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# PROBABILISTIC SAFETY EVALUATION OF A CONCRETE ARCH DAM BASED ON FINITE ELEMENT MODELING AND A RELIABILITY *L-R* APPROACH

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A b s t r a c t

The safety assessment of the Pacoima arch dam is investigated in this paper. A Load – Resistance (**L-R**) method was used to ensure that the dam is safe or if it is at risk of failure. The "probabilistic design system" ANSYS finite element software was used to calculate the probability of failure. The Monte Carlo (MC) method with 50,000 iterations utilized for simulation and the Latin Hypercube method were used for Sampling. Input random variables with normal distribution and coefficient of variation of 15% due to uncertainties were considered and the six random variables used are the concrete modulus of elasticity, Poisson's ratio of concrete, concrete mass, up-stream normal water level of the reservoir, and the allowable tensile and compressive strength of the concrete. Linear elastic behavior was assumed for the constitutive law of concrete material and if the stress exceeds the allowable stress of the concrete this is considered as a failure limit state. The maximum and minimum principal stresses were considered as the output parameter. Dam body safety was investigated only under self-weight and upstream hydrostatic pressure at the normal water level. The probability of failure of the dam body system was

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determined as $\beta^{system}$=3.98, the safety index as $p_f^{System} = 3.42\times10^{-5}$ and the dam is at risk of failure. The first and third principal stresses in the dam body were also $S1^{max} = 2.03MPa$ and $S3^{min} = 4.6MPa$ , respectively for the worst case of MC simulation.

Keywords: Monte Carlo simulation, uncertainty, Pacoima arch dam, hydro-static pressure, random variables, worst case

## 1. INTRODUCTION

A dam is one of the infrastructures of any country whose structural failure can result in significant loss of life and irreparable financial damage. The acceptable risk of failure to such structures is, therefore, much lower than that of conventional residential and industrial buildings. The real world is a world of uncertainties. Routine risk and safety assessments of dams are carried out by using the determination approach (safety factor) [27], particularly in the static analysis of dams, in which the physical and mechanical properties of the dam body materials and the hydrostatic pressure are assumed to be constant values. The probabilistic analysis approach seeks to more accurately assess the behavior of dams and has been used in many studies [1-5,7,9-17,26]. In such studies, the Probabilistic Design System (PDS) tool from ANSYS software is used to evaluate the probabilistic and reliability analysis of structures [4,6,20,24]. The ANSYS/PDS provides an efficient tool to assess the interactions, effects, and sensitivities between input parameters and output variability. However, none of the aforementioned studies looked at the reliability analysis of the concrete dams from the perspective of the physical and mechanical properties of the concrete and the up-stream hydrostatic pressure.

The purpose of this paper is a probabilistic safety assessment of a dam under usual loads including dam body self-weight and up-stream hydrostatic pressure on the dam. The ANSYS/PDS tool was utilized to perform the reliability analysis of a concrete arch dam using Monte Carlo Simulation (MCS) and Latin Hypercube Sampling (LHS). The performance criteria were defined using tensile stress. The innovational aspect of this paper is the investigation of dam safety by considering uncertainty in specific gravity, concrete strength, and upstream hydrostatic pressure. The Pacoima concrete arch dam has been selected as the case study for this paper.

## 2. A DESCRIPTION OF THE PACOIMA CONCRETE DAM

The Pacoima double-curved concrete arch dam is located in Los Angeles, California. The dam was completed in 1928 A.D and is shown in Figure 1. The Pacoima dam is 113-meters high with a crest length of 180 meters. The thickness of the dam varies from about 3m at the crest to 30m at the base of its crown cantilever. The eleven contraction joints in the dam body have beveled keys that are 30cm deep. The finite element modeling (FEM) of the dam body was done by assuming a rigid foundation and simplifying the geometry of the dam on the left abutment.

