RISK AND RELIABILITY ANALYSIS OF STABILITY OF EARTHEN DAMS

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ABSTRACT: The Kachchh region of Gujarat, India bore the brunt of a disastrous earthquake of magnitude $M_w = 7.6$ that occurred on January 26, 2001. The major cause of failure of various structures including earthen dams was noted to be the presence of liquefiable alluvium in the foundation soil. Results of back-analysis of failures of Chang, Tappar, Kaswati and Rudramata earthen dams using pseudo-static limit equilibrium approach presented in this paper confirm that the presence of liquefiable layer contributed to lesser factors of safety leading to a base type of failure that was also observed in the field. Following the earthquake, earth dams have been rehabilitated by the concerned authority and it is imperative that the reconstructed sections of earth dams be reanalyzed. It is also increasingly realized that risk assessment of dams is necessary in view of the large-scale investment made and probabilistic analysis is necessary. In this study, it is demonstrated that the probabilistic approach when used in conjunction with deterministic approach helps in providing a rational solution for quantification of safety of the dam and in the estimation of risk associated with the dam construction.

1. INTRODUCTION

1.1 Risk Analysis for Dams

In a broader framework, risk analysis is a systematic tool that allows the comparison of risks from different types of hazards. It facilitates the identification of the weak elements of a complex dam system and the hazards that mainly contribute to the risk. Thus, the vulnerability of a dam can be reduced by strengthening these weak elements. Management of safety of the existing dams is one of the important aspects in the dam engineering. Risk based approach combines the benefits of the well-established traditional approach in the dam safety analysis and risk assessment. The procedure provides valuable inputs to the dam safety decision making.

Risk estimation entails the assignment of probabilities to the events and responses identified under risk identification. The assessment of appropriate probability estimates is one of the most important tasks of the entire process. The outcome of this step is a calculation of the risk of failure. Probability estimation can be grouped into three general approaches depending on the type and quality of the available data. These include the analytical approach, the empirical approach, and the judgmental approach (Graham & Bartsch 1995).

The analytical approach is the most sophisticated of the three and it is often supported by the use of logical models for calculating probabilities.

The empirical approach utilizes existing databases to generate probability estimates based on historical frequencies.

The judgmental approach recognizes that many systems cannot be adequately described purely by means of analytical or empirical methods, and attempts to include the experience and the judgment of practicing engineers in guiding the estimation of probabilities.

Risk acceptance is an informed decision to accept the likelihood and the consequences of a particular risk. Risk acceptance is coupled to the risk reduction evaluation and is a basis for deciding what residual risk will be accepted for the affected community and structures.

USACE (1997) made specific recommendations on target probability of failure ($p_f$) and reliability indices ($\beta$) in geotechnical and infrastructure projects. The suggested guidelines are given in Figure 1, which indicate that a reliability index ($\beta$) value of at least 4.0 is considered to indicate good performance of the system and 3.0 for the above average performance.

1.2 Method of Total Risk Analysis

The total risk analysis methods for dam structures primarily have two separate components. International Commission of Large Dams (ICOLD 1989) provided a procedure for the total risk analysis of earthen dams in which the seismic hazard of dam site and risk rating of structure are considered separately.
As per ICOLD (1989) provisions, the total risk for embankment dam structures depends on two factors i.e. (i) the seismic hazard rating of the dam site, and (ii) the risk rating of the dam and appurtenant structures. For the seismic hazard analysis of a particular site, all possible seismic sources are identified and their potential for producing significant ground motion is evaluated using the procedure explained by Fraser and Howard (2002). The procedure for seismic hazard analysis of a dam site includes either Deterministic Seismic Hazard Analysis (DSHA) or Probabilistic Seismic Hazard Analysis (PSHA) (Kramer 2003). On the other hand, the risk rating of the dam is based on the capacity of the reservoir, the height of the dam, evacuation requirements, and the potential downstream damages. Bureau (2003) illustrated a procedure that combines the above-mentioned two factors, to define the total risk factor for embankment dam structures.

In the present study, firstly the approach of Bureau (2003) is used to evaluate the total risk factor for dams sections followed by detailed analysis based upon risk and reliability.

