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SYNOPSIS The factors involved in performing effective stress analysis of seismic stability problems are examined. The advantages of using a stochastic model for pore pressure generation are discussed. A simplified analysis of a hypothetical case is outlined to illustrate the factors involved in performing effective stress stability analysis.

INTRODUCTION

Recently developed methods for calculating pore pressure generation in soils due to cyclic loading have made effective stress seismic stability analysis feasible. Until the advent of these pore pressure generation models, only yes or no assessments of liquefaction or cyclic mobility potential were possible. While this type of safety evaluation may be acceptable for many engineering situations, there are a wide variety of problems in which failure can occur prior to complete liquefaction and a more accurate assessment of stability is required. Only effective stress stability analyses can solve this class of problems.

TOTAL STRESS SEISMIC STABILITY ANALYSIS

Total stress analyses of liquefaction potential have been in practice for a number of years. By comparing seismically induced shear stresses calculated by total stress wave propagation analyses to laboratory generated cyclic strength curves, zones within an earth mass which may achieve complete pore pressure mobilization (zero effective stress state) can be identified and assigned values of shearing strain potential. Both one and two-dimensional problems can be addressed with this type of analysis. For two-dimensional problems, this is the only method of seismic stability analysis described in the literature, while for one-dimensional problems, effective stress analysis and empirical correlations with penetration resistance have also been used.

The three primary disadvantages of these total stress analysis are:

1. They fail to discern cases where failure may occur prior to complete initial liquefaction (zero effective stress state).

2. Assumptions must be made to reconcile the irregular stress time histories predicted by the response analysis with the results of uniform cycle laboratory tests.

3. Softening of the soil and alteration of the response characteristics of the earth mass due to pore pressure generation cannot be accounted for.

Irregular shear stress time histories are usually reconciled with the results of uniform cycle laboratory tests via the concept of the equivalent number of uniform cycles. The irregular shear stress trace is converted to an equivalent number of uniform shear stress cycles of a representative magnitude, often taken as 0.65 τ_{max}, by assuming that the "damage" induced on the soil skeleton during a given shear stress cycle is directly proportional to the peak amplitude of the shear stress during that cycle. This represents an adaptation of the Palmgren-Miner (Palmgren, 1924; Miner, 1945) "linear accumulation of damage" hypothesis to the liquefaction phenomenon. One implication of this technique is that the resulting pore pressure is independent of the order in which the shear stress cycle arrive. As will be discussed later, this is not supported by either laboratory experiments or effective stress pore pressure analysis.

EFFECTIVE SEISMIC STABILITY ANALYSIS

Effective stress based seismic stability analysis can potentially overcome all of these shortcomings. Pore pressure development within an earth mass can be calculated from laboratory measured pore pressure development curves or from knowledge of soil properties for any given irregular shear stress time history. Time-domain analysis can account for softening of the soil structure due to pore pressure generation and consequent modification of response characteristics. A suite of normalized time histories can be evaluated to examine the effect of the order of the stress cycles on pore pressure development. Time-dependent contours of excess pore pressure can be developed and available strength within the soil mass along potential failure surfaces can be compared to applied loads to evaluate stability. This type of analysis could be used to calculate the seismic stability of footings based on gravity loads or the stability of earth slopes using a psuedo-static approach to superimpose seismic and gravity loads.

ONE-DIMENSIONAL ANALYSIS

A variety of methods exist to calculate the effective stress response of soil deposits under one-dimensional conditions. Some methods include the effect of diffusion in calculating time-dependent pore pressure generation, while others include pore pressure induced softening of the soil skeleton.

Finn, Lee and Martin (1977) have developed a computer program to implement their nonlinear pore pressure generation model. This program computes seismic pore pressure generation based on the initial stress state, the applied seismic stresses, and certain soil parameters. Although this method does predict the dependence of pore pressure generation on the order of the shear stress cycles, it does not account for pore water diffusion through the soil mass.

In their work on the effectiveness of gravel drains for improving site liquefaction resistance, Seed and Booker (1976) consider the diffusion of the seismically induced pore pressures through the soil. The effective stress pore pressure model of Seed, Martin, and Lysmer (1976) was used in this analysis. This model postulates a unique $\Delta u/\sigma_o'$ versus N/N_L curve, independent of the ratio of $\Delta u'/\sigma_o'$ where

Δu = seismically induced excess pore pressure

σ_o' = initial effective stress

N = the number of stress cycles of magnitude τ

N_L = the number of stress cycles of magnitude τ to initial liquefaction

τ = the applied shear stress during cycle N

The independence of the pore pressure generation curve from τ/σ_o' is essentially an assumption of linear accumulation of damage, or of the equivalent number of uniform cycles concept.

