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# Exceptional Issues in Offshore Earthquake Geotechnology

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# Exceptional Issues in Offshore Earthquake Geotechnology

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SYNOPSIS This Moderator's Report reviews the state-of-the-art report and papers submitted to the session on Offshore Earthquake Geotechnology. Selection of earthquake intensity and characteristics of ground motions for design of offshore structures, offshore source and attenuation characterizations, local site effects, and structure-foundation-soil interactions that may be exceptional to the offshore environment are discussed.

## INTRODUCTION

Offshore earthquake geotechnology has several key differences as compared with its terrestrial counterparts. Exceptional issues include the geology of the Continental Shelves; the environment in which soil deposition and consolidation take place; a water column that severely inhibits accurate determination of soil characteristics and recordings of ground motions; water waves and currents that provide an ever-present source of loadings; the characteristics of the structures and foundations sited on and in the soils; and the design guidelines, codes, regulations and procedures that are utilized in siting, designing, maintaining, and regulating the majority of the structures.

## STATE-OF-THE-ART-REPORT

In his SOA report, Part 1, Selnes (1981) addresses some of the unusual earthquake geotechnology aspects of offshore gravity or surface-supported platforms.

Important points presented in this paper include:

- Characteristics of platforms - their large size and mass, functions (drilling and production), and dynamic response (elastic and inelastic).
- Soils - difficulties of sampling, laboratory testing and testing in-situ, and the unusual properties of many offshore soils.
- Design Codes - advanced engineering guidance given by Det norske Veritas, American Petroleum Institute, and American Concrete Institute.
- Offshore seismic settings - unusual elements of shelf geology, traveling waves, attenuation, vertical ground motions, effects of overlying water.
- Influence of other loadings - developed by wind, waves, and currents.
- Analyses of soil response in low-strain and high-strain regimes.

This paper provides a useful review of some of the issues associated with descriptions of offshore earthquake ground motions and with characterization of soil response to such motions.

In addition to the design codes discussed by Selnes (1981), the Moderator would like to bring to the attention of the reader the earthquake design guidelines and regulations developed recently and published by the U. S. Geological Survey (1979) for design of steel and concrete offshore platforms.

The Moderator would like to discuss further the statement by Selnes (1981): "The soil surface waves are usually not important since strong ground motions traveling in soil will attenuate rapidly." Deep versus shallow source effects on the intensity and attenuation of ground motions near the earthquake epicenter (Patwardhan, 1978; Swanger and Boore, 1978; Woodward-Clyde Consultants, 1978); differences in soil displacement patterns that could have substantial influences on the stresses and deformations induced in the piles at depth (Bea, 1973, Bea et al., 1978); and the generally long dominant response periods of offshore platforms that fall into the long period surface wave range that can propagate for significant distances without large attenuation (Swanger and Boore 1978), all indicate that such a statement may be too broad a generalization.

SUBMITTED PAPERS

Seismic Design of the San Francisco Ocean Outfall (Gilbert, Eisenberg and Treadwell, 1981).

In this paper the authors describe design considerations for the offshore portions of a large, concrete sewer outfall pipeline that crosses the San Andreas Fault.

Addressed are development of fault motion characterizations, use of special sliding joints to accommodate fault displacements, and design analyses of a graded backfill to mitigate pore pressure effects and prevent damage by waves.

Useful guidelines are documented in this paper for soils exploration and design of buried outfall pipelines in an offshore wave and earthquake environment.

It would be useful to understand why a magnitude 8 earthquake with a peak ground acceleration of 0.6 g was chosen as the design criteria for a wastewater outfall.

Behavior of Clays Subjected to Slow Cyclic Loading and Large Strains (Saada and Shook, 1981).

Results are described from laboratory tests performed using a modified triaxial cell and a sedimented clay (Kaolin). Effects of varying consolidation histories and pressures, and varying modes of cyclic stressing are discussed as they influence large strain dynamic stress-strain properties (stiffness, damping) of the soil.

Exceptional issues include finding that the degrees of anisotropy and modes of stressing (compression, extension, torsion, one and two sided loadings) exert controlling influences on the high strain dynamic properties. Repeated high strains do not remove these influences. Isotropically consolidated clays generally failed sooner and had greater strains for a given cyclic stress than their anisotropic counterparts (for both normally and overconsolidated samples).

Attempts to utilize the Ramberg-Osgood and Masing models (with constant coefficients) to accurately describe measured dynamic stress, strain, and damping characteristics did not meet with success. Large errors were found, particularly for the high strain regions of response. No improvements in accuracy were found with use of degradation indices. This latter result was due to the tendency for a marked increase in the degradation index at high cyclic strain amplitudes.

To overcome the marked deficiencies of the constant coefficient analytical model, the authors suggest performing the laboratory tests in the stress, strain, consolidation conditions, and cyclic stress conditions of interest, and then developing the necessary constant coefficients of the Ramberg-Osgood-Masing models to properly fit the data.

