国际地震区划学术讨论会

会议论文集

PROCEEDINGS OF INTERNATIONAL SEMINAR ON SEISMIC ZONATION

DEC. 6—10, 1987

GUANGZHOU, CHINA

中国国家地震局主办

SPONSORED BY

STATE SEISMOLOGICAL BUREAU, PRC

METHODOLOGY FOR SEISMIC SAFETY EVALUATION FOR EARTH DAMS

M. K. Yegian[1]

Over the past two decades significant developments have been made in our understanding of the dynamic response of earth dams. Analytical procedures that have been developed vary in their degrees of sophistication ranging from the simple application of Newton's second law to three-dimensional finite element analyses. Notwithstanding, the estimation of the likelihood of failure or reliable performance of an earth dam during the period of its functional life remains to be a challenge to earthquake engineers.

Seismic safety evaluation of an earth dam involves the identification and determination of various parameters that describe in the analytical procedure the seismic loads on the dam and its resistance to these loads. In such a safety evaluation, there are many sources of uncertainty that have to be considered in order to make a realistic evaluation of the seismic risk associated with the dam. Uncertainties are present in the parameters that define the seismicity and geology of the region under investigation and the characteristics of the site upon which the dam is or will be founded. In addition, there are uncertainties in the parameters that describe the strength of the earthen materials used, the dynamic response of the dam analyzed, and the safety criteria adopted in the investigation. Finally, there is uncertainty in the professional judgement that invariably plays a role in the different stages of the seismic safety evaluation.

Typically, in the current practice, a deterministic approach is adopted in which conservative selections of parameters and assumptions are made to account for the various uncertainties

---

[1] Professor and Chairman, Department of Civil Engineering, Northeastern University, Boston, Massachusetts, USA

involved in the seismic safety evaluation of a dam. Generally, in such an investigation a safety criterion is adopted such as a minimum factor of safety or a limiting level of permanent dam deformation or stress, that when satisfied the dam is considered to be safe. Such an approach, when followed in the design of a new earth dam, may render the project economically unfeasible due to the compounding of conservatism. More seriously, in the seismic safety evaluation of an existing earth dam, application of the deterministic approach in which a general conservatism is adopted may lead to the conclusion that most such existing dams are unsafe; whereas a more realistic evaluation of the seismic safety performed using reasonable assumptions and parameters and accounting for the associated uncertainties may indicate that the level of seismic risk is acceptable to all parties concerned.

This paper describes the framework for a probabilistic approach to the seismic safety evaluation of earth dams. The method is based on the integration of the seismological and geotechnical inputs and their associated uncertainties in a logical and consistent manner to yield the likelihood of seismically induced damage to or failure of an earth dam.

Integrated Seismic Risk Analysis

Evaluation of the seismic risk of damage to or failure of a facility involves input from two other analyses hereafter referred to as Seismic Hazard Analysis (SHA) and Seismic Performance Analysis (SPA). Thus, the estimation of seismic risk involves the following three steps that are also described in Figure 1.

Step 1. Seismic Hazard Analysis considers the various seismic sources together with the frequency and characteristics of seismic excitations that may be generated, and yields probabilistic predictions of the occurrence of various seismic hazards that may be defined in terms of ground motion parameters at the site of the facility.

Step 2. Seismic Performance Analysis considers the seismic resistance of the facility using appropriate analytical procedures, and provides probabilistic predictions of the performance of the facility experiencing the various hazards described in the seismic hazard analysis.

Step 3. Seismic Risk Analysis In this step the results of the Seismic Hazard Analysis and the Seismic Performance Analysis are integrated over all hazards to yield the overall risk of damage to or failure of the facility. Figure 2 describes the integration involved in the Integrated Seismic Risk Analysis.

Such a procedure can be applied for any type of facility. In the research reported herein, special developments were made in both SHA and SPA that provide the necessary and appropriate input for the estimation of the seismic risk for an earth dam. The framework upon which the specific developments were made is presented in Figure 3. As shown in Figure 3 the selected approach to the estimation of the seismic risk for an earth dam is based on the use of matrices to display the outcomes from the three steps of the analysis.

The advantages of this matrix approach over more mathematically closed-form formulations that lead to the utilization of a computer are:

1. Results from each analysis are displayed for scrutiny, consistency, and for general observations or conclusions that themselves are advancements in the state-of-the-art. For example, damage probability matrices compiled from the Seismic Performance Analysis can be useful information that can indicate the adequacy of current design practices in relation to expected damages for different levels of seismic excitation.

2. The integration of the results from Seismic Hazard Analysis and Seismic Performance Analysis, to obtain estimates of risk can be done in a simple manner with the use of a calculator. This conveniently allows repeated application of the analysis for sensitivity purposes and for evaluation of the impact upon the relative risk, certain assumptions and design modifications considered.

