SEISMIC RISK OF LARGE DAMS IN BULGARIA

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ABSTRACT :

Most of the large dams in Bulgaria are situated in regions with high seismicity. The regulations that have been in force during the design and construction of the structures differ considerably from the modern codes. As a consequence a program for seismic assessment of the existing dams in Bulgaria has been prepared. It is essentially based on seismic risk assessment methodology. Because of the difference between the initial seismic design loads and the present code requirements a realistic analysis should be performed to take into consideration the capacity of the as-built structure. The methodology used for seismic risk assessment and the results reached are presented and discussed in the paper. The probabilistic seismic risk assessments for two concrete gravity dams and for one arch dam carried out recently are discussed. The obtained results are based on realistic assessment of the seismic hazard for the region, statistically and in-situ defined material properties and statistical definition of loads. For the aim of statistical characterization of the structure response under seismic excitation the Latin Hypercube Experimental Design (LHCED) procedure is used. The hydrostatic and hydrodynamic loads as well as the transient thermal loads are statistically represented. A list of failure scenarios for the dam is analyzed. As a result, the scenario with the highest probability of failure is determined. The acceptability of the probability of failure is discussed. In case of unacceptable probability of failure, measures for risk reduction are proposed.

KEYWORDS: seismic hazard, seismic risk, vulnerability, seismic response, dam analyses

1. INTRODUCTION

The three investigated dams have been constructed and finished from the early 50^s to the middle of 60^s of the last century. They are critical nodes of national water and power supply systems. Two of them are concrete gravity dams and the third one is a gravity-arch dam. They are located in areas with strong and moderate seismicity. The current paper analyzes only the risk of seismically induced failure of the dams. The evaluation of secondary risk due to flooding of dam downstream facilities and inhabited areas is not in the scope of this study.

1.1. Global description of DAM 1

The dam is constructed as a typical concrete gravity dam, and is located in a high mountain glacier valley. The main purposes of the dam are to regulate the water supply of Sofia as well as to generate electricity. The maximal storage volume of the dam is 15.3 million m^3. The length of the crest is 533 m with a maximal height of the wall of 50.7 m. The upstream face of the wall is practically vertical.. The downstream face is relatively steep with an inclination of 1:0.683. The wall is constructed from 35 separated blocks. The thickness of the crest is 3.4 m and the maximum thickness of the bottom of the wall is 36.40 m. In the seismic risk analysis a 2D finite element model is used. The generated FE element model of the wall and rock foundation and a global view of the dam are shown in Figure 1 and Figure 2. The dam is situated in a high seismic region and the structure is relatively slender due to the lack of seismic regulations at the time of the design and construction.

1.2. Global description of DAM 2

The hydro complex is situated in a relatively low and hilly region in the southern part of the country. The main purposes of the structure are power generation and regulation of the seasonally high water discharges. The dam’s wall is of the concrete gravity type with a maximal height of 67.50 m. The maximal storage volume of the reservoir is about 380 million m3. The wall is constructed of 25 blocks with 13 m width each and two 6.5 m wide end blocks. The total length of the crest is 338.00 m. All blocks have triangular cross section. The inclination of the upstream face of the wall is 1:0.09. The inclination of the downstream face is relatively steep with an inclination of 1:0.75. The global width of the crest is 8.80 m. The generated FE element model and a global view of the dam wall are shown in Figure 3 and Figure 4. The seismicity of the region is assessed as moderate.