Fardis (1979) has used the Seed, Martin, and Lysmer pore pressure generation model to develope a one-dimensional dynamic analysis that accounts for both pore pressure induced softening and diffusion through the soil skeleton. Fardis casts his method within a probabilistic framework to account for spatial variation of soil properties and uncertainties as to parameter values. The results of Fardis' analyses are time-dependent contours of pore pressure within the soil mass for given probabilities of excedence. Fardis suggests that this one-dimentional method could be used to evaluate the stability footings prior to initial liquefaction, ignoring interaction between the footing and the soil.

TWO-DIMENSIONAL ANALYSIS

For any level ground problem where interaction effects can be ignored, any of the above one-dimensional liquefaction models can be used to perform stability analysis. However, for level ground situations where interaction effects are significant, and for all cases where the ground surface and soil layers are not horizontal, one-dimensional response analyses are not adequate for stability assessments. Two-dimensional response analysis must be performed to properly determine induced seismic stresses. The great majority of seismic stability analyses are likely to fall into this category.

To the knowledge of the writers, no two-dimensional response analyses currently exists which can account for pore pressure diffusion and soil softening. The development of such a method is required to achieve the maximum degree of accuracy in seismic stability analysis. However, hybrid two-dimensional analysis can be performed using stress-time histories from total stress analysis together with effective stress pore pressure generation models to evaluate seismic stability. Such a hybrid model is currently under development at Stanford University under the auspices of the John A. Blume Earthquake Engineering Center. The cornerstone of this hybrid model is a stochastic formulation of the Finn, Lee and Martin nonlinear pore pressure generation model (Chameau, 1980).

STOCHASTIC MODEL

Although the same type of hybrid stability analyses might be performed using a deterministic model for pore pressure development, a stochastic model has several advantages. A stochastic model can allow for consideration of the effect of the order of arrival of the shear stress cycles in a frequency domain analysis, thus eliminating cumbersome time-domain methods in which a suite of time histories must be evaluated. Stability predictions based upon a unique time history may strongly depend on the particular time history.

The stochastic model allows the enginner to incorporate geotechnical, seismological, and analytical uncertainties into the stability assessment. Uncertainties in assessing pore pressure generation from laboratory tests, the inability to reproduce field stresses and soil fabric, and the inability to properly determine soil parameters can all be accounted for along with uncertainties regarding shear stress time history, source mechanisms, travel path, and attenuation laws.

The stochastic model also facilitates probabilistic evaluation of the damage potential associated with pore pressure build up for use in seismic hazard analysis. Although still rare in geotechnical problems, seismic hazard and risk analysis are becoming more prevalent in engineering practice, particularly for facilities with limited economic lifetimes in known seismic environments. In order to assess the viability of such projects, the owner needs to know the risk over the specified lifetime of the structure for the given seismic environment, the expected damage to the structure regardless of the potential for initial liquefaction, and the tradeoffs between alternative sites and construction methods. The results of the stochastic model can be used to calculate conventional factors of safety as well as for making these probabilities risk assessments.

ILLUSTRATIVE EXAMPLE

An illustrative example of a two-dimensional stability analysis is outlined herein to elucidate some of the stability analysis concepts described above and to illustrate the application of the stochastic model. The analysis outlined is a stability analysis for a bluff of height H composed of cohesive soil interlaced by a thin horizontal seam of liquefiable sand at depth d. This geometry was chosen so that the failure mode is easily inferred (rigid block sliding along the sand seam), thus eliminating cumbersome trial and error procedures. In order for failure to occur, the horizontal inertial force on the failure mass due to the horizontal earthquake acceleration $\ddot{x}(t)$ must exceed the shear strength of the sand seam and the tensile strength of the cohesive soil along the edges of the failure mass (Figure 1).

Assuming that the tensile strength of the cohesive soil remains constant during the earthquake, the problem of assessing the seismic stability of the bluff is reduced to the problem of assessing the shear resistance of the sand seam. The shear resistance of the sand seam is a function of the pore pressure in the sand, thus to assess the stability of the slope one must assess the pore pressure development within the sand seam.

In a total stress stability analysis, the results of a two-dimensional response analysis would be used to compute the average acceleration analysis "representative" shear stress, and the number of uniform cycles for each element within the soil mass. Based on the results of laboratory tests, the extent of the liquefied zone within the sand seam would be determined. If the liquefied zone extends to the face of the bluff, it can be said that the slope will fail. However, if only a portion of the sand seam has achieved complete initial liquefaction, the stability of the slope cannot be adequately assessed.

