SEISMIC RISK ASSESSMENT FOR LARGE DAMS

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ABSTRACT:

In the recent 50 years many dams have been constructed in Bulgaria. Almost all of them are situated in regions with high and moderate seismicity. The regulations and codes that have been in force during the design and construction of the structures differ considerably from the present norms. Because of a great difference between the initial seismic design loads and the present code requirements a realistic analysis should be performed to take into consideration all capacity reserves of the structures. In the proposed paper are presented and discussed the results of the probabilistic seismic safety assessments for several concrete gravity and arch dams carried out during the last years. The basic ideas of the methodology initially developed to perform PSA for Nuclear Power Plants are applied to assess the seismic risk for large critical dams. The obtained results are based on a realistic assessment of the seismic hazard for the region, statistically defined material properties and loads. For assessment of the statistical characteristics of structural behaviour under seismic excitation the “Latin Hypercube Experimental Design” (LHCED) procedure is used. The most dangerous dam failure scenarios for different types of dams are defined and investigated. The global seismic risk for each structure is estimated and discussed.

1 INTRODUCTION

The three dams under consideration have been constructed and finished from 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 the investigated dams are of concrete gravity type and the third is a gravity-arch dam. They are located in areas with strong and moderate seismicity. In the presented paper is analyzed only the risk of seismically induced failure of the dam walls. The evaluation of the secondary risk due to flooding of the facilities and inhabited areas located downstream the dams is not an object of this study.

1.1 Global description of DAM 1

The dam is constructed, as a typical concrete gravity dam, and is located in high mountain valley formed by glacier’s activity. The main purposes of the dam are to regulate the water supply system of Sofia water supply as well as electricity generation. The hydropower complex includes dam wall and reservoir, hydropower plant, water catchments and pressurized derivation tunnels. The maximal storage volume of the dam is 15.3 million m³. The length of the chest is 533 m with maximal height of the wall - 50.7 m. The upstream face of the wall is practically vertical with inclination 1:0.03. The downstream face is relatively steep with inclination 1:0.683. The wall is constructed from 35 separated blocks. The thickness of the crest is 3.4 m and the maximum dimension of the bottom of the wall is 36.40 m. In the seismic risk analysis 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 Fig.1 and Fig.2.

Despite the fact that the dam is situated in a highly seismic region the structure is relatively slender because of the lack of seismic regulations during its design and construction.
1.2 Global description of DAM 2

The hydro complex is situated in a relatively low hilly region in the southern part of the country. The main purpose of the structure is power generation and regulation of the seasonally high water discharges. The hydropower complex includes dam wall and reservoir, hydropower plant, pressure tunnel, spillways and falling gates, situated in the upper part of the dam blocks with spillways.

The dam wall is concrete gravity type with maximal height 67.50 m. The maximal storage volume of the reservoir is about 380 million m$^3$. The wall is constructed of 25 blocks with 13 m width each and two end blocks with width of 6.5 m. The total length of the crest is 338.00 m. The spillway is situated in the middle of the wall. 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 inclination 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 Fig.3 and Fig.4. The seismicity of the region is assessed as moderate.

1.3 Global description of DAM 3

The hydro complex was built in the southern part of the country. The main purpose of the complex is electric power generation. The main parts of the complex are dam wall, main outlet, spillways, and hydropower plant. 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 a part of a vertical cylinder and the downstream face is shaped by circle curves with different radii. The wall is constructed from 21 separated blocks. The thickness of the crest is 5.0 m and the maximum dimension
of the bottom of the wall is 31.60 m. The arch wall is supported by two blocks that are founded in the slopes of the natural terrain. The general view of the 3D FEM of the wall is given in Fig. 5.

During the construction works rock zones with decreased bearing capacity were encountered in the zone where the left supporting block had to be founded. That led to implementation of the additional upgrading measures in the left bank of the river. To strengthen the rock strata under the left supporting block of the wall 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 Fig. 6. The seismicity of the region is assessed as moderate.