1.2.1 Bureau (2003) Approach

This method considers various risk factors and weighting points to approximately quantify the Total Risk Factor (TRF) of any dam. The TRF depends on the dam type, age, size, downstream risk potential, and the dam vulnerability, which depends on the seismic hazard of the site. The TRF is expressed as:

\[
TRF = \left[ (CRF + HRF + ARF) + DHF \right] \times PDF \tag{1}
\]

The dam structure influence is represented by the sum of capacity, height, and age risk factors \((CRF + HRF + ARF)\). The Downstream Hazard Factor \((DHF)\) is based upon population and property at risk. The rating of vulnerability is a function of the site-dependent seismic hazard and the observed performance of similar dams, as defined by a Predicted Damage Factor \((PDF)\).

(a) *Influence of Structure*—The values of \(CRF\), \(HRF\) and \(ARF\) are obtained from Tables 1a & 1b, respectively.

<table>
<thead>
<tr>
<th>Risk factor</th>
<th>Contribution to total risk factor (weighting points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (acre-feet)</td>
<td>Extreme High Moderate Low</td>
</tr>
<tr>
<td>(&gt;50,000)</td>
<td>6 (5) (4) (3)</td>
</tr>
<tr>
<td>(50,000-1,000)</td>
<td>(4) (3) (2) (1)</td>
</tr>
<tr>
<td>(1000-100)</td>
<td>(3) (2) (1) (0)</td>
</tr>
<tr>
<td>(&lt;100)</td>
<td>(4) (3) (2) (1)</td>
</tr>
</tbody>
</table>

(b) *Downstream Risk*—The downstream Evacuation Requirement Factor \((ERF)\) depends on the human population at risk. The downstream Damage Risk Index \((DRI)\) is based on the value of private, commercial, industrial, or government property in the potential flood path. These factors should preferably be obtained from a combination of detailed dam breach, inundation mapping, and economic studies. The DHF should be updated whenever new information becomes available or when the dam is repaired, modified, or raised as in Table 1c.

(c) *Seismic Vulnerability Rating*—Dam vulnerability curves from observed seismic performance of dams during earthquakes, can be used to compute a Predicted Damage Index \((PDI)\). The PDI depends on the dam type, on the site seismic hazard, and...
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on the tectonic environment. The expected ground motion at the dam site for the scenario earthquake considered is expressed by the Earthquake Severity Index (ESI), a robust estimate of the severity of shaking for dam evaluation purposes (Bureau et al. 1985). The ESI is expressed as:

\[ ESI = PGA \times (M_w - 4.5)^3 \]  

(2)

where, the PGA is measured in g, and \( M_w \) is the moment magnitude of earthquake. The PDI depends on the ESI at each dam site, for each postulated earthquake scenario, and is obtained from geographical relationships shown in Figure 2.

Table 1d: Downstream Hazard Factor Based on NID (Bureau 2003)

<table>
<thead>
<tr>
<th>NID's downstream hazard potential rating</th>
<th>Loss of human lives</th>
<th>Economic, Environmental, or life losses</th>
<th>Downstream hazard Factor (DHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>None expected</td>
<td>Low, generally limited to owner’s property</td>
<td>2</td>
</tr>
<tr>
<td>Significant</td>
<td>None expected</td>
<td>Yes or probable but not strictly required</td>
<td>12</td>
</tr>
<tr>
<td>High</td>
<td>Likely, one or more expected</td>
<td>Yes</td>
<td>24</td>
</tr>
</tbody>
</table>

Bureau & Ballentine (2002) empirically selected the coefficient 2.5 to provide consistency between vulnerability estimates obtained from site-specific ground motion estimates defined by the ESI or when such estimates were not available, from a combination of a dam type factor and a seismic zone factor derived from the uniform building code zone factor.

(d) Total Risk Factor—The last step of the total risk assessment is the ranking of a dam by deciding TRF and assignment of a risk class, ranging from I (Low risk) to IV (extreme risk), as shown in Table 2.

Table 2: Definition of Dam Risk Class (Bureau 2003)

<table>
<thead>
<tr>
<th>Total Risk Factor (TRF)</th>
<th>Dam Risk Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 to 25</td>
<td>I (Low)</td>
</tr>
<tr>
<td>25-125</td>
<td>II (Moderate)</td>
</tr>
<tr>
<td>125-250</td>
<td>III (High)</td>
</tr>
<tr>
<td>&gt;250</td>
<td>IV (Extreme)</td>
</tr>
</tbody>
</table>

The risk class can be used to establish the need for more detailed seismic safety evaluations and to establish priorities for such evaluation. The use of above approach is illustrated with reference to the selected earthen dams located in the Kachchh region of Gujarat (as presented in the next section) and based upon that detailed analysis about the safety of the dam sections are presented both in deterministic as well as in probabilistic terms.

