Visual Abstract

Study of structural stability of a concrete gravity dam using a reliability approach

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ABSTRACT. Dam safety is a priority at the international level, it requires a large amount of data that allows analysts to make optimization on its structural stability, the latter is based on the estimation of the probability of failure from the effects of stress and resistance acting on the dam-reservoir system. This investigation is to establish a methodology in order to optimize the safety of a concrete gravity dam in operation by carrying out a risk analysis which includes the identification of the sources of danger in terms of scenarios that can occur due to a failure on the dam-reservoir system on an implication of natural hazards (floods, earthquakes) and technical accidents such as malfunction of a spillway gate, drain valve, drainage system or important silting. Reliability methods provide a basis for the probabilistic assessment of the structural safety of a dam. They make it possible to take into account in a probabilistic context, the uncertainties in the data associated with the calculation parameters used in the justifications of structural stability and make it possible to assess as closely as possible the intrinsic safety of a concrete gravity dam.

KEYWORDS. Probability of failure; reliability of dam; first order reliability method; Monte Carlo simulation; Latin Hypercube Sampling.

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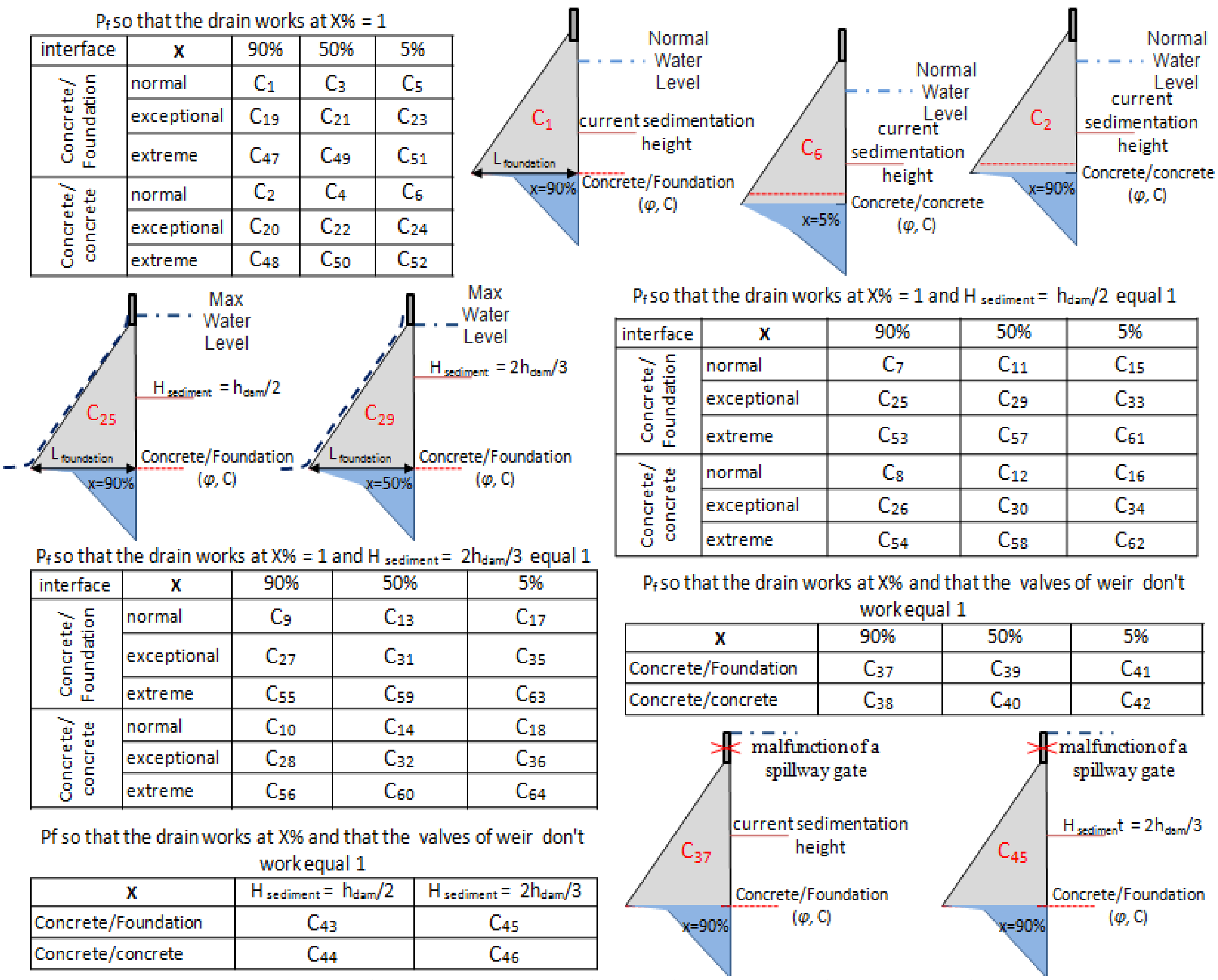
INTRODUCTION

In recent years, various research projects have focused on the field of risk management for construction projects, that are affected by a variety of risk categories such as economic, environmental, political, financial, geological and technical risk, etc. During their service life, they involve many authorities whose interests and needs must be taken into account in the decision-making system in order to ensure the success of the project [1]. The failure history of dams enables risk analysts to know the failure scenarios. It provides information on what can happen to other dams in service, this analysis presents a field in full development, the result obtained presents a mathematical inflection of the uncertainty related to the parameters introduced in the dam stability calculation which means that the uncertainty is expressed in terms of failure probabilities. Contrary to traditional deterministic approaches, probabilistic methods have been increasingly recognized for their facing uncertainties in the face of modern engineering problems, they are necessary to investigate the effect of uncertainty in the input data on the stability of structural systems [2].

According to the International Commission on Large Dams (ICOLD) the term risk implies a certain form of action in the face of uncertainty it has a universal meaning but can be interpreted in different ways. However, Dominic Reeve (2010) has described risk as a probability of failure or default, consequences can be measured in many forms but often converted to monetary values, so risk has units of expenditure rates ($/month, quarter, or year) [3]. It is referred to as *R* and is defined as the expected consequences *C* associated with a given activity multiplied by the probability *P* that this event will occur [4, 5]. Risk assessment provides a structured and systematic examination of the probability of damaging events with their consequences and also is the essential element serving as the basis for the entire safety management process [6].

