SEISMIC ANALYSIS OF EARTH SLOPES - A CASE STUDY

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SUMMARY

A previously developed model is used to provide a probabilistic seismic stability analysis for a natural slope located near Slingerlands, New York. Three types of possible earthquake sources are investigated, namely, a point, a line and an area source. It is concluded that (a) the present model is useful in assessing the reliability of soil slopes under both static and seismic conditions, and (b) the probability of failure of a soil slope is greatly affected by the type of the earthquake source involved and the values of the seismic parameters that are associated with it.

INTRODUCTION

In a conventional static or seismic stability analysis, the safety of a soil slope is measured by means of a factor of safety. The confidence, however, with which one should view this factor is open to question. To overcome the shortcomings associated with the conventional analysis, geotechnical engineers have suggested the use of a more rational approach to design, based on probability theory and reliability analysis.

In the present case study, use is made of a model developed by A-Grivas et al (1979) in order to provide a probabilistic stability analysis of an earth slope under earthquake loading. This model is capable of accounting for significant uncertainties associated with conventional pseudo-static methods of seismic stability analysis. More specifically, it accounts for (a) the variability of material strength parameters, (b) the uncertainty in the exact location of potential failure surfaces, and (c) the uncertainty in the value of the maximum slope acceleration during an earthquake. The safety of the slope is measured in terms of its probability of failure (rather than the conventional factor of safety) the numerical values of which are obtained through a Monte Carlo simulation of failure. A detailed description of the model and the associated assumptions can be found in A-Grivas et al (1979).

SEISMIC LOAD AT SLOPE SITE

The site of the slope, reported in the literature to have failed (Gray et al, 1976), is near Slingerlands, New York (a part of the Hudson-Champlain Lowland physiogrpahic province of the State of New York). The possibility of an earthquake is an important design factor in the area for which a seismic risk analysis has provided the following relationship between the annual rate of earthquakes n_m and the Richter magnitude m (A-Grivas, et al, 1978):

$$n_m = \exp(1.6 + 0.203m - 0.182\, m^2), \quad 2 \leq m \leq 7 \qquad (1)$$

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The probability with which an earthquake may occur with magnitude greater than m is given as the ratio of n_m over n_{m_o}; i.e.,

$$P[M > m] = \frac{n_m}{n_{m_o}}$$

where P[ ] denotes the probability of the event in brackets and n_{m_o} is the average number of earthquakes per year with magnitude larger than the lower limit (m_o = 2) and can be found from Eq. 1 to be equal to n_{m_o} = 3.59.

Introducing into the above expression the value of n_m from Eq. 1 and substituting 3.59 for n_{m_o}, it is found that

$$P[M > m] = 0.279 \exp(1.6 + 0.203\ m - 0.182\ m^2), \quad 2 \leq m \leq 7 \qquad (2)$$

The cumulative distribution F(m) of m is equal to the complement of Eq. 2, or, $F(m) = P[M \leq m] = 1 - P[M > m]$. Introducing Eq. 2 into this expression, one has

$$F(m) = 1 - 0.279 \exp(1.6 + 0.203m - 0.182\ m^2), \quad 2 \leq m \leq 7 \qquad (3)$$

For F(m) to be a cumulative distribution, it has to be multiplied by the constant k, so that when F(m) is evaluated at the upper bound of m (m_1 = 7) it becomes equal to unity; i.e.,

$$F(m_1) = k[1 - 0.279 \exp(1.6 + 0.203m_1 - 0.182\ m_1^2)] = 1$$

from which, after substituting for m_1 = 7, it is found that k = 0.99923 ≃ 1.0. Therefore, one has that Eq. 3 is a very good approximation of the cumulative distribution of m.

The probability density function of the earthquake magnitude can be determined from Eq. 3 by taking the derivative of F(m) with respect to m. Thus,

$$f(m) = -0.057 + 0.102\ m \exp(1.6 + 0.203\ m - 0.182\ m^2), \quad 2 < m < 7 \qquad (4)$$

The maximum horizontal ground acceleration at the site of the slope is determined with the aid of two attenuation relationships that have been previously proposed for this region and are denoted in this work as Case 1 and Case 2, respectively. These are the following:

$$a_{max} = 1100\ e^{0.5m}\ (R + 25)^{-1.32} \qquad \text{(Case 1)} \qquad (5a)$$

$$a_{max} = 1.183\ e^{1.15m}\ R^{-1.0} \qquad \text{(Case 2)} \qquad (5b)$$

where m is the earthquake magnitude and R is the distance between the earthquake source and the site of the slope.

STABILITY ANALYSIS UNDER STATIC CONDITIONS

Conventional Analysis

In Fig. 1 are shown schematically the geometry of the slope under investigation and the associated parameters. Four limiting equilibrium stability methods were used (Gray et al, 1976), namely, (a) ordinary method of slices, (b) Bishop's Modified method, (c) Spencer's method, and (d) Huang's stability charts. For the conditions used in this study, the values of the conventional factor of safety FS that correspond to each method are listed in Table 1.

