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On the Reliability–Based Safety Analysis of the Porsuk Dam

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Abstract

Dams are large hydraulic structures constructed to meet various project demands. Their roles in both the environment and the economy of a country are so important that their design and construction should be carried out with a negligibly small risk. Conventional design approaches are deterministic, which ignore variations in the governing variables. To offset this limitation, high safety factors are considered that increase the cost of the structure. Reliability-based design approaches are probabilistic in nature since possible sources of uncertainties associated with the variables are identified using statistical information, which is incorporated into the reliability models. Risk analysis with the integration of risk management and risk assessment is a growing trend in dam safety assessment. This study deals with the probabilistic evaluation of safety of gravity dams. A computer program based on the probabilistic treatment of random loading and resistance terms will be used for the safety analysis. A case study is conducted to illustrate the use of this program.

Key words: Risk analysis, Dam safety, Probabilistic safety, Monte–Carlo simulations.

Introductory Remarks

People live in an environment where there exist various risks. Balancing a variety of risks that may have technological, personnel and economic aspects is the ultimate concern of an engineer in reaching the desired goals. With lack of knowledge about risk or when these risks are in conflict with societal concerns, problems occur in risk management (Rowe, 1981). With a classical deterministic approach, very high factor of safety values are assigned and this causes high costs for the project. That is why the aim should be project optimization with respect to failure probability and project cost. A logical and systematic approach to analyzing various uncertainties involved in design and analysis is provided by the concepts and methodologies of risk-based design procedures.

Risk management is the systematic application of management policies, procedures, and practices to the task of identifying, analyzing, assessing, treating, and monitoring risk (ICOLD, 1999). The risk management process is divided into 2 categories: assessing the risk and controlling it. Risk assessment can be useful in determining the types of problems in the system and the corresponding solution approaches. The term "risk assessment" is used to describe the total process of risk analysis, which includes both the determination of levels of risk and social evaluation of risks. In risk assessment, judgments are made about taking the risk and the people in charge will be required to deal effectively with the consequences of the failure event (ICOLD, 1999). In risk estimation, loading, system response, final probabilities, and the consequences of various dam failure and no-failure scenarios are determined, so that an estimation of various consequences can be made (Bowles et al., 1998). These resulting estimates are then applied to various branches of the event tree model. Risk reduction alternatives are developed and analyzed in a similar manner for the proposed structure by changing various inputs to represent the improved performance of each alternative. The outcome of this analysis results in the calculation of the risk of failure. Fault-trees and event-trees are helpful in risk estimation.

Although the risk-based design approaches for hydraulic structures are increasingly applied, it is impossible to quantify the overall safety of a dam because of some undetected deficiencies. However, the approach to achieve maximum dam safety is well understood from the viewpoints of design, construction, operation, and maintenance. Therefore, the most important prerequisite for dam safety is the professional competence of people associated with the dam over its life span. Dam safety must take precedence over all other considerations. Therefore, the concepts have been continuously developed through time for better understanding and for more logical approaches to the design of dams. The dam safety community is still unable to reach a common decision about using risk-based approaches (Darbre, 1998) instead of classical safety concepts, e.g., the Swiss Concept (Biedermann, 1997). This paper deals with the description of a risk-based safety evaluation of concrete gravity dams. A case study will be introduced by using recently developed software, CADAM (Leclerc et al., 2004), to assess the safety level of an existing dam. This program can also be used in the reliability-based design of a concrete gravity dam by performing quick successive test runs to account for the effects of various geometric properties and loading possibilities.

Probabilistic versus Deterministic Approaches

In the application of risk, it may be recalled that the design would be made to accept failure and loss of life, or that risk assessment is a way of avoiding expensive structural repairs to a dam. In addition, it is generally thought that using risk entails quantitative risk assessment, which is a highly complex and time-consuming analysis. Conversely, many dam safety professionals think that the use of deterministic standards results in zero risk to the public. Unfortunately, this viewpoint is based on misconceptions in the engineering community about the definitions of Probable Maximum Precipitation (PMP) and the Maximum Credible Earthquake (MCE). In reality, these values are estimates of the theoretical maxima that commonly approach the theoretical upper limits.

After the appearance of risk analysis in structural safety, the community was widely curious about its relation to deterministic approaches. New risk-based approaches for dam safety make the standards and the codes better by adding the information lacking for design and operation. These two should be properly addressed in the latter. Kreuzer (2000) states that reliability indices comply with such a uniform format that uncertainty can be quantified without weakening the request for uniformity by these indices. However, they do not provide any protection against subjectivity of decisions or against human errors. That is why whenever non-quantifiable factors enter a safety assessment, risk analysis is a better approximation for more realistic results. The factor of safety in traditional design standards provides a confidence level that is widely accepted. However, uncertainty in the factors of safety is ignored, which makes the design inconsistent.