To optimize the reliability of a dam, it is important to take into account the natural ultimate cases (high floods, earthquakes) and the degree of operation of the operating equipment. The probabilistic modelling of resistances and stresses by building a class of dam-reservoir system data that have uncertain behaviour by risk treatment models by combining the previous cases between them to create scenarios, gives an important axis to improve the structural and functional safety in a dam, this analysis technique by using a set of Algerian dams (Boussiaba, Oued Fodda, Beni Harroun, Koudiat Acerdoune, Hamiz and Tichy Haf) will be the subject of context under the title; structural stability study of a concrete gravity dam by reliability optimization approach.



P_f so that the drain works at X% = 1

interface	x	90%	50%	5%
Concrete/ Foundation	normal	C_1	C_3	C_5
	exceptional	C_{19}	C_{21}	C_{23}
	extreme	C_{47}	C_{49}	C_{51}
Concrete/ concrete	normal	C_2	C_4	C_6
	exceptional	C_{20}	C_{22}	C_{24}
	extreme	C_{48}	C_{50}	C_{52}

P_f so that the drain works at X% = 1 and $H_{sediment} = h_{dam}/2$ equal 1

interface	x	90%	50%	5%
Concrete/ Foundation	normal	C_7	C_{11}	C_{15}
	exceptional	C_{25}	C_{29}	C_{33}
	extreme	C_{53}	C_{57}	C_{61}
Concrete/ concrete	normal	C_8	C_{12}	C_{16}
	exceptional	C_{26}	C_{30}	C_{34}
	extreme	C_{54}	C_{58}	C_{62}

P_f so that the drain works at X% = 1 and $H_{sediment} = 2h_{dam}/3$ equal 1

interface	x	90%	50%	5%
Concrete/ Foundation	normal	C_9	C_{13}	C_{17}
	exceptional	C_{27}	C_{31}	C_{35}
	extreme	C_{55}	C_{59}	C_{63}
Concrete/ concrete	normal	C_{10}	C_{14}	C_{18}
	exceptional	C_{28}	C_{32}	C_{36}
	extreme	C_{56}	C_{60}	C_{64}

P_f so that the drain works at X% and that the valves of weir don't work equal 1

x	90%	50%	5%
Concrete/Foundation	C_{37}	C_{39}	C_{41}
Concrete/concrete	C_{38}	C_{40}	C_{42}

Pf so that the drain works at X% and that the valves of weir don't work equal 1

x	$H_{sediment} = h_{dam}/2$	$H_{sediment} = 2h_{dam}/3$
Concrete/Foundation	C_{43}	C_{45}
Concrete/concrete	C_{44}	C_{46}

Figure 1: Combination between structural reliability and functional reliability (proposed scenario).

JOB REQUIREMENTS

Uncertainty can affect several parameters that are included in the calculation of the stability of a dam such as; concrete and sediment density, ice thrust, operating water levels, etc. In this computation the random variables considered are the angle of friction 'φ' and the cohesion 'C'. On the one hand corresponding along the dam foundation interface, it is assumed that the uncertainty is produced by the change in the space where samples were taken (heterogeneous foundation) and by inaccuracies relative to the laboratory during shear tests. On the other hand, in the body of the dam (concrete-concrete) the variation of 'φ' and 'C' is produced by the phenomenon of concrete degradation, it was supposed a Gaussian distribution to the laws governing these physical characteristics.

In order to optimize the safety of a dam it is necessary to take into consideration the normal case of operation and the natural ultimate cases (high floods, earthquakes), the reliability analysis will be made according to the different situations of load combinations, i.e, normal, exceptional and extreme cases, this type of optimization is called structural reliability. Recently, Abdollahi *et al.* [7] proposed an uncertainty aware framework for dynamic shape optimization of gravity dams under stochastic loads. The suggested reliability-based design optimization (*RBDO*) study is not only efficient in incorporating different source of uncertainties but also guarantee system safety accurately.

Another type of optimization called functional reliability groups together the operating rates of the operating equipment; spillways gates, drain valves, drainage system and the degree of silting in the dam (sediment elevation) these factors influence directly on the stability of dam, the combination between these parameters and the cases of operation mentioned above gives different scenarios (C_i) called possible operating scenarios that may encounter a dam during its service life for example; the combination of normal operating cases (normal water level) with the drainage operating rate (X% =90%, 50%, 5%) gives the scenarios C_1, C_3, C_5 at the concrete/foundation interface and C_2, C_4, C_6 at the concrete/concrete interface and under the same conditions when the elevation of the sediments equal to half the height of the dam we will have C_7, C_{11}, C_{15} and C_8, C_{12}, C_{16} (Fig. 1). The P_f value obtained is the result of the calculation by the methods; First Order Reliability Method, Monte Carlo Simulation and Latin Hypercube Sampling which give an estimate of the reliability of the dam for each scenario C_i in relation to the landslide phenomenon, the most likely value among these three methods gives an approach to optimize the reliability of the dam under study (Fig. 2).

