

**Risk - Based Methodology for
Seismic Rehabilitation of Earth Dams**

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Abstract

A methodology for seismic risk analysis of earth dams is described. The procedure utilizes seismological and geotechnical inputs together with the associated uncertainties and provides estimates of seismic risk of damage and failure of earth dams. An example case study of an earth dam is described and the benefits of the procedure in a risk-based decision analysis of seismic rehabilitation of the dam is illustrated.

Introduction

Concern about seismic safety of earth dams continues to receive increased attention by owners, engineers and regulatory agencies. During the past two decades, there have been significant developments made in our understanding of the dynamic response of such geotechnical structures. One of the important advancement made in engineering analysis is in the estimation of seismically-induced permanent deformations in an earth dam. During a seismic event, if in an earth dam the shear stresses exceed the resisting shear strength of the soils, permanent deformations will be induced. Such deformations can be excessive specially if the soils have tendency for loosing shear strength due to potential increase in excess pore pressures. Therefore, seismic safety of an earth dam is assured if, in the future, earthquake-induced

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permanent deformations within the dam, and thus potential loss of freeboard, is within acceptable limits.

Despite the advancements made, estimation of the likelihood of seismically-induced failure of an earth dam, and especially of an existing dam, still remains a challenge. There are many sources of uncertainty in seismic safety evaluation of an embankment or an earth dam. Uncertainties exist in: 1) the parameters that define the seismic load; 2) the soil properties and their spatial variation within the dam and its foundation; 3) the analytical procedures and their ability to make realistic prediction of the response of the dam; and 4) the criteria used for defining safety (e.g. the minimum required height of freeboard or the minimum acceptable factor of safety against instability).

The current practice of seismic safety evaluation of an earth dam typically follows a deterministic approach. To account for the various uncertainties listed earlier, conservative assumptions and selection of parameters are made. Because of potential compounding of conservatism a deterministic approach can sometimes lead to the conclusion that a dam, particularly an existing one, is unsafe; whereas a probabilistic evaluation, in which the uncertainties are accounted for more realistically, may indicate that the level of risk is acceptable to all parties concerned.

Yegian et al. (1991a) described a probabilistic approach for seismic safety evaluation of earth dams. The method involves the integration of seismological and geotechnical inputs and their uncertainties in a consistent manner to yield the likelihood of seismically-induced damage and catastrophic failure of a dam. This approach can be used to compare the effects of alternative design or rehabilitation schemes on the seismic risk and their associated costs of construction. The application of this risk-based seismic safety evaluation can enable the identification of the most important parameters, assumptions and design criteria affecting the evaluation of the safety of the dam. Most importantly, it provides a means by which a designer can avoid the trap of compounded conservatism that may lead to significant costs with little reduction in risk.

This paper briefly describes the risk-based methodology for seismic safety evaluation of earth dams. To illustrate the application and the benefits of such an approach an example earth dam is selected and two alternative rehabilitation schemes are described and compared. The

seismic risks associated with the two alternatives are calculated and discussed in the context of the corresponding construction costs. Conclusions are provided that demonstrate how a risk-based methodology can provide calculations of relative risks that are useful in the decision process for seismic rehabilitation of an existing earth dam.

Seismic Risk Analysis: an Overview

An earth dam can incur seismic damage by different mechanisms, referred to as modes of failure. Two primary modes of seismic damage are considered in this approach. *Mode 1* is associated with permanent deformation of the dam that may accumulate during the course of the earthquake leading to overtopping of the dam due to loss of freeboard. *Mode 2* failure mechanism is related to possible slope instability at the end or immediately following the earthquake excitation due to reduction of shear strength of the dam material or its foundation during the shaking.

In recent years, a number of analytical procedures have been developed for calculating permanent deformations (Newmark 1965, Makdisi & Seed 1978, Lin and Whitman 1986, Ambraseys & Menu 1988, Yegian et al. 1991b). In most of these methodologies the characteristics of the seismic excitation plays an important role in the estimation of permanent deformations. The peak ground acceleration, frequency content, duration and random nature of the ground motion affect the magnitude of the accumulated permanent deformations.

