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PROBABILISTIC EVALUATION OF DAM BASE SLIDING

Gabriele Fiorentino[1], **Luca Furgani**[1], **Simone Magliano**[1], **Camillo Nuti**[1]

[1] Department of Architecture, University of Roma Tre
Largo Giovanni Marzi 10, Rome, Italy
e-mail: gabriele.fiorentino@uniroma3.it

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Abstract. *Concrete gravity dams represent a relevant part of the 500 large dams existing in Italy. Most of them were built following obsolete seismic design criteria, so they need to be verified with modern seismic analyses according to the new Italian Code on Dams (2014). Many of the parameters utilized in this evaluation are affected by large uncertainties. In the paper we present a procedure based on Monte Carlo simulation which evaluates the probability of exceedance of the sliding equilibrium of the dam obtained via static or response spectrum analysis in case of seismic action, as well as the probability of exceedance of different sliding displacements via nonlinear dynamic analyses. The application to four seismic sites (of different seismic hazard) and to three dams with different heights is presented.*

1 INTRODUCTION

The seismic risk connected to the collapse of a large dam is very high and it has to be assessed with appropriate methods of analysis. According to the new Italian Code on Dams (2014) concrete gravity dams need to be verified using response spectra with 1950 years return period for existing dams and 2500 years return period for new dams.

The evaluation of seismic safety of large concrete gravity dams is nowadays a challenging topic specially in country as Italy where great part of the existing 500 dams have to be reassessed. Modern codes require to take into account all the uncertainties using characteristic values and safety factors. To high risk and strategic structures as dams it could be useful to solve this problem using a full probabilistic approach. In the following the Monte Carlo method is used to take into account the parameters uncertainty.

Programs as CADAM [1] already permit to compute the probability that the SSF is smaller than 1, however CADAM doesn't perform dynamic analyses and it's not possible to obtain the actual value of the residual slip.

Considering the definitions of the modern limit states associated to the collapse and the loss of service it is fundamental to estimate the damage produced by the earthquake. To obtain these information dynamic nonlinear analysis are requested.

Some studies stated that the base sliding is the most probable failure mechanism which can produce the collapse in a concrete gravity dam [2] The aim of this work was to develop a program capable to evaluate the probability to have a sliding at the base of a concrete gravity dam, to compute the probability of having a base displacement and to evaluate if this could lead to damage or collapse of the dam.

The program was developed using an increasing degree of complexity of analysis, starting from equivalent static analyses to understand which combinations of values of the input variables could lead to a Sliding Safety Factor SSF<1. Then these combinations were assigned to a simplified SDOF system to perform nonlinear dynamic analyses using acceleration time histories. Knowing the evolution of the base displacement it is possible to understand if there could be failure of some part of the dam due to the base sliding.

2 INPUT DATA

2.1 Random variables

The variables considered in Monte Carlo simulation analysis are the water level, friction angle and the Young modulus of elasticity of the concrete. All variables have a lognormal distribution.

The water level governs the design of the dams. During an earthquake the level of the impounded water plays an important role acting with an additional hydrodynamic pressure, changing the modal periods of the structure and, as consequence of this, the seismic actions. Considering that the maximum flood has a little probability to occur together with the earthquake, it’s useful to take into account the probability associated to the water level.

In the present study, on the base of some water level registrations, reporting the daily variation in a 5 years of observation, it is assumed that the maximum level is equal to the total height of the dam and the minimum level is 75% of the total height. The friction angle variation was chosen after an evaluation of the experimental values documented in literature [3]. The average value chosen was 40° with a minimum of 35° and a maximum of 45°. The associated standard deviation was 1,5°. The contribution given by cohesion was neglected.

For the Young modulus, referring to real data observed on existing dams, the average value chosen was $24{,}7x10^6$ kN/m^2, the minimum value $18{,}78x10^6$ kN/m^2 and the maximum 29,08 $x10^6$ kN/m^2. Standard deviation was chosen as $1{,}5x10^6$ kN/m^2.

2.2 Seismic input

In seismic areas where PGA > 0,15g for a 475 years return period, the Code requests a specific seismo-tectonic study in order to evaluate the response spectra.

In this work four Italian dam sites (Table 1) requiring seismic hazard assessment and with different seismicity from 1 site to 4 site were chosen, and the seismic input for a return period of 1950 years was evaluated.