Figure 1. **DAM 1** – global view

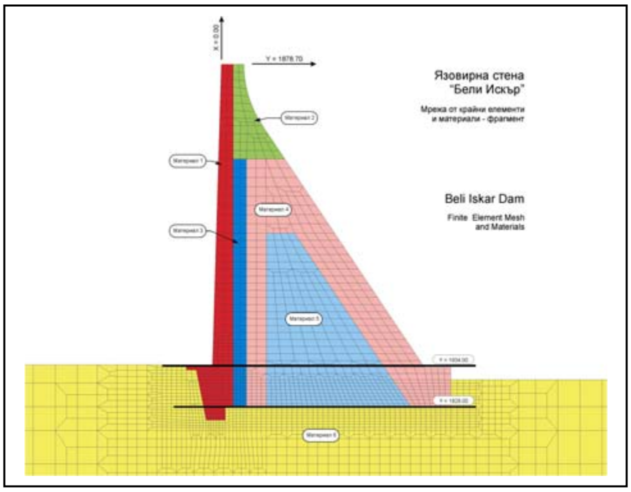

Figure 2 **DAM 1** – finite element model

Figure 3. **DAM 2** – global view

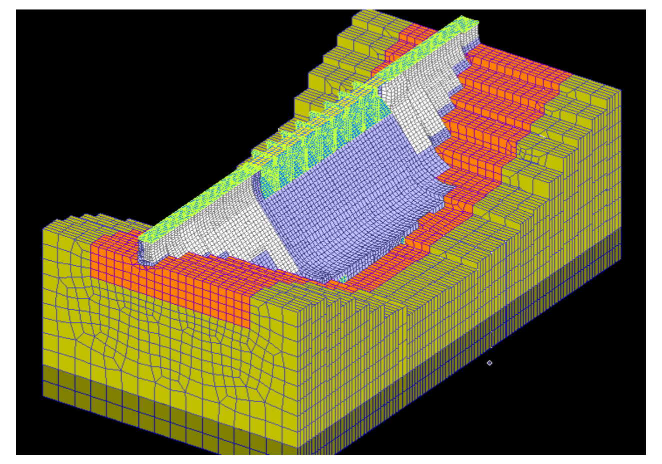

Figure 4. **DAM 2** – 3 D finite element model

1.3. Global description of DAM 3

The hydro complex is in the southern part of the country. The main purpose of the complex is electric power generation. The maximal storage volume of the dam is about 530 million m^3. It is an arch-gravity concrete dam with a height of 103.50 m. The upstream face of the wall is part of a vertical cylinder and the downstream face is shaped by circular curves with different radii. The wall is constructed from 21 separate blocks. The thickness of the crest is 5.0 m and the maximum thickness at the bottom of the wall is 31.60 m. The arch wall is supported by two blocks founded in the slopes of the terrain. The general view of the 3D FEM of the wall is given in Figure 5.

During the construction, weak rock zones were encountered in the zone where the left supporting block had to be founded. This led to the implementation of additional upgrading measures in the respective bank. To strengthen the rock strata under the supporting block an artificial underground concrete skeleton has been constructed. This construction passes through the weak rock zones and transfers all loads directly to the firm rock. The upgrading structure of the left riverbank is shown in Figure 6. The seismicity of the region is assessed as moderate.

2. BASIC PROCEDURE

The basic ideas for performing a Probabilistic Safety Analysis (PSA) of critical structures are applied hereafter for large dams. The general formulation is presented in Franzini, et al. 1984. The presented method has been further developed and based on principles, methods, and techniques used in the PSA of structures described in Borges & Kastaneta 1971, Ang & Tang 1984, Murzeweski 1974, Lomnitz & Rosenblueth 1976, Bolotin 1979. This procedure has been applied for seismic PSA of several large dams in Bulgaria.

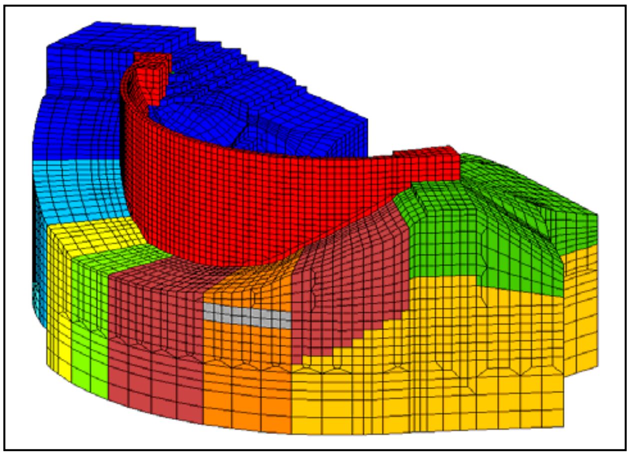

Figure 5. **DAM 3,** General view of the FEM.