The likelihood of *Mode 2* (namely, post-earthquake slope stability) failure depends on the severity of the earthquake ground motion as well as on the post-earthquake characteristics of the foundation soil and dam materials. Yegian et al. (1991a) described simple procedures for calculating the likelihood of seismic damage occurring due to *Mode 1* and *Mode 2*. In these procedures the magnitude of the earthquake plays an important role. Hence, in seismic risk analysis of earth dams in addition to the level of the peak ground acceleration, the associated earthquake magnitude is also needed.

Seismic risk analysis of an earth dam is performed in the following three steps (Yegian et al. 1991a):

Step 1. *Seismic Hazard Analysis (SHA)*, in which the various seismic

sources and the characteristic of the seismic excitation that can be generated by these sources are considered to calculate the annual probability of exceeding different levels of seismic hazard. Current SHA procedures typically provide the annual number of events causing acceleration A to exceed a specified level a , $\lambda(A \geq a)$. However, this total number of events, $\lambda(A \geq a)$, will generally have contributions from different ranges of seismic magnitude M due to varying site-to-source distances associated with the different seismic sources. Yegian et al. (1991a) described a procedure to calculate the expected number of events, $\lambda(\Delta A, \Delta M)$, having acceleration and magnitude within the ranges of ΔA and ΔM , respectively. Thus, a matrix of $\lambda(\Delta A, \Delta M)$ for different ranges of A and M constitute the results of a SHA useful in seismic risk analysis of earth dams.

Step 2. *Seismic Performance Analysis (SPA)*, in which the probabilities of damage and failure of an earth dam conditioned upon specified seismic loads are determined. For Modes 1 and 2 described earlier the probabilities of damage and failure associated with specified values of ΔA and ΔM can be calculated following the procedures presented by Yegian et al. (1991b). The resulting "conditional" probabilities for each mode can again be presented in matrix form where $P(DS_i | \Delta A, \Delta M)$ is the probability of the dam experiencing damage state i , (DS_i), if the acceleration and the earthquake magnitude are within the respective ranges of ΔA and ΔM .

Step 3. *Seismic Risk Analysis (SRA)*, in which the results from SHA and SPA are integrated to yield the overall risk of damage or failure of a dam. This integration can be accomplished numerically using Equation 1.

$$\lambda(DS_i) = \sum_{\text{all } A} \sum_{\text{all } M} P(DS_i | \Delta A, \Delta M) \cdot \lambda(\Delta A, \Delta M) \quad (1)$$

where $\lambda(DS_i)$ is the expected annual number of events causing damage state i , $\lambda(\Delta A, \Delta M)$ is the annual number of events having acceleration range of ΔA and magnitude range of ΔM , and $P(DS_i | \Delta A, \Delta M)$ is the probability of damage state i occurring for each given ranges of ΔA and ΔM .

Equation 1 gives the expected annual number of events associated with damage state i . The probability of at least one event causing a specified level of damage to a dam during the design life of the dam can be calculated assuming a Poisson's arrival process. For example, the probability of at least one catastrophic failure (C/F) (loss of freeboard) occurring in t years can be calculated from

$$P[\text{catastrophic failure in } t \text{ - years}] = 1 - e^{-\lambda(C/F)t} \quad (2)$$

where $\lambda(C/F)$ is the annual number of events causing catastrophic failure of the dam and is calculated using Equation 1.

Example Application

To illustrate the various steps involved and the benefits of the application of a seismic risk analysis, a dam located in Massachusetts is selected for a case study. A typical cross-section of the dam is shown in Figure 1. The upstream shell consists of medium dense sands. The downstream section has primarily medium dense sands and gravels. The dam is founded on glacial till overlying bedrock. Geotechnical field investigations indicated presence of a layer of loose sand with low blow counts at about 40 feet (13 m) below the crest of the dam, extending under the entire downstream shell. Placement of a fill, as shown in Figure 1, was proposed to provide the additional freeboard (for hydrological considerations) and to reduce the seismic vulnerability due to presence of the potentially liquefiable loose sand layer. One rehabilitation scheme (Option 1) would be to raise the crest elevation from the existing 755 ft to 760 ft thereby, providing an additional 5 ft of freeboard and a berm to increase safety against seismically-induced failure. Another alternative (Option 2) would be to raise the crest elevation by 10 ft with correspondingly larger berm for increased safety against seismically-induced failure (Figure 1).