Again, the potential fallacies of using low-strain analyses and results for high-strain conditions are well pointed out. Useful experimental results are given in this paper to assist in recognizing the influences of stress anisotropy and rotation of principal planes during cyclic loading.

Long-Term Measurements of Ground Motions Offshore (Reece, Ryerson and McNeill, 1981).

This paper describes design and initial experience with a self-contained seafloor accelerometer system to record strong ground motions. Details on the sophisticated placement, sensor array, power, data memory, telemetry, and retrieval systems are provided.

Analysis of records from the Santa Barbara Sunrise earthquake (August 21, 1979, $M_L = 3.2$) indicates much larger amounts of attenuation offshore than expected from analyses of onshore records. Strong motions were found to be associated with the primary and reflected surface wave arrivals (14 miles from epicenter). In view of the very weak motions involved in the recordings and the limited amount of data, one must carefully approach interpretations based on the analyses presented.

Development of competent and reliable instrumentation systems to make measurements offshore is a major need in earthquake geotechnology in the oceans. This well-written paper documents a major step forward in such endeavors.

Offshore Caissons on Porous Saturated Soil (Gazetas and Petrakis, 1981).

In this paper, a formulation is developed to analyze the dynamic response of a surface-supported caisson resting on a poro-elastic medium. Biot's Theory, Darcy's Law, Linear Wave Theory, and linear wave propagation mechanics are combined to study a soil-structure interaction problem.

The results indicate rocking oscillations are strongly influenced by fluid compressibility (degree of saturation) while swaying oscillations are little affected. Soil porosity is shown to have its primary influence through shear modulus and bulk density.

This is a useful analytical model for developing insights into soil-structure interactions involving very low-strain (elastic) behavior, particularly in cohesionless soils that may contain free gas in-situ.

One must carefully apply and interpret results from such models. The real world is full of inelastic and nonlinear behavior, particularly when one is concerned with the performance of offshore structures subjected to intense earthquakes. It is well to recall that satisfactory performance (no substantial loss of utility) of structures in intense earthquakes is a fundamental concern of the design engineer.

EXCEPTIONAL ISSUES

The author would like to highlight several exceptional issues raised in the state-of-the-art report and submitted papers to this session.

Selection of Earthquake Intensity and Characteristics of Ground Motions

Selection of earthquake intensity and characteristics of ground motions for design of a platform are intended to include consideration of platform response characteristics and desired safety of the facility. Guidelines for conducting such a selection have been given by the Marine Board of the National Research Council (1980). Three basic methods are outlined: Experience with Prototype Structures, Projected Lifetime Maxima, and Reliability Analyses.

Analytical hindcasting, based on historic and geologic data, is suggested as an appropriate technique for developing environmental exposure characterizations (quantitative description of the severity of environmental parameters and the likelihood of occurrence). Environmental design criteria are comprised of the environmental parameters and analysis procedures used to establish design loads. Environmental design criteria are not solely a function of the environment, but also depend on analytical models, structural criteria, required structural performance, safety, hazard mitigation measures, and economics.

General guidelines for performing offshore studies to define design earthquake intensities and characteristics of ground motions are given by the California Division of Mines and Geology (1980). These guidelines suggest Regional, Site, and Use analyses. The Regional analyses include bathymetry or submarine geomorphology, structural and/or tectonic patterns, relationship of regional structure to those of the project area, seismicity of the area, regional faults (active or inactive), and sediment and rock materials. The Site analyses include bathymetry, geologic structure, location of faults, seismicity, geologic hazards, surficial sediments, bedrock characteristics, and hydrologic characteristics.

Use analyses include relative stability of all geologic materials under natural conditions and those imposed by the platform, designation of mitigating measures where facilities are to be placed on foundation materials susceptible to movements, potential for seismic activity, potential for geologic related hazards, consideration of procedures and/or alternatives for mitigating measures, consideration of future design and construction studies that may be required, proposed methods of inspection and control, and operational aspects of the platform.

## Source and Attenuation Characterizations

Spatial, temporal and rupture characteristics of earthquake sources in a region exert a dominant influence on the ground motions expected at a given site. Geologic, geophysic, and seismic instrument data provide evidence with which to assess earthquake source characteristics. Studies of potential earthquake sources are intended to provide quantitative information on location, level of activity, probability, and distribution of future energy releases.

Offshore earthquake sources can present unique characteristics in comparison to their onshore counterparts; for example, plate subduction zones. Deep sources located in such zones are indicated to produce surface ground motions substantially different from those associated with shallow sources (Idriss, 1978; Patwardhan, 1978; Woodward-Clyde Consultants, 1978).