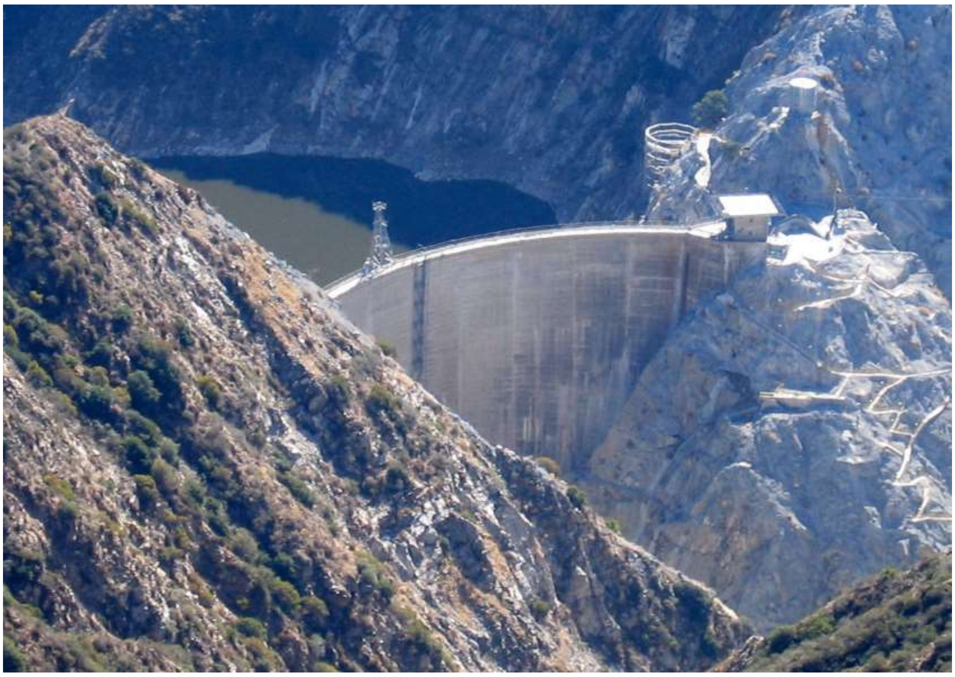

Fig. 1. View of Pacoima dam

## 3. FE MODELING AND DETERMINISTIC ANALYSIS

The dam was discretized in thickness by two layers of 8-noded brick elements $(SOLID185)$. Each node has three degrees of freedom comprised of translations in the nodal X, Y, and Z directions. 243 nodes and 104 solid elements were used in the FE model. The minimum number of elements were utilized to save computational cost. The frequency of the first symmetric mode of the dam body is obtained at 5.42 Hz with a damping ratio of 5%. The FE model degrees of freedom (DOF) is 972 of which 135 are supported DOF. Nodal displacement constraints were applied to the nodes located on the dam base and left and right abutments of the dam body. The modulus of elasticity and Poisson's ratio of mass for concrete was taken as 21.9GPa and 0.2, respectively. The mass density of the concrete is chosen as $\rho = 2230\,kg/m^3$ [8]. Loads applied to the dam include the dam body self-weight and up-stream hydrostatic pressure [18,21-23]. Thermal loading is not considered in this study. The hydrostatic pressure of the normal level of the reservoir is shown in Figure 2. The hydrostatic pressure applied to the upstream face is perpendicular to the surface of each solid element. In Figure 2, the contour of the hydrostatic pressure is visible. To verify the application of water level on the upstream, the equation of hydrostatic pressure can be controlled. By dividing the value of hydrostatic pressure at base level by $\gamma_w = 9810N$, the height of the upstream water is obtained and is equal to 90m.

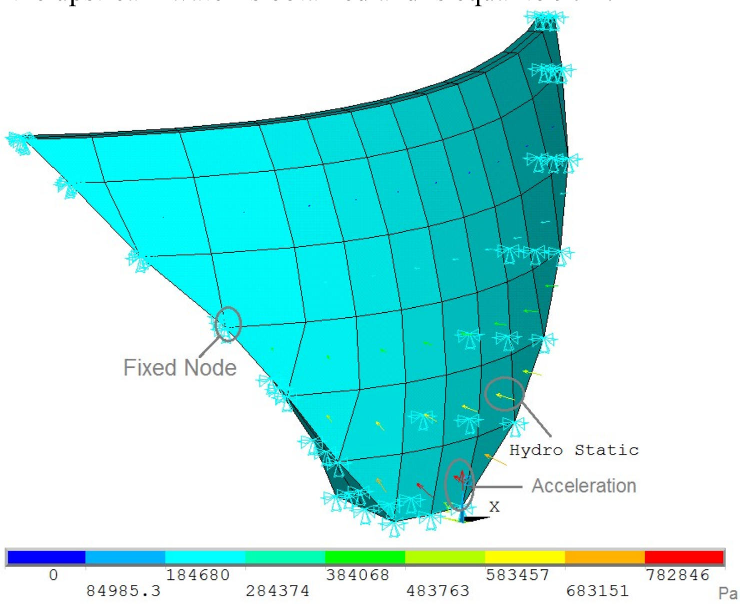


Fig. 2. Hydro-static pressure in upstream (US) face of dam body in normal water level

Next, the dam was analyzed under usual loads, dam body self-weight, and up-stream hydrostatic pressure. The dam structure is also statically analyzed. The distribution of minimum (S3) and maximum principal (S1) stress under the assumed loading is shown in Figure 3. The minimal value of principal stress $S3^{min} = -2.18$ MPa and maximum principal stress $S1^{max} = 0.94$ MPa are lower than their allowable limits, i.e. $S3^{allow-\min} = -23.39$ and $S1^{allow-\max} = 2.65$, respectively. The deterministic analysis of the Pacoima concrete dam showed that the required safety is provided for the loadings considered as usual loadings. The highest tensile stress elements are located at mid-height of the left abutment on the upstream face. The highest compressive stress elements were located at mid-height of the left abutment on the outward face.