The question therefore is: which rehabilitation option (1 or 2) should be adopted? Obviously, Option 2 provides larger margin of safety than Option 1. But how much larger and at what cost?

If one follows a deterministic approach then the answer to the above question will depend primarily on the level of acceleration A and the associated magnitude M that is selected in design. For example, it will be

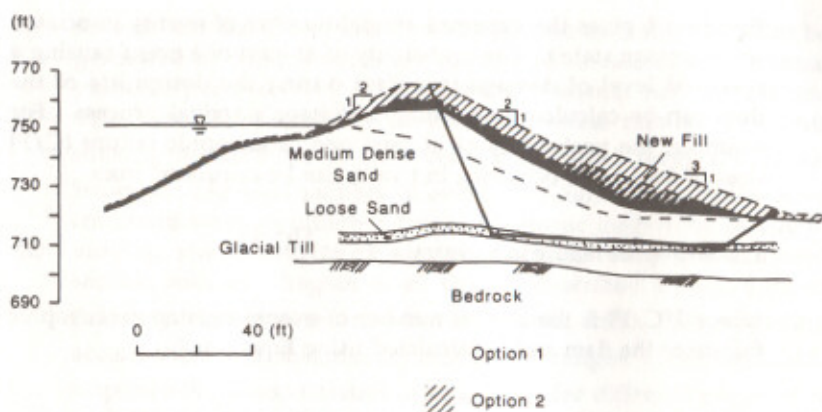


FIG. 1. Cross Section of Dam Considered in Example Case Study (1 ft = 0.305 m)

demonstrated later in the paper that if a maximum acceleration of 0.2g associated with the maximum historical earthquake of $M=6.5$ is considered, then under both rehabilitation schemes the dam is very likely to fail. On the other extreme, if an acceleration of 0.1g is assumed then the existing dam, as well as the dam under both rehabilitation schemes, will be safe against failure. To complicate matters further, if an acceleration level of 0.12g is selected, as prescribed by the Massachusetts building code, then the safety of the dam will depend on the associated magnitude (which the building code does not specify), and the rehabilitation scheme selected.

It is quite evident that without properly considering the seismicity of the region and the likelihood of the seismic load it is difficult to make an informed and cost effective decision regarding the rehabilitation of the example dam. A deterministic approach based on a conservative assumption of $A=0.2g$ and $M=6.5$ would necessitate the in-situ densification of the loose sand layer together with some placement of fill to provide additional freeboard. But the necessity and cost-effectiveness of this decision can not be quantified unless a risk-based methodology is followed.

Risk-Based Analysis

The two rehabilitation alternatives described earlier were investigated and the corresponding seismic risks were computed and compared.

The Seismic Hazard Analysis for the case study was performed and the results were reported in detail by Yegian et al. (1991b). Table 1 summarizes these results in a matrix format. The adoption of matrices to display the results of both SHA and SPA not only facilitates the calculation of seismic risk but also demonstrates clearly the major contributing sources. The numbers in Table 1 show $\lambda(\Delta A, \Delta M)$, the annual number of earthquakes that may cause peak ground acceleration range of ΔA and having a magnitude range of ΔM . For example, it is noted from Table 1 that approximately 3 earthquakes in 10,000 years may occur in the region investigated (numbers are rounded-off for the purpose of illustration). Of these 3 earthquakes, one may be smaller than magnitude 5, another may have a magnitude between 5 and 6, and the other between 6 and 6.8. Although each of these events may cause same level of acceleration $A > 0.2g$ they may have different detrimental effects on the dam. The larger magnitude events will cause larger pore pressures in the loose sands; hence, contributing more to the possibility of post-earthquake slope failure.

