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Original Research Article

RELIABILITY ASSESSMENT AND SENSITIVITY ANALYSIS OF CONCRETE GRAVITY DAMS BY CONSIDERING UNCERTAINTY IN RESERVOIR WATER LEVELS AND DAM BODY MATERIALS

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Abstract

An elaborate safety assessment of the Pine Flat (PF) concrete gravity dam (CGD) has been conducted in this paper. Structural analysis was performed by taking into account the uncertainties in the physical and mechanical properties of the dam body materials and the reservoir water level. The coefficient of variation of 5 and 10 percent and the Gaussian distribution (GAUS) are assigned to random variables (RVs). Sensitivity analysis (SA) of the RVs is done, and important parameters introduced. SA is done to identify the most influential RVs on the structural response. Also, the modulus of elasticity of concrete is the most effective parameter in response to horizontal deformation of the dam crest. The concrete density and US hydrostatic pressure height are the most effective parameters, and the Poisson's ratio is the insignificant parameter on the dam response. To be confident in the safety of the dam body under usual loading, including the dam weight and the upstream (US) hydrostatic pressure, the reliability index (RI) has been obtained by Monte Carlo simulation. The RI for the coefficients of variation of 5 and 10 percent were obtained at 4.38 and 2.47, respectively. If the dispersion of RVs is high, then the dam will be at risk of failure.

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1. INTRODUCTION

In this research, the analysis of the concrete PF dam body was carried out considering the epistemic uncertainties in reservoir water level and the physical and mechanical properties of the dam body material. Probabilistic safety analysis leads to more realistic results than deterministic analysis (DA) of structures. This is due to the randomness of the inherent nature of the structural strength and the loads applied to the structure. Much research has been conducted on the probabilistic-based analysis of concrete dam structures [2,3,10,12,13,15-17,30]. One of the most widely used methods in reliability analysis is the Monte Carlo simulation (MCS). This method is very accurate despite the high required computational time (CT) for the analysis. The MCS method is used in the references [3,6,11,16,17,21,30-33] to assess the probabilistic safety of concrete dams. In some studies, the evaluation of the failure functions (FF) has been obtained by analytical formulation [3,6,16,18,32,33] and in others; the finite element (FE) analysis method has been used [5,7,10,13-15,17,25,26,29,30]. Different FF have been assigned to the safety assessment of concrete gravity dams as a system in various investigations [3,9,10,11,15-17,25,32]. ANSYS is a powerful Multiphysics simulation software that has a PDS (Probabilistic Design System) toolbox which provides probability-based analysis and SA for the users [22,29]. In this paper, the PF CGD reliability assessment is done by utilizing the PDS toolbox and MCS method for the first time. An introduced procedure for the probabilistic safety assessment of concrete gravity dams based on the Bayesian framework is presented that will be useful to dam analysts.

2. THE PINE FLAT CGD DESCRIPTION

The dam studied in this paper is a PF CGD. The dam is located in the US state of California. Construction of the dam began on the Kings River in 1947 and completed in 1954. The downstream view of the CGD is shown in Figure 1. The dam is made of 37 monoliths. The structural height of the highest monolith and crest length of the dam are 122 and 550 meters, respectively. The highest non-overflow crown cantilever section of the dam is shown in Figure 2(Left). A case study of probabilistic safety evaluation and SA was performed on the highest non-overflow crown cantilever of this dam.

Fig. 1. Downstream View of the Pine Flat CGD

3. FINITE ELEMENT MODELING AND DA

Finite Element (FE) Modeling is widely used in various types of analysis by numerous researchers and engineers worldwide. The Mechanical ANSYS program, a general-purpose FE code, is widely used in civil engineering structural analysis applications [7, 23-30]. The PF dam body model with a 122m high non-overflow section is simulated as a two-dimensional FE model. A numerical model is created in the software ANSYS Mechanical APDL (ANSYS Parametric Design Language). The dam base, fixed against translation, is considered as an FE boundary condition. The hydrostatic pressure was defined according to a water level of 116.2m, as shown by a red arrow in Figure 2(Right). The hydrostatic pressure of the water on the US face was assigned as shown in Equation 3.1. where γ_{ω} is the specific weight of the water and h is the height of the reservoir [19].