Risk analysis of dam safety fundamentally differs from traditional deterministic approaches for the following reasons (Kreuzer, 2000). Risk analysis replaces a deductive with a more inductive approach to study safety. It also addresses decision-making under uncertainty, which is fully integrated in the process of risk analysis. Furthermore, risk analysis replaces a limit-state analysis, which leads to a deterministic safety statement, through a sequential probabilistic path-to-failure process. Finally, it can be stated that risk analysis replaces fixed, single-value terms with accumulated probabilities.

Safety Analysis of Gravity Dams

The dead weight and the base width of concrete gravity dams are the governing variables that must be large enough such that overturning and sliding tendencies are overcome. The possible forces acting on concrete gravity dams are dead load, hydrostatic forces, uplift force, silt force, ice load, earthquake load, and temperature stresses, which are only important for gravity dams having grouted contraction joints. In the safety analysis, the structural safety performance of the dam is assessed with respect to overturning, sliding and shear, uplifting, and overstresses. As the dams are very large structures, the modeling of earthquake forces is of importance in their safety analysis. Earthquake forces may be modeled by either Pseudo-Static seismic analysis or Pseudo-Dynamic analysis.

Pseudo-Static Analysis

In this analysis, the inertia forces induced by the earthquake are computed as the product of the dead weight of the dam and the earthquake acceleration. The dynamic amplification of inertia forces along the height of the dam, due to its flexibility, is neglected. Earthquake force on the dam body (dam inertia), Q, is computed from

$$Q = kD \tag{1}$$

where k is the effective peak ground acceleration coefficient and D is the total weight of the dam. The added horizontal hydrodynamic force H_d(y) increasingly follows a parabolic distribution for an assumed rigid gravity dam with vertical upstream face (Leclerc et al., 2001).

$$H_d(y) = \frac{2}{3} K_\theta C_e k_h \sqrt{h}(y^{1.5}) \tag{2}$$

where H_d(y) is the additional total hydrodynamic horizontal force acting above the depth y for a unit width of the dam, k_h is the horizontal seismic acceleration coefficient applied at the base of the dam expressed in terms of peak ground acceleration or spectral acceleration (fraction of gravitational acceleration), h is the depth of the reservoir, y is the distance below the reservoir surface, C_e is a factor depending principally on the depth of water and the earthquake vibration period characterizing the frequency of the applied ground motion, and K_θ is the correction factor for the sloping dam faces with angle θ from the vertical. To compute the horizontal force, $K_{\theta H}=\cos^2\theta$ can be used as a first approximation, while the vertical force can be estimated from $K_{\theta V}=\sin\theta\cos\theta$. The Westergaard approximation for the C_e coefficient is

$$C_e = \frac{7.99}{\sqrt{1 - 7.75\left(\frac{h}{1000 t_e}\right)^2}} \tag{3}$$

in which the denominator is a correction factor in kN.s.m to account for water compressibility, and t_e is the period to characterize the seismic acceleration imposed on the dam in seconds.

Pseudo-Dynamic Analysis

In Pseudo-Dynamic analysis, the maximum response due to the fundamental mode of vibration is represented by equivalent lateral forces and is computed directly from the earthquake design spectrum without a response history analysis. The effects of dam-foundation-rock interaction and of reservoir bottom materials, in addition to the effects of dam-water interaction and water compressibility, are included in this simplified analysis of the fundamental mode response. The equivalent lateral forces associated with higher vibration modes, which are computed by a static correction method, are also included. This correction method is based on the assumptions that (Chopra, 1988) the dynamic amplification of the modes is negligible; the interactions among the dam, impounded water and foundation rock are not significant; and the effects of water compressibility can be neglected. In Pseudo-Dynamic analysis, the dynamic amplification of the inertia forces along the height of the dam is recognized but the oscillatory nature of the amplified inertia forces is not considered.

A few parameters are required in the simplified analysis procedure to describe the dam-water-foundation rock system: E_s (Young's modulus of elasticity of the structure), ξ_1 (viscous damping ratio which can be taken as 5%), H_s (the height of the dam from base to the crest), and η_f (constant hysteretic damping coefficient of the foundation rock, which can be taken as 0.10 in the absence of information on damping properties of the foundation rock). The computation of earthquake response of the dam is organized in 4 parts (Chopra, 1988): earthquake forces and stresses due to the fundamental vibration mode, earthquake forces, and stresses due to the higher vibration modes, initial stresses in the dam due to various loads, and total stresses in the dam.