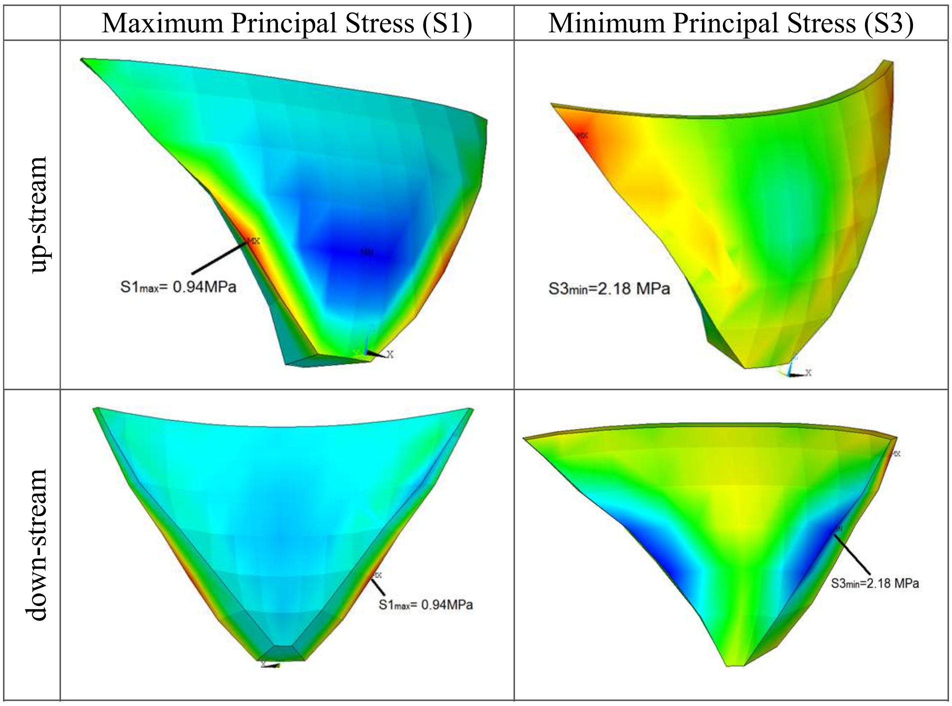


Fig. 3. Principal stress contour of the dam under usual load

## 4. DAM RELIABILITY ASSESSMENT PROCEDURE

In recent decades, structural reliability theory has been regarded as very expensive research. Monte Carlo simulation is nevertheless a suitable method for structural reliability analysis. In order to assess the reliability of the system, the Monte Carlo simulation and Latin hypercube sampling techniques were used to analyze the Pacoima arch dam. In probabilistic and reliability analysis of structures, the load-resistance model is widely used in accordance with equation (4.1) [4,9,13,15,16,20]. Both capacity and demand functions are implicit. The failure function of the system is described as Equation 4.1. Where $C(\mathrm{X})$ is the capacity of the system, and $D(\mathrm{X})$ is the structural demand due to external actions, therefore, when $GF$ is less than zero $\left(\mathrm{GF}(\mathrm{X})<0\right)$, the demand exceeds capacity, which is defined as failure. For the safety of the structure, the capacity of the system must exceed its demand $\left(\mathrm{GF}(\mathrm{X})>0\right)$, otherwise, the probability of failure using Equation 4.2 is computable. The reliability of the structure is defined by Equation 4.3.

$$GF(\mathrm{X}) = C(\mathrm{X}) - D(\mathrm{X}) \tag{4.1}$$

$$P_f = \frac{N_{GF \prec 0}}{N_{sim}} \tag{4.2}$$

$$R = 1 - P_f \tag{4.3}$$

Where $N_{SIM}$ is the number from the Monte Carlo simulation. In the design of concrete arch dams, the maximum tensile stress of the dam body must be less than its allowable stress values [18,21-23]. Dam failure is assumed to be due to cracking in the dam body. The maximum existing stress in the dam body under imposed loads should be limited to the allowable stress of its materials. Reliability analysis using Monte-Carlo simulation is done for 50000 time generations $(i:1:50.000)$. So, we have $GF_i;C_i;D_i$ instead of $GF;C;D$. The "$i$" subscription, assigned for the $i^{th}$ failure function as well as capacity and demand functions, relates to the $i^{th}$ simulation loop. In order to save computational time, the analysis is performed in batch mode. The procedure followed in the present research to assess the dam body safety level is shown by the flow chart in Figure 4.