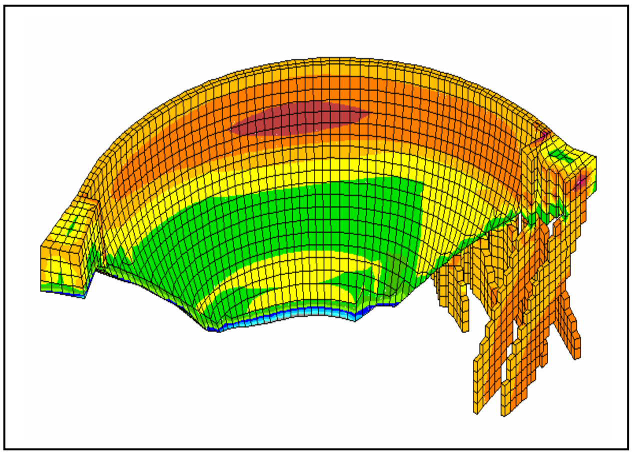

Figure 6. **DAM 3,** Upgraded structure at the left bank

The goals of the seismic risk assessment are to evaluate the probability of failure of a dam for an expected lifetime due to a seismic event, to determine the most critical scenarios of failure, and to prescribe measures for risk reduction. The probability of failure of a dam for an expected lifetime can be obtained from the annual frequency of failure, $ßE$, determined by the relation given in Franzini, et al., 1984:

$$\mathbf{ßE = \int [d[ß(x)]/dx]\ P(f|x)} \tag{1}$$

where $ßE$ is the annual frequency of dam failure due to seismic events; $ß(x)$ is the annual frequency of exceedance of load level x (for example, the variable x may be peak ground acceleration); $P(f|x)$ is the conditional probability of dam failure at a given seismic load level x. The function P is known as a fragility function. The problem requires assessment of the seismic hazard $ß(x)$ and the fragility $P\ (f|x)$.

The probabilistic seismic excitation $ß(x)$ is described by hazard curves obtained from the seismic hazard analysis. The hazard curves show the variation of the ground motion parameter (maximum seismic horizontal acceleration), depending on the frequency of its exceedance. As a result of the seismic hazard analysis, a set of equal hazard acceleration response spectra on the free field of the investigated site are calculated too. The hazard analysis is based on probabilistic models of the site region that describe the occurrence of earthquakes. The hazard models are based on complex analyses of the regional tectonics, review of the historical seismicity, identification of the seismic source zones, development of earthquake recurrence relationships, proper attenuation functions.

A second step in the seismic risk evaluation is the generation of fragility curves for each damage scenario that is assessed as critical for the investigated dam. A fragility curve describes the conditional probability for realization of a particular failure scenario as a function of the used seismic load parameter (peak acceleration). The procedure for the fragility curves' development for dams is described in details in Kostov at al., 1998.

Generally, in the generation of each fragility curve the following steps are considered:

- For each defined seismic hazard level the parameters of the structural response are defined statistically (median values and standard deviation);
- The bearing capacity of the structure should be statistically defined too;
- The conditional probabilities of failure for each seismic level are calculated being discrete values of the fragility curve;
- The generated fragility curve is approximated as a log-normal distribution function.

Finally, the fragility curve is combined with the seismic loading to estimate the annual frequency of realization of each critical scenario. The global risk for the seismically induced dam failure is presented by the scenario with the highest frequency of occurrence.

3. SEISMIC HAZARD ANALYSIS

The seismic hazard analysis procedure proposed by Cornell, 1968 is used to assess the parameters of the probabilistic excitation. The mathematical model of the seismic activity of the site region is defined on the base of the available tectonic, geological and seismological information. The uncertainties in the model related to the natural phenomena (random uncertainties) and the modelling are considered by a set of hypothesis forming the branches of the logic tree. The ground motion attenuation relationships used for the models are based on the analysis of strong motion data records from earthquakes in the Balkan region, Italy, and USA.