$$P_{hs} = 0.5\gamma_{\omega}h^2 \tag{3.1}$$

The discretization of the dam body was done using 192 isoparametric 4-noded quad elements. The two dimensional 4-node structural solid element (PLANE182) is defined by four nodes having two degrees of freedom at each node: translations in the nodal x and y directions. Plane stress is defined for quad element behavior by considering 0 for KEYOPT(3)[19]. Linear elastic behavior is considered for material behavior. The mechanical and physical properties assigned to the dam body concrete material are listed in mean values in Table 1(μ values). The defined load combination includes the dam body self-weight and the US hydrostatic pressure, each with a load factor of 1 $(StUnusual = SelfW + US\_HySt)$. The run time for FE discretization, hydrostatic loading, applying boundary conditions, and deterministic static analysis by reading written macro is approximately 2 seconds (Laptop Specifications: ASUS N551, i7-4720HQ CPU@2.60GHz, RAM:8GB). In DA, all material properties and loading parameters were considered as constant values. The DA results are shown in Figure 3. The maximum tensile stress, minimum compressive stress, and crest horizontal deflection values in the DA analysis are obtained as $S_{1\max} = 1.27MPa; S_{3\min} = 2.1MPa$ and $U_x = 0.84cm$, respectively. Allowable values for tensile stress, compressive stress, and crest deflection are $S_{1\max} = 2.4MPa; S_{3\min} = 30MPa$ and $U_x = 1.2cm$, respectively[1,17,33].

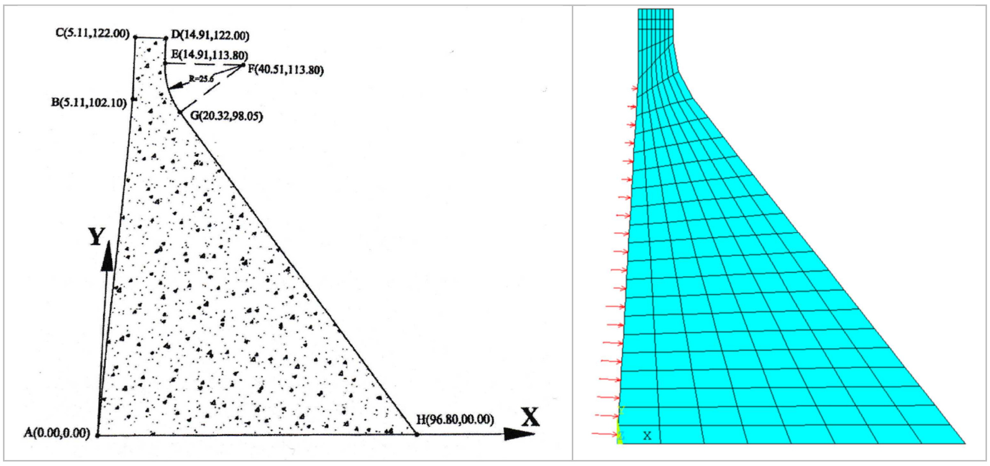


Fig. 2. Non-overflow crown cantilever: Cross-section geometry (left) and Hydro-static pressure in the US face in normal water level (right)