A more complete assessment of the bluff could be ascertained if an effective stress pore pressure generation model was used to evaluate the pore pressure U_i in each element within the soil mass. Then, the factor of safety of the bluff can be evaluated as

$$\frac{\sum_i^L (\sigma_i - U_i)\tan\phi \ell_i + T_o d}{\sum_i^L \rho(\ddot{X}_i)_{max}\, d\ell_i}$$

where

- ϕ' = friction angle of the fine sand
- τ_o = tensile strength of the cohesive soil
- ρ = mass density of the cohesive soil
- ℓ_i = length of element i
- $(\ddot{X}_i)_{max}$ = maximum acceleration in element i

The factor of safety must be evaluated for all values of L to find the minimum value. If the factor of safety is less than 1.0, this analysis would predict the maximum possible size of the failure mass as the length of sliding block at which the factor of safety equals 1.0. If the Finn, Lee, and Martin effective stress pore pressure model was used in this analysis, then by calculating the factor of safety for a suite of response analysis for earthquake inputs of the same design magnitude, uncertainties associated with the choice of a particular earthquake record could be resolved.

The advantages of the effective stress analysis over the total stress analysis is that it enables computation of the factor of safety and it can predict failure in cases where the extent of the liquefied zone is limited. A stochastic pore pressure generation model has several additional advantages over deterministic pore pressure models. The stochastic model automatically takes into account the uncertainty concerning the order in which the shear waves arrive, method of analysis, the stochastic model accounts for the fact the

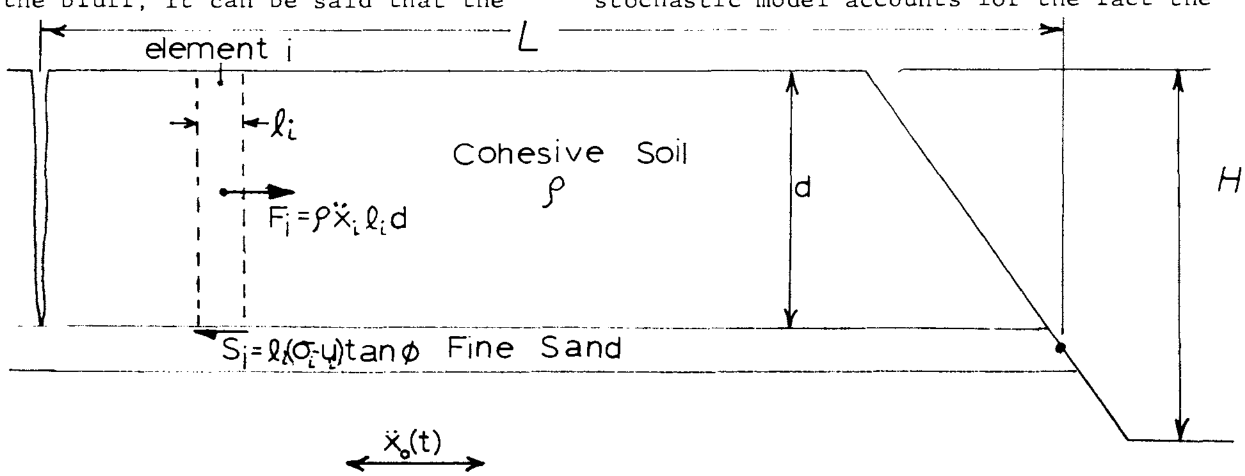

Figure 1. Geometry of Hypothetical Analysis

maxima in pore pressure and acceleration may not coincide, and the stochastic model facilitates computation of a probability of failure for use in risk analysis.

The probability statement for the stability of the bluff can be written as

$$(P_f)_L = P[\sum_i^L (\ddot{X}_i \rho d \ell_i) > T_o d + \sum_i^L (\sigma_i - U_i) \tan\phi \ell_i]$$

where $(P_f)_L$ = the probability of a block of length L failing

The probability of failure of the entire bluff is then calculated by considering the condition probability of every block L from zero to infinity. Since X_i and U_i are functions of time, the probability of failure is also time dependent. This accounts for the fact that the maximum horizontal acceleration and the maximum pore pressure may not occur at the same time.

This type of complete probabilistic assessment is currently under development as part of the Stanford research program.

SUMMARY

This paper describes the factors involved in making effective stress seismic stability analysis. Such methods are necessary to assess ground deformation and damage due to pore pressure generation, regardless of the potential for initial liquefaction. At the present time, only one-dimensional problems can be evaluated in a manner accounting for nonlinearities in soil behavior, pore pressure diffusion, and softening of the soil skeleton. At the present time, effective stress stability analyses of two-dimensional problems are only possible using shear stress time histories from total stress response analysis. A stochastic model is presented which facilitates both nonlinear frequency domain analysis of pore pressure generation for such hybrid two-dimensional analysis and calculation of probabilities of pore pressure excedence and damage for use in seismic risk analysis. Simplified analysis of a hypothetical case was outlined to illustrate some of these principles.

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