CONSIDERATION OF EARTHQUAKE RESISTANT (CLASS I) SLOPES AND DAMS

by

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SYNOPSIS

This paper is intended to be a brief evaluation of analytical techniques and design criteria used in the assessment of the safety of slopes and dams subject to seismic loading. Consideration is given to stability criteria, namely liquefaction and sliding of downstream slopes. Particular emphasis is placed on the desirability of using Bishop's and Newmark's methods for determining dynamic factors of safety (F.S.) and possible resultant displacements. Acceptability of dynamic factors of safety less than unity is also discussed.

INTRODUCTION

The concern for safety of slopes adjacent nuclear installations and the dynamic behavior of dams, especially those which retain emergency shutdown water for nuclear reactors, has become a topic of increasing complexity and discussion over the past few years. As a result, various techniques and methods of analysis have developed over the past decade to assess the various problems associated with embankment design under seismic conditions. Those discussed herein, namely liquefaction and slope stability, have been encountered by the authors in recent licensing procedures in Europe and the United States. In addition to the stability and liquefaction issues discussed briefly herein, dynamic finite element analysis has become an increasingly popular tool available to the engineer. However, due to space and time considerations, it is not discussed herein.

LIQUEFACTION POTENTIAL AS A DESIGN CONSIDERATION

Investigations of recent earthquakes indicate that besides considering the gross behavior and rotational stability of dams and slopes, the liquefaction potential of the foundation materials and placed fills must be considered. For example, in the Alaska Earthquake of 1964, flow slides in cohesionless soils due to liquefaction and slides in clay deposits due to liquefaction of sand lenses were noted. Similar phenomena were also noted in the San Francisco Earthquake of 1957 and in Rinihue, Chile in 1960. In the San Fernando Earthquake of 1971, the upstream face of the Lower San Fernando Dam of the Van Norman Reservoir failed due to liquefaction(1,2) and upon emptying the reservoir, numerous sand boils were evident in the reservoir floor indicating liquefaction in the subsoils.

To preclude the potential for liquefaction in the design of earth dams, a first check of the grain-size characteristics and relative density of the proposed materials against the Japanese criteria(3,4) and/or Seed's Simplified Method(5) is appropriate. These techniques are intended to give only a qualitative indication of the liquefaction susceptibility; i.e., no well-defined F.S. is obtained in either of these methods

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of analysis. They do however, forewarn of potential liquefaction based on experience gained from the Niigata and Alaska Earthquakes, and should, therefore, be included in the design procedure for Class I dams and slopes. If the potential for liquefaction cannot be immediately dismissed on this basis, then dynamic triaxial testing and dynamic response analyses of the dam are considered necessary. In this manner, it is usually possible to gain a quantitative insight into the degree of risk involved.

NEWMARK'S METHOD FOR ROTATIONAL STABILITY

Newmark performed model studies to determine the effects of earthquake acceleration on sloping surfaces.(6) This enables a prediction of the amount of displacement that will occur when the computed F.S. is less than unity. As a limiting equilibrium method, it tacitly assumes that no movement will occur when the computed dynamic F.S. is greater than 1.0.

The Bishop short method of analysis is most often used to determine the potential failure surface with the lowest dynamic F.S. for earthquake conditions. This critical circle is then analyzed by Newmark's method to determine the maximum displacement that might occur under the earthquake, and to examine the performance of the slope in relation to the predicted movement.

All conventional methods of stability analyses are categorized as limiting equilibrium in nature. This implies that for a static F.S. greater then unity, no movements will occur along the potential failure arc. To be conservative and to account for possible variation in assumed conditions, a typical F.S.=1.5 is considered acceptable for static conditions.

Under earthquake analyses, the induced horizontal stresses within the potential failure mass are taken into account by including a force equal to the earthquake acceleration times the weight of the assumed sliding mass. This results in an additional driving moment applied about the center of rotation. Thus, the dynamic problem is reduced to a pseudo-static analysis, which necessarily implies application of the earthquake loads for an indefinite period of time. No attempt is made to recognize the time variation of acceleration during the postulated earthquake. Further, the cyclic nature of the direction of application of the seismic force is also ignored. Intuitively, one recognizes the conservativeness of this overall approach. Usually, the vertical component of the acceleration is neglected in the slope stability analyses; this is justified on the basis that the probability of the maximum horizontal and maximum vertical accelerations occurring simultaneously is extremely small. Since the effect of the horizontal acceleration on the computed F.S. is usually much more pronounced than the vertical acceleration, the seismic design is based only on the former. Furthermore, the probability of the maximum vertical component of acceleration acting upwards concurrent with the outward direction of the maximum horizontal acceleration is also small. This is the only possible loading combination that could cause a decrease in the F.S. from what is computed by ignoring the vertical component.

FACTOR OF SAFETY

This section discusses acceptable F.S. and the possible movements associated with a reduced F.S. It is intended to show the acceptability of a reduced F.S. during earthquake conditions, providing the displacements computed by Newmark's method are satisfactorily small.

The state of the art of stability analysis under earthquake conditions is such that the most-often used approach is simply to accept a low F.S. due to the known conservatism of the analysis. The widespread use of this approach is readily evident in the Proceedings of the IX International Congress on Large Dams.(7) As discussed therein, a F.S. as low as unity is accepted by many agencies for earthquake conditions, including the U.S. Army Corps of Engineers. The tacit assumption, of course, is that the resultant displacements are acceptably small.

Two built-in margins of safety are not reflected in the dynamic safety factor. Firstly, the analyses of forces and moments are two dimensional, and thereby neglect the shear resistance mobilized along the sides of the shear zone. Because of this, embankment shear failures under static loads typically do not occur with a safety factor of 1.0. Instead, a safety factor of about 0.9 defines real soil shear failure. Thus, a computed static safety factor of 1.0 is more nearly a true safety factor of $\frac{1.0}{0.9} \simeq 1.1$.

A second margin of safety is the fact that neither the pseudo-dynamic nor the dynamic F.S. considers the effect of the periodic short duration reversals of motion inherent in earthquakes. Thus, even if the safety factor is less than unity, complete embankment failure will not occur unless the static safety factor is also less than unity. Newmark has shown that if the static safety factor exceeds unity, while the pseudo-dynamic or dynamic F.S. are less than unity, the embankment will undergo finite displacement rather than complete failure. So long as the vertical component of the displacement is smaller than the freeboard, loss of water or catastrophic failure will not occur.

CONCLUSIONS

This paper has presented brief comments on the appropriateness of using Bishop's and Newmark's methods for analyzing the stability of slopes or dams subjected to seismic design criteria. The acceptability of lower-than-usual factors of safety is discussed, together with the suggestion that a displacement criterion should be used to assess the performance of the slope or dam during postulated earthquake loading conditions. In addition to the conventional methods of stability analysis, it is recommended that the liquefaction potential of the soils be assessed.

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