The mean, median, 15-th percentile and 85-th percentile hazard curves are computed assuming a lognormal distribution of the peak acceleration at a given annual probability of exceedance. The values of the estimated seismic accelerations for different return periods are given in Table 1. In a similar way the equal hazard response spectra for five hazard levels with different annual probability of exceedance, respectively, are obtained.

Table 1. Hazard seismic absolute accelerations

	Acceleration (g)	**RETURN PERIOD**				
		475	**1000**	**10000**	**100000**	**1000000**
DAM1	Median	0.242	0.303	0.561	0.933	1.430
	15%	0.217	0.273	0.509	0.853	1.310
	85%	0.269	0.338	0.619	1.020	1.550
DAM2	Median	0.0785	0.1130	0.1940	03120	0.4660
	15%	0.0630	0.1040	0.1810	0.2930	0.4390
	85%	0.0977	0.1220	0.2080	0.3320	0.4940
DAM3	Median	0.0893	0.1190	0.2040	0.3270	0.4860
	15%	0.0726	0.1090	01890	0.3010	0.4600
	85%	0.1100	0.1300	0.2190	0.3480	0.5130

4. STATISTICALLY FORMULATED MATERIAL PROPERTIES AND LOADING

4.1. Strength and elastic properties of the materials

The statistical definition of the material properties are carried out based on the processing of available material characteristics: measured in-situ values, archive data (obtained during the construction period), data from the monitoring systems, and data obtained using destructive and non-destructive testing of the structure materials. As an example, for **DAM 1** (see Figure 2) 7 material types are identified; 5 of them describe the concrete zones of the dam body and 2 - the rock foundation. For each material type the mean value and the variation coefficient of the material characteristics (static and dynamic compressive, tensile and shear strength, cohesion, angle of internal friction and elastic module) are determined. For example, for the concrete at the downstream surface of the wall the mean value of the static tensile strength is R_{ts} = 2.60 MPa with variation coefficient V_{ts} = 0.27, the dynamic tensile strength is R_{td} = 3.00 MPa with V_{td} = 0.36; the respective values for concrete of the upstream side of the wall are R_{ts} = 3.56 MPa with V_{ts} = 0.21 and R_{td} = 3.94 MPa with V_{td} = 0.48. The mean value of the dynamic elastic module for the different zones of the wall varies from 15100 to 36300 MPa with variation coefficient V_E = 0.2, Poison ratio μ = 0.29 and volume density, ρ_{cp}, from 2170 to 2350 kg/m^3 with V_d=1,80-3.50%. For the different zones in the rock foundation the material characteristics vary as follow: dynamic elastic modulus – from 31000 to 42000 MPa, the internal friction – from 37.5 to 39.6^o and cohesion – from 0.25 to 0.30 MPa.

4.2. Thermal loads

The thermal distributions in the dam bodies are obtained by transient heat transfer analysis (computer code NISA, 1992) performed for a period of one year. Based on statistical data from long term meteorological observations in the region the mean (normal) site specific temperature is obtained and it is assumed as a mean temperature in the analysis. The variation of the ambient temperature from the mean one is for a year with average amplitude of deviations of the mean month temperatures. The value of the water temperature for each month at different depths of the dam reservoir (0 m., -5 m., -10 m and -15 m) are calculated as average values of the average monthly temperatures from the monitoring records. Typical functions of variation of the ambient and water temperatures, used as analyses' input are shown in Figure 7. As a result from the transient heat analysis the temperature at each point of the dam at any time for the one-year period is determined. The stresses from the thermal loading then are calculated from the temperature difference in adjacent nodes of the structure.