## 4.1. Random Variables

In this paper, the parameters listed in Figure 5 are those whose epistemic uncertainties were included in the reliability study as random variables. For probabilistic analysis, it is necessary to define the resistance and load parameters (modulus of elasticity of concrete, Poisson ratio of concrete, concrete density, and up-stream hydro-static pressure), which can be seen in Table 1. The normal distribution (N) is considered for the random variables in the present study. To generate random variables with the Gaussian distribution, there is a need to define mean value $(\mu)$ and standard deviation $(\sigma)$ for each variable. The values in Table 1 are selected according to available literature [8,24]. The values of allowable tensile stresses were then calculated according to the compressive strength of the concrete and standard deviation of 15%. To simplify, the standard deviation value for all random variables was considered equal and in the reliability analysis with PDS, the confidence and significance levels were set as 95 and 2.5% respectively.

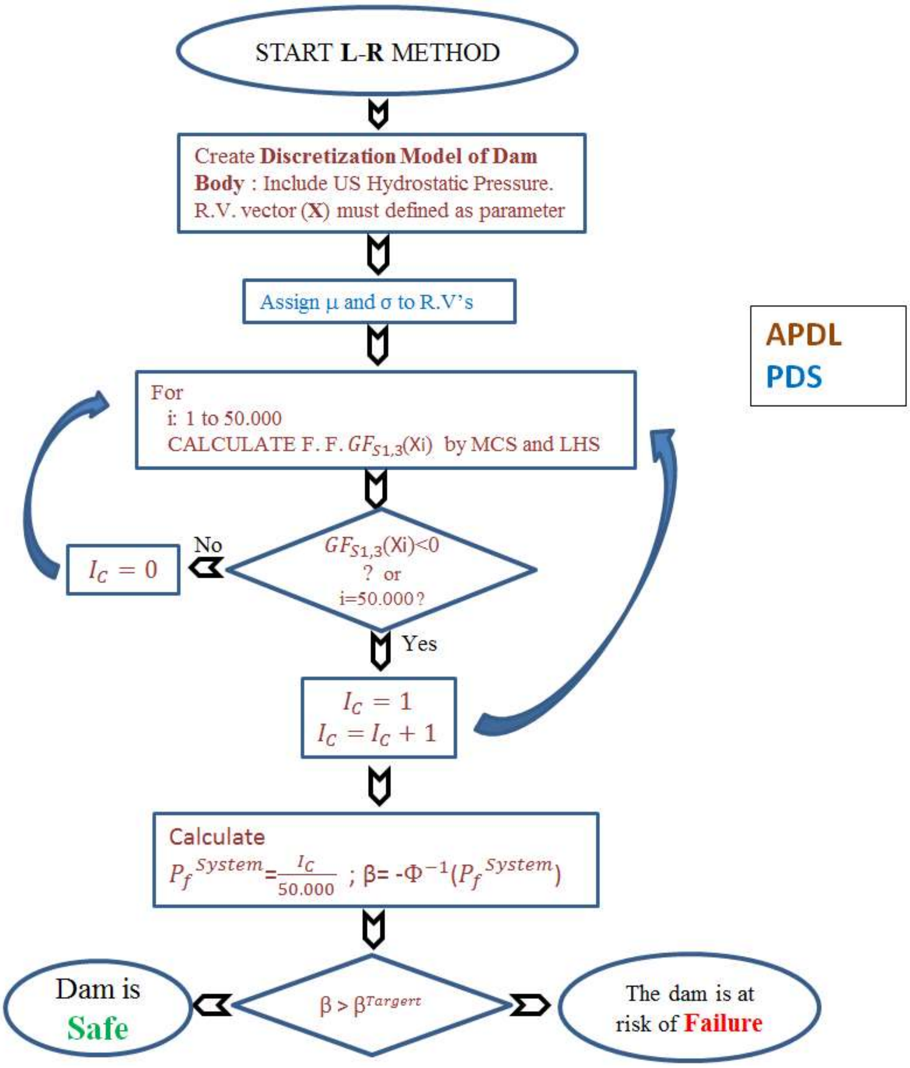


Fig. 4. Flow chart of the procedure of Reliability Analysis used in the present study