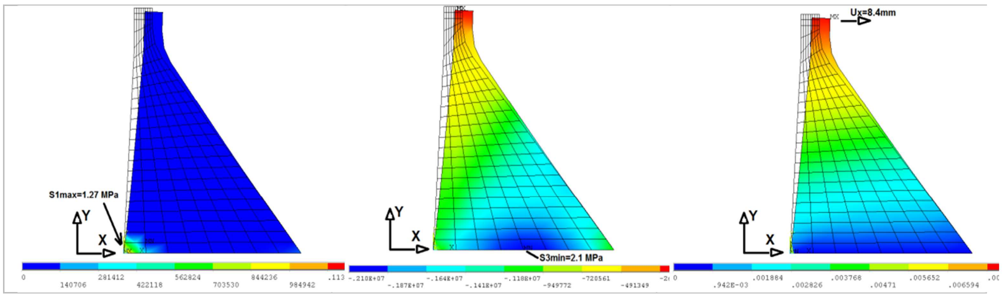


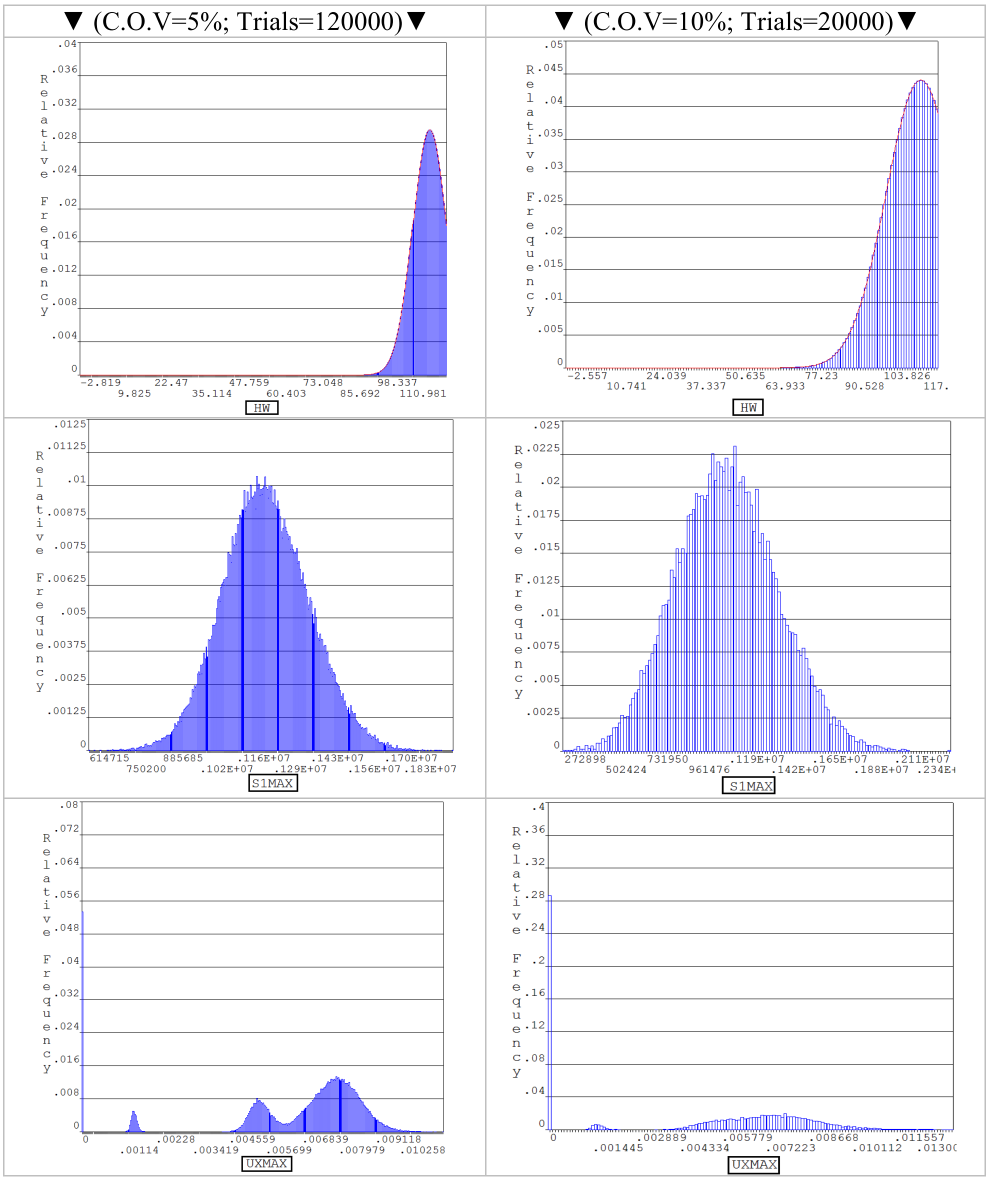
Fig. 3. DA results: Maximum tensile stress (left), Minimum compressive stress (middle), and Crest horizontal deflection (right)