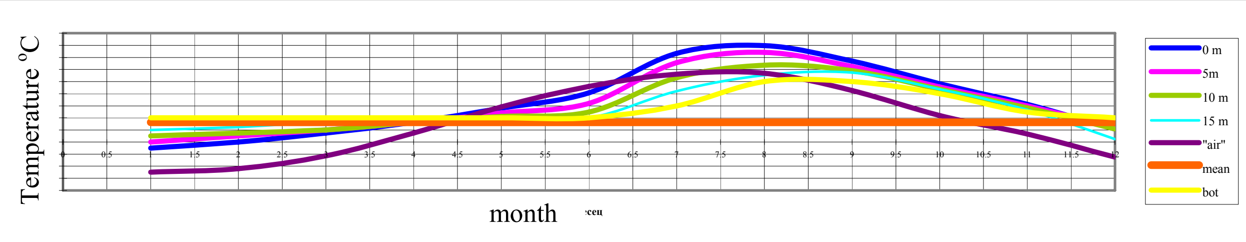

Figure 7. Temperature curves for heat analysis **(DAM 1)**

A set of 10 temperature loadings, calculated from the temperature difference in adjacent nodes of the structure, is generated to be used in the probabilistic analysis. The temperature loadings are uniformly distributed in a one-year period and each loading has equal probability of realization.

4.3. Hydrostatic, hydrodynamic and filtration pressure

Based on the long term observations of the water level in the lakes the median, maximum and minimum water levels as well as their standard deviations were obtained. For the water levels, a uniform distribution around the mean level, normalized between maximum and minimum value, is assumed. The uplift forces, the water pressure on the grouting curtain, the hydrostatic and dynamic pressure are perfectly correlated with the water level. The effects of the hydrodynamic pressure are considered by added masses lumped at the nodal points of the upstream side of the wall. The added water masses are determined by the relationship in Norms for design of buildings and structures in earthquake regions (1987).

4.4. Statistical formulation of the seismic excitation of the dam

For each seismic hazard level the seismic input is presented by a set of acceleration response spectra and the corresponding acceleration time histories. Those spectra are generated based on the statistics of the equal hazard spectra obtained by the seismic hazard analysis. Each one of the generated spectra is used as a target spectrum for generation of acceleration time histories (three statistically independent generations representing two horizontal and one vertical component). The maximum vertical accelerations are obtained by scaling of the horizontal ones with random numbers with mean value of 0.5 (or 0.67) and a standard deviation of 0.3.

5. ASSESSMENT OF THE RESPONSE STATISTICS

5.1. Finite Element Model

To determine the response and to perform statistics of the results complex finite element models of the dam structure with rock foundation are used. The non-linear behaviour of the dam structures is taken into account.

5.2. Probable failure scenarios and controlled parameters of the seismic response of the system "wall-rock foundation"

The probable failure scenarios for different dams depend on their unique characteristics (type and specific geometry of the wall, parameters of the foundation and base rock, dimensions and slenderness of the wall, material characteristics, seismic environment, etc.). For concrete gravity dams the most typical failure modes are connected with the exhausting of the bearing capacity of the wall or foundation. When the material's strengths in respective zones have been exceeded, intensive cracking occurs, and the possibility of dam failure should be estimated depending on the location of the cracked zones, the depth of the cracks in the wall body, and the possibility of the water penetration in the opened cracks. Another typical failure mode for concrete dams is the loss of global stability, horizontal sliding, or overturning of the critical wall blocks. The failure of the arch dams also may be the result of the failure of the supporting end blocks of the wall transferring horizontal forces to the canyon's banks.

5.3. Critical parameters of the dam response

To assess the risk of the seismically induced damage or failure of the concrete gravity and arch dams the following critical parameters are to be controlled:

- Maximum tensile and compressive stresses in the walls and supporting blocks (for arch dams);
- Averaged value of the tensile stresses in the upstream side and the depth of wall cracking;
- Maximal values and concentration of the shear stresses in the body of the walls;
- Shear stresses in the base joint and respectively the horizontal sliding force;
- Normal stresses in the base joint and respectively the resistance against the horizontal sliding.
- Maximum values of the dam overturning and resisting moments

5.4. Computational Procedure

The multiple deterministic analyses are performed with computer code NISA (1992) and Stardyne 4.0. The computational procedure is based on an advanced Monte Carlo method (Latin Hypercube Experimental Design, LHCED) for simulation. The main steps of the computation are as follows:

- Preparation of input variable samples by Latin Hypercube Experimental Design procedure;
- Computation of stresses due to static and dynamic loads;
- Stress superposition;
- Evaluation of the critical zones and the maximum values of the control parameters;
- Statistics of the results.