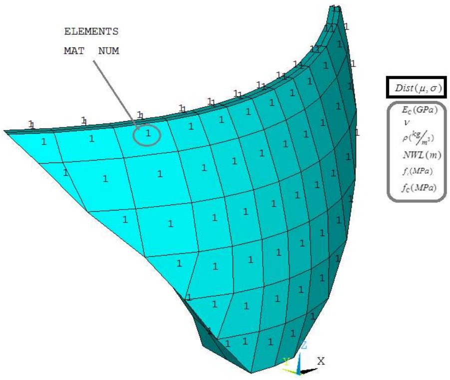


Fig. 5. Probabilistic properties assigned to Random Variables

Table 1. Random variables defined in the finite element model of the dam

| Random Parameters $X = x_1, x_2, \ldots, x_i, \ldots, x_6$ | Index | Unit | Distribution | Mean $(\mu)$ | Standard deviation $(\sigma)$ | Reference |
|---|---|---|---|---|---|---|
| Modulus of Elasticity | $E_C$ | GPa | Normal | 21.9 | 3.28 | [1,6,7] |
| Poisson Ratio | $\nu$ | - | Normal | 0.2 | 0.03 | [6] |
| Density | $\rho$ | $kg/m^3$ | Normal | 2230 | 334.5 | [3,14,27] |
| Normal Water Level | NWL | m | Normal | 90 | 13.5 | [5,26] |
| Tensile Strength | $f_t$ | MPa | Normal | 2.65 | 0.3975 | [1,3,7,24] |
| Compressive Strength | $f_C$ | MPa | Normal | 23.39 | 3.508 | [7] |

## 4.2. Limit State (LS)

Cracking in any element of the dam body was considered as a local failure mode. Crack formation due to tensile stresses at any point in the dam body is checked in terms of maximum principal stress ( $\sigma_1$ ). The tensile strength of concrete has been taken into account as a function of the compressive strength of concrete. The resistance model for principal tensile stress of materials was obtained from the formula proposed by Raphael in Equation 4.4 [18,21-23]:

$$f_t' = 0.324 \times f_c'^{2/3} \quad ; f_t', f_C' \text{ in MPa} \qquad (4.4)$$

Where, $f_C'$ is the uniaxial compressive strength of concrete. For dam concrete of $f_c' = 23.39 MPa$, allowable tensile strength would be $f_t' = 2.65 MPa$. When the principal stresses exceed allowable stresses, the cracking and crushing of concrete occur. The failure functions $(GF_{S1}, GF_{S3})$ were obtained based on limit states function in Equations 4.5 and 4.6. For $i = 1$ to $i = 50.000$, the values of $GF_{S1-i}$

and $GF_{S3-i}$ were calculated. The probability of system failure is the number of $\mathrm{GF}_{\mathrm{S1,3\_i}}(\mathrm{X}) < 0$ divided by 50.000 (total simulation).

$$GF_{S1\_i}(X) = S1_i^{allow} - S1_i^{\max} \tag{4.5}$$

$$GF_{S3\_i}(X) = S3_i^{allow} - S3_i^{\min} \tag{4.6}$$

$$P_f^{System} = P\left[P_f^{\,t} \bigcup P_f^{\,c}\right] = P\left[GF_{S1} < 0 \bigcup GF_{S3} < 0\right] \tag{4.7}$$

## 5. RESULTS AND DISCUSSION

$\mathrm{N_{sim}} = {}^{30}\!/_{\mathrm{p_f}} \sim {}^{100}\!/_{\mathrm{p_f}}$ was suggested to obtain the probability of failure. In the present study, with fewer simulations, the probability of failure was obtained and $N_{sim} = 50.000$ simulations were considered for the probability of failure computing. The simulated samples of six random variables are shown in Figure 6.