In order to complete the Pseudo-Dynamic analysis, the spectral acceleration ($S_a(\tilde{T}_1, \tilde{\xi}_1)$) or, in other words, the pseudo-acceleration ordinate of the earthquake design spectrum at period $\tilde{T}_1$ and damping ratio $\tilde{\xi}_1$ should be determined as a function of earthquake characteristics. If a response spectrum is not available for the site under investigation, then theoretical or design formulations are needed in order to obtain the spectral acceleration coefficient. In Turkey, the Ministry of Public Works and Settlement has provided a specification called "Specification for Structures to be Built in Disaster Areas". Determination of the spectral acceleration coefficient corresponding to 5% damped elastic design acceleration spectrum is presented as follows (RTMPWS, 1997):

$$A(T) = kIS(T) \quad (4)$$

where A(T) is the spectral acceleration coefficient, and k is the effective horizontal ground acceleration coefficient. The values for this coefficient depend on the seismic zones. In Turkey, k values are 0.4, 0.3, 0.2, and 0.1 for the first, second, third, and fourth seismic zones, respectively, I is the building importance factor, which is 1.5 for power generation and distribution facilities (RTMPWS, 1997), S(T) is the spectrum coefficient, which is given as

$$S(T) = 1 + 1.5T/T_A \quad (0 \leq T \leq T_A) \quad (5)$$

$$S(T) = 2.5 \quad (T_A \leq T \leq T_B) \quad (6)$$

$$S(T) = 2.5 \quad (T_B/T)^{0.8} \quad (T > T_B) \quad (7)$$

in which T is the building natural period, and T_A and T_B are the spectrum characteristic periods (RTMPWS, 1997).

Probabilistic stability analysis of gravity dams may be carried out by executing a recently developed software named CADAM (Leclerc et al., 2004). It performs the analysis of a single 2-dimensional monolithic gravity dam-foundation reservoir system subdivided into lift joints. It assigns lift joints with their relevant features and specifies drain location and its effectiveness. The program accounts for the effects of post-tension cables. In the safety evaluation, the Pseudo-Static and Pseudo-Dynamic analyses are performed. The possibility of cracking is also checked. Five load combinations, i.e. normal operating, flood, seismic-1 (Pseudo-Static analysis), seismic-2 (Pseudo-Dynamic analysis), and post-seismic, are considered. Estimation of the probability of failure of a dam-foundation-reservoir system is carried out using the Monte-Carlo simulation. It is based on the generation of random numbers for probability of failure, which include the uncertainties in loading and strength parameters in an implicit manner.

Case Study

This study deals with the probabilistic safety analysis of an existing concrete gravity dam in Turkey. The Porsuk Dam is selected as a study model. It is a concrete gravity dam, situated on the Porsuk Stream, a tributary of the Sakarya River, 25 km southwest of Eskişehir. It is used for irrigation, flood control, and domestic and industrial water supply. Most of the inputs and properties of the Porsuk Dam are presented in Table 1. Apart from the available data for the software to be run, some of the inputs are obtained by combining the available data with the related information present in other references. This study is specifically carried out in order to assess the difference between deterministic and risk-based approaches. In conventional deterministic approaches, safety factors are calculated using forces and moments from the assigned dimensions. As long as the minimum requirements of safety factors are satisfied, the effect of further increases in safety factors on the overall stability cannot be assessed on a rational basis. A more realistic evaluation of safety can be achieved using the concept of probability of failure, which can be obtained through a probability-based method.

The probability distribution of reservoir water levels should be estimated. The relevant data are obtained from the DSI (2004). A chi-square test is applied to check the goodness of the probability distribution function (PDF) assigned. There are 60 available items of water elevation data, which are obtained from the monthly operation of the reservoir. Frequency analysis is performed by ignoring some data according to the outlier test proposed by the US Water Resources Council (1981). In the analysis, the outlier test is performed for the 10% significance level, whereas the confidence level is chosen as 95% for the chi-square test. After the outlier test is performed, 3 items of data are discarded. Thus, the normal probability distribution function is fitted to 57 data items out of 60. According to the calculations, the standard deviation of the fitted normal distribution function is obtained as 1.706 m. The normal operating level is proposed to be 45.6 m (Seçkiner, 1999). Therefore, this value is used as the mean of the upstream water elevations for probabilistic analyses.

Table 1. Input data for stability analysis of the Porsuk Dam.

