PROBABILITY OF LIQUEFACTION DUE TO EARTHQUAKE

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SYNOPSIS

One of the most destructive phenomena experienced in past earthquakes is "liquefaction" of the foundation soils. As there are many unknown parameters which must be postulated in characterizing the motion from an earthquake as well as dynamic soil strength, difficulties exist in the present day deterministic evaluation of soil liquefaction. Presented in this paper is a case study to illustrate probabilistic procedure to evaluate soil liquefaction potential utilizing the results of an engineering seismic risk analysis. Utilizing probability theory and standard liquefaction analyses, a probabilistic assessment of liquefaction potential was derived which takes into account the probabilistic nature of earthquake input, actual laboratory test results and engineering evaluation.

INTRODUCTION

Recent earthquake disasters have demonstrated the necessity of earthquake resistant design. One of the most destructive phenomena experienced in past earthquakes is "liquefaction" of the foundation soils. The subject of soil liquefaction has been studied by various investigators and a general method (1) of evaluation liquefaction potential has been subsequently established through the use of laboratory test data and computer oriented analysis. A simplified procedure (1) has also been developed. Both require that the analysis be performed deterministically.

As there are many unknown parameters which must be postulated in characterizing the motion from an earthquake, difficulties exist in the present day deterministic evaluation of soil liquefaction. A rational probabilistic procedure has been proposed (2) to evaluate soil liquefaction potential utilizing probability theory and standard liquefaction analyses. A probabilistic assessment of liquefaction potential can be derived which takes into account the probabilistic nature of earthquake input, laboratory test results and engineering evaluation.

The application of this procedure is illustrated through an actual case history. Liquefaction considerations for a proposed nuclear power plant site were studied previously (3) in a deterministic manner. A safe shutdown earthquake was selected based on the seismic history of the general area. The dynamic strength of the underlying soil media was determined through a comprehensive field and laboratory program. The deterministic factor of

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of safety against liquefaction was obtained for various strain levels. In this paper, a probabilistic evaluation of liquefaction potential is presented and compared to the deterministic case. The probability of liquefaction may be used to supplement the deterministic factor of safety and enhance our engineering judgement with respect to assessing liquefaction potential due to earthquake excitation.

SITE DESCRIPTION

The potential plant sites are located along the east coast of the Florida peninsula. Subsurface investigations were performed and deterministic procedures were used to establish the liquefaction potential. The evaluations utilized the conventional safety factor approach namely a ratio of available strength to induced stress; safety factors of 1.2 or greater were generally acceptable. Following are the selection of a safe shutdown earthquake based on the seismic history of the general area and the liquefaction considerations both deterministically and probabilistically.

SEISMICITY

Epicentral locations for all known and postulated earthquakes in peninsular Florida having a reported intensity of IV Modified Mercalli (MM) (4) or greater are plotted on Figure 1. Historic earthquake data has been assembled for a 200 mile radius of the various sites. The earthquake data has been compiled from U.S. Department of Commerce reports on U.S. Earthquakes and earthquake reports (5). As shown on Figure 1, earthquakes in Florida have been infrequent, of low to moderate intensity (III-VI MM), and have epicenters at least 100 miles from the sites. The other minor earthquakes within the state have been randomly scattered, and there is no evidence that any are related to observed structural features.

Most of the major earthquakes of the world have been related to distinct geologic structural features. The strains associated with the continuing deformation of these features are the proximate causes of the earthquakes. However, in the Southeastern United States, with the absence of both contemporary mountain building and continuing faulting, earthquakes are more difficult to explain. Although various hypotheses have been advanced relating the earthquakes to structural features in this region, there is no direct evidence of their association. The geologic evidence suggests that southeast earthquakes are the result of minor adjustments from the residual strains associated with earlier movements or with continuing warping. Hence it is conservatively assumed that the maximum earthquake in the region is assumed to occur anywhere within the region or tectonic province.

The tectonic province concept can be thought of as having a combination of both deterministic and probabilistic characteristics. It is deterministic in the sense that the distribution and size of future earthquakes may be predicted from a given set of observed and interpreted conditions, i.e., for areas containing consistent geological features, there is a consistency of earthquake potential.