Site	Location (Region)	PGA for Tr=475 yrs	PGA for Tr=1950 yrs
1	Calabria	0,27g	0,46g
2	Abruzzo	0,26g	0,42g
3	Toscana	0,22g	0,35g
4	Piemonte	0,15g	0,25g

Table 1: Dam sites considered for seismic input evaluation

To evaluate response spectra a hybrid method combining both PSHA and DSHA was used, referring to the works of Bommer [4] and Ordaz [5]. The entire procedure is fully described in a previous work [6].

The target response spectra is evaluated with the Ground Motion Predictive Equation ITA10 [7]. A value of 1,5 standard deviation is added to the median value after a comparison with the Italian Code and the probabilistic response spectrum.

3 EQUIVALENT STATIC ANALYSIS

3.1 Monte Carlo method

In the Monte Carlo method a distribution of probability which characterizes the epistemic uncertainty and the variability of the parameter in space and time is associated to each random variable. The output of the analysis is than computed n times through the random extraction of input variables obtaining n values of the response of the system. Given a large number n it is possible to obtain the probability distribution of the output variable, and to calculate the statistic moments of the distribution.

According to the law of large numbers as the number of experiments or simulations increases the average of the results should be closer to the expected value. It is therefore necessary to define a minimum number of analyses to perform in order to obtain a stable solution. In this work a criteria suggested by Melchers [1] is used, so a minimum of 20.000 analyses is adopted.

Latin Hypercube sampling method was used to exclude values with no physical meaning (e.g. height of impounded water bigger than the height of the dam) limiting the sample within a specific interval of the probability distribution.

3.2 Sliding Safety Factors

The aim of the simplified static analysis is to rapidly identify the input data combinations which could be critical for the structure. The Sliding Safety Factor (SSF) is a parameter which can be useful to evaluate the probability of the base sliding of the structure. The SSF is defined as the ratio between the sum of the stabilizing forces and the sum of the destabilizing forces. There is a possibility of sliding when SSF<1. In this work three different SSF were considered:

1. Static SSF: is the most simple SSF because depends only on static forces, easy to evaluate. Remembering that cohesion was neglected, it is possible to write:

$$SSF_{st} = \frac{(W - U_P) \cdot tg\varphi}{P_W} \tag{1}$$

   Where W is the weight of the dam, Up is the uplift pressure, tgφ is the tangent of the friction angle. Pw is the hydrostatic pressure on the upstream wall of the dam.

2. Dynamic SSF - 1° vibration mode: this SSF considers the dynamic contribution of the first mode of vibration, as proposed by Fenves and Chopra [8].

$$SSF_{dyn1} = \frac{(W - U_P) \cdot tg\varphi}{P_W + f_1(y)} \tag{2}$$

   Where f1(y) is the seismic force acting on the dynamic system formed by the dam and the impounded water, for the first vibration mode.

3. Dynamic SSF - 1° vibration mode and higher modes: this SSF considers the dynamic contribution of the first mode of vibration and the contribution of the higher modes.

$$SSF_{dyn2} = \frac{(W - U_P) \cdot tg\varphi}{P_W + f_1(y) + f_d(y)} \tag{3}$$

   This factor was considered to obtain the failure set to be analyzed in the second part of the program.

For each value of SSF the failure probability of exceedance has been obtained.

3.3 Static analyses output

In Figure 1, considering a dam with 100 m height and for site 1 seismic input the probability density functions of the random variables defined as input are displayed. From left to right the friction angle, water level and Young Modulus PDF are showed.