Source-to-site transmission or attenuation characterizations provide a link between description of potential earthquake sources and the characterization of local site effects. Important changes in the intensity, frequency-energy content, pulse sequencing, and variability of ground shaking occur as the result of seismic wave propagation along the travel path from source to site.

Offshore attenuation settings can be unique. Geology and sediments of the Continental Slopes and Shelves, combined with unique earthquake source characteristics and platform response characteristics, require careful examination. Analytical models have been and are being developed to recognize such unique characterizations (Lysmer, 1978; Idriss, 1978; Swanger and Boore, 1978). At present, they lack corroboration with measured data. Until such corroboration is provided, a suggested alternative is to select ground motion or structural response parameters that are most applicable to the dynamic characteristics of the structure-foundation system being designed, and select or develop an attenuation relationship that is based on data which best match local site conditions, local regional geologic and tectonic framework, range of source parameters, and distances of interest (Idriss, 1978; Marine Board, 1980)

Figures 1 and 2 summarize results from one recent study that recognized source and attenuation characteristics unique to an offshore area (Patwardhan, 1978). Figure 1 shows normalized acceleration response spectra for a site in the eastern Gulf of Alaska (shaded band). The response spectra are compared to those contained in the API guidelines (1980). Good agreement is indicated.

Figure 2 shows normalized acceleration response spectra for a site in Cook Inlet, Alaska. The response spectra differ significantly from those of API. Spectral accelerations are much lower, about one-half those of API for periods greater than about 0.3 sec.

The eastern Gulf is dominated by earthquake sources that have significant surface rupturing, a strike-slip fault environment. This environment is geologically similar to that of much of California, where the bulk of recorded ground motion data have been obtained. API spectra are based on response spectra derived from ground motions associated with shallow sources. Given that the eastern Gulf has been modeled appropriately, then one would expect the agreement that is indicated in Fig. 1.

The western Gulf is dominated by deep earthquake sources, primarily a subduction, plate-collision zone. This environment is geologically similar to that of portions of South America and Japan. In developing source and attenuation models for the western Gulf, recordings of ground motions from geologically similar areas were segregated from those recorded in dissimilar geologic environments. Deep sources were indicated to generate little surface wave activity in comparison to that of shallow sources (Idriss, 1978; Patwardhan, 1978). This dif-

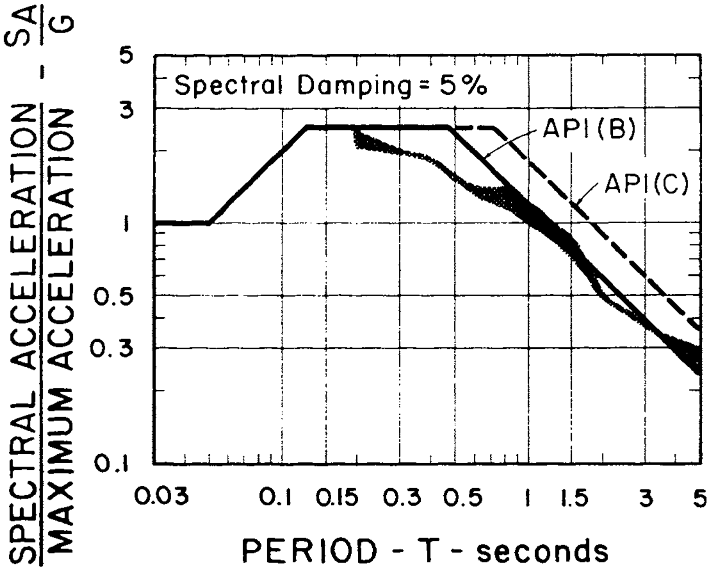

Fig. 1. Eastern Gulf of Alaska Normalized Acceleration Response Spectra

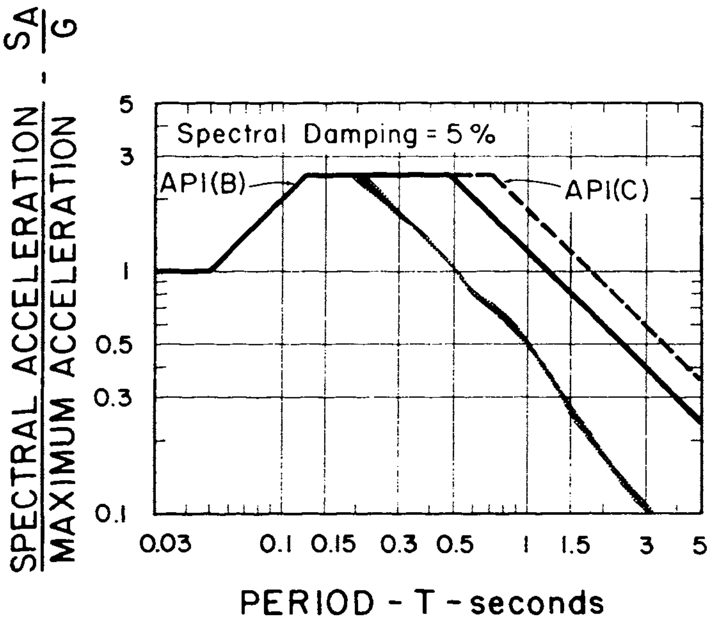

Fig. 2. Western Gulf of Alaska, Cook Inlet, Normalized Acceleration Response Spectra