3. Allows easy identification of the parameters and factors that contribute more significantly to the risk and consequently requiring special attention in the safety investigation.

Although the mathematical formulation is simple for risk calculation, it permits the evaluation of the input used in the risk calculation to be based on rigorous and sophisticated state-of-the-art analysis. For example, damage probabilities can be computed empirically, subjectively, employing simple analytical procedures or three-dimensional finite element analysis.

Application to Earth Dams

A review of current practice of the seismic analysis of earth dams indicates that for earth dams and especially those consisting of granular materials, pseudostatic analysis is no longer considered as a reliable approach. Instead, seismic safety evaluation of earth dams are now being based on the potential for the dam to experience permanent deformations.

Newmark proposed a simple sliding-block model for the calculation of permanent deformations using a rigid-plastic, force-displacement relationship characterizing the sliding mass. In recent years there have been many developments of analytical procedures for calculating permanent deformations which are invariably based on Newmark's simple concept. It is evident, from a review of these procedures that the characteristic of the seismic excitation plays an important role in the estimation of permanent deformations in earth dams. In addition to the peak ground acceleration or displacement, the nature of the time history record including the frequency content and duration will determine the magnitude of the accumulated permanent deformation.

Based on Newmark's model, a simple analytical procedure for the calculation of permanent deformations was developed. The parameters that describe the seismic event in the deformation analysis include: the peak ground acceleration, the number of equivalent uniform cycles, N_{eq}, and the predominant period of the motion. Using probability theories and the analytical procedure developed the probability of exceeding a specified level of permanent deformation can be calculated. Thus, damage probabilities calculated based on accumulated permanent deformations depend upon not only the peak acceleration but also the number of equivalent cycles of application of the seismic load. Hence it is imperative that the results from the Seismic Hazard Analysis not only express the number of events causing acceleration to exceed a certain level but also provide the distribution of these events with respect to the number of cycles that they would cause.

Current probabilistic seismic hazard analysis procedures provide the number of events causing acceleration to exceed a specified value "a." This total number of events may consist of a variety of magnitudes and hence have a varying number of equivalent cycles. The mathematical formulation used in a conventional seismic hazard analysis procedure was modified to permit the calculation of the distribution of the magnitude or number of cycles for each level of acceleration considered. The results from this modified seismic hazard analysis can be expressed in matrix form as shown in Figure 3.

Once the SHA matrix for a particular site and the SPA matrix for a specific earth dam are filled in the annual number of events causing damage level D_k can be calculated by

$$\lambda(D_k) = \sum_{\text{all } A} \sum_{\text{all } N_{eq}} P[D_k | \Delta A, \Delta N_{eq}] \cdot \lambda(\Delta A, \Delta N_{eq})$$

Benefits of Seismic Risk Analysis for Earth Dams

The application of an Integrated Seismic Risk Analysis for earth dams can provide estimates of relative risks that can be useful in the design or safety decision analysis of an earth dam. Also, a risk-based safety evaluation can help identify the importance and implications of various assumptions, hypotheses and criteria used in the design or safety evaluation process and avoids compounding of conservatism.

Summary

A methodology for estimating the seismic risk of damage to or failure of an earth dam is presented. The procedure provides a framework for the evaluation of seismic risk incorporating uncertainties associated with both the seismic hazard and the seismic performance of the dam experiencing these hazards. Special developments in seismic hazard and seismic performance analyses are described that relate to the seismic safety evaluation of earth dams.

Acknowledgement

This paper is based on a research effort to develop an Integrated Seismic Risk Analysis for Earth Dams, supported by the National Science Foundation under Grant Number DFR84-12124. This support is gratefully acknowledged. The author also thanks his colleague Eugene Marciano and graduate student Vahe Ghahraman for their contributions to this research program.