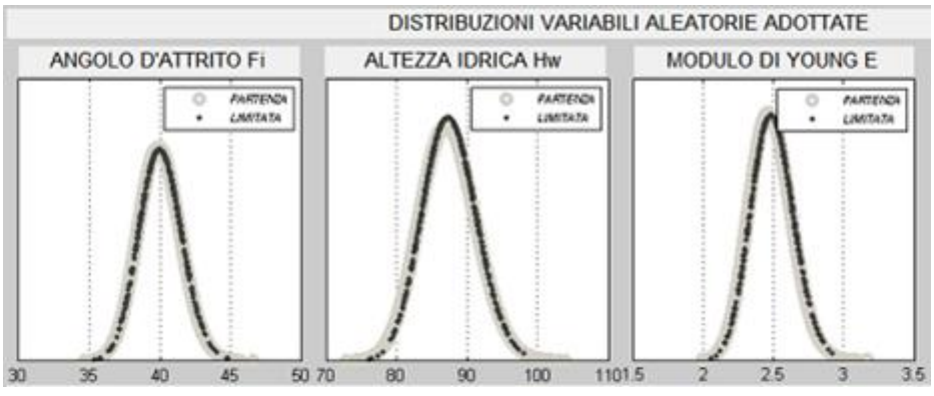

Figure 1: Results of the static equivalent analysis

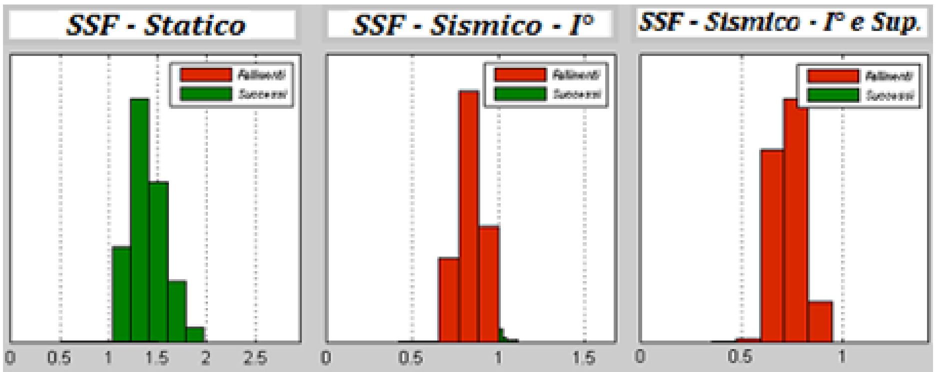

Figure 2: Relative frequencies of SSF

Figure 2 shows the results of the Monte Carlo analysis for the three SSF obtained on the base of a static analysis. For each SSF the histogram represents the values of SSF obtained with all the analyses. The values are displayed in green when the SSF>1, whereas the values for SSF<1 are displayed in red. A table reporting the number of failures for each SSF factor and the probability that each SSF could be minor than 1 is given.

4 DYNAMIC ANALYSES

4.1 Dynamic analyses

The dam is modeled as an equivalent SDOF system defined by the Nuti-Basili method [9] which includes fluid-foundation- structure interaction. According to this, the mass is increased to take into account reservoir contribution, the stiffness is modified to reproduce the effects of the interaction with the foundation and the damping is increased to consider both the contribution of fluid and soil. To evaluate the residual displacement produced during the earthquake, a nonlinear roller was introduced at the base of the system. A frictional sliding resistance was used for this scope.

The system depicted in Figure 3 is analyzed using the open source program "Opensees" using a set of 20 accelerograms scaled in order to match the response spectra chosen as target. In static analyses there is a base sliding only if SSF<1, but when dynamic analyses are performed it could be possible to have base sliding also for SSF major than 1. For this reason for dynamic analyses all SSF minor than 1,1 were considered. The second output includes all the statistical parameters of the analysis with the purpose to correlate the SSF values with the base sliding values.

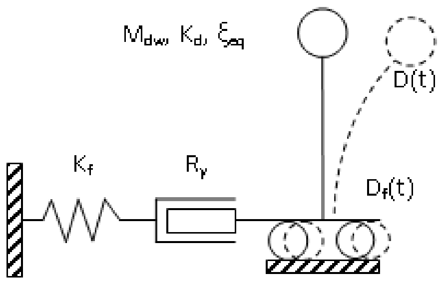

Figure 3: SDOF system

It is possible to perform the dynamic analyses considering different initial values. There are three options:

1. Only values of the basic variables that lead to SSFmin, SSFmax, SSFav (average SSF).
2. All the initial values that brought to a base sliding are considered.
3. All the initial values are considered.

4.2 Dynamic analyses output

Let us first show the case of the response to a single accelerogram obtained for site 1, where PGA=0,46g. The response spectrum of the acceleration time history is given in Figure 4 compared with the target response spectrum. Figure 5 shows the comparison between the linear and nonlinear displacement at the top of the 100 m dam, while Figure 6 displays the sliding response at the base .