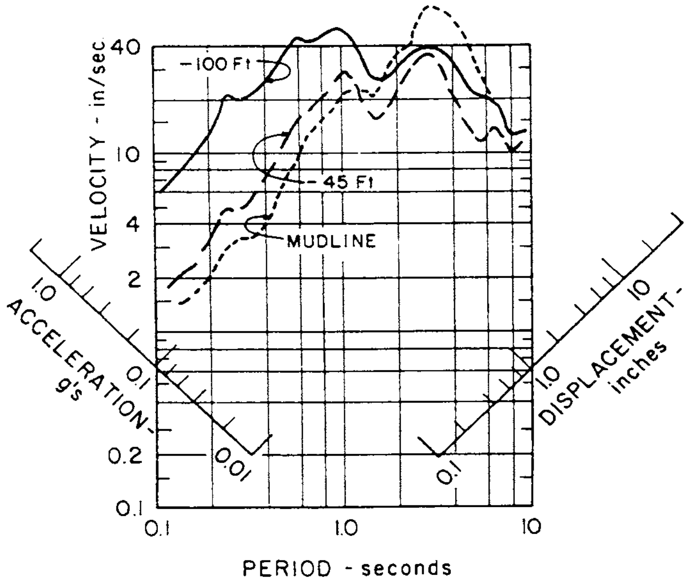

Fig. 3. Elastic Response Spectra for 100-ft Thick Soil Column

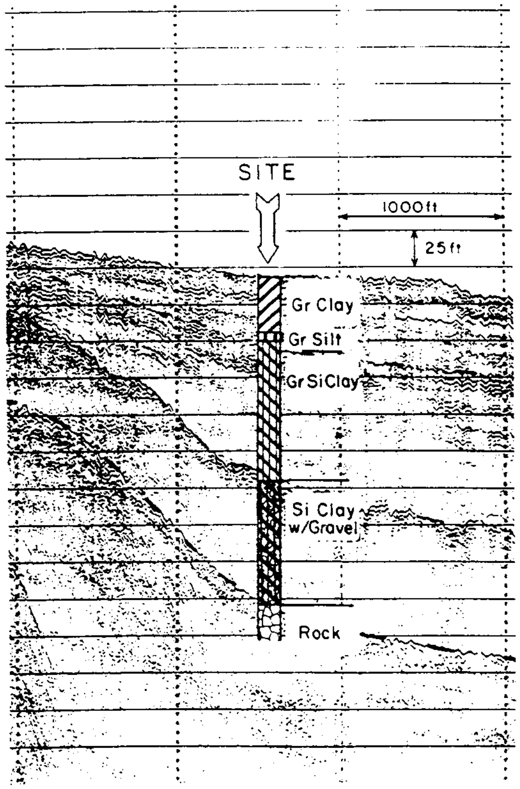

Fig. 4. High Resolution Seismic (Boomer) Profile of Sediments Surrounding a Site in the Eastern Gulf of Alaska

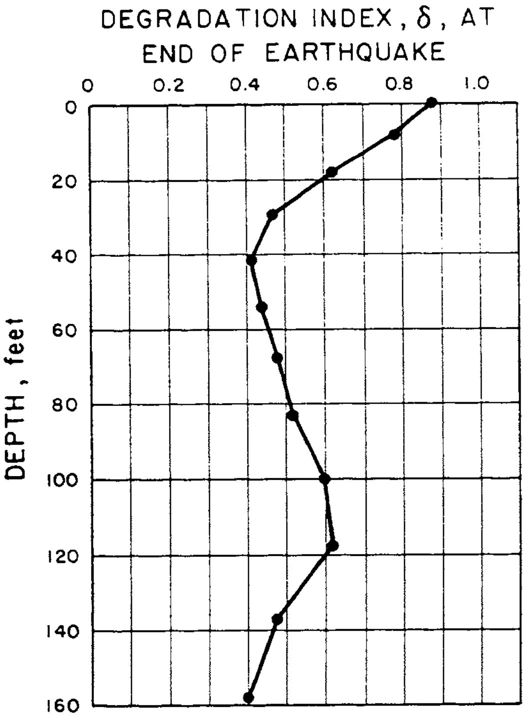

Fig. 5. Degradation in Soil Stiffness and Increase in Excess Pore Pressures at End of Earthquake Excitation (δ = Current/ Initial Stiffness)

ference has particular importance in the areas close to the sources where motions are intense and for structures, such as offshore platforms, that have long periods (greater than 1 sec).