From this assumption that earthquake activity is consistent over a region, it follows that the frequency of earthquakes to be expected can be determined based on the number of events in a given region during a given interval of time; this is a probabilistic concept.

SAFE SHUTDOWN EARTHQUAKE AND OPERATING BASIS EARTHQUAKE

All nuclear power plants in the United States must be designed to withstand a Safe Shutdown Earthquake (SSE) as well as an Operating Basis Earthquake (OBE). The SSE is the largest vibratory ground motion that could affect the plant; the plant must be able to shut down safely following such an event, even if some components of the plant are damaged. The OBE is the vibratory ground motion through which the safety features of the plant must remain functional while the plant stays in operation. Should a plant experience an earthquake greater than the OBE, it must be shut down for inspection and checking prior to resumption of operation, but it need not be shut down if the earthquake is equal to or less than the OBE. Thus, the OBE functions as a threshold, above which large economic penalties occur when the plant is shut down.

In order to comply with the minimum accepted acceleration as stipulated by 10 CFR 100, Appendix A, of the U.S. Nuclear Regulator Commission, the plant should be designed for a maximum horizontal ground surface acceleration of 0.10 g (SSE), which was based on conservative relationship (6) between the MM intensity and the ground acceleration. This very conservative surface acceleration is double the maximum acceleration appropriate for the maximum earthquake which has occurred in the site's seismotectonic region during the past 200 years.

LIQUEFACTION CONSIDERATIONS

Previous Study

Extensive subsurface investigations were performed at the various sites. A detailed description of one particular subsurface investigation and foundation evaluation was presented previously (7). In addition, a deterministic evaluation of soil liquefaction was conducted (3). It was concluded (3) that the factor of safety against cyclic strain level of 10 percent is 1.3 under the postulated SSE conditions. The mean relative density minus one standard deviation was conservatively used for establishing the dynamic shear resistance. It should be noted that the factor of safety will depend on the postulated ground acceleration and selection of the dynamic soil strength. The nature of the complex ground vibration and nonhomogeneous foundation soil suggests that a single value could not possibly cover the spectrum of its variations.

Stochastic Approach

For purposes of defining a liquefaction probability let R and S be random variables representing the soil strength and seismic-induced stress respectively, and r and s be specific values of the corresponding random variables. The probability of soil liquefaction (P_{ℓ}) can be defined as

$$P_{\ell} = \mathcal{P}(R \leq S) \tag{1}$$

Let f_{RS} (r,s) be the joint density function of the random variables R and S. The probability of soil liquefaction is obtained by integrating the density function within the proper domain.

$$P_{\ell} = \iint_{R \leq S} f_{RS}(r,s)\, dr\, ds \tag{2}$$

It is assumed that R and S are independent, i.e., the dynamic soil strength and the seismic-induced stress are independent quantities.

$$P_{\ell} = \iint_{R \leq S} f_R(r)\, f_S(s)\, dr\, ds \tag{3}$$

where $f_R(r)$ and $f_S(s)$ are density functions of R and S, respectively, as shown on Figure 2. Introducing $F_R(r)$ and $F_S(s)$ as cumulative density functions of R and S respectively, it is easily shown, by integrating Equation 3, that:

$$P_{\ell} = \int_0^{\infty} f_S(s)\, F_R(s)\, ds \tag{4}$$

$$= \int_0^{\infty} (1 - F_S(r))\, f_R(r)\, dr \tag{5}$$

where R and S are assumed positive only.

In other words, Equation 4 defines the probability of liquefaction such that, for each possible seismic-induced stress value, the soil strength is less than or equal to it. Similarly, Equation 5 defines the probability of liquefaction that for each possible strength value, the seismic-induced stress exceeds it. Therefore, the probability of liquefaction, P_{ℓ}, covers the whole spectrum of possible variations in both seismic-induced stress and soil strength. The value of P_{ℓ}, which is always smaller than one, depends on the variations in parameters R and S. Figure 2 shows the superposition of $f_R(r)$ and $f_S(s)$ together with a deterministic value of the factor of safety based upon selected strength and stress values.