4. **RVS DESCRIPTION**

In the present study, seven parameters related to the physical and mechanical properties of concrete, concrete material resistance, allowable deflection of dam crest, and applied pressure on the US face are considered randomly, as shown in Table 1. The Gaussian shape is considered for random parameters except for first parameters. The truncated Gaussian shape was adopted for random parameters of the US Water Level. To generate RVs with the Gaussian distribution shape, there is a need to define mean value (μ) and standard deviation $(\sigma_{5\%};\sigma_{10\%})$ for each variable. The coefficient of variation of 5 and 10 percent is considered for the statistical nature of RVs and the values in Table 1 are selected according to technical literature. Random parameters must be defined in the PDS toolbox of ANSYS software. In the probabilistic analysis (PA), confidence and significance levels were set as 95% and 2.5%, respectively. MCS of 120000 and 20000 are considered for the coefficient of variation of 5 and 10 percent, respectively. Histograms of various random parameters are as shown in Figure 4 and the histogram of the first variable (H_W) has achieved a truncated bell-shaped due to the limitation in the non-overflow section of the dam height. Both the allowable and existing implicit RV histogram shapes $(f_t;f_C;U_{Crest})$ are multimodal.

Table 1. RVs defined in finite element model of the dam

Random Parameters $\mathrm{X} = x_1, x_2, \ldots, x_i, \ldots, x_7$	Index	Unit	DA	PA			
				PDF parameters			
				PDF	μ	$\sigma_{5\%};\sigma_{10\%}$	Ref.
US Water Level	$\mathbf{H_W}$	m	116.2	TGAU	116.2	5.81; 11.62	[2,14,15,16]
Poisson Ratio	NOO-DAM	-	0.2	GAUS	0.2	0.01; 0.02	[1,2]
Density	DEN_Dam	kg/m^3	2436	GAUS	2436	122;244	[1,3,20,30]
Elasticity Modulus	Ex_Dam	GPa	22.98	GAUS	22.98	1.15;2.3	[10,15]
Allowable Tensile Strength	f_t	MPa	1.2	GAUS	1.2	0.06;0.12	[1,33]
Allowable Compressive Strength	f_C	MPa	30	GAUS	30	1.5;3	[25]
Allowable Crest Deflection	UCre.allow	cm	1.2	GAUS	1.2	0.06;0.12	[2,17]



▼ (C.O.V=5%; Trials=120000)▼

▼ (C.O.V=10%; Trials=20000)▼

Fig. 4. Histogram of RVs with $C.O.V. = 5\% and 10\%$

5. FAILURE MODES AND RELIABILITY ASSESSMENT

Three Failure modes were considered for the PF concrete gravity dam as shown in Figure 5. The dam FF are assumed to be independent [4,25,26]. The three limit states are shown as components of the dam system, which are in series, however, the occurrence of each alone leads to the failure of the dam system. This assumption is for simplification. The mean value of the drift capacity has been taken as being equal to 0.02%, which is considered appropriate for very stiff structures such as concrete gravity dams [17]. In the present paper, drift capacity is considered to be a factor of 0.5 due to static usual load combination. In order to establish the PA of the dam system, MC simulation and Latin hypercube sampling (LHS) methods are utilized. The Load-Resistance method was utilized for the probabilistic assessment of the PF dam [7,10,14-17,21,25, 26]. The FF of each component of the dam system is described as Equation 5.1. where $C(\mathrm{X})$ is the capacity of the dam system, and $D(\mathrm{X})$ is the structural demand of the dam system due to self-weight and external actions. Therefore, when GF_i is less than zero $\left(GF_i(\mathrm{X}) \prec 0\right)$, the demand exceeds the capacity and system failure occurs. For the safety of the dam system, dam capacity must be larger than its demand $\left(GF_i(\mathrm{X}) \succ 0\right)$, otherwise, the probability of system failure using Equation 5.2 is computable. Safety Index (RI) and Reliability for the dam system are defined by Equations 5.3 and 5.4, respectively. The annual target RI value recommended by the various references for concrete dams and important structures is in the range of about 4.2-6 $\left(4.2 \prec \beta^{T\arg et} / year \prec 6\right)$ [2,4,14,20,21,25,30,34].

$$GF_i(\mathrm{X}) = C_i(\mathrm{X}) - D_i(\mathrm{X}) \tag{5.1}$$

$$P_f^{system} = \frac{\sum\limits_{S1,S3,UX} N_{GF_i \prec 0}}{N_{sim}} or \frac{I_C}{k} \tag{5.2}$$

$$\beta^{system} = -\Phi^{-1}\left(P_f^{system}\right) \geq \beta^{T\arg et} \tag{5.3}$$

$$R^{system} = 1 - P_f^{system} \tag{5.4}$$

Reliability analysis using Monte-Carlo simulation is done for k time generation $(i:1:k)$. The "i" subscription assigned for each FF to the system capacity and demand functions relates to the i^{th} simulation loop. In order to save computational time, the analysis is performed in batch mode. Each execution in batch mode takes 27 seconds. The procedure of present research to assess probabilistic safety assessment of the PF dam system is shown by the flow chart in Figure 6.