The computational procedure and application of the LHCED procedure, Iman & Conover., 1981, to set the input variables contributing to the response of the dam are described in details in Kostov at al. (1998). The procedure is applied for each of the accepted levels with annual probability of exceedance 0.00211, 10-3, 10-4, 10-5 and 10-6. The results for each safety level are statistically processed separately.

5.5. Statistics of the results

For the statistical processing of the response, a normal distribution of response parameters is assumed. The mean values and the standard deviation of the generated response quantities for the controlled parameters for each critical zone are estimated. The mean values and the respective standard deviation of the tensile zone length in the base joint of the wall for all seismic loading levels are computed as well.

5.6. Conditional probability of failure due to seismic excitation

The probability of failure expressed by the annual probability of occurrence of the investigated scenario is computed under the assumptions that the load and the resistance (strength) are log-normally distributed. The conditional probability of failure is computed by the expression:

$$\mathbf{P_f= \int FR(x)fL(x)dx} \tag{2}$$

where FR(x) is the resistance distribution function and fL(x) is the density function of the seismic loading.. For each failure scenario the conditional probabilities of failure for each investigated seismic level are calculated and a fragility curve for the particular scenario (conditional probability of failure vs PGA) is generated. The fragility curve is obtained from the computed discrete values of the conditional probabilities for each seismic level. For this purpose the function that passes through those discrete values is approximated with cumulative log-normal distribution functions. The approximation is done by the least square method.

6. GLOBAL SEISMIC RISK ASSESSMENT

6.1. Seismic risk

The risk for seismic failure of the studied dams, expressed as annual probability of occurrence of the most critical failure scenarios, is calculated by integration of the hazard curves together with the specific fragility curves. The LHCED procedure is applied for the integration in order to take into account the uncertainties in the hazard assessment and in the conditional probability of failure (fragility curves). Samples of size 10 are used. The seismic hazard curves are generated in such a way that their mean value and standard deviation correspond to the mean values and standard deviations of the peak ground accelerations on the site for different annual probability of exceedance. In Table 2 there is a presentation and comparison of the values of the estimated seismic risk for the investigated dams, expressed in two ways: as annual probability of occurrence of the most critical failure scenarios considered, calculated with 85% confidence level and calculated as probability of failure for a 50 year operational life of the facility.

Table 2. Estimated seismic risk

№	**Scenarios**		seismic risk	
			in 50 years	annual
1.	Damages due to the exceedance of the tensile strength of the concrete in the upstream side of the wall	DAM 1	*0,00720*	*1.46E-4*
		DAM 2	*0.00068*	*1.36E-5*
		DAM 3	*0.00163*	*3,28E-5*
2.	Damages in the wall due to the exceedance of the critical length of the tensile zone in the upstream side of the wall	DAM 1	*0.07045*	*1.46E-3*
		DAM 2	*0.01055*	*2.12E-4*
		DAM 3	*0.00083*	*1,67E-5*
3.	Damages in the wall due to loss of global stability – horizontal sliding	DAM 1	*0.00643*	*1.29E-4*
		DAM 2	*0.00061*	*1.23E-5*
		DAM 3	*0.00008*	*1.61E-6*
4.	Damages due to the deep sliding of the supporting blocks	DAM 3	*0.00016*	*3,26E-6*
5.	Damages in the wall due to loss of global stability – overturning of the wall	DAM 1	*0.09343*	*1.96E-3*
		DAM 2	*0.000689*	*1.38E-5*
6.	Damages due to the development of non linear deformations in the wall concrete or rock foundation	DAM 2	*0.000624*	*1,25 E-5*
		DAM 3	*0.000053*	*1,06E-6*
7.	Local damages in bridge structure above the spillway	DAM 2	*0.027862*	*5,65E-4*

The acceptable levels of the seismic risk for large dams are not fixed directly into the regulations and should be estimated case by case in dependence of the structure's importance. One possible approach to assess the acceptability of the calculated seismic risk is to compare the calculated values with the limits assessed for other important industrial facilities, e.g. nuclear power plants. For non critical structures the probability of exceedance of the design seismic excitation considered in the national code is 5% for a 50 years operational life.