The seismic-induced stress is a function of the ground acceleration level which in turn depends on the earthquake intensity level. An engineering seismic analysis provides a rational approach to evaluate the earthquake intensity level at the site based on the regional seismicity and attenuation behavior. The region surrounding the site was subdivided into areas of similiar seismicity and statistical properties of seismic events were developed for each area. The affects of events in different provinces were attenuated to the site. The probability function of a site intensity was established. The probability function of the ground acceleration was then obtained by the transformation of random variables using the established relationship (6) between the ground acceleration and earthquake intensity. It was found that the probability of a peak acceleration at least 0.05 g felt at the site is 1.3% over the 40 year life. The seismic-induced stresses under various acceleration levels were calculated for the site soil column by using the SHAKE computer program. This program utilized the site dependent soil modulus and damping properties as established from both field shear wave velocities and laboratory tests.

The stress ratio causing 10% cyclic strain was determined from stress controlled, cyclic loaded triaxial tests conducted on representative samples of the materials encountered at the site. Undistrubed samples were obtained from the lower blow count zones and a statistical evaluation was made on the scatter of the soil resistance (Figure 3). In general, the soil strength is a function of the acceleration/magnitude level. For simplicity, it is assumed that the soil strength is independent of the acceleration level, and its selection is based on an equivalent cycle of 10 which is generally compatable with an acceleration level of 0.1 g. This assumption will result in a conservative value of P_{ℓ} when the acceleration level is less than 0.1 g and an unconservative value when acceleration level is greater than 0.1 g. It should be noted that test results show that very little variation in the stress ratio was observed with equivalent cycles greater than 10. Furthermore, the probability density function is very small when the acceleration level reaches beyond 0.1 g. The overall effect of this simplified assumption will yield a conservative probability of liquefaction. The results of this case study showed that the probability of liquefaction at the site is on the order of 10^{-8} during the 40 year life of the plant.

CONCLUSIONS

The paper generally discusses the deterministic method of liquefaction evaluation as well as a probabilistic approach to defining conservatism in our engineering approach to the liquefaction problem. Because of the lack of overall definition of an appropriate level of seismic design conservatism, many times elements in the seismic design chain are reviewed in isolation from other elements, such as the siting and other engineering areas. With respect to this particular aspect of siting, namely, liquefaction, it is particularly comforting to find that the probability associated with our conventional deterministic approach is acceptibly low.

