity Ratio. The Plasticity Index is based on the amount of water required to transform a remolded soil from semisolid to a liquid state. It is a function only of the size shape and mineralogy of the soil particles and the pore water.

CONCLUSION

This report has presented a detailed study of the response of the Treasure Island site during the Loma Prieta earthquake. It shows that the behavior during the earthquake was as might be expected. The site was analyzed using the computer program SHAKE gave an accurate assessment of site response and soil amplification. Choice of appropriate material properties is essential for an accurate assessment, although the analysis was rather insensitive to shear velocities.

Significant findings are:

- SHAKE can predict site response and soft site amplification given an accurate assessment of the subsurface soil properties.
- Treasure Island amplification was dependent upon the Bay Mud properties.
- San Francisco Bay Muds resembles the Mexico City clays in being stiffer with straining than otherwise expected. This is related to its Plasticity Index.
- Engineers should be alert to the presence of high plasticity clay deposits as a potential source of ground motion amplification.

ACKNOWLEDGMENT

The author wishes to thank Professor Kyle Rollins, Brigham Young University, for providing the Loma Prieta earthquake record and site data on Treasure Island. His assistance is most appreciated.

REFERENCES

DeAlba Pedro, et al., Deep Instrumentation Array at Treasure Island Naval Station, in publication.

Egan John A., et al. (1990), "Evaluation of Interior Area Performance for Naval Station Treasure Island, San Francisco, California", Geomatrix Consultants, Oct 1990

Egan, John A., and Zihi-Liang Wang (1991), "Liquefaction Related Ground Deformation and Effects on Facilities at Treasure Island, San Francisco, During the 17 October 1989 Loma Prieta Earthquake," in Proceedings from the Third Japan-US. Workshop on Earthquake Resistant Design of Lifeline facilities and Countermeasures for Soil liquefaction, National Center for Earthquake Engineering Research, State University of New York at Buffalo, Feb 1991.

Hryciw, Roman D., et al. (1991), "Soil Amplification at Treasure Island During the Loma Prieta Earthquake," in Proceedings Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Mar 11-15 1991, St. Louis, Missouri.

Lew, Marshal (1991), "Characteristics of Vertical Ground Motions Recorded During the Loma Prieta Earthquake," in Proceedings Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Mar 11-15 1991, St. Louis, Missouri.

Lodde, P. F. (1982), "Dynamic Response of San Francisco Bay Mud," MS Thesis, University of Texas at Austin, 1982.

Rollins, Kyle, et al., "Soil Amplification at Treasure Island During the Loma Prieta Earthquake," in publication.

Schnabel Per B., et al. (1972), "SHAKE, A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites," EERC 72-12 University of California, Berkeley, California, Dec 1972.

Seed H. B., et al. (1987), Relationships Between Soil Conditions and Earthquake Ground Motions in Mexico City in the Earthquake of Sep 19, 1985," EERC 87-15 University of California, Berkeley, California, Oct 1987.

Seed R. B., et al. (1990), EERC 90-05 "Preliminary Report on the Principal Geotechnical Aspects of the Oct 17, 1989 Loma Prieta Earthquake," College of Engineering University of California, Berkeley, California, Apr 1990.

Seed R. B., et al. (1991), "Liquefaction of Soils in the 1989 Loma Prieta Earthquake," in Proceedings Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Mar 11-15 1991, St. Louis, Missouri.

Seed R. B., S.E. Dickenson, and C.M. Mok (1992), "Seismic Response of Soft Clay Sites: Recent Lessons," EERI Forty-Fourth Annual Meeting, San Franciso, Feb 6-8 1992.

Sharma H. D. (1991), "Performance of a Hazardous Waste and Sanitary Landfill Subjected to Loma Prieta Earthquake," Proceedings Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Mar 1991, St. Louis, Missouri.

Vucetic M., et al. (1991), "Effect of Soil Plasticity on Cyclic Response," Journal of Geotechnical Engineering Vol. 117, No. 1, Jan 1991.