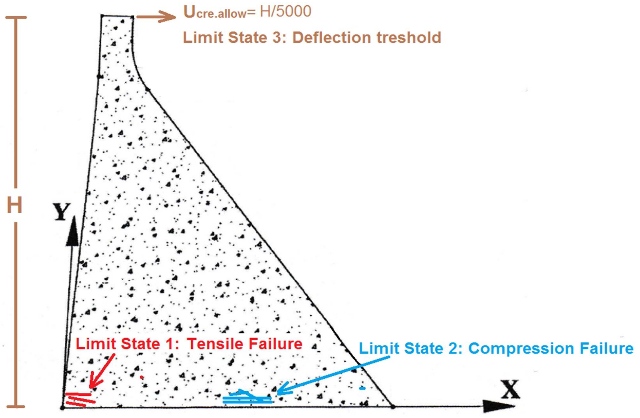


Fig. 5. Considered limit states for dam body system failure

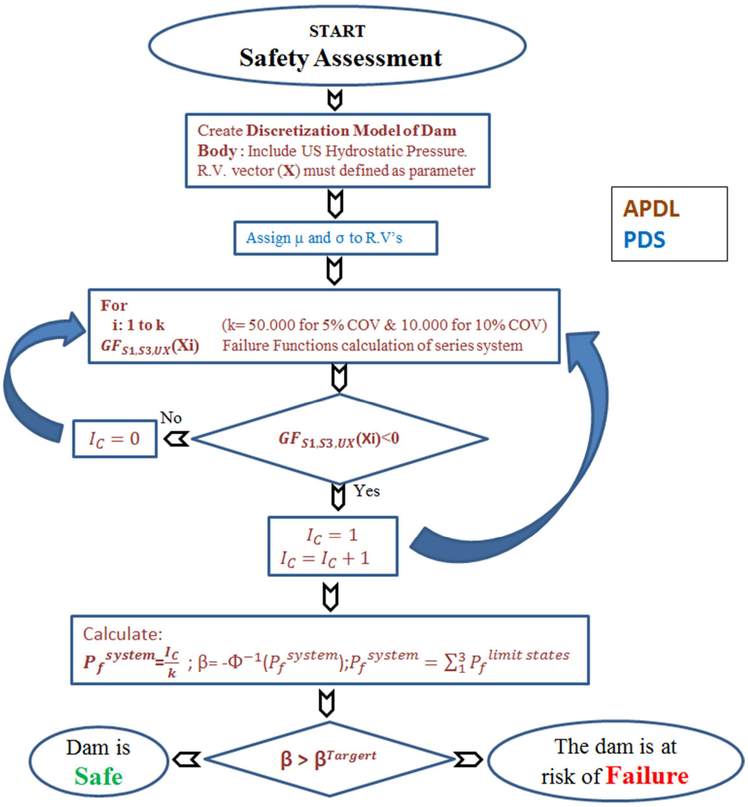


Fig. 6. Flow chart of the procedure of Reliability Analysis used in the present study

The fault trees of structural failure for the dam system are shown in Figure 7. Three independent components are considered as the series systems [4,14,17,25,26]. With increasing dispersion in RVs, the probability of failure increases, and the safety index decreases. The obtained safety index (RI) values are 4.32 and 2.47 for 5% and 10% dispersions, respectively. Therefore, if the dispersion of RVs is considered to be 10%, the dam system is at risk of failure. The dam system has no risk of failure for the 5% percent dispersion of the RVs. The cumulative density function (CDF) of FF and negative values for $\left(GF_{UX}^{COV=5\%}(\mathrm{X}) \prec 0; GF_{S1}^{COV=10\%}(\mathrm{X}) \prec 0; GF_{UX}^{COV=10\%} \prec 0\right)$ are shown in Figure 8. The probability of failure of the PF dam in different MCS trials and RVs dispersion are shown in Table 2. Positive correlations were seen between $S_{1\max}$, $S_{3\min}$, and U_{Xcrest} with the H_W as shown in Figure 9. As the US water level increases, maximum tensile stress and horizontal crown deflections increase and minimum compressive stress decreases. The MCS results show that the horizontal deflection of the crest is about zero for a US water level of less than 102 m.