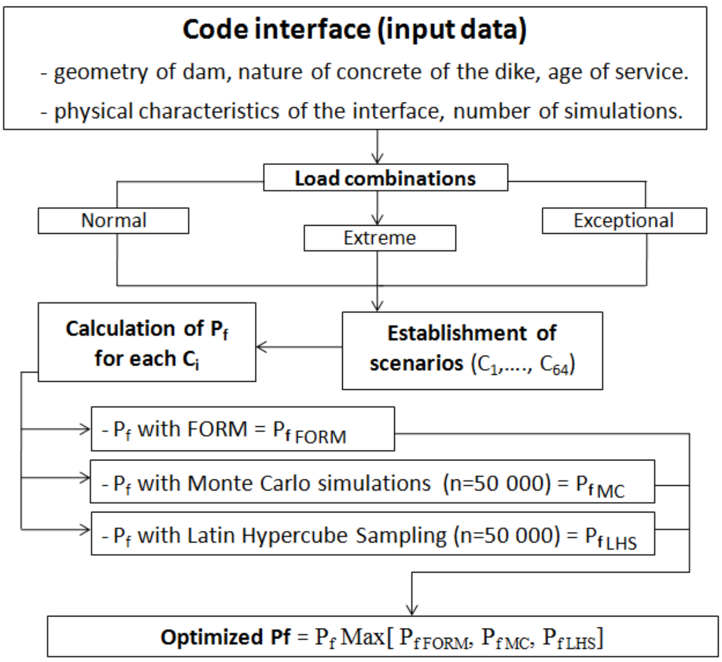


Figure 2: Flowchart for calculating the probability of dam failure

LITERATURE REVIEW

According to some historians, the start of probability calculus is linked to the industrial revolution in the 17th century and is intimately linked to the emergence of combinatorics, whose development will accompany that of probability calculus [8]. In the field of structural construction, experience has shown that gross error is the common cause of structural failure, the understanding of the human contribution to failure has grown considerably through major accident studies, Matousek's work, based on the investigation of 800 cases of major damage to structural construction, has shown that human and gross errors contributed to 75-90 per cent of accidents, including; ignorance, negligence, insufficient knowledge and underestimation [4, 9]. Thus, in any evaluation of strengths and loads there will be uncertainties related to variability in space (e.g. heterogeneity of foundations) and time (ageing) and variability in the response of the structure to a specific load. The probability of failure is considered as a rating on a scale, it is based on a detailed scaling and normalized to a scale of 1 to 5, the ratings are converted to a theoretical probability of failure [10] (Tab. 1). This probability of failure ranking can be used to provide an indication of the potential need for repair work to be undertaken by reference to risk reduction guidelines (Fig. 3).

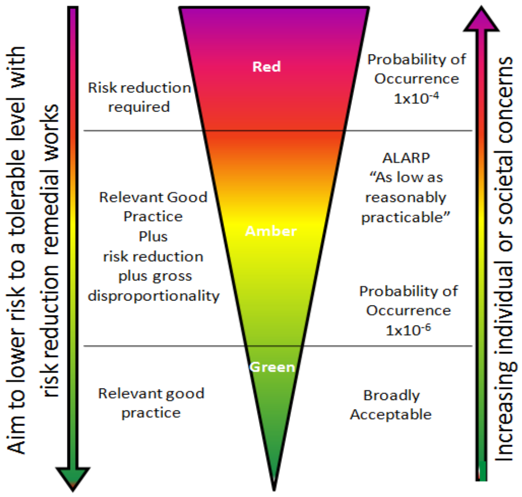


Figure 3: Regions of risk as a function of probability of failure [10, 11]

Probability classes	Description	Indicative value of the annual probability of default P_f
Likely (5)	The hazard may occur or a very bad data status has been established on the hazard.	10^{-2}
Very common (4)	The hazard will be quite frequent or a poor state of data has been established regarding hazard.	10^{-3}
Unlikely (3)	The hazard may occur occasionally or a moderate state of data has been established about the hazard.	10^{-4}
Unusual (2)	The hazard may occur infrequently or a good state of data has been established about the hazard.	10^{-5}
Rare (1)	the hazard can only occur in exceptional circumstances or when a very good state of data has been established on the hazard.	10^{-6}

Table 1: Relationship between Probability rating and probability of failure [10, 12)]

In the physical modelling the strength of a technical element is modelled as a random variable S, the element is exposed to a load L which is also modelled as a random variable [13]. The distributions of strength and load at a specific time t are shown in Fig. 4. A failure will occur as soon as the load is higher than the strength, the reliability R_i of element i is defined as the probability that the strength is greater than the load.

$$R_i = P(S > L) = P(A) \tag{1}$$

where $P(A)$ denotes the probability of event A

The load will usually vary with time and can be modelled as a time dependent variable $L(t)$, the element will deteriorate over time due to failure mechanisms such as corrosion, erosion and fatigue, so the strength of the element will also be a function of time $S(t)$ [13].

The failure time T of element i is the (shortest) time to $L(t) > S(t)$, a possible realisation of $S(t)$ and $L(t)$ is in Fig. 5.

$$T = \min[t; S(t) < L(t)] \tag{2}$$

The reliability $R_i(t)$ of the element can be defined as:

$$R_i(t) = P(T > t) \tag{3}$$

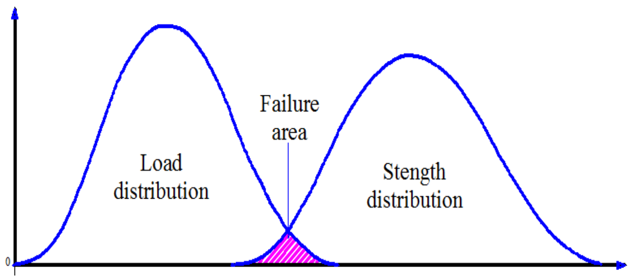


Figure 4: Load distribution and resistance.

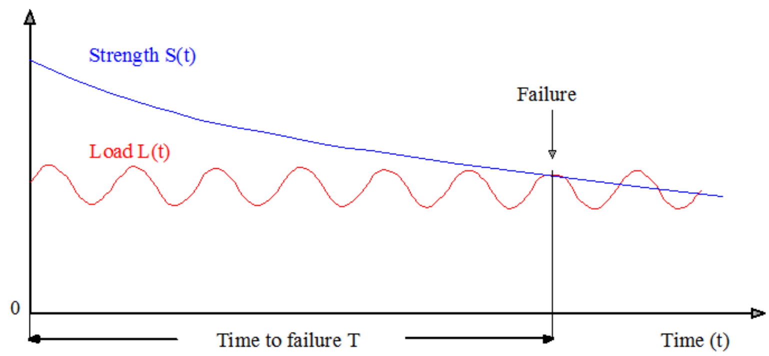


Figure 5: Failure time and load-resistance relationship.

The dam failure history is intended to assist risk analysis teams in estimating probability, it provides information on what has happened to other dams. Dams can fail gradually or instantaneously, the type of failure depends on the initial cause and the type of dam [14], the failure may be natural due to natural deterioration of the structure, extraordinary natural events such as heavy rains and extreme floods, earthquakes, differential settlements, rock slides, piping problems, seepage, wave action, etc., or man-made caused by bombardment, sabotage, demolition for the public good, poor construction or design, poor location, and burial of animals [14]. Since the failure of the Teton Dam (USA) in 1976, significant progress has been made and society continues to increase its demands for safety, reliability of critical infrastructure, design, construction and operation of dams should be integrated into the risk management framework where dam safety is not only a federal, state or local issue, it can affect people and property across locations, state and even national borders [15, 16]. Concrete gravity dams are usually built from many monoliths, when a concrete gravity dam fails, one or more monoliths are washed away [17].