Peak Ground Acceleration (g) Magnitude Range	ANNUAL NUMBER OF EVENTS, λ (10^{-4})					
	$0.0 \leq A < 0.05$	$0.05 \leq A < 0.1$	$0.1 \leq A < 0.15$	$0.15 \leq A < 0.2$	$0.2 \leq A < 0.25$	$A > 0.25$
$4.33 \leq M < 5.0$	1467.50	41.22	7.87	2.67	1.07	1.25
$5.0 \leq M < 5.5$	392.80	18.51	4.17	1.25	0.55	0.64
$5.5 \leq M < 6.0$	163.30	12.04	2.54	0.98	0.37	0.46
$6.0 \leq M < 6.5$	68.19	7.22	1.86	0.73	0.36	0.44
$6.5 \leq M < 6.8$	12.90	1.72	0.67	0.21	0.12	0.18
TOTAL	2113.69	80.71	17.11	5.84	2.47	2.97

TABLE 1. Seismic Hazard Analysis Results for the Example Site

The likelihood of damage or failure incurred by the dam under these different levels of seismic excitations can be calculated through a Seismic Performance Analysis described earlier. For the two alternate rehabilitation schemes of the example dam, the seismic performance and the seismic risk analyses results are presented.

Option 1

Probabilities for three damage states were calculated. These damage states, defined in terms of permanent deformations, D_T , are as follows: no or minor damage ($D_T < 2'$), heavy damage ($2' \leq D_T < 5'$), and catastrophic damage ($D_T \geq 5'$) which is associated with loss of freeboard.

The survival of a dam from an earthquake depends on its safe performance during (Mode 1) and immediately after the earthquake (Mode 2). Figure 2 shows an event tree of seismic performance analysis that describes the condition for which a dam is considered failed. From this figure it is noted that if a dam experiences failure in either of the two

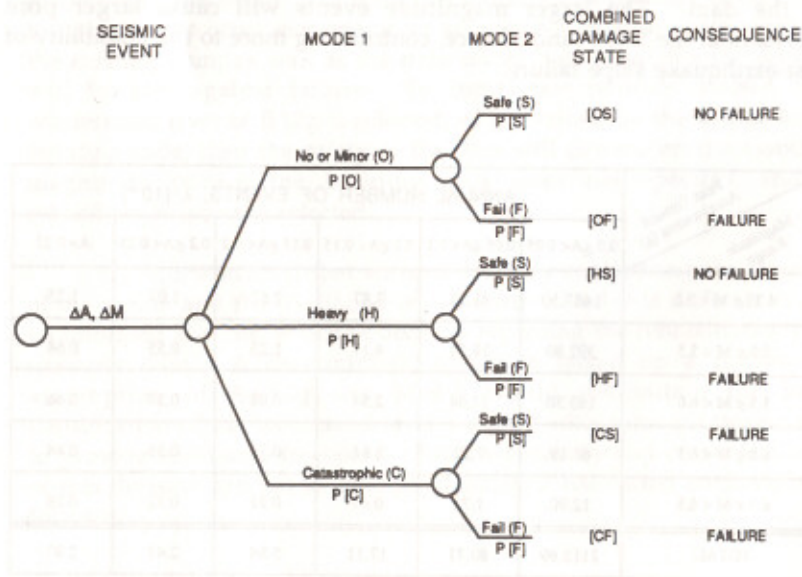


FIG. 2. Event Tree of Seismic Performance Analysis

(or in both modes) it is considered failed. Hence, the damage probabilities for Mode 1 and Mode 2 can be combined as described by the event tree. Table 2 shows the calculated (combined) probabilities for the example dam considering Option 1 rehabilitation scheme (Figure 1).

The numbers in the SPA matrix shown in Table 2 give the probabilities of failure for each acceleration and magnitude range ΔA and ΔM . For example, for $A \geq 0.2g$, it is most likely that the dam will fail [$p(\text{failure}) = 0.97$], whereas, for $A < 0.1g$ the probability of the dam