## Local Site Effects

Local site effects can significantly modify characteristics of incoming earthquake surface and body waves. The influence of local site conditions is primarily a function of local geology, faults, soils, thickness of alluvium, proximity to basin edges or discontinuities, cyclic and dynamic stress-strain characteristics of the soils and rock, the overlying water column, and the manner in which seismic waves arrive at the site.

Both analytical and empirical procedures for evaluating such effects have been developed. Analytical procedures (Idriss, 1978; Lysmer, 1978; Swanger and Boore, 1978) provide useful insights, given realistic input information on soils, boundary conditions, and incoming ground motions.

Data from recordings of strong ground motions provide a useful alternative approach to characterize local site effects (Seed et al., 1974; Mohraz, 1976; Blume, 1973; Newmark, 1973; Idriss, 1978). Three approaches have been used: statistical normalized response spectra, scaled recorded ground motion time histories, and artificial ground motion time histories.

For pile-supported platforms, it is not only necessary to have representative ground motions for the soils near the mudline, but as well, ground motions for the soils along the length of the piles and well-conductors (Bea, 1973, Bea et al.,1978). Thus, some form of analysis must be used to infer the motions at depth, based either on the motions derived for the mudline soils (a deconvolution process) or motions derived for the basement or boundary sediments (Idriss, 1978; Lysmer, 1978).

Figure 3 shows response spectra derived from a vertically-propagating shear wave nonlinear analysis of a 100-ft thick layer of soft clay overlying bedrock (refer to Fig. 7) (Bea et al., 1979). Note the very large differences between the response spectra at the base of the soil layer (-100 ft) and at the mudline. Large amplifications at the mudline are noted for periods greater than about 2 sec. However, note that these amplifications are not present at shallow depths (-45 ft).

Pile-founded structures receive a major part of their input vertical motion from the lower parts of the piles (e.g., -100 ft) and a major part of the input horizontal motion from the intermediate parts of the piles (e.g., -45 ft). Mudline or surface elastic response spectra can provide potentially misleading results. Inelasticity in the soils and the foundations can significantly modify the implications derived from surface-based elastic response spectra (Whitman and Protonotarious, 1977).

Slope stability or deformability is a key issue associated with local site effects. A shallow geophysics record through a site in the eastern Gulf of Alaska is shown in Fig. 4. Soils at the site are classified as firm alluvium, of the order of 200 ft thick, overlying bedrock.

Response of this particular soil and site have been studied extensively (Idriss et al. 1975; Idriss, 1978; Moriwaki and Doyle, 1978). Figure 5 shows the profile of degradation index (measure of the current value of soil stiffness expressed as a fraction of the initial stiffness) at the end of shaking (85 sec) by a base motion having a peak acceleration of 0.33 g's. A nonlinear vertically propagating shear wave analysis code (DCHARM) was used to produce the results (Idriss et al., 1976; Moriwaki and Doyle, 1978). The soil properties characterizations were based on high strain laboratory test results.

The values of degradation index in the range of 0.4 at depths of 40 and 140 ft suggest considerable reduction in soil stiffness and substantial increases in pore pressure. The results indicate that slightly more intense shaking or longer duration shaking could produce a slide or slope failure at this site.

Figure 6 shows the results of a nonlinear finite element analysis (Bea et al., 1980a) of peak shear stresses induced in the soils at the site by a storm wave having a height of 100 ft and a period of 15 sec. Such a storm condition has a comparable return period or probability of occurrence with that of the earthquake studied. Shear stresses in the soils under the wave crest and at a point one-quarter of the wave length