Characteristics	Value
Height (from river bed)	49.70 m (Orhon et al., 1991; DSI, 1998)
Elevation of river bed	844.65 m (Orhon et al., 1991)
Crest elevation	894.35 m (DSI, 2004)
Upstream face slope, n	0.00 (Seçkiner, 1999)
Downstream face slope, m	0.85 (Seçkiner, 1999)
Depth of normal reservoir level (H_n)	45.60 m (Seçkiner, 1999) (This will be used in CADAM as the mean upstream water elevation)
Depth of maximum reservoir level (H_m)	48.20 m (Seçkiner, 1999)
Crest thickness (T_c)	4.50 m (Seçkiner, 1999)
Bottom width (B)	39.4 m (Orhon et al., 1991)
Tailwater depth	6 m (Seçkiner, 1999)
Specific weight (concrete)	24 kN/m^3 (Seçkiner, 1999)
Submerged specific weight of sediment	11 kN/m^3 (Seçkiner, 1999)
Height of sediment accumulation	3 m (Seçkiner, 1999)
Angle of repose of sediment	31° (Seçkiner, 1999)
Geological formation of foundation	Peridotite (Orhon et al., 1991)
Horizontal peak ground acceleration	0.30g (RTMPWS, 1997)
Vertical peak ground acceleration	0.20g (Newmark, 1973)
Ice thickness	0.52 m (Seçkiner, 1999)
Rate of temperature increase	2.8 °C (Seçkiner, 1999)
Ice load per unit length	100 kN/m (Thomas, 1976)
Uplift reduction coefficient	0.6 (Seçkiner, 1999)
Drain position and elevation	3.54 m from heel ; 16.85 m (Orhon et al., 1991)
Angle of internal friction	55° (peak) (Leclerc et al., 2001 ; CDSA, 1995) 45° (residual)
Allowable compressive stress in concrete	3750 kN/m^2 (Seçkiner, 1999)
Allowable compressive stress at foundation	4000 kN/m^2 (Seçkiner, 1999)
Allowable shear stress at foundation	1500 kN/m^2 (Seçkiner, 1999)
Compressive strength of concrete	30 MPa (Analysis Committee, 1971)
Cohesion	931 kPa (Leclerc et al., 2001)

As the software CADAM can calculate the stability and reliability against seismic action, the input for horizontal and vertical peak ground accelerations are needed. The Porsuk Dam is located in the second seismic zone (GDDAERD, 2004; MTA, 2004). After the related horizontal peak ground acceleration is obtained (RTMPWS, 1997), the vertical peak ground acceleration is determined by the relation given by Newmark (1973), who states that the vertical to horizontal ratio of the earthquake acceleration is 2/3. Since the horizontal peak ground acceleration is 0.3g, the vertical peak ground acceleration becomes 0.2g.

A suitable spectral acceleration coefficient is also assigned, which is needed for the Pseudo-Dynamic analysis. There are 2 possible sets of data to be analyzed in CADAM. Thus, the case study contains these sets. In order to have a spectral acceleration coefficient, earthquake data should be obtained from the available data, so that the response spectrum can be drawn and the needed spectral acceleration coefficient can then be obtained. However, there are no such data for the Porsuk Dam site close to Eskişehir province. That is why the data of an earthquake, with similar properties that may occur in Eskişehir, are found in a database containing earthquake records (PEER, 2000). This earthquake has almost all the properties of a possible earthquake that may occur in the Porsuk Dam area. Distance to the nearest fault is estimated to be approximately 10 km (GDDAERD, 2004; MTA, 2004). The geological formation is detected as A Rock (Geomatrix, 2000). Horizontal peak ground acceleration is determined as 0.3g (RTMPWS, 1997). Earthquake magnitude is estimated to be between 5.9 and 6.2 (Wells and Coppersmith, 1994). Using this information, the most likely earthquake is determined as the Whittier Narrows Earthquake, which occurred in the USA on 1 October 1987 (Figure 1). Two other items of data that are needed to find the spectral acceleration coefficient are the fundamental vibration period of the dam, $\tilde{T}_1$, and the damping ratio of the dam, $\tilde{\xi}_1$, which are obtained as 0.163 s and 0.132, respectively. In the PEER database, no earthquake spectrum for a damping ratio of 13% is available, whereas it is given for 10% and 15% (PEER, 2000). Thus, the weighted average of the 2 spectral acceleration coefficients corresponding to these damping ratios is calculated. As can be seen from Figure 1, the horizontal spectral acceleration for the damping ratios of 10% and 15% are 0.494g and 0.449g, respectively. Thus, the spectral acceleration coefficient for the first set of data is 0.465g. According to the specifications of the Ministry of Public Works and Settlement (RTMPWS, 1997), the following values are taken: k = 0.3, I = 1.5, and S(T) = 2.5, to result in A(T) = 1.125g (second data set).

The random variables should be defined in CADAM for the probabilistic analyses. There is limited information in the literature concerning the uncertainties of resistance and loading variables. The uncertainties required in safety analyses, which are expressed in terms of coefficients of variation and the corresponding PDFs, are presented in Table 2 with reference to previous studies reflecting reliability-based analyses of some hydraulic structures, e.g., Yanmaz (2003). There are several more random variables that can be assigned into probabilistic analysis, namely residual cohesion, residual friction coefficient, reservoir flood level, silt elevation, silt volumetric weight, floating debris, and last applied external force. However, there are no available probabilistic data for all these variables. That is why residual cohesion, residual friction coefficient, silt elevation, and silt volumetric weight are regarded as deterministic variables (Table 1).