2 BASIC PROCEDURE

The basic ideas of the procedure for performing a Probabilistic Safety Analysis (PSA) of critical structures (NUREG/CR-2300, 1983) used in the nuclear industry are applied hereafter for a large dam structures. The general formulation is presented in Franzini, et al. 1984. The presented method has been further developed and based on the principles, methods, and techniques used in the probabilistic safety assessment of structures (Borges & Kastaneta 1971, Ang & Tang 1984, Murzeweski 1974, Lomnitz & Rosenblueth 1976, Bolotin 1979). This procedure was applied in the seismic PSA of several large dams in Bulgaria.

The aim of the seismic risk assessment is to evaluate the probability of failure of the dam for the expected lifetime of the structure due to seismic initiating events, to determine the most critical scenarios of failure and most critical sections in the dam structure and finally to prescribe measures for risk reduction. The probability of failure of the dam for the expected lifetime can be obtained from the annual frequency of failure, $\beta E$, determined by the relation (Franzini, et al., 1984):

$$\beta E = \int [d(\beta(x))/dx] P(f|x) \, dx$$

where $\beta E$ is the annual frequency of dam failure due to seismic events, $\beta(x)$ 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 $\beta(x)$ and the fragility $P(f|x)$.

The probabilistic seismic excitation $\beta(x)$ is described by hazard curves obtained from probabilistic seismic hazard analysis. The hazard curves show the variation of the selected 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 the use of
probabilistic models of the site region that describe the occurrence of earthquakes. The hazard models are based on complex analyses including description of regional tectonic, review of historic seismicity, identification of seismic source zones, and development of earthquake recurrence relationships.

The second step for the seismic risk evaluation is the generation of the fragility curves for each damage scenario that is assessed to be critical for the investigated structure. The fragility curve describes the conditional probability for realization of the particular failure scenario as a function of the chosen seismic load parameter (seismic peak ground acceleration). The procedure for obtaining the fragility curves for the dam is described in details in (Kostov et al., 1998).

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

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

Finally each 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 OF THE SITE

The seismic hazard analysis procedure proposed by Cornell, 1968 is used to assess the parameters of the probabilistic seismic excitation. The mathematical model of the seismic activity of the regional surrounding of the site is defined on the base of the available tectonic, geological and seismological information. The uncertainties in the mathematical 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 countries, Italy, USA.

From the discrete distributions of frequency of exceedance for various levels of maximum acceleration the mean, median, 15th-percentile and 85th-percentile hazard curves are computed assuming 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 A, B, C, D and E, with annual probability of exceedance 0.00211, 0.001, 0.0001, 0.00001 and 0.000001, respectively, are obtained.

Table 1 Hazard seismic absolute accelerations

<table>
<thead>
<tr>
<th>Acceleration (g)</th>
<th>RETURN PERIOD (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>475</td>
</tr>
<tr>
<td>DAM1</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.243</td>
</tr>
<tr>
<td>Median</td>
<td>0.242</td>
</tr>
<tr>
<td>15%</td>
<td>0.217</td>
</tr>
<tr>
<td>85%</td>
<td>0.269</td>
</tr>
<tr>
<td>DAM2</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.0804</td>
</tr>
<tr>
<td>Median</td>
<td>0.0785</td>
</tr>
<tr>
<td>15%</td>
<td>0.0630</td>
</tr>
<tr>
<td>85%</td>
<td>0.0977</td>
</tr>
<tr>
<td>DAM3</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.0912</td>
</tr>
<tr>
<td>Median</td>
<td>0.0893</td>
</tr>
<tr>
<td>15%</td>
<td>0.0726</td>
</tr>
<tr>
<td>85%</td>
<td>0.1100</td>
</tr>
</tbody>
</table>
4 STATISTICALLY FORMULATED MATERIAL PROPERTIES AND LOADING