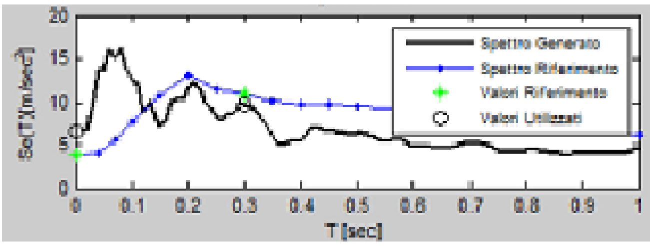

Figure 4: Comparison between single accelerogram (blue) and target response spectra (black) for site 1- H=100 m

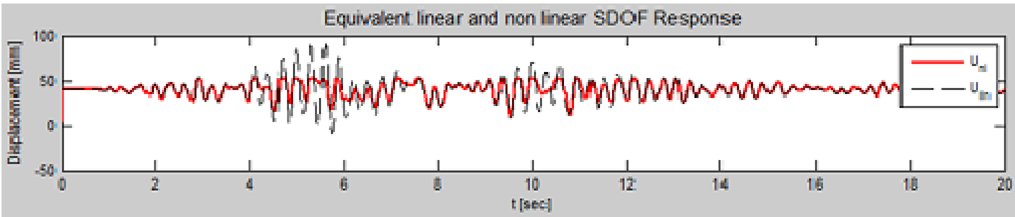

Figure 5: Equivalent linear and nonlinear SDOF response for site 1 - H=100 m

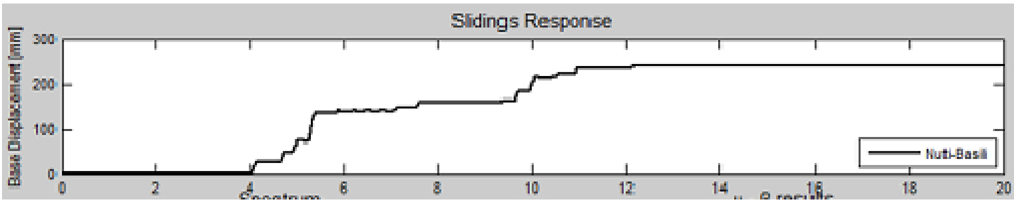

Figure 6: Sliding displacement at the base of the dam for site 1 - H=100 m

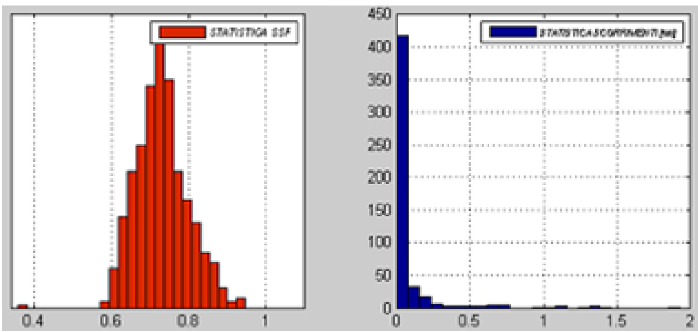

Figure 7: a) SSF statistic b) Base sliding statistic

In Figure 7 are displayed two histograms showing the outcomes of the SSF minor than 1,1 and of the base sliding. Probabilities to assume a value of base sliding displacement included in a certain interval are also reported. In Figure 8 the most critical values of acceleration (i.e. structural period) are reported.

5 APPLICATION

5.1 Case studies and results

The two stage procedure is applied to three concrete gravity dams with different height: 100 m, 75 m and 50 m using the seismic input of the 4 sites studied defined above. The failure probability of the three structures is computed taking into account the results of simplified static analyses and the dynamic nonlinear analyses.

The probability of exceedance of SSF=1 has been obtained with static analysis and the probability of exceedance of displacement δ>0, 0,10 and 1 meter has been obtained by dynamic analysis. For the four sites these results are shown in figure 8. From a sensitivity analysis it seems that the most influent parameter is the water level hw. The larger the water level the larger is the probability of failure also in case of seismic action. The effect of the water level changes for different dam heights and region (i.e. seismic hazard).

The probability rapidly decreases in the dynamic case if the probability to have a base sliding capable to trigger the collapse of the structure (δ>1 m). In fact the probability to have base sliding is 100%, the probability to have a sliding major than 10 cm is 64,4% and the probability to have a sliding major than 1 m is only 13,4%.