Damage State	Peak Ground Acceleration Magnitude Range (ΔM)				
	$0.0g \leq A < 0.10g$				
	4.3 - 5	5 - 5.5	5.5 - 6	6 - 6.5	6.5 - 6.8
No/Minor (< 2')	1.0	1.0	1.0	1.0	1.0
Heavy (2' - 5')	0	0	0	0	0
Catastrophic (> 5')	0	0	0	0	0
	$0.1g \leq A < 0.15g$				
No/Minor (< 2')	0.978	0.960	0.857	0.400	0.021
Heavy (2' - 5')	0.001	0.003	0.008	0.014	0.001
Catastrophic (> 5')	0.021	0.037	0.135	0.586	0.978
	$0.15g \leq A < 0.2g$				
No/Minor (< 2')	0.515	0.022	0.021	0.020	0.020
Heavy (2' - 5')	0.025	0.002	0.002	0.002	0.001
Catastrophic (> 5')	0.460	0.976	0.977	0.978	0.979
	$0.2g \leq A < 0.25g$				
No/Minor (< 2')	0.022	0.021	0.020	0.020	0.019
Heavy (2' - 5')	0.002	0.002	0.002	0.001	0.001
Catastrophic (> 5')	0.976	0.977	0.978	0.979	0.980
	$A > 0.25g$				
No/Minor (< 2')	0.021	0.020	0.020	0.019	0.019
Heavy (2' - 5')	0.002	0.002	0.001	0.001	0.001
Catastrophic (> 5')	0.977	0.978	0.979	0.980	0.980

TABLE 2. Damage Probability Matrix for Rehabilitation Option 1 (Example Case Study)

experiencing a seismically-induced failure is inappreciable. These results restate the argument made earlier that a deterministic approach to the seismic safety evaluation of this dam will yield significantly different conclusions depending upon the level of acceleration selected (0.1g or 0.2g) for analysis.

To calculate the seismic risk of the example dam the results from SHA (Table 1) and SPA (Table 2) are integrated using Equation 1. Table 3 shows the annual number of seismic events causing different damage levels. From this table it is also noted that the overall seismic risk of failure of the example dam is about 5.8% considering a 50-year life for the dam.

SEISMIC RISK				
Damage State	Consequence	Annual Number of Events (10^{-3})	Annual Probability	Probability in 50 Years
OS	No or Minor	221.054	0.9988	94.06%
HS	Heavy	0.015	0.024×10^{-3}	0.12%
C/F	Failure	1.21	1.2×10^{-3}	5.82%

TABLE 3. Seismic Risk Analysis Results for Rehabilitation Option 1 (Example Case Study)

Option 2

The preceding analyses and calculations for Option 1 were repeated considering an alternate remediation scheme shown in Figure 1. In this option an additional 10 ft freeboard is provided to the existing dam and the berm correspondingly is larger than that of Option 1. This scheme not only provides added safety against overtopping but also further reduces the liquefaction susceptibility of the loose sand layer.

Seismic Hazard Analysis results shown in Table 1 are valid also for this case because the results are expressed in terms of bedrock accelerations and are independent of the dam properties and configuration. However, the SPA results change because of increased safety provided in this option. Tables 4 presents the SPA results.

Peak Ground Acceleration Magnitude Range (ΔM) Damage State	$0.0g \leq A < 0.10g$				
	4.3 - 5	5 - 5.5	5.5 - 6	6 - 6.5	6.5 - 6.8
No/Minor (< 2')	1.0	1.0	1.0	1.0	1.0
Heavy (2' - 10')	0	0	0	0	0
Catastrophic (> 10')	0	0	0	0	0
$0.1g \leq A < 0.15g$					
No/Minor (< 2')	0.991	0.972	0.906	0.559	0.022
Heavy (2' - 10')	0.002	0.006	0.024	0.049	0.003
Catastrophic (> 10')	0.007	0.022	0.070	0.392	0.975
$0.15g \leq A < 0.2g$					
No/Minor (< 2')	0.728	0.023	0.022	0.022	0.021
Heavy (2' - 10')	0.080	0.005	0.004	0.003	0.003
Catastrophic (> 10')	0.192	0.972	0.974	0.975	0.976
$0.2g \leq A < 0.25g$					
No/Minor (< 2')	0.023	0.022	0.022	0.021	0.021
Heavy (2' - 10')	0.005	0.004	0.004	0.003	0.002
Catastrophic (> 10')	0.972	0.974	0.974	0.976	0.977
$A > 0.25g$					
No/Minor (< 2')	0.023	0.022	0.021	0.020	0.020
Heavy (2' - 10')	0.005	0.004	0.003	0.003	0.002
Catastrophic (> 10')	0.972	0.974	0.976	0.977	0.978

TABLE 4. Damage Probability Matrix for Rehabilitation Option 2 (Example Case Study)

Once again, using Equation 1 the results of SHA (Table 1) are integrated with those of SPA (Table 4) to estimate the seismic risk of damage and failure of the dam for this option. Table 5 presents these results.