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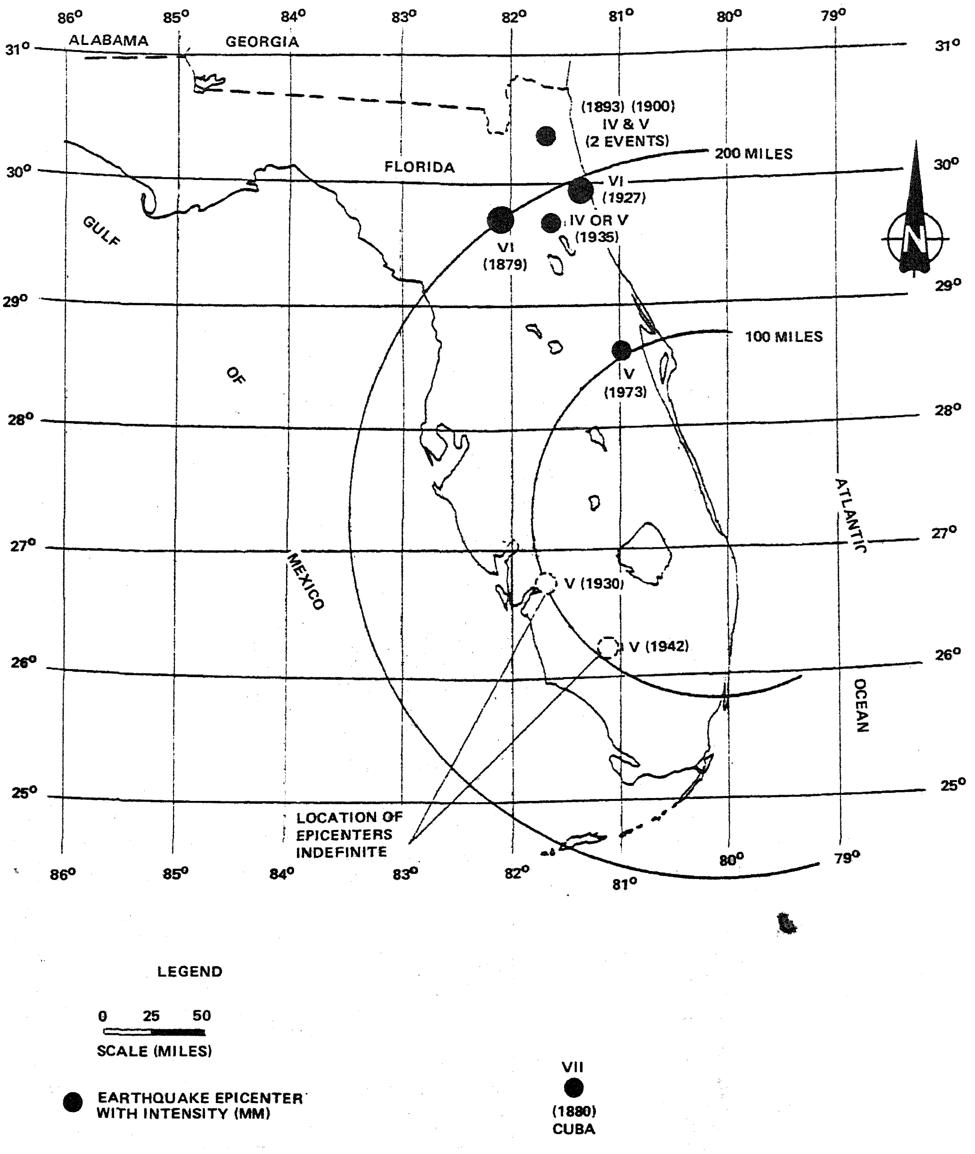
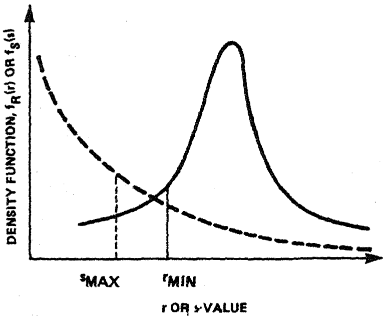


FIGURE 1
LOCATIONS OF EARTHQUAKE
EPICENTERS OF INTENSITY IV MM
AND GREATER



CONVENTIONAL FACTOR OF SAFETY
(DETERMINISTIC APPROACH)

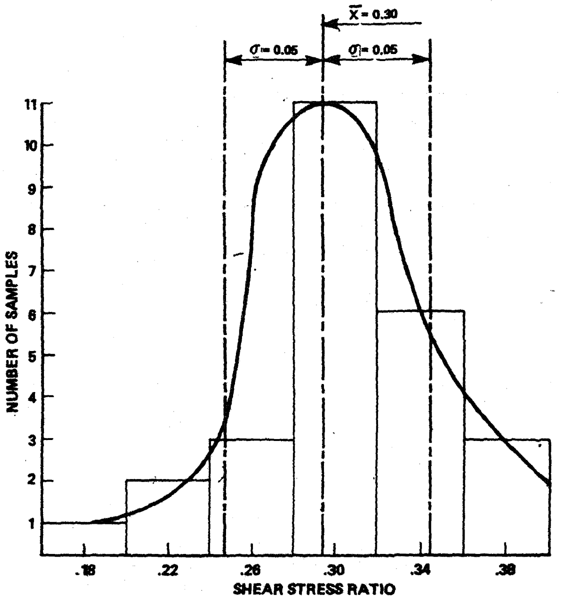
$$F.S. = \frac{\text{STRENGTH}}{\text{STRESS}} = \frac{r_{MIN}}{s_{MAX}}$$

PROBABILITY OF LIQUEFACTION
(PROBABILISTIC APPROACH)

$$P_\ell = P\,(R \leq S)$$

$$= \iint_{R \leq S} f_R(y)\ f_S(x)\ dx\ dy$$

FIGURE 2
FACTOR OF SAFETY AGAINST LIQUEFACTION
AND PROBABILITY OF LIQUEFACTION



26 SAMPLES (U.D. TUBES)

FIGURE 3
STATISTICAL ANALYSIS OF
SHEAR STRESS RATIO