STRUCTURAL RELIABILITY

The reliability of an engineering system can be defined as the ability to fulfil its design purpose for a specified period of time. This ability can be measured using the probabilistic theory that it will perform the function for which it was designed under given conditions and for a given duration.
Structural reliability is formulated in terms of a vector of structural system random variables, $X = \{X_1, X_2, ..., X_n\}$, where $\{X_1, X_2, ..., X_n\}$ are the basic random variables which can describe loads, structural system dimensions, materials and these characteristics and properties of the cross-section [18, 19]. A limit state function, $g(X) = 0$ describes the operation of the system in terms of the basic random variables X, where S is the strength of the material making up the structure and L is the stresses (loads) exerted on the structure [20].
The safety margin M and the limit state function g can be written in the general form:

$$M = g(X) = g(S,\ L) \tag{4}$$

When we place ourselves in the physical space, the space formed by S and L, we notice that the limit state function allows us to divide the physical space into three domains (Fig. 6):

- $g(S, L) < 0$: failure domain;
- $g(S, L) = 0$: limit state;
- $g(S, L) > 0$: safety range.

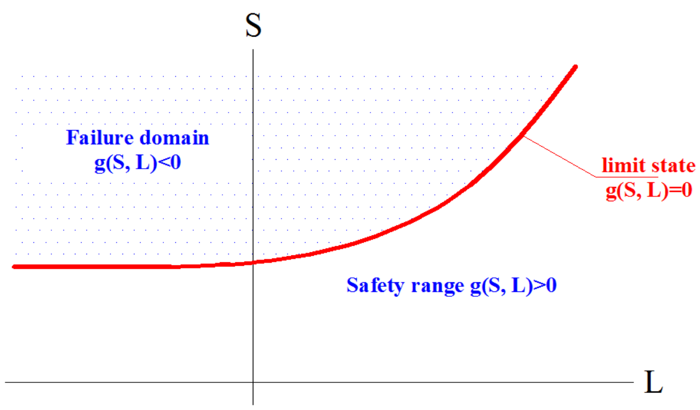


Figure 6: Failure domain, limit state and safety range.

An analysis space can be defined for concrete dams based on two vectors; structural reliability models (X-axis) and deterministic models (Y-axis), as shown in Fig. 7.

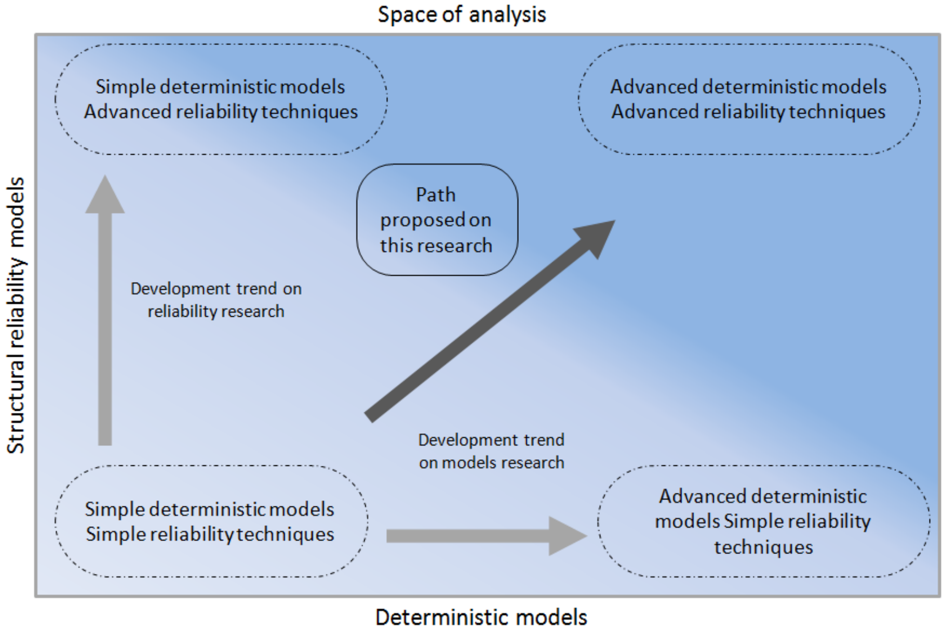


Figure 7: Space for structural analysis of dam reliability [21].

The horizontal and vertical arrows in the figure above show the development trends followed by knowledge in each of its corresponding individual domains and an arrow indicates the diagonal direction combining advanced analytical methods for the behaviour of concrete dams with structural reliability methods, in order to obtain better estimates of the probability of failure in the context of risk analysis [21]. During the life cycle of a structure the failure rate follows the convex curve shown in Fig. 8, it contains three phases; early failure phase due to design errors, phase where the failure rate is practically constant for a large part of the lifespan when degradation mechanisms are not manifested, third phase when the degradation phenomenon starts, leading to an increase in the failure rate; it is during this phase that preventive maintenance can improve structural reliability and extend its lifespan [22].

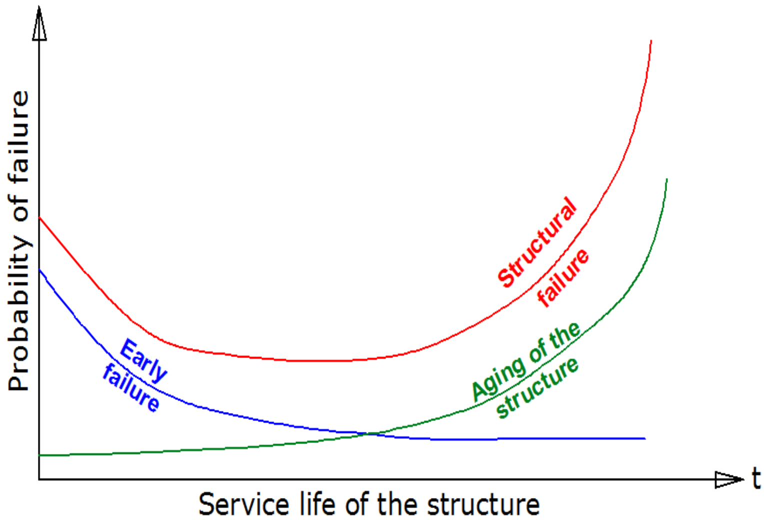


Figure 8: Bathtub curve [22].