2. EARTH DAMS IN KACHCHH, GUJARAT, INDIA

The Kachchh region of Gujarat, India is one of the most seismically active regions in the country (seismic zone V as per BIS: 1893–2002). The Allah Bund earthquake in 1819 (\( M_w >7.0 \)), Anjar earthquake in 1956 (\( M_w = 7.0 \)), and Bhuj earthquake in 2001 (\( M_w = 7.6 \)) are the few major earthquakes occurred in the past including the disastrous 2001 Bhuj earthquake.

In Kachchh, major fault zones trend generally east-west, and the Kachchh Mainland Fault has a length of about 100 km and passes through the epicentre area where the Bhuj earthquake occurred. It is presumed that this is the fault on which the Bhuj earthquake occurred, though no surface rupture was observed (Krinitzsky & Hynes 2002). A detailed discussion on the geological features of the Kachchh region of Gujarat, India and information on the effect of Bhuj earthquake on the economic and social life of the people could be gathered in the available literature (EERI- Special Earthquake Report 2001).
For the total risk analysis of the four selected earth dam sections i.e. Chang, Tapar, Rudramata, and Kaswati, located in the region, Deterministic Seismic Hazard Analysis (DSHA) of the four dam sites is performed and results are presented. All the possible seismic sources have been identified on the basis of local geological features and seismic history of the region. The following four steps were used for the DSHA (Kramer 2003).

For the DSHA, the following attenuation relationship developed by Iyengar & Raghukanth (2004) is used to calculate the Peak Ground Acceleration (PGA) acting on the dam sites. Table 3 provides the results of the DSHA analysis of the four dam sites located in the Kachchh region, Gujarat, India.

Further, the information provided in Tables 3 & 4 has been used for the estimation of different risk factors involved in the estimation of Total Risk Factor (TRF) of all the four dam sections as given in Table 5. Finally, the value of TRF for all the four dam sections are calculated and the assessments of the risk associated with dam sections are made based upon those TRF values (Table 6).

The values of TRF obtained for different dam sections indicate that except Kaswati dam section all the other three dam sections fall in the high risk class. Hence, detailed seismic safety evaluations of these dam sections are required and the priority for the risk based profiling system or portfolio risk management of the dam sections can be in the following order: Rudramata > Tapar > Chang > Kaswati. Hence, based on the total risk analysis, extensive studies for analyzing and ensuring the safety of the dam sections is conducted.

3. SAFETY ANALYSIS OF EARTH DAMS

The failure of most of the earthen dams during Bhuj earthquake is attributed to presence of liquefiable layer beneath the foundation although the liquefaction of foundation soil was relatively localized in the earthquake affected area. Since the earthquake struck in the middle of a prolonged dry season, the liquefaction of the foundation soil beneath majority of earthen dams was limited (Singh et al. 2005). Due to insufficient geotechnical data, although it was difficult to assess the liquefaction susceptibility of the foundation soil under the pre-earthquake conditions. It is well understood that the top 2.0 to 3.0 m layer of foundation soil was susceptible to liquefaction, especially on the downstream side and the effect was limited to reduction in strength of the foundation soil (Singh et al. 2005).

Table 7 summarizes the performance of the dam sections during Bhuj earthquake. After the earthquake, various remedial
measures were implemented by the concerned authority (Narmada Water Resources & Water Supply Department, Government of Gujarat, India) either to reconstruct or rehabilitate the earthen dams in the affected region.

The objective is to perform the pseudo-static stability analysis of the four earthen dam sections that faced varying level of damages during Bhuj earthquake (i) to understand the failure mechanism, and (ii) to understand the behaviour of the dams under earthquake loading conditions. Further, the rehabilitated dam sections are also analyzed. In addition to limit equilibrium based approach; the probabilistic analyses of the four dam sections are also performed to assess the safety of dams under static and pseudo-static loading conditions to assess their stability for future earthquakes. The probabilistic analysis is performed combining the limit equilibrium approaches with Monte Carlo Simulations (MCS).