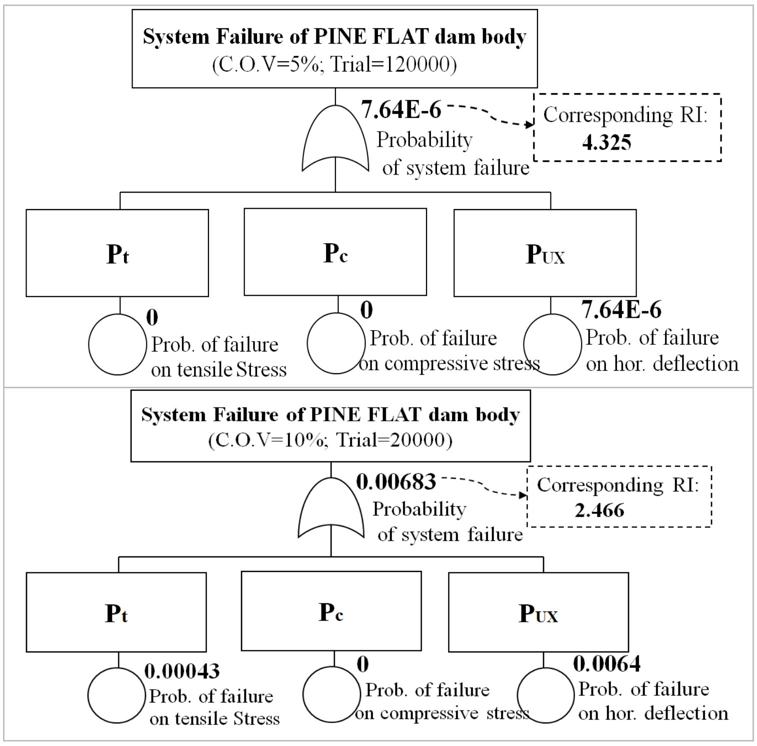
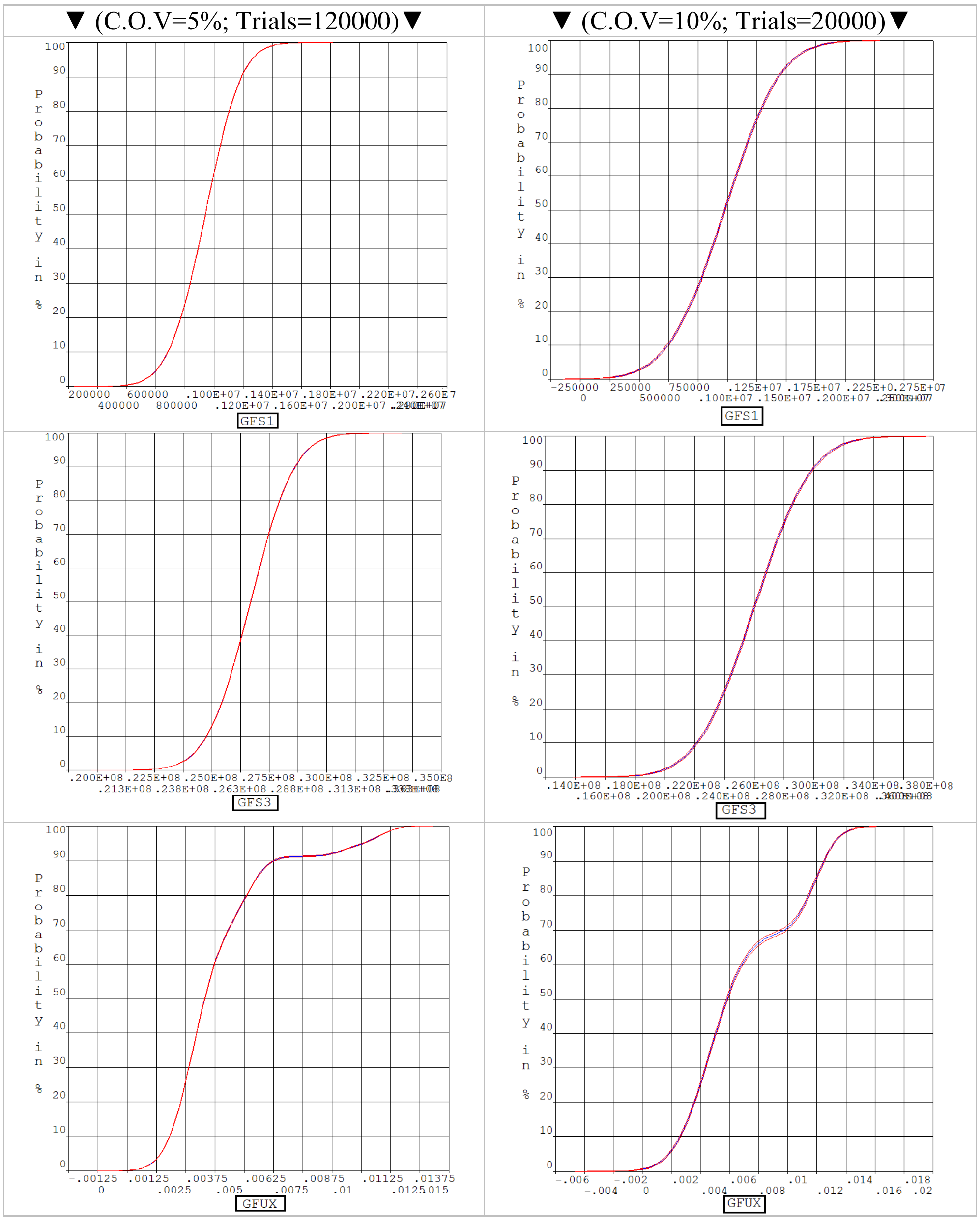