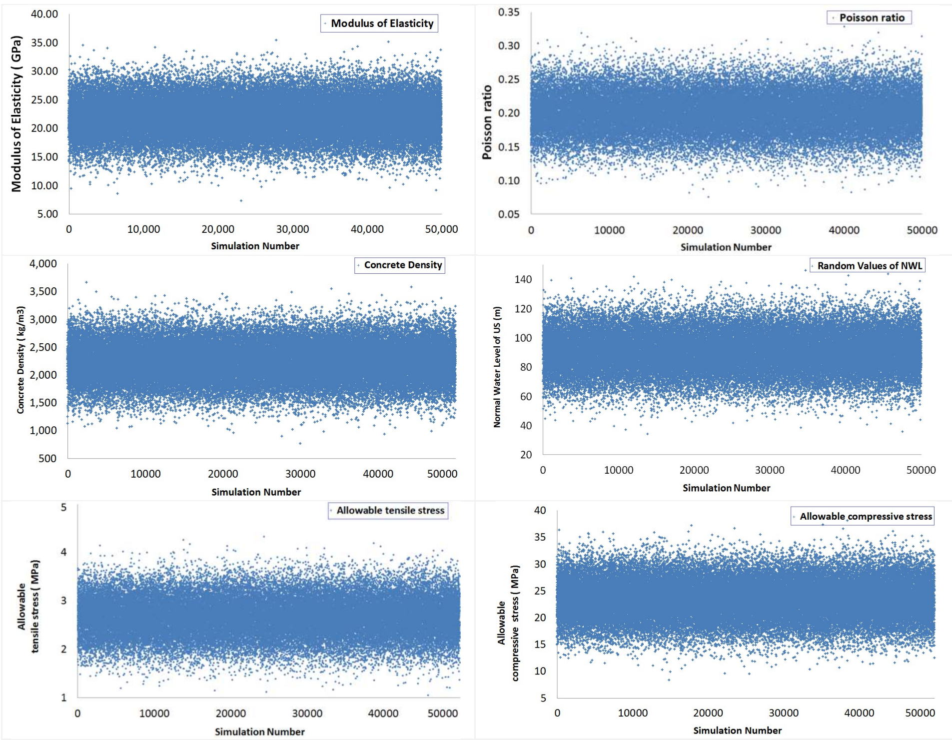


Fig. 6. Samples history of random variables

The number of cloud points in this figure is equal to the number of simulations. The results history for the maximum existing tensile stress in the dam body in each simulation loop is shown in Figure 7. The L-R model for maximum stress is shown in Figure 8. Both Load and Resistance were considered as random parameters. As shown in Figure 8, most of the resistance model samples were above the load effect samples. In Figure 9, the tensile failure function is plotted and the value of the two samples of all simulations was negative $\left(N_{GF_{S1}\prec 0}=2\right)$. In all simulation loops, minimum existing compressive stress being less than allowable compressive stress means the probability of crushing failure in the dam body was zero ($p_f^c=0$). The compressive failure function is also shown in Fig. 10 with no negative values for samples $\left(N_{GF_{S3}\prec 0}=0\right)$.

The Failure tree of the dam body system is shown in Fig. 11. Therefore, the system probability of failure and the reliability index were calculated as $p_f^{System}=3.42\times10^{-5}$ and $\beta^{System}=3.98$, respectively.

The probabilistic analysis of the Pacoima dam has shown that the required safety is not provided for the limit state and the dam body is at risk of failure. The most vulnerable elements in tensile and compressive stress were located in the left abutment at mid-height of the dam body. The worst value for tension failure function obtained was $GF_{S1}=-110943.04Pa$ for MCS number 44400. The negative value of the failure function means that cracking will occur in some elements. The first and third principal stresses for the worst case are $S1^{\max}=2.03MPa$ and $S3^{\min}=-4.6MPa$, respectively (Figures 12 and 13). Random variables in MCS number 44400 are shown in Table (2).

The annual target reliability index value recommended by the various references for concrete dams and important structures is in the range of $\left(4.2<\beta^{\mathrm{Target}}/\,\mathrm{year}<6.0\right)$ [1]. The reliability index value obtained in this study was not within this range, so the dam is at risk of failure. Cumulative Distribution Functions (CDF) of failure functions (first and third principal stresses) are shown in Figures 14 and 15.