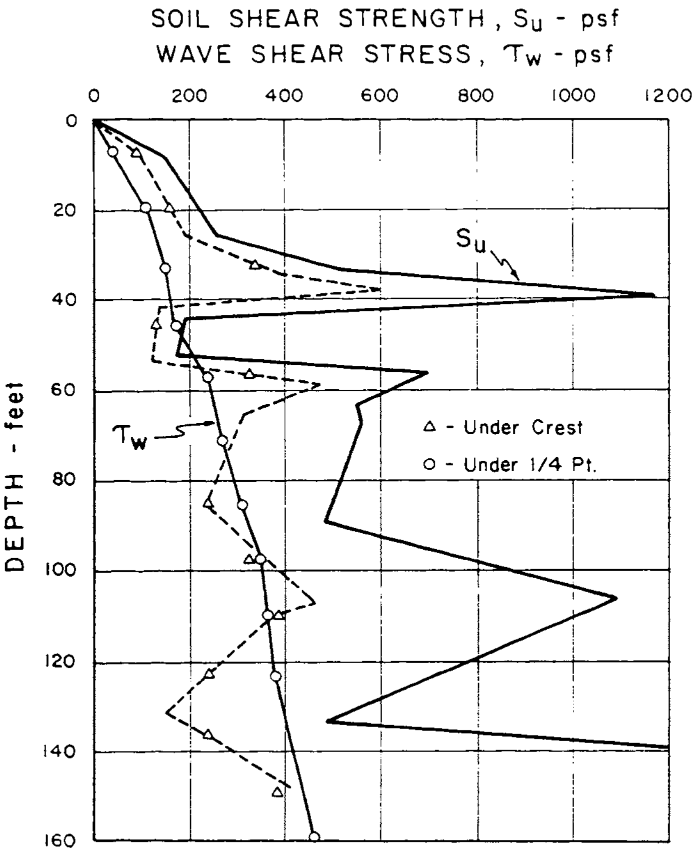

Fig. 6. Shear Stress Induced in Soil by Storm Waves Compared with Undrained Soil Shear Strength

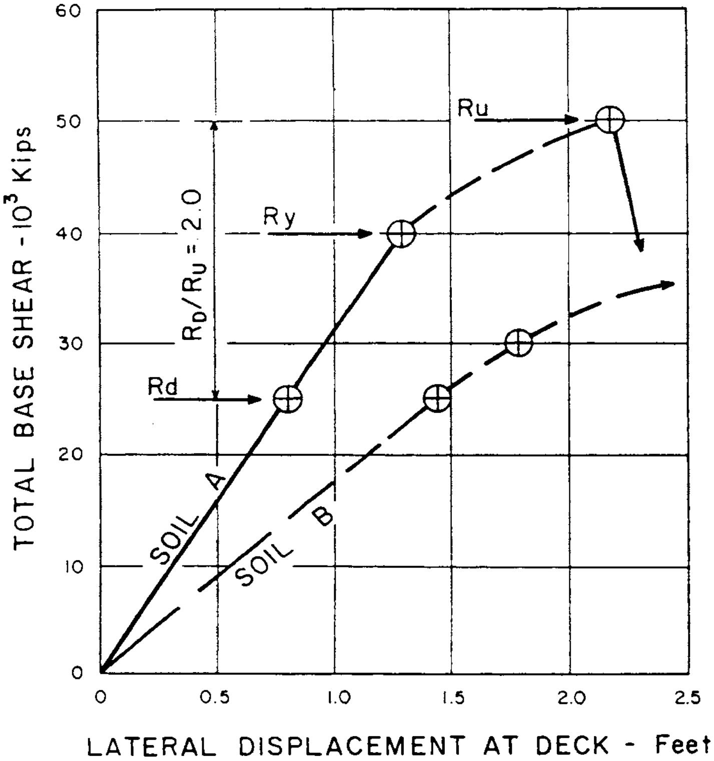

Fig. 8. Elastic and Inelastic Response of Structure-Foundation-Soil System to Earthquake Induced Loadings