Fig. 7. Fault tree of structural failure of the dam system


▼ (C.O.V=5%; Trials=120000) ▼

▼ (C.O.V=10%; Trials=20000) ▼

Fig. 8. CDF of the dam system FF

Table 2. Probability of failure of PF dam in different trials and dispersions

RI	**MCS Trials**		
	20000	50000	120000
C.O.V.=5%	β = NAN $p_t = 0$ $p_c = 0$ $p_{UX} = 0$	β = NAN $p_t = 0$ $p_c = 0$ $p_{UX} = 0$	$\beta = 4.324$ $p_t = 0$ $p_c = 0$ $p_{UX} = 7.6\times10^{-6}$
C.O.V.=10%	$\beta = 2.466$ $p_t = 4.3\times10^{-4}$ $p_c = 0$ $p_{UX} = 6.44\times10^{-3}$	$\beta = 2.43$ $p_t = 5.42\times10^{-4}$ $p_c = 0$ $p_{UX} = 7.05\times10^{-3}$	$\beta = 2.41$ $p_t = 5.82\times10^{-4}$ $p_c = 0$ $p_{UX} = 7.29\times10^{-3}$

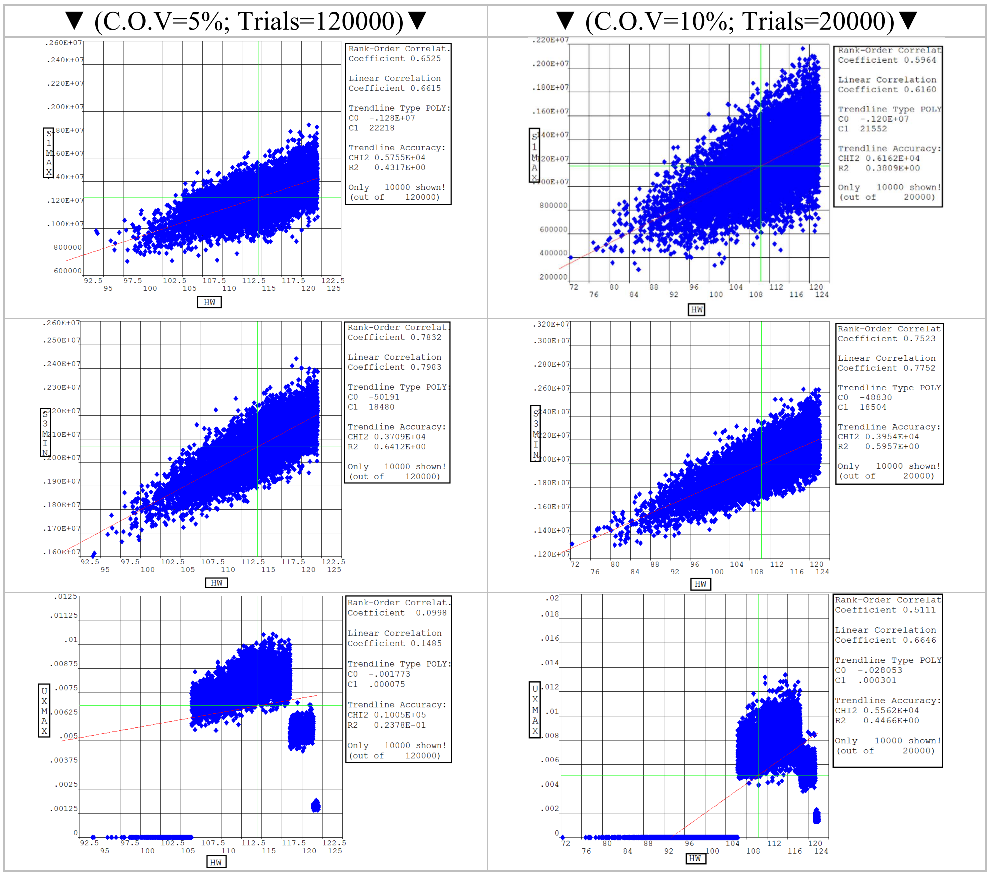


Fig. 9. Correlations between $S_{1\max}$, $S_{3\min}$, and U_{crestX} with the H_W

6. SA OF RESPONSES TO RVS

The reliability analysis process also requires a high computational cost so, the SA is presented to overcome this problem. The SA method is done by PDS, which uses Spearman ranking for the particular type of correlation [22]. In order to reduce the computational time, only significant parameters affecting limit functions in the RA procedure can be considered. The SA of load effects parameters $\left(S_{1\max}, S_{3\min}, U_{Xcrest}\right)$ on RVs is shown in Figure 10. Increasing the concrete density of the dam body leads to a decrease in the maximum tensile stress. The random parameter of the Poisson ratio has a small effect (Insignificant) on the response parameters of S_{1max}. Increasing the US pressure level leads to an increase in the minimum compressive stresses. The random parameters of the Poisson ratio and concrete modulus of elasticity have a small impact on the response parameter of S_{3min}. Increasing the concrete modulus of elasticity leads to a decrease in the horizontal deflection of the crest. Insignificant parameters such as the Poisson ratio of concrete materials should be ignored.