Second level reliability calculation methods

In this level the form of the limit state is essential, it has explicit writing or by default with approximation. The estimation of the probability of failure can be carried out by analytical methods of the *FORM* (First Order Reliability Method) and *SORM* (Second Order Reliability Method) type. Reliability is defined as the probability of a function g(X), it is performance function which is greater than zero, $P\{g(X)>0\}$, it is the probability that the variables random $X = (X_1, X_2,..,X_n)$ will be in the safe region and is defined by g(X)>0. The failure can be defined as the probability $P\{g(X)<0\}$, i.e. the probability that the random variables $X = (X_1, X_2,..,X_n)$ will be in the failure region and is defined by g(X)<0 [23, 24, 25]. So if the joint probability density function of X is $f_x(X)$, the probability of failure is evaluated with the integral:

$$P_f = P\{(g(X) < 0\} = \int_{g(x)<0} f_x(x)dx \tag{5}$$

Reliability is calculated by:

$$R_i = 1 - P_f = P\{g(X)>0\} = \int_{g(x)>0} f_x(x)dx \tag{6}$$

The first step is to find the most probable point of failure in the space of standard variables, and then the limit state function is approximated by its first Taylor expansion (*FORM*) or second order (*SORM*) around the point of conception [26]. The First Order Reliability Method reduces calculation difficulties by simplifying the $f_x(X)$ integral and approximating the performance function g(X) so that solutions to formula 5 and 6 are easily obtained [27]. The performance function g(X) is approximated by the Taylor expansion of the first order (linearization), for this purpose this method has the name first-order reliability it simplifies the functional relationship and reduces the complexity of the failure probability calculation, as it is implicitly expressed as a mean and standard deviation [27, 28]. The probability integrations in formula 5 and 6 are visualized with a two-dimensional case in Fig. 9 which shows the conjoint of X that is $f_x(X)$ and its contours, which are projections of the area of $f_x(X)$ onto the plane X_1-X_2 that have the same values or probability density.

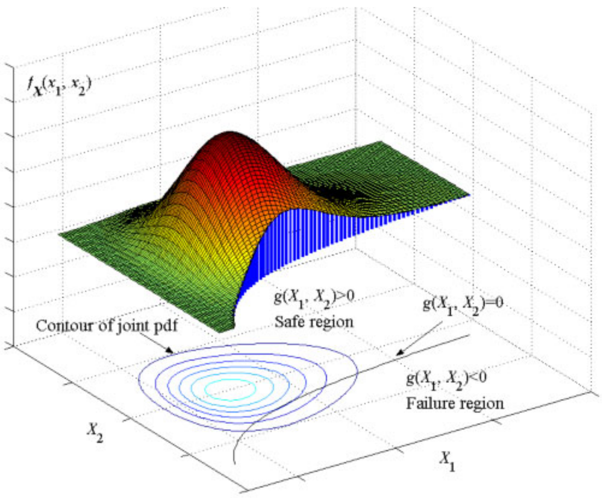


Figure 9: Probability integration [26, 27]

The hypothesis is to consider that the surface of the integral $f_x(X)$ forms a hill and this is cut by a knife with a curved blade g(X) = 0, the hill is divided into two parts, the left part will be on the side of g(X) > 0 as shown in Fig. 9. The left volume on the left is the probability integration in formula 7 which presents the reliability, in other words the reliability is the volume below $f_x(X)$ on the side of the safe region where g(X) > 0 [27]. The first-order reliability procedure is described by three (03) steps which are as follows:
Step 1: The original space of the basic variables should be transformed into a standard Gaussian space, called U-space.
Step 2: Then you have to look for the famous Design Point in the new space.

Step 3: Finally, the failure surface must be approached at this point to obtain an approximation of the probability sought [18].

Reliability index

The geometrical interpretation of the reliability index β when placed in a normalized space corresponding to the physical space is the minimum distance between the origin O of the normalized space and the limit state curve, it is determined as the distance between the mean and the point of failure ($M = 0$) in units of standard deviation, it is the most probable value of failure [20, 25]. The relationship between the reliability index and the probability of failure can be estimated by the following table:

β	1.28	2.32	3.72	4	4.27	4.5	4.75	5.20
P_f	10^{-1}	10^{-2}	10^{-4}	3.2×10^{-5}	10^{-5}	3.4×10^{-6}	10^{-6}	10^{-7}

Table 2: Relation reliability index β and probability of failure P_f [29]

Third level reliability calculation methods

In this technique the structural reliability methods encompass a complete analysis of the problem and involve integration of the probability density function, random variables are extended to the safety domain and are the most general in reliability techniques whose approach is to obtain an estimate of the integral by numerical mean [3]. In this context it can cite Monte Carlo simulations and the Latin Hyper cube method.

Monte Carlo Simulations

This method offers a powerful means to evaluate the reliability of a system, due to its capability of achieving a closer adherence to reality, it may be generally defined as a methodology for obtaining estimates of the solution of mathematical problems. It is based on the repetition of system sampling, however, the number of simulated realizations is large in the control an acceptable precision to estimate the probability of failure [28].
Consider for example the problem of integral I, it is a question of approaching:

$$I = \int_0^1 \mathrm{g(x)dx} \tag{7}$$

Various classical methods of a deterministic type exist; rectangles, trapezoids and Simpson. The Monte Carlo method consists in writing this integral in the form:

$$I = \mathrm{E}[\mathrm{g}(U)] \tag{8}$$

where U is a random variable according to a uniform law on [0; 1], if $(\mathrm{U_i})_{i\in N}$ is a sequence of independent random variables and a uniform law on [0; 1] [28], then:

$$\frac{1}{\mathrm{n}}\sum_{\mathrm{i=0}}^{\mathrm{n}} \mathrm{g}(U_i) \rightarrow \mathrm{E}\ [\mathrm{g}(U)] \tag{9}$$

In other words, if $u_1, u_2, u_3, u_4, \ldots, u_n$, are randomly selected numbers in [0; 1].
$\frac{1}{\mathrm{n}}[\mathrm{g(u_1)+g(u_2)+g(u_3)+\ldots\ldots+g(u_n)}]$ is an approximation of $I = \int_0^1 \mathrm{g(x)dx}$ after definition problem in terms of design random variables and identification of these probabilistic characteristics in terms of probability density function and associated parameters (mean and standard deviation), the generation of values for these random variables followed by deterministic problem assessment for each data set gives us a conclusion on the probability

of failure of the system under study [28, 30]. Thus this method is the process that is used to estimate the sampling of the probability of failure of a structure, if N_f is the number of simulation cycles in which the structure fails and N is the total number of simulation cycles, the probability of failure P_f is expressed by [28, 30]:

$$P_f = \frac{N_f}{N} \tag{10}$$

Latin Hyper cube Sampling method

If we are talking about an array of symbols or numbers and each appears only once, the array is called a "Latin square", extending this concept to higher dimensions for many design variables represents the term "hyper cube". Hence, this method is the sampling method in a Monte Carlo approach, it is also known as “stratified sampling technique” [28]. Each random variable can be subdivided into *n* intervals of equal probability, there are *n* points of analysis, randomly mixed, so each of the *n* compartments has 1/*n* of the probability of distribution. The general steps of this method are:

1- Decompose the distribution of each variable into *n* non-overlapping intervals with equal probability.
2- Select a value at random in each interval in relation to its probability density.
3- Repeat steps 1 and 2 until you have selected values for variables, such as x_1, x_2, ..., x_k.
4- Combine the *n* values obtained for each x_k with the *n* values obtained for the other at random $x_{j\neq i}$ see Fig. 10.

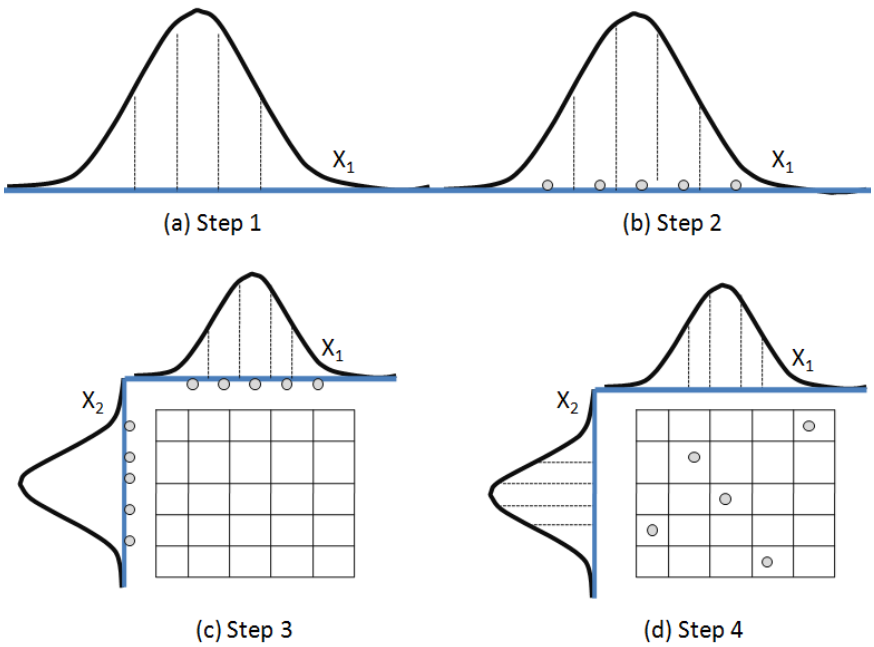


Figure10: Basic concept of LHS with two variables and five realizations [28]

APPLICATION OF THE MODELS

The application of the three reliability methods on the Beni Harroun dam gave failure probabilities during certain scenarios, each scenario having its own specific load combinations, e.g. P_f estimated in scenario 47 (C_{47}) is the probability of failure at the landslide in relation to the dam-foundation interface when the dam is subjected to seismic loading and when the functional probability for the drainage system to operate at 90% is equal to 1. The calculation code retains the most unfavourable probability of failure (P_f = 3.51x10^{-3}) among the results of the three reliability calculation methods. The results are shown in Tab. 3.

Scenarios	Calculated P_f			Optimized P_f = Max [$P_{f\,FORM}$, $P_{f\,HL}$, $P_{f\,MC}$]
	$P_{f\,FORM}$	$P_{f\,HL}$	$P_{f\,MC}$	
C_{11}	4.1x10^{-4}	4.1x10^{-4}	4.09x10^{-4}	4.1x10^{-4}
C_{12}	10^{-7}	10^{-7}	10^{-7}	10^{-7}
C_{35}	4.4x10^{-3}	4.61x10^{-3}	4.82x10^{-3}	4.82x10^{-3}
C_{36}	10^{-7}	10^{-7}	10^{-7}	10^{-7}
C_{47}	3.2x10^{-3}	3.35x10^{-3}	3.51x10^{-3}	3.51x10^{-3}
C_{48}	10^{-7}	10^{-7}	10^{-7}	10^{-7}

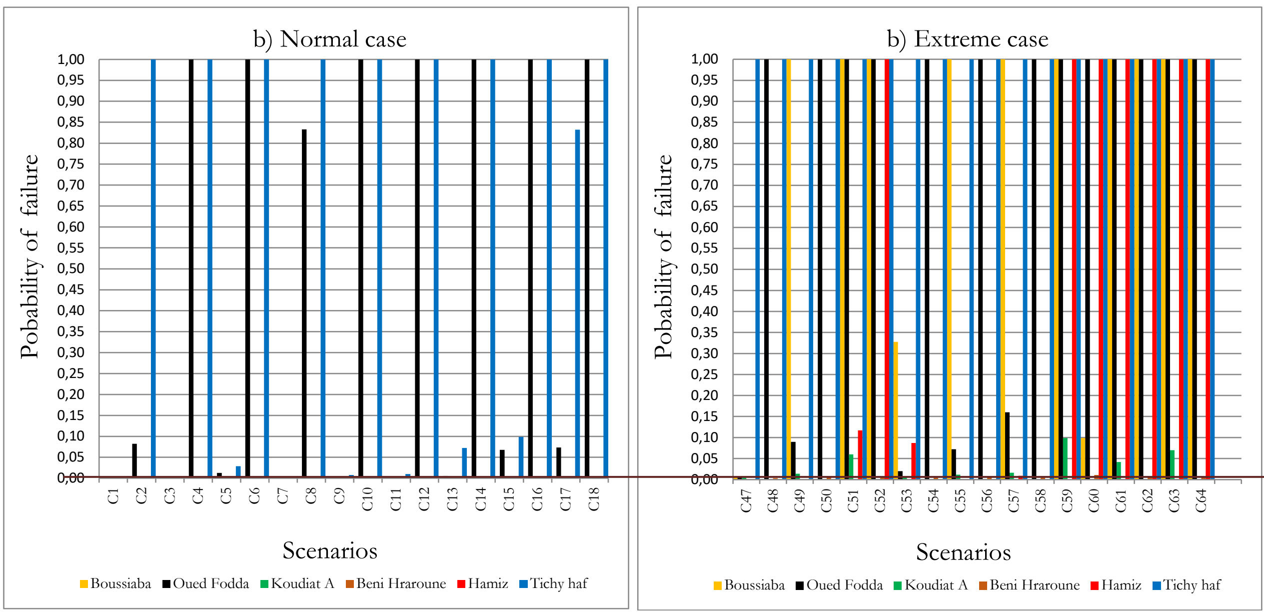
Table 3: P_f of the Beni Harroun dam during the scenarios; C_{11}, C_{12}, C_{35}, C_{36}, C_{47}, C_{48}