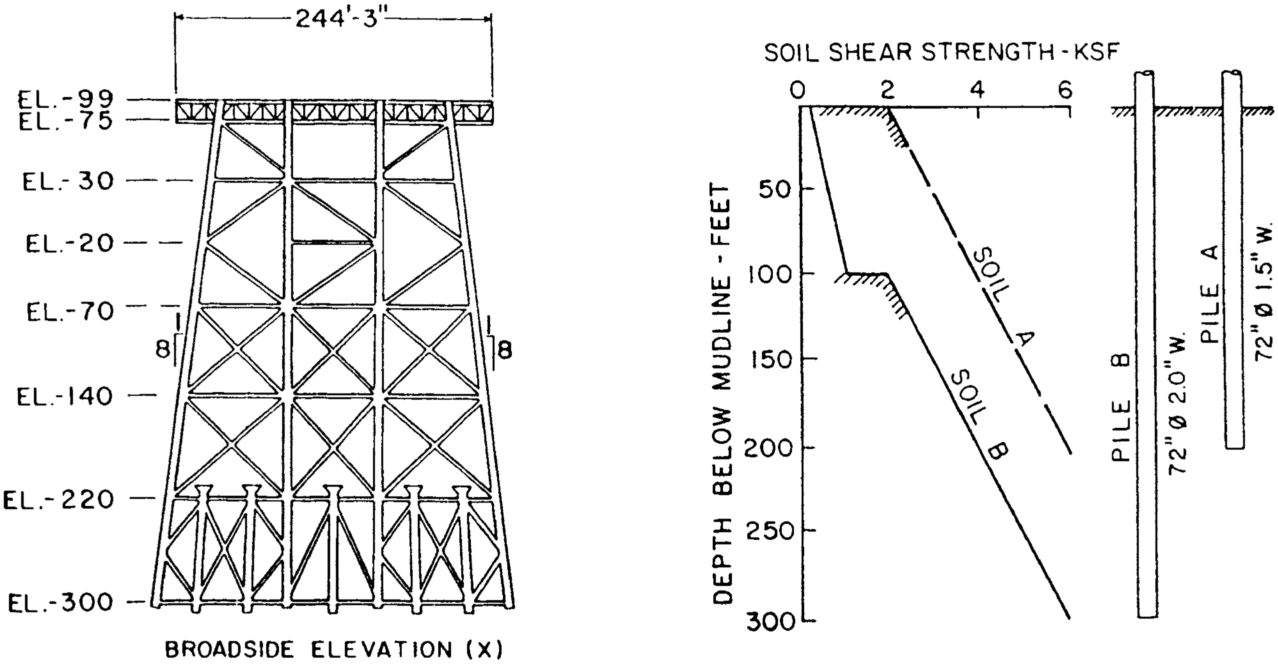

Fig. 7. Platform and Soil Conditions for Sites in Eastern Gulf of Alaska

ahead or behind the crest are shown. Comparison of wave-induced shear stresses with the undrained shear strength (miniature vane) of the soils indicates a high potential for exceeding the shear strength at depths of 40 and 140 ft.

Intense earthquakes and storms can have similar effects on an offshore soil site. There is a potential interaction between the two sources of loadings. Excess pore pressures generated by one source, which if not dissipated, could lead to a much different response than indicated by these results.

## Structure-Foundation Soil Effects

A most important element of offshore earthquake geotechnology is an understanding of the potential response characteristics of the platform to be designed for a given site. The loads experienced by the platform, and hence by the foundation elements, are strongly dependent on the stiffness, mass, and energy dissipation characteristics of the platform, as well as the characteristics of the ground motions. The foundations of pile and mat-supported platforms generally contribute significantly to the stiffness and energy dissipation characteristics of the system. They can markedly affect the deformation and force transmission characteristics of the platform system (Bea, 1973, Bea et al., 1979).

Shown in Fig. 7 is a conventional, steel, 12-leg platform designed according to API guidelines (1980) for 300 ft of water and for the soil conditions shown. The response of the platform to earthquake-induced loadings is shown in Fig. 8 (Bea et al., 1979). The platform response is characterized as the maximum lateral displacement measured at the upper deck level versus the peak total base shear induced by earthquake ground motions. The elastic design lateral loading is indicated as Rd, yield loading as Ry, and ultimate loading as Ru.

The structure founded on the stiff soils (Soil A) is able to withstand motions that induce loadings twice those of the design intensity. Ductilities (ratio of maximum displacement to elastic displacement) of the order of 2 are indicated. The structure founded on the soft soils (Soil B) never develops loadings in excess of 1.4 times the design loading. This is due to the inability of the weaker soils to transmit the motions to the superstructure as efficiently as the stronger soils.

Figures 9 and 10 are based on results of field pile-loading tests (Bea, 1980b; Kraft et al., 1981). These data show that the axial and lateral load carrying capacity of driven piles in clays can be substantially increased by high rates of loading. This rate-of-loading effect in increasing the resistance and stiffness of the piles is chiefly centered in the similar effects in the soils that support the piles (Poulos, 1981).

At loading rates typical of those associated with the earthquake response of platforms, increases in load carrying capacity of 30 to over 100 percent are indicated. Even larger increases in stiffness are possible (Bea, 1980b; Kraft et al., 1981). While such increases in capacity and stiffness are potentially beneficial to the piles, due to the increased transmissibility of the foundation, the additional inertial loadings induced in the superstructure may lead to unanticipated loadings in the superstructure and increased loadings on the foundation elements.

The last exceptional issue to be discussed is that of the factors-of-safety utilized in design of the foundation elements. Factors-of-safety used in design should be a function of the design loadings and the probabilities associated with other possible loadings (Moses and Russell, 1980). In the case of the API guidelines (1980), constant factors-of-safety are specified for axial loadings on pile foundations; 2.0 for dead loadings and 1.5 for dead plus live loadings.

The factors-of-safety also should be influenced by the methods used to characterize the soils, procedures used to describe the ultimate capacity and tolerable deformations of the piles, geometry of the foundation-superstructure systems (effective redundancy and ability to redistribute overloads), and the desired reliability of the system. This is an important area for further research (Moses and Russell, 1980).

## CONCLUSIONS

The state-of-the-art report and papers submitted to the session on Offshore Earthquake Geotechnology have addressed an interesting cross-section of important issues associated with this relatively new and rapidly evolving area of civil engineering in the oceans. Development of design approaches and guidelines, soil and foundation response characterizations, instrumentation, and realistic analytical models and procedures are exceptional issues for continued research.

A challenge to offshore engineers is to perceptively apply existing technology, using a full measure of judgment in such applications, and to communicate to researchers the realities and problems that need to be addressed to allow the state of practice to go forward.