4.1 Strength and elastic properties of the materials

The statistical definition of the material properties was carried out based on the processing of the available data concerning characteristics of the materials - measured in-situ values, archive (obtained during the construction of the dam), data from the monitoring systems and data obtained using destructive and non-destructive testing of the structural materials. As an example, for DAM1 were identified 7 material types (see Fig.2) – 5 of them describe the concrete zones of the dam body and 2 - for the rock foundation. For each type of material the mean value and the variation coefficient of the material characteristics (static and dynamic compression, tensile and shear strength, cohesion, angle of internal friction and the 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 \( R_{ts} = 2.60 \text{ MPa} \) with variation coefficient \( V_{ts} = 0.27 \), of the dynamic tensile strength \( R_{td} = 3.00 \text{ MPa} \) with \( V_{td} = 0.36 \); the respective strengths of the concrete of the upstream side of the wall are \( R_{ts} = 3.56 \text{ MPa} \) with \( V_{ts} = 0.21 \) and \( R_{td} = 3.94 \text{ MPa} \) with \( V_{td} = 0.48 \). The mean value of the dynamic elastic module for different zones of the wall varies from 15100 to 36300 MPa with variation coefficient \( V_E = 0.2 \), Poison ratio \( \mu = 0.29 \) and volume density - \( \rho \) - from 2170 to 2350 kg/m\(^3\) with \( V_d = 1.80 \)-3.50%. For different zones of 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\(^\circ\) 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 this temperature is assumed as the mean temperature in the heat 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 meteorological records. Typical functions of variation of the ambient and water temperatures, used as input in the analyses 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 thermal loading then are calculated from temperature difference in adjacent nodes of the structure.

![Temperature curves for heat analysis (DAM1)](image)

A set of 10 temperature loadings, calculated from temperature difference in adjacent nodes of the structure, is generated to be used in the probabilistic analysis. The temperature loadings are uniformly distributed in 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 reservoirs the median, maximum and minimum water levels as well as its standard deviation were calculated. A uniform distribution is assumed for the water levels around the mean level, normalized between maximum and minimum value. The uplift forces, the water pressure on the grouting curtain, the hydrostatic and the hydrodynamic pressure are assumed to be perfectly correlated with the water level. The effects of the hydrodynamic pressure study are considered by added masses lumped at the nodal points of the upstream face of the dam 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 on the dam

For each seismic hazard level (A, B, C, D and E) the seismic loading is presented by a set of acceleration response spectra and the corresponding acceleration time histories. Those spectra are generated on the base of 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 three components - two horizontal $H_1$ and $H_2$ and one vertical $V$). The maximum accelerations of the vertical components are obtained from the horizontal ones by scaling with random numbers with mean value of 0.5 (or 0.67) and 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 dam wall, parameters of the wall foundation and base rock, dimensions and slenderness of the wall, characteristics of the used materials, seismic environment, etc.). For concrete gravity dams the most typical failure modes are connected with the exhausting of the bearing capacity of the materials of wall or foundation. When the strength of the materials in respective zone has been exceeded the intensive cracking occurs and possibility for dam failure should be estimated in dependence on the location of the cracked zones, on the depth of the cracks in the wall body and on the possibility of the water penetration in the opened cracks. Other typical failure mode for concrete dams is the loss of global stability – horizontal sliding or overturning of the parts of the wall. The failure of the arch dams also may be result of the destruction of the supporting end blocks of the wall transferring horizontal forces to the banks of the canyon.

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 controlled:

- Maximal values of the tensile and compressive stresses in the both sides of the walls;
- 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;
- Maximal values of the tensile and shears stresses in the supporting blocks (for the arch dam);
- Maximal values of shear stresses in the base joint and control of the horizontal sliding force;
- Maximal values of the normal stresses and control of the resistance against the horizontal sliding.
- Maximum values of the dam overturning and resisting moments
5.4 Computational Procedure

The deterministic analyses are carried out by the computer code NISA (1992) or 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.