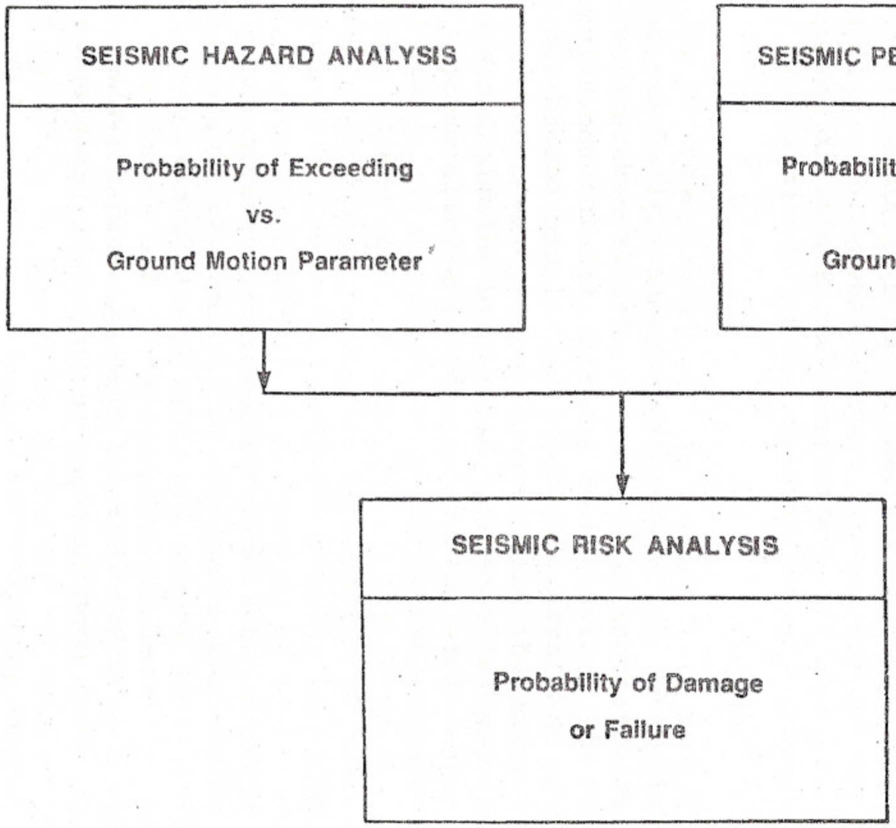
SEISMIC HAZARD ANALYSIS
Probability of Exceeding
vs.
Ground Motion Parameter
SEISMIC PERFORMANCE ANALYSIS
Probability of Damage or Failure
vs.
Ground Motion Parameter
SEISMIC RISK ANALYSIS
Probability of Damage
or Failure

FIGURE 1

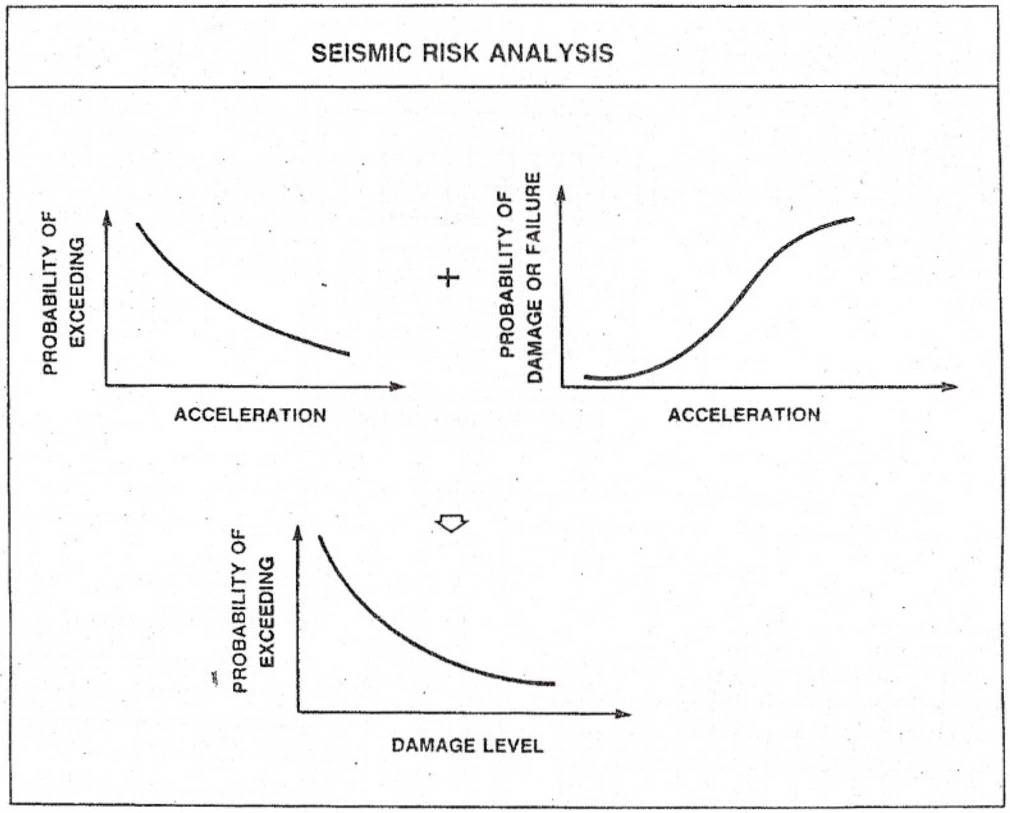
SEISMIC RISK ANALYSIS
PROBABILITY OF EXCEEDING
ACCELERATION
+
PROBABILITY OF DAMAGE OR FAILURE
ACCELERATION
PROBABILITY OF EXCEEDING
DAMAGE LEVEL