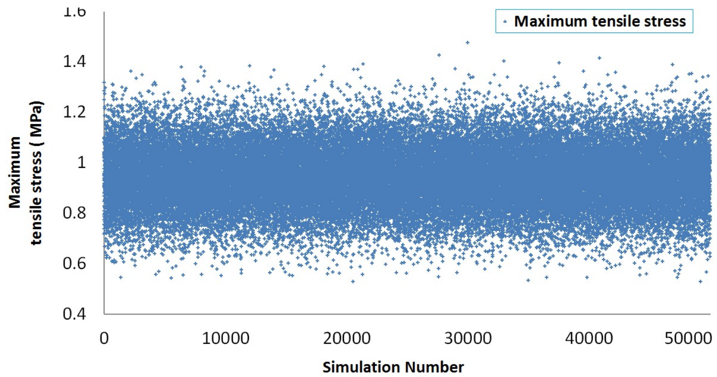


Fig. 7. Results history of load effect

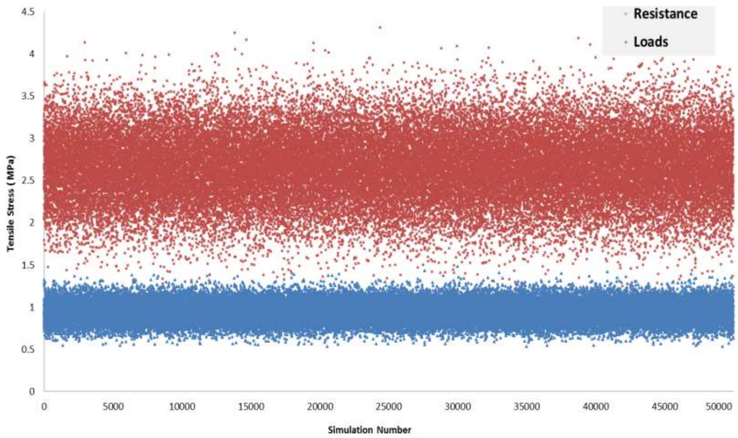


Fig. 8. Results history of load – Resistance model of dam

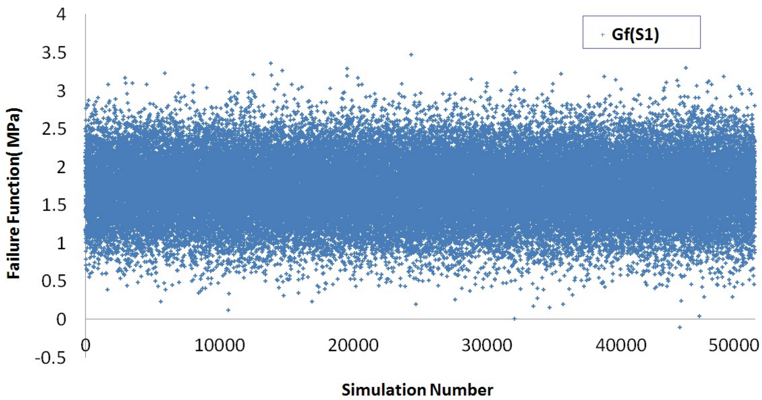


Fig. 9. Results history of tensile failure function

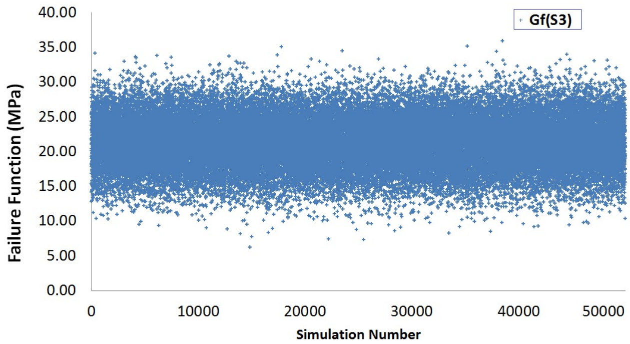


Fig. 10. Results history of compressive failure function

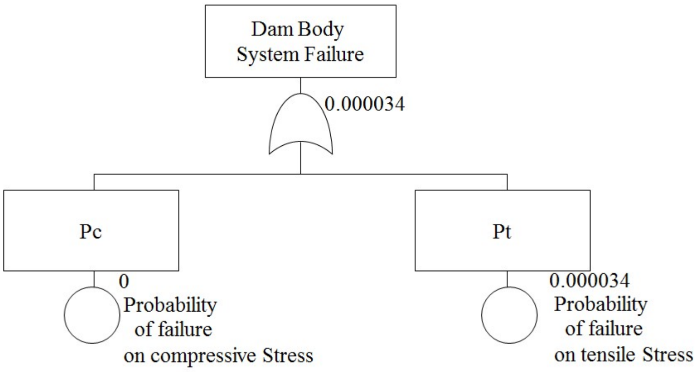


Fig. 11. Fault tree of concrete arch dam system

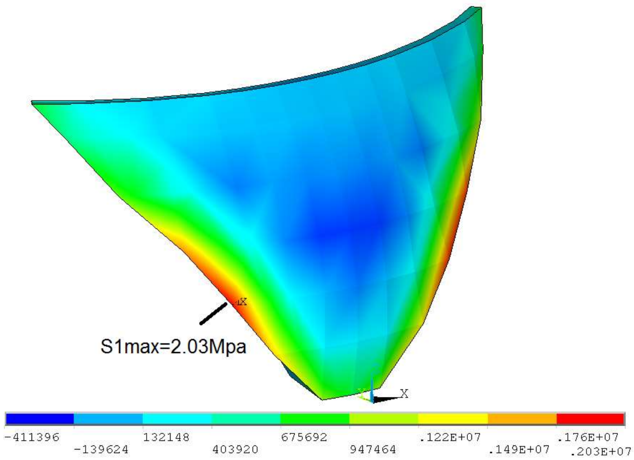


Fig. 12. Maximum principal stress of the dam US face (in Simulation number 44400)

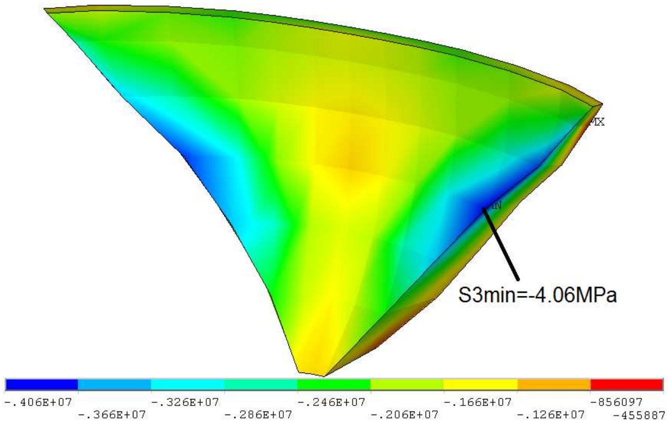


Fig. 13. Minimum principal stress of th dam DS face (in Simulation number 44400)