Comparison of Options 1 and 2

In Tables 3 and 5 the overall calculated seismic risks for the two rehabilitation options are presented. A comparison between the results

SEISMIC RISK				
Damage State	Consequence	Annual Number of Events (10^{-3})	Annual Probability	Probability in 50 Years
OS	No or Minor	221.174	0.9989	94.63%
HS	Heavy	0.044	0.043×10^{-3}	0.21%
C/F	Failure	1.060	1.060×10^{-3}	5.16%

TABLE 5. Seismic Risk Analysis Results for Rehabilitation Option 2 (Example Case Study)

of Options 1 and 2 presented in these tables show that the reduction in seismic risk of failure of the dam is relatively small — 5.8% in 50 years for Option 1 and 5.2% in 50 years for Option 2. Another parameter that can be used to compare the relative risks is return period. The return period of a catastrophic event is defined by the inverse of the annual probability of that event. Thus, as shown in Table 6, the return period of a seismically induced catastrophic failure of the dam considering Option 1 is about 830 years and for Option 2 is about 940 years — not a significant increase in the return period.

Although Option 2 does provide a reduced seismic risk, it should be noted that this benefit is at an increased cost associated with larger scope of remedial construction. Table 6 summarizes, for the two options, the necessary volume of compacted fill. As indicated in the table, the volume of fill required for Option 2 is more than twice as that for Option

Rehabilitation Scheme	Probability in 50 Years	Return Period (years)	Volume of Construction (c.y.)	Cost of Construction (\$)	Expected Loss During Life (\$)
Option 1	0.058	833	8,000	48,000	58,000
Option 2	0.052	943	18,000	108,000	52,000

TABLE 6. Costs and Benefits of the Two Seismic Rehabilitation Options for the Dam Considered (Example Case Study)

1. To illustrate the benefit of seismic risk calculations in a cost/benefit analysis calculations were made of the cost of the required fill and of the expected loss if the dam were to be replaced following a seismically-induced failure. The cost for borrow and placement of fill was assumed to be about \$6./cy. The replacement cost of the dam including removal of old embankment materials was assumed to be about one million Dollars. The political and social consequences of failure are not considered; and failure of the dam is not expected to cause fatalities. The expected loss due to potential failure of the dam during its 50 year life was calculated by multiplying the replacement cost by the failure probabilities of the two options.

Table 6 shows the rehabilitation costs for the two options and the corresponding expected losses from the likely failure of the dam by an earthquake during a 50 year time period. The results, again, demonstrate, in monetary terms, that by adopting Option 2 instead of 1 the reduction in the seismic risk and hence in the expected loss is relatively insignificant (\$6000.) compared with the up-front increase in construction cost of \$60,000.

Conclusions

A risk-based methodology for seismic rehabilitation of earth dams was described. To illustrate the benefits of the application of a probabilistic seismic risk analysis, an example dam was analyzed. Two alternate rehabilitation schemes (Options 1 and 2) were investigated and the relative risks and their associated costs were compared.

For this example, since the dam is located in a low seismicity region, the seismic risk and the associated expected loss is small. Furthermore, Option 2 for rehabilitation of the dam, compared to Option 1, provides little reduction in seismic risk at significantly increased cost. These conclusions were arrived at because of the probabilistic approach followed in the seismic safety evaluation of the example dam. A deterministic approach based on a conservative selection of a peak ground acceleration of 0.2g would result in very costly and, certainly from the seismic risk point of view, unnecessary rehabilitation programs.

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Appendix II. Conversion Units

1 ft = 0.305 m