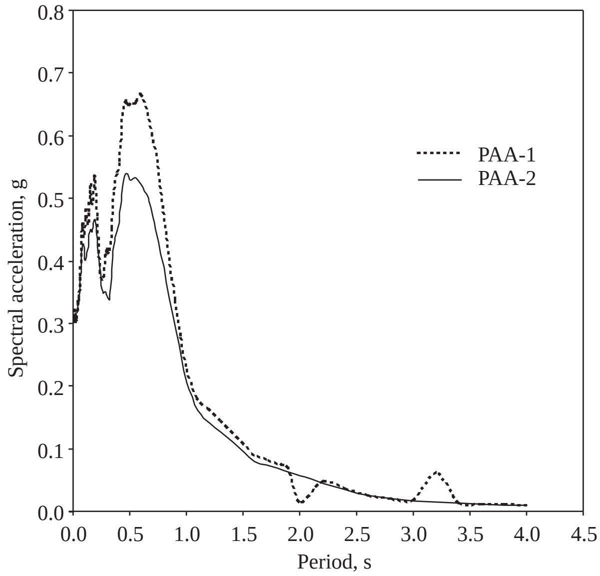

Figure 1. Whittier Earthquake - spectral acceleration.

Discussion of Results

The load parameters, inputs including the geometry report, and the results are available within the program after it is executed. In the case study, 2 sets of input data are entered into CADAM and the results are investigated. The only difference between these sets is in the spectral acceleration coefficient, which is 0.465g for data set 1 and 1.125g for data set 2. These values are used in the Pseudo-Dynamic analysis.

In Monte-Carlo analysis, the number of simulation cycles, i.e. the number of trials to generate random numbers, influences the level of reliability. The number of cycles required in a Monte-Carlo simulation to determine the exact reliability must be large in order to obtain a significant sampling of simulation events. The accuracy of the mean risk under a particular simulation cycle may be estimated by the coefficient of variation of failure probability, δ_f, which decreases with increasing sample size. Therefore, simulations should be carried out several times for large cycles such that the corresponding value of

Table 2. Random variables in the probabilistic analysis.

Variable	μ	σ	δ	PDF	Reference
Tensile strength (kPa)	3000	300	0.10	Normal	Ang and Tang (1990)
Peak cohesion (kPa)	931	46.5	0.05	Normal	Present Study
Peak friction coefficient	1.428	0.057	0.04	Normal	Ang and Tang (1990)
Normal operating depth (m)	45.6	1.706	0.037	Normal	Present Study
Drain efficiency	0.6	0.18	0.3	Normal	Assumed
Ice load (kN)	52	15.6	0.3	Normal	Assumed
Horizontal PGA(g)	0.3	0.075	0.25	Normal	Ang and Tang (1990)

δ_f is relatively small. According to Johnson (1999), it is desirable to have $\delta_f < 0.1$. Variations of δ_f against the number of simulation cycles are shown in Figure 2. It is observed that as the number of simulation cycles increases δ_f approaches a constant value, which is approximately 0.006. Therefore, it can be considered that further increases in the number of simulation cycles would not lead to significant accuracy in the computations (Yanmaz, 2003). To this end, a 50,000-cycle is brought into the analysis (Figure 2).

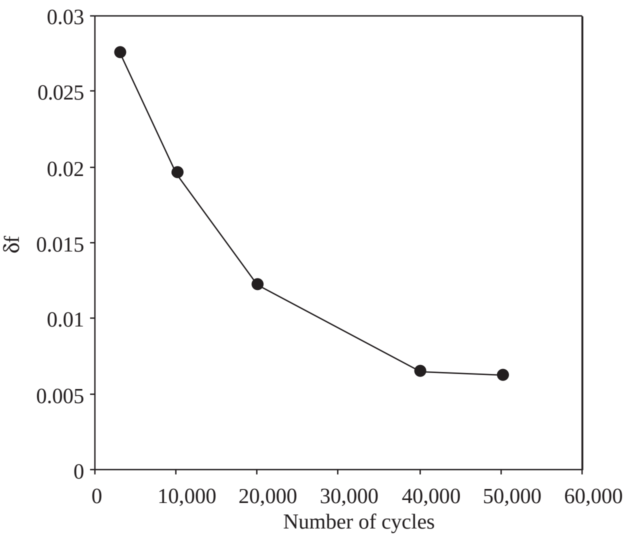

Figure 2. Variation of δ_f against the number of simulation cycles.

The forces that are considered in the usual combination are dead load, hydrostatic (upstream and downstream), uplift, silt, post-tensioning, applied external forces, and ice load. In the flood combination, the forces are as in the usual combination but instead of ice load, floating debris is considered. The forces that are considered in seismic analysis are those in the usual combination and seismic forces. The same forces are considered in the usual combination for the post-seismic combination. In this case study, there are no post-tensioning, floating debris, or applied external forces on the dam. The following paragraphs are devoted to the evaluation of the results, possible causes of failure and management of different inputs.