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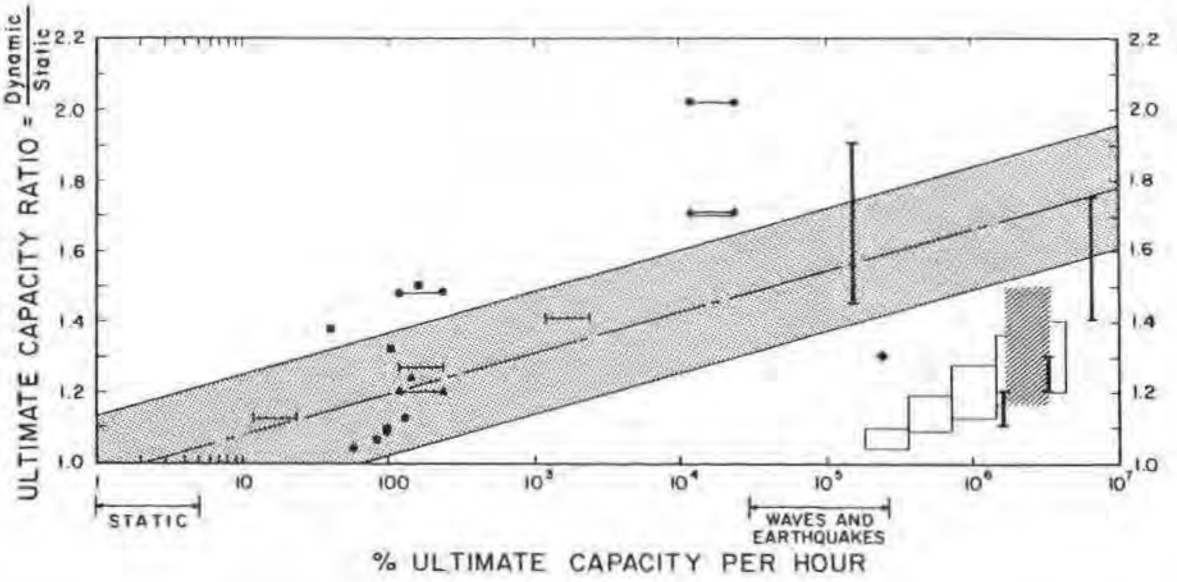

Fig. 9. Pile Axial Load Tests: Effect of Rate of Loading on Ratio of Maximum Dynamic to Static Resistance

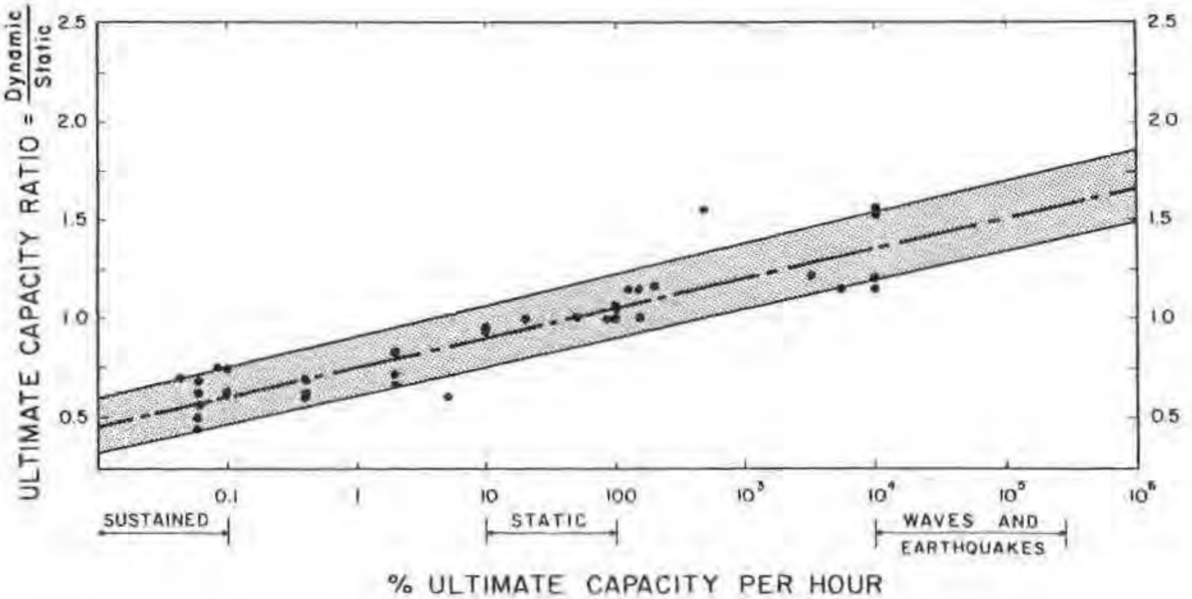

Fig. 10. Pile Lateral Load Tests: Effect of Rate of Loading on Ratio of Maximum Dynamic to Static Resistance

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