The application of the models was carried out on six (06) Algerian dams (Boussiaba, Oued Fodda, Beni Harroun, Koudiat Acerdoune, Hamiz and Tichy Haf), the characteristics of these dams are moved in Tab. 4.

Dams	Type of concrete	Age of service	Talus fruit		Height of the dyke (m)	Foundation length (m)	Ratio foundation length/dike height (R)
			upstream	downstream			
Boussiaba	BCR	< 50 years old	0	0.725	50.67	37.63	0.74
Oued Fodda	BCR	50 to100 years old	0.1	0.675	101	67.5	0.67
Koudiat Acerdoune	BCV	< 50 years old	0.4	0.5	121	102	0.84
Beni Harroun	BCR	< 50 years old	0	0.8	118	93	0.79
Hamiz	Masonry	> 100 years old	0.25	0.5	50	47	0.94
Tichy Haf	BCR	< 50 years old	0	0.5	83.5	40	0.48

Table 4: Geometrical characteristics and service age of the dams to be studied

The following figure shows the failure probability histogram for the three load combinations; normal, exceptional and extreme, it gives us the most probable P_f for each assumed scenario.



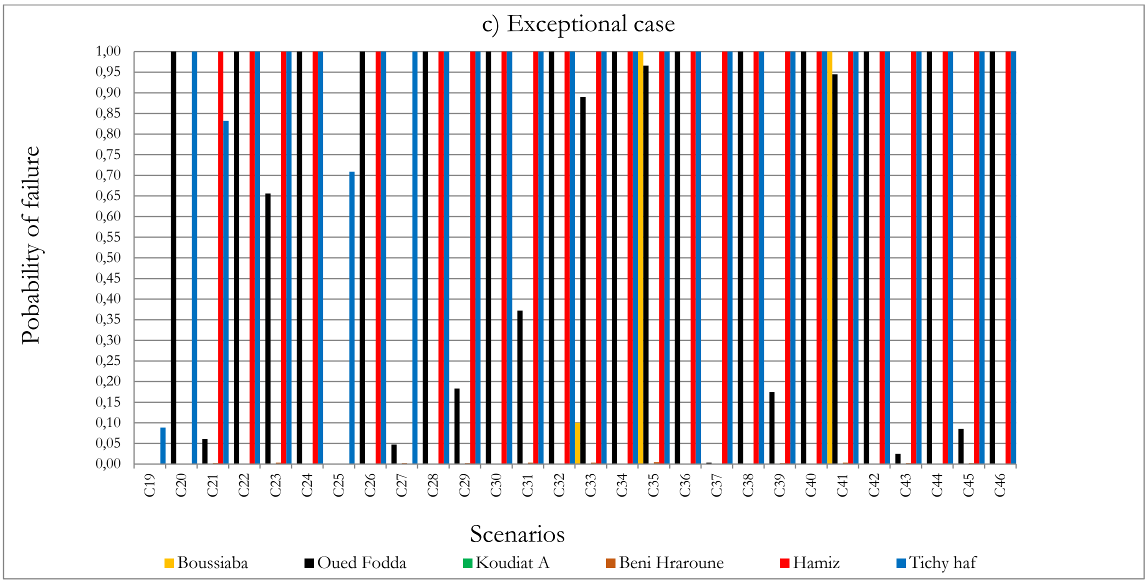


Figure 11: The histogram of failure probabilities for different load request scenarios

If we consider that the probability for each scenario C_i (from C_1 to C_{64}) to happen is P_{Ci} = 1, the number of scenarios giving a likely probability (P_f > 0.01) will be:

$$N_{P_{f\,\text{Likely}}} = \sum_{i=1}^{64} (P_{f\,Ci} > 0.01) \tag{11}$$

The ratio between $NP_{f\ \text{Likely}}$ and the total number of scenarios will be:

$$R_{\text{Likely}} = \frac{N_{P_{f\,\text{Likely}}}}{64} \tag{12}$$

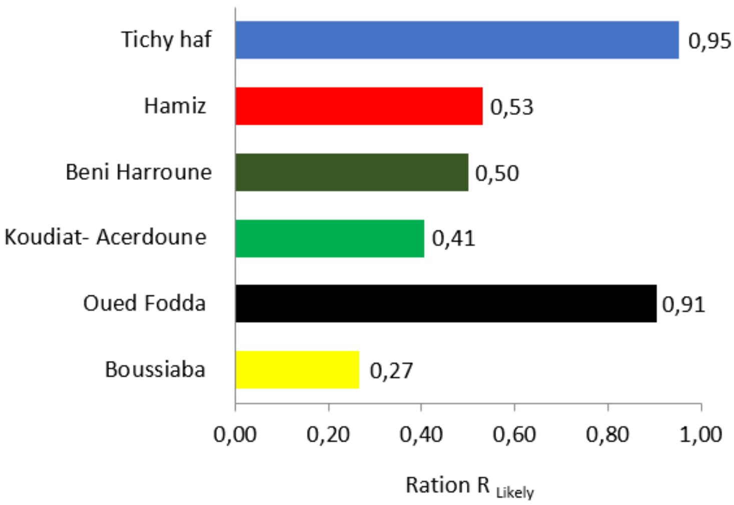


Figure 12: Ratio of cases giving a likely probability and the total number of scenarios for the dams studied