In the analyses with the usual and flood combinations, the seismic forces are excluded from the calculations and the dam is determined to be safe without any risk. Furthermore, the analyses of after-seismic events prove to have almost full reliability. Figure 3 presents the safety factors when Monte-Carlo simulations are run for all load combinations of data set 1 in the CADAM software (Leclerc et al., 2004). Cases of usual, flood, seismic-1, and seismic-2 load combinations are denoted as 1, 2, 3, and 4, respectively, in the abscissa of this figure. The values of probability of failure for both data sets are given in Table 3. Most of the results in Table 3 are the same, but the values of probability of failure for seismic dynamic analyses differ.

The tensile strength value is taken as 10% of the compressive strength of the material, which is taken as 30 MPa (CDA, 1999). In the analysis with seismic-1 combination, only one type of failure is determined, which is the failure because of the residual sliding safety factor. In addition, an increment in the probability of failure is observed for the overturning safety factor towards the downstream. When the

Table 3. Probability of failure values for different load combinations.

Output Parameters	Usual	Flood	Seismic-1	Seismic-2 (Data Set 1)	Seismic-2 (Data Set 2)	Post-Seismic
U/S crack length (% of joint)	0.00000	0.00000	0.00000	0.00000	0.08540	0.00000
Sliding Safety Factor (peak)	0.00000	0.00000	0.00000	0.00000	0.08540	0.00000
Sliding Safety Factor (residual)	0.00000	0.00000	0.93284	0.93856	0.99642	0.00002
Overturning Safety Factor toward U/S	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Overturning Safety Factor toward D/S	0.00000	0.00000	0.06150	0.24722	0.92276	0.00000
Uplifting Safety Factor	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

material properties are entered as inputs in CADAM, the cohesion is entered as zero in the residual shear strength window. Actually, this value can be taken up to 100 kPa if supported by tests but it is advised to consider it as zero in the absence of tests (Leclerc et al., 2001). For sliding stability, key trenches are very important. However, in CADAM, there are no definitions of these, but the angle of friction is advised to be considered as 55° for peak and 45° for residual angles of friction (CDSA, 1995).

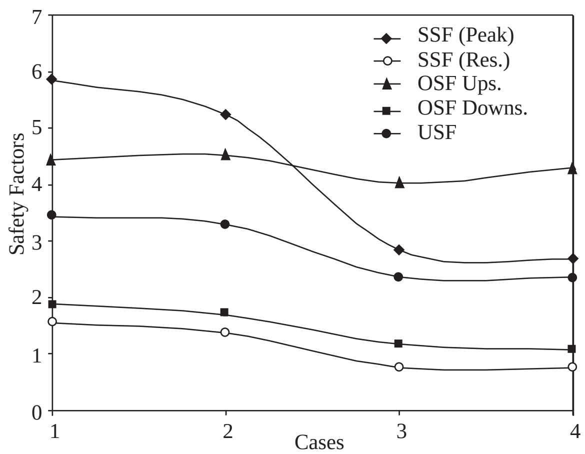

Figure 3. Safety factors for all load combinations of data set 1.

In both data sets, the horizontal spectral acceleration is very high. In addition, in data set 2, spectral acceleration is 1.125g, which is determined from the specification of the Republic of Turkey, Ministry of Public Works and Settlement (1997). When the program is executed with 1.125g in seismic-2 combination, the failure reasons are determined as residual sliding safety factor and even overturning safety factor towards the downstream (Table 3). Cracks are observed throughout the dam as well. These show that there will be 100% failure in the proposed dam if such conditions occur. With the given spectral acceleration, forces within the dam increase so high that there is no way for the dam to resist this stress. As can be seen in Figure 3, the safety factors decrease as the case changes from 1 to 4.

In risk analysis, instead of safety factors, the probability of failure is more important. In certain cases, the safety factors may be smaller than the required limiting values but keeping the reliability values relatively high. This is because of the nature and elements of the random variables, i.e. the mean, the standard deviation, and the cut-off values.

Variations in normal and uplift stresses throughout the height of the dam need to be investigated. To reduce the number of possible combinations, this analysis is only carried out for the usual loading. In the analysis of the Porsuk Dam, a reduction factor is used in the uplift force consideration because of an existing drain, which is located 16.85 m above the base. In CADAM, the uplift pressure is calculated for each joint. The uplift pressure distribution along the height of the dam at the level of joints is presented in Figure 4. The uplift force decreases rapidly at the drain level. Uplift distributions for the rest of the load combinations are the same as for the usual combination. Additional analysis is carried out to observe the variation of vertical normal stresses on both sides of the dam throughout the height of the dam. An analysis for the normal stress distribution for different loading combinations is performed in order to observe whether or not the stresses at joint levels exceed the allowable values. It should be noted that the normal stress values are adapted from the effective stress analysis. The values of the stability analysis are not considered here. Figure 5 shows the upstream normal stress distribution of data set 1. The normal stress analyses show that the usual, flood, and post-seismic combinations have compressive values within the allowable limits, i.e. 1/3 of the allowable compressive stress. When seismic-1 and seismic-2 combinations are investigated, very high tensile stresses for the upstream are observed. For both of the seismic combinations, the tensile stresses are so high that they exceed the limit value for tension, i.e. 10% of the allowable compressive stress, and may cause failure of the dam (Figure 5).