Table 2. Random values for variables in MCS number 44400

| Random Parameters $X = x_1, x_2, ..., x_i, ..., x_6$ | Index | Value | Unit |
|---|---|---|---|
| Modulus of Elasticity | $E_C$ | 20913967430 | Pa |
| Poisson Ratio | $\nu$ | 0.19 | - |
| Density | $\rho$ | 2096.78 | $kg/m^3$ |
| Normal Water Level | NWL | 106.39 | m |
| Tensile Strength | $f_t$ | 886251.6 | Pa |
| Compressive Strength | $f_C$ | 16724497.6 | Pa |

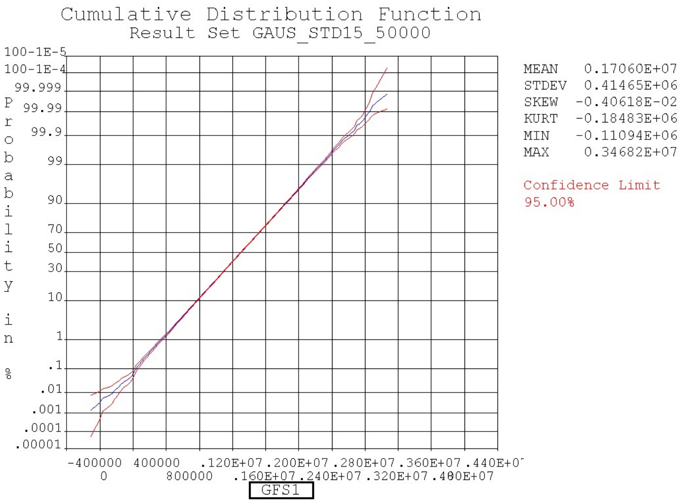


Fig. 14. CDF of Tensile Stress Failure Function

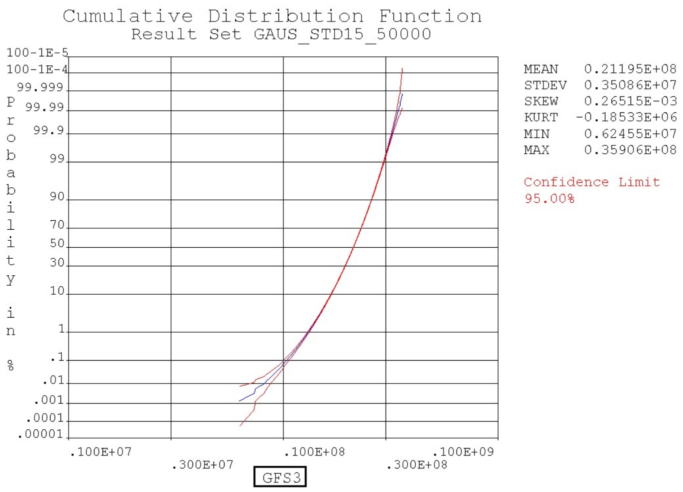


Fig. 15. CDF of Compressive Stress Failure Function

## 6. CONCLUSION

The purpose of this paper was a probabilistic safety assessment of the Pacoima arch dam under usual loading. In the structural analysis, the dam body self-weight and up-stream hydrostatic pressure were considered as usual loading and the foundation was considered rigid. A methodology to determine the reliability index of concrete dams was presented. The load-resistance method was used to calculate the probability of failure functions then, using the Gauss standard function and probability of failure, the reliability index was obtained. To ensure the dam is safe, the Reliability Index must be larger than the Target Reliability Index. A normal distribution and a coefficient of variation of 15% were chosen for the production of the random variables. In the deterministic analysis of the Pacoima dam, safety was confirmed, while in the probabilistic analysis, the dam was at risk of failure. This failure presented as cracking of the left abutment elements at the mid-height of the dam body. These are the most vulnerable regions of the dam. The worst value for the tension failure function obtained was $GF_{S1} = -110943.04\text{Pa}$ for MCS number 44400. Maximum and Minimum stresses were $S1^{max} = 2.03\text{MPa}$ and $S3^{min} = -4.6\text{MPa}$, respectively. The negative value of the failure function means that cracking will occur in vulnerable areas. The probability of failure was obtained by Monte Carlo simulation of value $p_f^{System} = 3.42\times10^{-5}$ ($\beta^{System} = 3.98$). The Reliability index of the Pacoima Dam is lower than the recommended Reliability index of $\beta^T = 4.2$. It is clear that the dam safety margin under the combination of its self-weight and the reservoir hydrostatic pressure loads is insufficient. Therefore, the Pacoima Dam is at risk of failure under the assumed conditions. From the results of the statistical study, important decisions must be made regarding retrofitting the dam so long as the reliability index of the dam reaches the target confidence level.

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