FIGURE 2

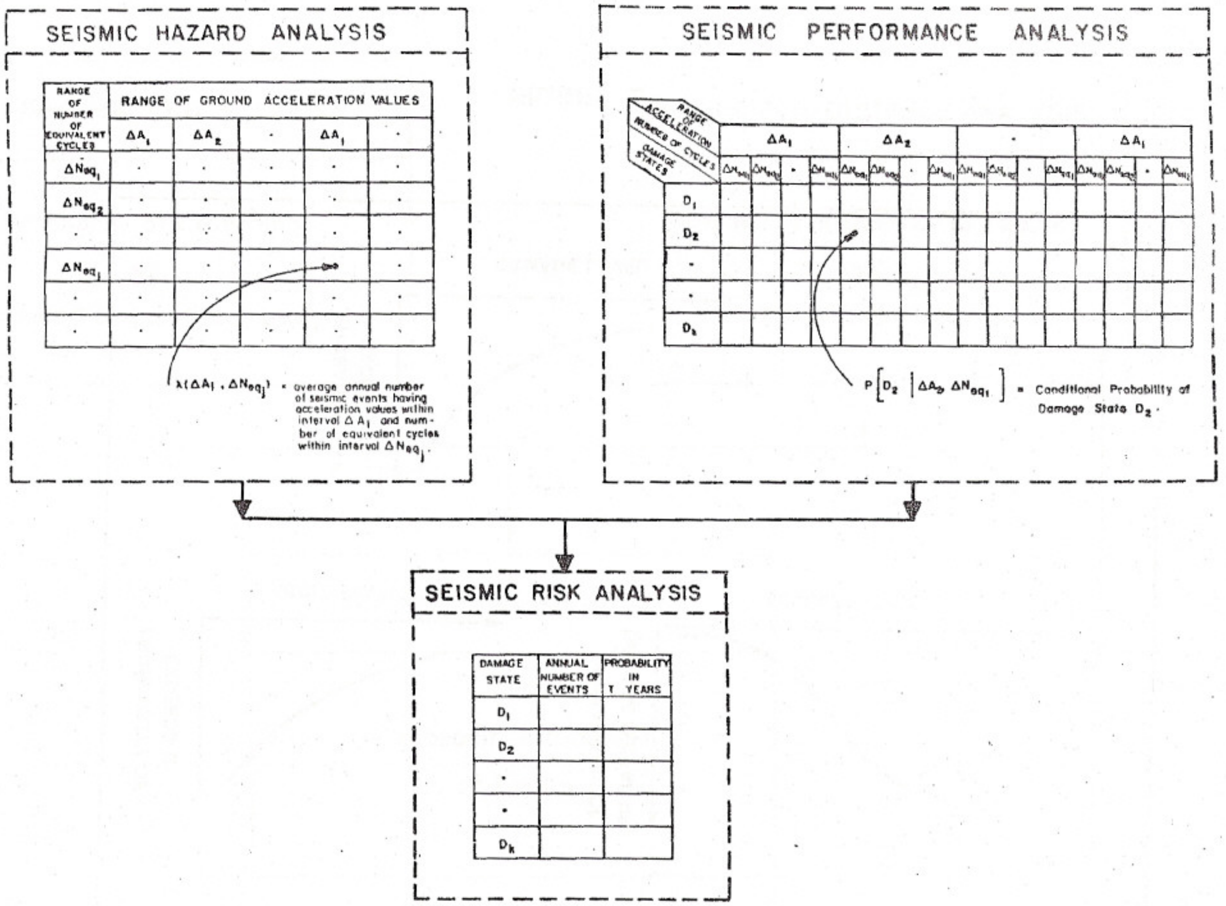
SEISMIC HAZARD ANALYSIS
RANGE OF NUMBER OF EQUIVALENT CYCLES
RANGE OF GROUND ACCELERATION VALUES
ΔA_1
ΔA_2
ΔA_i
ΔN_{eq_1}
ΔN_{eq_2}
ΔN_{eq_j}
$\lambda(\Delta A_i, \Delta N_{eq_j})$ = average annual number of seismic events having acceleration values within interval ΔA_i and number of equivalent cycles within interval ΔN_{eq_j}.
SEISMIC PERFORMANCE ANALYSIS
RANGE OF ACCELERATION
NUMBER OF CYCLES
DAMAGE STATES
ΔA_1
ΔA_2
ΔA_i
ΔN_{eq_1}
ΔN_{eq_2}
ΔN_{eq_j}
D_1
D_2
D_k
$P\left[D_2 \mid \Delta A_2, \Delta N_{eq_1}\right]$ = Conditional Probability of Damage State D_2.
SEISMIC RISK ANALYSIS
DAMAGE STATE
ANNUAL NUMBER OF EVENTS
PROBABILITY IN T YEARS
D_1
D_2
D_k

FIGURE 3