According to these results we can see that the R $_{\text{Likely}}$ of the Tichy Haf dam is 0.95 it is the most important among the dams studied, this majority is expressed by the type of dam (arch gravity dam) and its stability is not only

ensured by its own weight taken in the calculation but it is also ensured by the effect of transmission of part of the force S to the banks. The Oued Fodda dam is in second place with a value of R_{Likely} = 0.91 and the Hamiz dam is in third place with a value of 0.53. These important values are caused by the degradation of the physical properties (angle of friction and cohesion) of the dam material due to the fact that the service life is considerable. Depending on the relationship between probability rating and probability of failure (Tab. 1), P_f at normal load combinations C_1, C_2,..., C_{18} are strictly rare ($P_f \leq 10^{-6}$) in; Boussiaba, Hamiz and Koudiat Acerdoune dams except $P_{f\,C17}=9\times10^{-6}$ when the functional probability for $H_{sediment}= 2h_{dam}/3$ and the drain to function at 05% equal to 1 ($P_{C17}=1$) at that moment the destabilizing shear and normal forces are high. On the contrary P_f is unlikely at dam of Beni Harroun $P_f \geq 10^{-4}$ in the dam/foundation interface due to the mixed nature of the foundation (limestone with fractured zones, decompressed marl and rift breach), this variety leads to an extended standard deviation value for 'φ' which makes failure unlikely. For Oued Fodda dam P_f is rare, unusual and unlikely in C_1, C_3, C_7, C_9 and C_{11}, they correspond to a combination of normal load but with a functional probability for each scenario arriving equal to 1 (P_{Ci} =1). $P_{f\,C1}$ is the failure estimate when the drain is operating at 90%, same situation for C_7 but with siltation of sediment at half h_{dam} ($H_{sediment}=h_{dam}/2$) and for C_9 $H_{sediment} = 2h_{dam}/3$. $P_{f\,C3}$ is the estimated failure when the drain is operating at 50% and the same case for C_{11} but with $H_{sediment} = h_{dam}/2$. For the rest of the scenarios, P_f is very known and probable, this value is caused by the drainage system, and we note that the rate of drain operation has a major influence on the stability of dams. According to these results, it can be noticed that P_f tends towards 1 with the growth of shear forces due to hydrostatic forces; normal, exceptional and ultimate when it is caused by malfunctioning of the discharge and overflow gates during flood periods (C_{37},...C_{46}). Other sharp forces may occur during earthquakes due to the generation of an inertial force within the dam and a hydrodynamic force added to the hydrostatic forces, thus silting forces which will be proportional to the height of the sediment. The impact of the normal effort related to the forces of the suppressions on the value of P_f is proportional to the degree of drainage activity, we note for Boussiaba dam during an earthquake $P_{f\,C47} = 6.7\times10^{-3}$ when the drain is operating at 90% and $P_{f\,C51} = 1$ when it is operating at 05%. If one compares the results of the dams recently in service during certain ultimate scenarios (high sediment height); Koudiat Acerdoune gave us low P_f compared to those of Beni Harroun and Boussiaba, one can justify this difference by the geometrical nature of the profile across the dam of Koudiat Acerdoune (0.4 upstream and 0.5 downstream) on the other hand Boussiaba and Beni Harroun have a zero upstream fruit with respectively 0.725 and 0.8 downstream.
Another supporting factor is the ratio R, which is equal to the length of the foundation and the height of the dam (R= [$L_{foundation}/h_{dam}$], $R_{Boussiaba}$= 0.74 $R_{Beni\ Harroun}$= 0.79 and $R_{koudiat\ Acerdoune}$= 0.84, i.e. as soon as R tends towards 1, the dam becomes stable (Fig. 13).

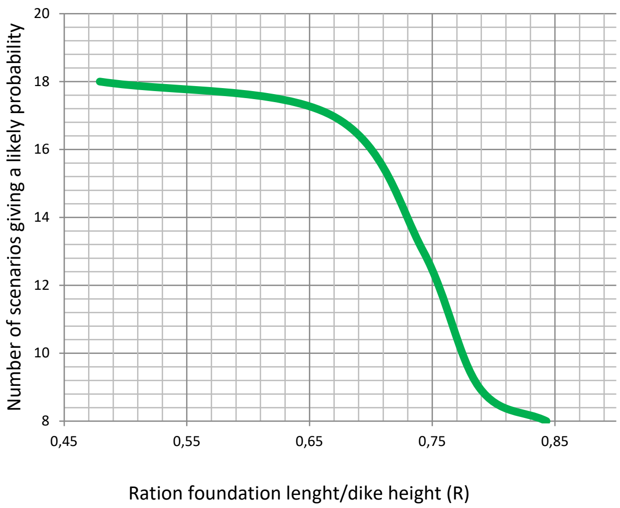


Figure 13: Number of scenarios giving a likely probability as a function of ratio R.

Conclusion

The uncertainty can affect several parameters that are included in the calculation of the stability and dimensioning study, generally this study are based on a deterministic approach in which parameters take fixed values without taking into account uncertainty. In this work the objective is to estimate the reliability of some Algerian concrete gravity dams during the scenarios proposed in relation to the phenomenon of sliding, the uncertain parameters that have taken are; the friction angle 'φ' and the cohesion 'C' and those are random variables in space or in time along the dam-foundation interface and in the body of the dike (concrete-concrete). Different load combinations have been proposed which are called failure scenarios (C_i) that can encounter a dam during its service life as shown in Fig.1, the assumption is to accept the probability of a scenario C_i equal to 1 (P_{Ci} = 1), the calculation of the probability of failure by the three methods (First Order Reliability Method, Monte Carlo Simulations and Latin Hyper cube Sampling) has given us close and at times equal values and the idea is to take the most unfavorable value between these methods and consider it as the probability of failure to increase the safety margin. The exploitation of these results is an achievement in time to quantify the reliability of a dam by optimizing a maintenance and inspection policy, an example; On Friday August 07, 2020, the Beni Harroun dam site received seismic activities with a magnitude of 4.9 on the Richter scale according to the Astrophysical and Geophysical Astronomy Research Center (CRAAG), so if we accept that the operating rate for the drainage system is 90%, the P_f at the time of the earthquake will be less than 3.51×10^{-3} and 10^{-7} respectively at the interface and at the heart of the dike, it is the inflection of the scenarios C_{47}, C_{48} according to Fig. 1 and if it will have a strong flood the probability of failure will be $P_{f\,C19}=1.1\times10^{-3}$ and if there will be a failure in the drain valve or spillways gates during this flood $P_{f\,C37}=1.18\times10^{-3}$. In conclusion this study is a means of control for the safety of a dam knowing that the scenarios proposed can cover the events which encounter this type of structure during its service life.

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