The analysis of the estimated global seismic risk shows that:

- The most probable failure scenario for DAM 1 and DAM 2 is the loss of global stability. The estimated annual values of the global seismic risk are 1.96E-3 for DAM1 and 1.23E-5 for DAM2.
- The most probable failure scenario for DAM 3 (concrete arch dam) is the deep sliding in the rock foundation of the supporting blocks. The annual probability of failure value is 3, 26E-6.
- The global seismic risk for DAM 2 and DAM 3 can be estimated as acceptable. The calculated values are comparable to the seismic risk estimated for the safety related elements of nuclear power plants and the facilities can be used without any limitations.
- The global risk for seismically induced loss of global stability for DAM 1 is rather high. The probability of occurrence of this scenario is about 0.1 for a period of 50 years. Based on the results, a seismic upgrading of the dam global stability has been recommended.
- Other scenarios with high probability for occurrence are those connected with the exceedance of the tensile strength of the concrete or the exceedance of the length of the tension zone in the dam wall. Those scenarios may not cause a complete dam failure. Only their simultaneous action could be dangerous for the dam stability. In this case, if they are considered to act together, the respective probability of occurrence should be reduced significantly and would be within the acceptable limits.

6.2. Sensitivity analysis

To assess the influence of the uncertainties of the input data on the seismic risk and to estimate maximum probable values, a sensitivity analysis is performed. The influence of the uncertainties of material strength characteristics, of the seismic hazard parameter variation, etc. on the results is studied.

The influence of the model uncertainties on the values of the global seismic risk can be assessed by varying the number of the particular LHCED combination of system parameters used in the statistical processing of the results. Usually 10 runs are enough to obtain statistically confident results. Further increase of the run number leads to minimal changes in the median value of the system response parameters. At the same time, the greater number of realizations reflects in the minimization of the standard deviation in the results and leads to more favourable results for the seismic risk. The number of realizations applied in the reported studies (10) is enough for good assessment of the median values of the response parameters and implements acceptable conservatism in the assessment of their standard deviation and, respectively, in the calculated global seismic risk. The assessment of the influence of the uncertainties in material strength parameters and seismic input is performed for central values of the seismic risk (these with 50% probability of exceedance). The sensitivity analysis for uncertainties of the seismic hazard and strength parameters is performed for the following cases:

- 30% decrease of the strength parameters of the concrete and base rock;
- 30% decrease of the mean values of the hazard acceleration curves;
- Simultaneous influence of the material strength parameters reduction and increase of the seismic hazard is studied as the most unfavorable combination.

The results of the sensitivity analysis for the probable failure scenarios for DAM3 are shown in Table 3.

Table 3 Seismic risk (total probability of occurrence per year), sensitivity analysis

№	Scenarios	Seismic risk			
		mean	**+ 30% seis. hazard**	**-30% strength parameters**	**simult. action**
1.	Damages due to the exceedance of the allowable tensile stresses in of the upstream side of the wall;	*1,89E-5*	*6.13 E-5*	*9.45 E-5*	*2.96 E-4*
2.	Failure due to the sliding of the right supporting block	*1,63E-5*	*5.65 E-5*	*8.57 E-5*	*2.72 E-4*
3.	Failure due to the sliding of the left supporting block	*1,33E-5*	*4.51 E-5*	*6.99 E05*	*2.32 E-4*
4.	Damages due to the occurrence of critical crack	*9,28E-6*	*3.40 E-5*	*5.36 E-5*	*1.75 E-4*

CONCLUSION

The values of the total probability of failure for DAM 2 and DAM 3 can be considered as low. It is of the same order of magnitude as the seismic risk of a critical structure in a nuclear facility. The probability for seismically induced loss of global stability for DAM 1 is rather high. Measures for upgrading to enhance the dam stability have to be implemented or the maximum exploitation water level in the dam reservoir shall be lowered.

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