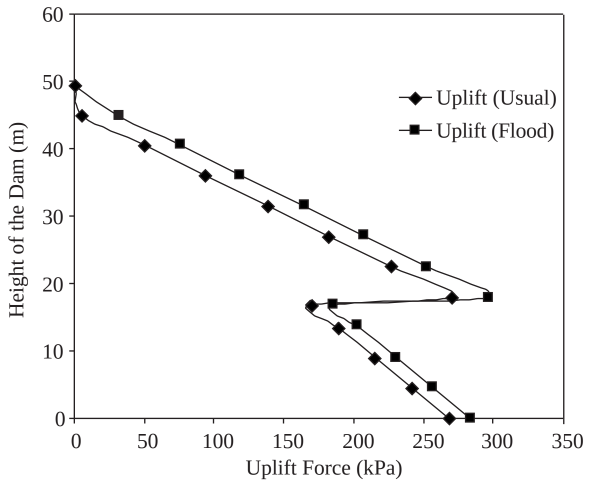

Figure 4. Uplift distribution along the height of the dam.

Sensitivity analyses are performed to observe the effect of variations in statistical information. Additional data available in the future may change the coefficients of variation of the relevant variables involved in the phenomenon. In fact, various possible combinations of PDFs and coefficients of variation should be considered. To reduce the number of possible combinations, only the following analysis is carried out. To this end, the coefficient of variation of each random variable is increased by 10%, 20%, and 30%, while the means of these random variables and the corresponding PDFs are kept constant. The analyses are run using seismic-1 load combination in CADAM because the earthquake effect is included in this combination and it is the same for both data sets 1 and 2 as the horizontal spectral acceleration is not needed. The results of sensitivity analysis, i.e. the safety factors and failure probabilities, are presented in Figures 6 and 7. Figure 6 clearly shows that all of the mean values of the safety factors increase slightly as the coefficients of variation increase. This may be due to the fact that increasing coefficients of variation would cover wider ranges of relevant variables involved in safety analysis. Results of the analysis indicate that the failure probability of the overturning towards the downstream increase, whereas the failure probability of residual sliding decrease as the coefficients of variation increase (Figure 7). Since the failure probabilities for uplifting, peak sliding, and

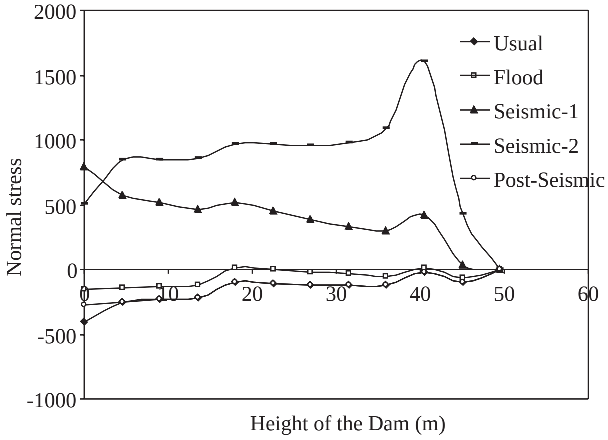

Figure 5. Upstream normal stress values of data set 1.

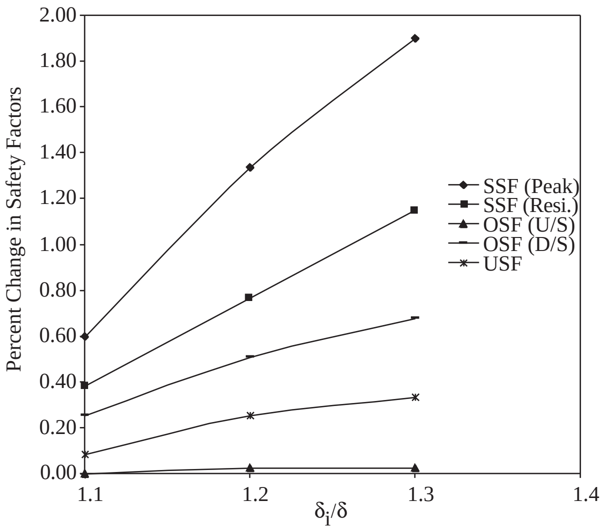

Figure 6. Percent changes of safety factors in sensitivity analysis.

overturning towards the upstream safety factors are zero, these are not included in Figure 7. As a concluding remark, an increase in the coefficients of variation does not significantly affect overall stability.