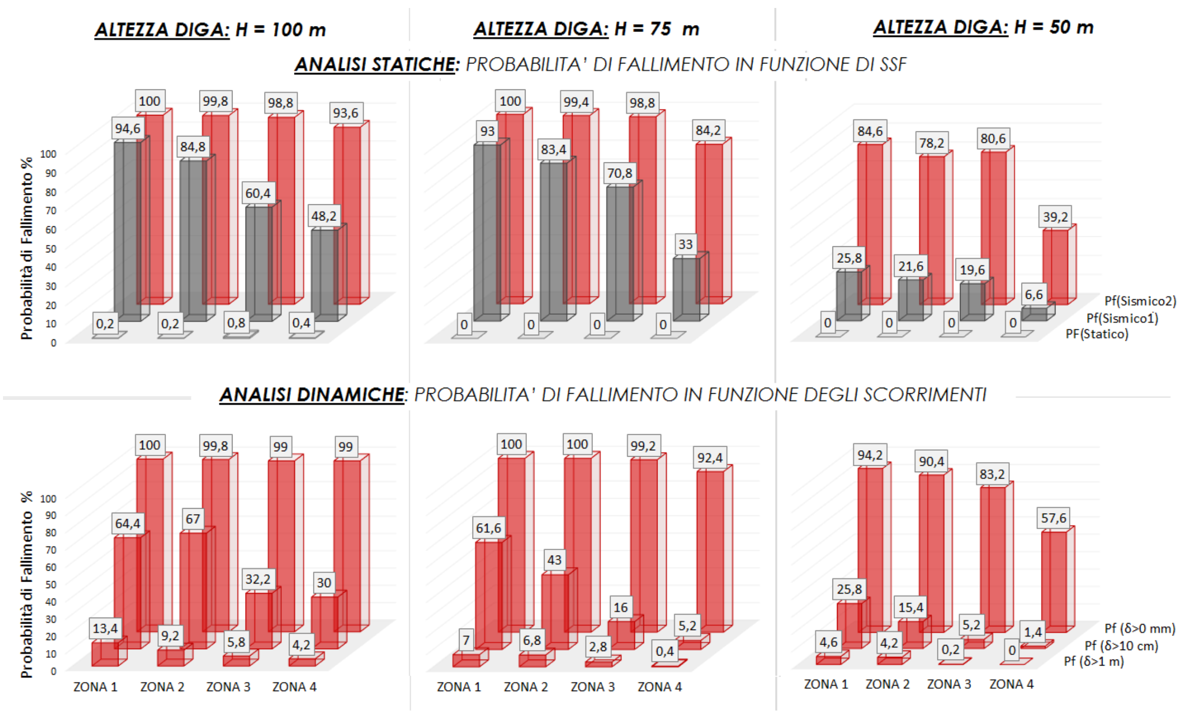

Figure 8: Probabilities of failure for dams with height H=50, 75, 100 m and for sites 1,2,3,4

Comparing the static case $P_{fsismico}1$ or 2 with the dynamic case one notes that the latter is slightly larger. The static cases in which higher modes are included are very similar to the dynamic for δ>0.

If one accept to have δ=0,10 m as a failure the dynamic values are smaller than the static even with a single mode ($P_{fsismico}$1). Higher modes give a substantial contribution for all cases, especially when the probability of sliding is smaller: see for example site 4, dam H=75 m and site 1, dam H=50 m.

6 CONCLUSIONS

Great part of the Italian concrete gravity dams have been built following obsolete design criteria and now need to be verified against seismic action with a modern approach as that proposed in the new Italian Code concerning Dams Safety (2014). Several studies show that base sliding should be the first mechanism leading this type of structure to collapse. In this work a procedure to study the base sliding taking into account the uncertainty of the input parameters is presented. As preliminary check the Sliding Safety Factor (SSF) of static or response spectrum analysis is evaluated using a Monte Carlo simulation procedure. If the SSF<1 it is necessary to carry out nonlinear dynamic analyses to evaluate the residual slip after the earthquake. In this work the base sliding is obtained using the Nuti-Basili simplified method [9] which evaluates it by means of nonlinear dynamic analysis of an equivalent SDOF system that takes into account the interaction of the structure with the foundation and with the impounded water. The two stage assessment procedure was implemented in a Matlab software and applied to four dams with different heights considering four levels of seismic hazard.

The results obtained demonstrate the effectiveness of the method and the useful information given to rapidly estimate the risk connected to the sliding of a concrete gravity dam, considering the main parameters at hand and their dispersion. It represent a powerful tool for a preliminary but meaningful analysis of concrete gravity dams.

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