TABLE 1. VALUES OF FACTOR OF SAFETY UNDER STATIC CONDITIONS

No.	Method of Analysis	Factor of Safety
1	Ordinary Method of Slices	1.55
2	Bishop's Modified Method	1.63
3	Spencer's Method	1.48
4	Huang's Method	1.52

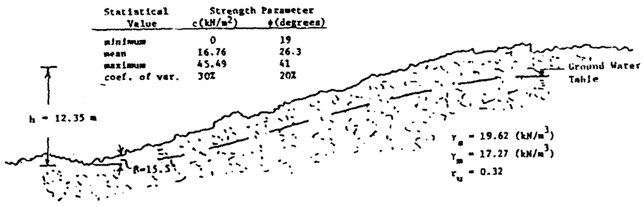

FIGURE 1. GEOMETRY OF THE SLOPE AND MATERIAL PARAMETERS USED IN CASE STUDY

Probabilistic Analysis

The probabilistic model presented by A-Grivas et al (1979) was used to determine the probability of failure of the slope under static conditions. One thousand iterations were specified in the Monte Carlo simulation of failure and it was found that the probability of failure was equal to 0.147; or, $p_f = 0.147 \simeq 0.15$.

PROBABILISTIC SEISMIC STABILITY ANALYSIS

Using the same model, a probabilistic pseudo-static stability analysis is conducted using regional parameters that are pertinent to the Northeastern U.S. Three types of earthquake sources are considered, namely, a point, a line and an area source. Fig. 2 shows the variation of p_f with distance R between the point source and the slope. In the case of the line source, p_f is found as a function of the distance D between the center of the fault and the slope's site, the length ℓ of the fault and its orientation (angle θ) relative to the slope. Fig. 3 shows p_f vs distance D for $\theta = 45°$ and two values of the fault length ($\ell = 100$ km and $\ell = 250$ km). Finally, Fig. 4 shows p_f as a function of the radius R for the case of an area source.

ACKNOWLEDGEMENT

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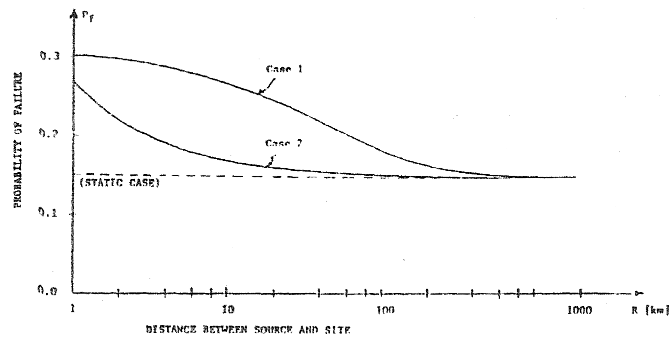

FIGURE 2. PROBABILITY OF FAILURE VS. DISTANCE FROM POINT SOURCE

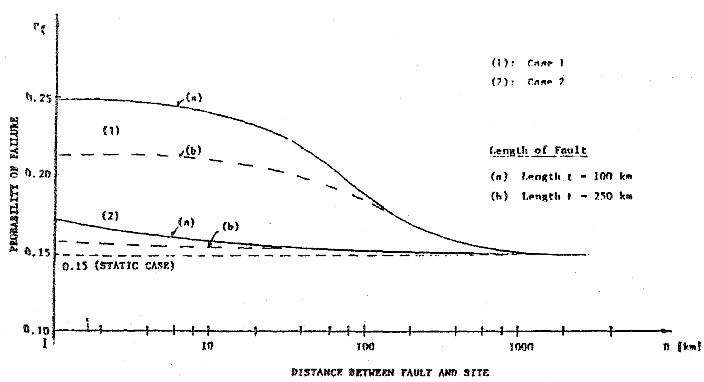

FIGURE 3. PROBABILITY OF FAILURE VS. DISTANCE BETWEEN FAULT AND SLOPE (θ = 45°)

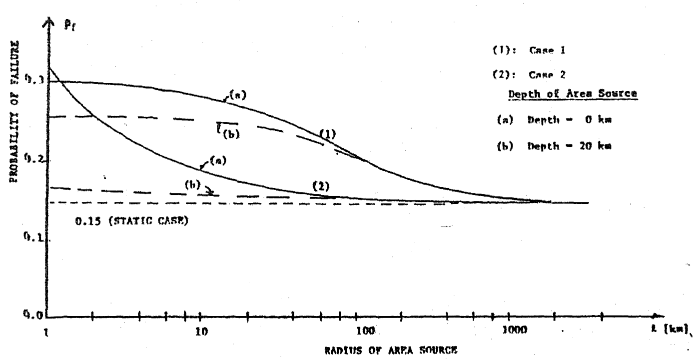

FIGURE 4. PROBABILITY OF FAILURE VS. RADIUS OF AREA SOURCE