Although several researchers in the past highlighted the limitations and drawbacks of the pseudo-static approach (Seed et al. 1969; Gazetas 1987), the positive point in favour of the approach lies in the fact that the method can quantify the degree of safety associated with a structure under pseudo-static loading, representing earthquake loading. Since the present work examines the stability and the associated reliability both from deterministic and probabilistic approach considerations for the old dam sections as well as reconstructed dam sections, the use of pseudo-static approach is deemed satisfactory.

The following sections provide the results of the analysis of the four dam sections. The stability analysis of the dam sections are carried out using the commercially available software SLIDE (2005), which has options for both conventional limit equilibrium approaches as well as probabilistic analysis combining limit equilibrium approaches with Monte Carlo simulations.

### 3.1 Estimation of Input Soil Properties

It is well understood that during earthquake loading, pore pressure is developed and there is not enough time available for the dissipation of developed pore water pressure. Due to this reason, an undrained loading condition exists during earthquake loading in most of the soils.

Hynes-Griffin & Franklin (1984) indicated that a conservative estimate of factor of safety is made when the pseudo-static limit equilibrium analysis is performed with 20% reduction in soil shear strength and stiffness parameters, which are obtained under static conditions. In the present study, the shear strength and stiffness parameters of the embankment dam materials obtained using tri-axial test results were reduced by 20% to obtain the design parameters. Typical values of input soil properties used in the analysis of the Chang dam sections is provided in Table 8.

### 3.2 Pseudo-Static Coefficient

For the selection of appropriate value of horizontal seismic coefficient, Bureau of Indian Standards (BIS: 1893–2002), which has been revised after the earthquake of 2001, provides guidelines in this direction. India is divided into four zones in the increasing order of impact (II, III, IV and V) and the dams that failed in Bhuj region of Gujarat belong to Zone V. Gujarat State Disaster Management Authority (2007) prepared guidelines for seismic design of earth dams and embankments. The recommended value of design horizontal coefficient $\alpha_d$ is given by $\frac{ZIS}{2R_g}$, where, $Z$ is a zone factor which is taken as 0.36 for zone V, $I$ is the importance factor for dams (1.0 for ordinary embankments) and $S_g$ is the response acceleration coefficient depending on local site conditions and fundamental period and is obtained as 2.5. This leads to a design coefficient of 0.15.

The code also specifies an allowable pseudo-static factor of safety of 1.0 for earth and rockfill dams and embankments under pseudo-static loading conditions. The effects of vertical accelerations are neglected (Kramer 2003).

### 3.3 Liquefaction Analysis of Ground

In the present study, a procedure based on field SPT test results, as explained in Youd et al. (2001), is used to find the liquefaction resistance of the soil. The attenuation relationship developed by Iyenger and Raghukant (2004) for the calculation of peak horizontal acceleration ($a_{max}$) is used.

After the remedial measures were taken, liquefaction resistance of the in situ foundation soil at the four dam locations is obtained. Figure 3 shows a typical variation of factor of safety of the in situ soil against liquefaction at the Chang dam site, which indicates it is safe.

### 3.4 Results of Analysis of the Dam Sections

Limit equilibrium based pseudo-static factor of safety of the selected dam sections are performed using modified Bishop’s approach available as an inbuilt option in the SLIDE software. For the probabilistic analysis, coefficient of variation (CoV%) for the input soil properties are taken from the published literature and it is provided in Table 9.
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Table 9: Suggested Values of Coefficient of Variation (%) for Soil Parameters (Duncan 2000)

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit weight (γ)</td>
<td>7%</td>
</tr>
<tr>
<td>Angle of internal friction (ϕ)</td>
<td>13%</td>
</tr>
<tr>
<td>Shear strength (c)</td>
<td>20%</td>
</tr>
</tbody>
</table>

In the probabilistic analysis using Monte Carlo simulations combined with limit equilibrium approach, the number of simulation cycles used in the present is 40,000. Typical results of the analysis of the old Chang dam section are shown in Figures 4a & 4b.