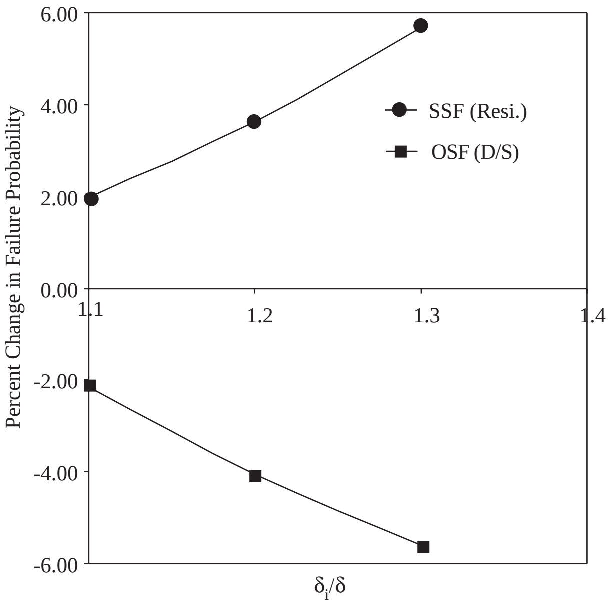

Figure 7. Percent changes of failure probabilities in sensitivity analysis.

Conclusions

There is a need to ensure that the design standards and criteria of dams meet contemporary requirements for operational and public safety as dams get older. If a dam is going to be constructed, then besides the safe-design concerns, cost concern is also an important issue. Reliability-based designs decrease the cost since risk is computed using a more realistic basis reflecting the probabilistic nature of all loading and resistance parameters. However, deterministic dam design approaches yield huge project costs since very high safety factors are adopted, which are unnecessary in most cases. This paper deals with the probabilistic assessment of the probability of failure of a concrete gravity dam under various possible failure modes. As a case study, the Porsuk Dam, which is a concrete gravity dam situated close to Eskişehir, is analyzed using CADAM software, which is based on Monte-Carlo simulations to determine the reliability. Under normal conditions, the Porsuk Dam is determined to be safe, but in the event of a severe earthquake, a high risk of failure is obtained. It should, however, be stated that the analyses are carried out for certain combinations of governing parameters. In fact, several additional scenarios can be generated to observe the variation of dam safety under almost universal conditions. As a concluding remark, the risk-based analysis of the Porsuk Dam needs to be supplemented by integrating risk management and risk assessment steps into the methodology, which is assumed to be the goal of future research.

The probabilistic evaluation of the safety of an existing dam can be achieved using related information obtained from continuous monitoring. To this end, periodic reviews of hazard determinations and safety decisions for all dams should be required, especially when safety evaluations are based on criteria less conservative than the probable maximum flood or the maximum credible earthquake. Research efforts designed to provide better bases for estimating magnitudes and frequencies of extreme floods and earthquakes, for estimating the reactions of dams to such natural hazards, and for establishing acceptable levels of risks should be continued. As there is progress in seismology, hydrology, meteorology, and the relevant databases, and as the public becomes aware of the risk concept, a review of dam safety practices and standards should be periodically formulated in this respect. It is now the time for Turkey to develop contemporary dam safety guidelines based on risk analysis and management concepts that should be prepared by authorized and experienced people.

Nomenclature

A(T)	spectral acceleration coefficient;
C_e	factor depending principally on depth of water and the earthquake vibration period characterizing the frequency content of the applied ground motion;
D	total weight of the dam;
D/S	downstream;
E_s	Young's modulus;
h	total depth of the reservoir;
$H_d(y)$	additional total hydrodynamic horizontal force acting above the depth y for a unit width of the dam;
H_s	height of the dam from base to the crest;
I	building importance factor;
k	seismic coefficient;

k_h horizontal seismic acceleration coefficient applied at the base of the dam expressed in terms of peak ground acceleration or spectral acceleration;
K_θ correction factor for the sloping dam faces with angle θ from the vertical;
MCE maximum credible earthquake;
OSF overturning safety factor;
PAA pseudo absolute acceleration (horizontal spectral acceleration);
PDF probability density function;
PMP probable maximum precipitation;
Q earthquake force on the dam body (dam inertia);
S(T) spectrum coefficient;
SSF sliding safety factor;
$S_a(\tilde{T}_1, \tilde{\xi}_1)$ pseudo-acceleration ordinate of the earthquake design spectrum;
T building natural period;
T_A, T_B spectrum characteristic periods;
$\tilde{T}_1$ fundamental vibration period of the dam including the influence of dam foundation rock interaction and of impounded water;
t_e period to characterize the seismic acceleration imposed on the dam;
U/S upstream;
USF uplifting (floating) safety factor;
y distance below reservoir surface;
δ coefficient of variation;
δ_f coefficient of variation of failure probability;
δ_i initial coefficient of variation;
η_f constant hysteretic damping coefficient of the foundation rock;
μ mean value;
ξ_1 viscous damping ratio;
$\tilde{\xi}_1$ damping ratio of the dam and
σ standard deviation.

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