Fig. 10. SA of RVs on load effects parameters

7. CONCLUSION

In the present paper, the reliability assessment of the PF CGD has been carried out considering the inherent uncertainties in the mechanical and physical properties of the dam body materials and the reservoir water level. The epistemic uncertainties in the concrete of the dam body, the US water level, and the allowable values of tensile and compressive stress of the concrete, as well as the allowable horizontal deformation of the crest in stream direction, are considered. The dam body structure was analyzed under its self-weight and upstream hydrostatic pressure. In the PA, the MC method is used to simulate RVs and parameters. The Gaussian and truncated Gaussian distributions are assumed to produce random values. In both cases, the coefficient of variation is 5% (with 120000 trials) and the coefficient of variation is 10% (with 20000 trials), PA is done. In order to conduct a probabilistic safety assessment of PF CGD, the PDS in ANSYS software was used. The results of probabilistic safety analysis have shown that the dam is not at risk of failure for the low dispersion $(C.O.V.=5\%)$ of RVs $(\beta=4.324)$. Also, the dam is at high risk of failure for the high dispersion $(C.O.V.=10\%)$ in RVs $(\beta=2.41)$. The SA is done to identify the most effective random parameters to dam response. The Spearman ranking method was utilized for SA of dam response to RVs. The random parameter of the Poisson ratio is of minimal effect on the dam response parameter.

Conflict of Interest
The authors declare that they have no conflict of interest.

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