It is evident from the figures that the Factors of Safety (FS) and reliability index (β) values are quite low. It also illustrates the occurrence of base type failure due to presence of liquefiable layer in the foundation soil as shown in Figure 4a. Similar results were also obtained for other dam sections where there was an existence of liquefiable layer in the foundation soil. The analysis is also performed considering a hypothetical case in which the liquefiable layer is non existence. The estimated values of factor of safety are more than unity and also the slip surface is confined to slopes. Hence, the presence of liquefiable layer not only reduced the stability but also changed the failure pattern e.g. from slope to a base type failure mechanism, which is also observed during field reconnaissance. The typical results of the analysis of all the old Chang dam sections is summarized in Table 10.

An investigation to assess the safety of the rehabilitated dam sections was made using deterministic and probabilistic approaches. The analysis was performed for reservoir full condition as well as sudden drawdown condition (considering water level at the ground surface) under static and pseudo-static loading conditions.

Table 10: Results of the Analysis of the Old Chang Dam

<table>
<thead>
<tr>
<th>Conditions of liquefiable layer in the foundation soil</th>
<th>FOS (det.)</th>
<th>FOS (mean)</th>
<th>β (%)</th>
<th>Reliability index (β)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With consideration of liquefiable layer</td>
<td>0.96</td>
<td>0.97</td>
<td>98.28</td>
<td>2.24</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>0.88</td>
<td>98.28</td>
<td>2.24</td>
</tr>
<tr>
<td>Without consideration of liquefiable layer</td>
<td>1.05</td>
<td>1.05</td>
<td>31.17</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>1.06</td>
<td>1.07</td>
<td>20.96</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Fig. 3: Variation of Factor of Safety against Liquefaction (FSL), Raw and Corrected SPT Profile (N60)

Fig. 4a: Pseudo-Static Analysis of the Old Chang Dam Section with Consideration of Liquefiable Layer beneath the Foundation

Fig. 4b: Pseudo-Static Analysis of the Old Chang Dam Section without Consideration of Liquefiable Layer beneath the Foundation

Fig. 5a: Pseudo-Static Analysis of Reconstructed or Rehabilitated Chang Dam Section at Reservoir Full Condition (U/S side)

Fig. 5b: Pseudo-Static Analysis of Reconstructed or Rehabilitated Chang Dam Section at Reservoir Full Condition (D/S side)
Figure 5 shows typical results of the pseudo-static analysis of the Chang dam section under reservoir full condition. It may be noted that the deterministic and mean factor of safety indicated in figures are defined separately. The former is related to the deterministic approach (limit equilibrium approach), while the latter is the average of all the values of factor of safety obtained from the number of Monte Carlo simulations. The results of deterministic and probabilistic analyses of the rehabilitated Chang dam sections are summarized in Table 11.

The results presented in the table clearly indicate that the older sections have factor of safety close to 1.0 and the low reliability index (β) values. The reconstructed dam sections have higher factors of safety as well as reliability index values that are considered appropriate in the context of values recommended by USACE (1997).

Table 11: Results of the Analysis of New Chang Dam Section (Reservoir full condition)

<table>
<thead>
<tr>
<th></th>
<th>FOS (det.)</th>
<th>FOS (mean)</th>
<th>β (%)</th>
<th>Reliability index (β)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static analysis</td>
<td>Pseudo-static analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US side</td>
<td>1.91</td>
<td>1.92</td>
<td>0.00</td>
<td>4.14</td>
</tr>
<tr>
<td>D/S side</td>
<td>2.04</td>
<td>3.07</td>
<td>0.00</td>
<td>3.42</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

The results of the analysis of the four old dam sections revealed that the presence of a liquefiable layer beneath the foundation was the major cause of the failure of the dam during Bhuj earthquake resulting in the base type of failure that occurred. These features also captured in the analysis, where it is shown that consideration of liquefiable layer in the foundation soil reveals base type failure of the slopes of the embankment dams, while it shows slope failure when the liquefiable layer was not taken into consideration. The results of analysis of the rehabilitated dam sections using deterministic and probabilistic approaches show that the values obtained for Factor of Safety (FS) and reliability index (β) are in the acceptable range.

It is also increasingly realized that risk assessment of dams is necessary in view of the large-scale investment made and probabilistic analysis is necessary. In spite of the lack of extensive geotechnical data necessary for the probabilistic analysis, through reasonable assumptions in the probabilistic characterization of input parameters like cohesion, angle of internal friction, unit weight it is demonstrated that the probabilistic approach when used in conjunction with deterministic approach helps in providing a rational solution in terms of quantifying the safety of the dam and in the estimation of risk associated with the dam construction.

REFERENCES