In details the computational procedure and applying of the LHCED procedure (Iman & Conover, 1981) to set the input variables contributing to the response of the dam structure are described in detail in Kostov et al. (1998).

The procedure is applied for each of the accepted five levels with annual probability of exceedance 0.00211 (level A), 10-3 (level B), 10-4 (level C), 10-5 (level D) and 10-6 (level E). The results for each safety level are statistically processed separately.

5.5 Statistics of 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 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 events

The probability of failure expressed by the annual probability of occurrence of 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:

$$P_f = \int FR(x)f_L(x)dx$$  \hspace{1cm} (2)

where $FR(x)$ is the distribution function of the resistance and $f_L(x)$ is the density function of the seismic loading distribution. For each failure scenario the conditional probabilities of failure for each investigated seismic level are calculated and respectively the fragility curve for the particular scenario (conditional probability of failure vs PGA for each seismic level) is generated.

6 GLOBAL SEISMIC RISK ASSESSMENT

6.1 Seismic risk

The risk for seismically induced failure of the investigated dams expressed as annual probability of occurrence of the most critical failure scenarios is calculated by integration of the seismic hazard curves together with the specific fragility curves 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.

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 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 are presented and compared the values of the estimated seismic risk for the investigated dams, expressed in two ways: as annual probability of occurrence for the most critical failure scenarios considered calculated with 85% confidence level as well as probability of failure for 50 year exploitation life of the facility.

The secondary risk for the facilities and inhabited areas located downstream the dams is not considered in this seismic risk assessment.
Table 2 Estimated seismic risk

<table>
<thead>
<tr>
<th>No.</th>
<th>Scenarios</th>
<th>seismic risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>in 50 years</td>
</tr>
<tr>
<td>1.</td>
<td>Damages due to the exceedance of the tensile strength of the concrete in</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the upstream side of the wall</td>
<td>DAM 1 0.00720</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAM 2 0.00068</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAM 3 0.00163</td>
</tr>
<tr>
<td>2.</td>
<td>Damages in the wall due to the exceedance of the critical length of the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tensile zone in the upstream side of the wall</td>
<td>DAM 1 0.07045</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAM 2 0.01055</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAM 3 0.00083</td>
</tr>
<tr>
<td>3.</td>
<td>Damages in the wall due to loss of global stability — horizontal sliding</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAM 1 0.00643</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAM 2 0.00061</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAM 3 0.00008</td>
</tr>
<tr>
<td>4.</td>
<td>Damages due to the deep sliding of the supporting blocks</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAM 3 0.00016</td>
</tr>
<tr>
<td>5.</td>
<td>Damages in the wall due to loss of global stability — overturning of the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>wall</td>
<td>DAM 1 0.09343</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAM 2 0.00069</td>
</tr>
<tr>
<td>6.</td>
<td>Damages due to the development of non linear deformations in the wall</td>
<td></td>
</tr>
<tr>
<td></td>
<td>concrete or rock foundation</td>
<td>DAM 2 0.00062</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAM 3 0.00005</td>
</tr>
<tr>
<td>7.</td>
<td>Local damages in bridge structure above the spillway</td>
<td>DAM 2 0.027862</td>
</tr>
</tbody>
</table>

The acceptable levels of the seismic risk for large dams are not fixed directly into the normative regulations and should be estimated case by case in dependence of the structural 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 as critical structures of the nuclear power plants. As a higher possible value of the possible seismic risk (applicable for non critical structures) the probability of exceedance of the design seismic excitation considered in Bulgarian national regulation which is 0.05 for 50 years exploitation life may be accepted.

The analysis of the estimated global seismic risk shows that:

- The most probable failure scenario for DAM1 and DAM2 is the loss of global stability. The estimated 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 value of the seismic risk 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 safety related elements of nuclear power plants and the facilities can be exploited 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 in period of 50 years. Based on the results of deterministic check of the dam safety (according the actual codes) and calculated global seismic risk a seismic upgrading to enhance the dam global stability has been recommended and designed.
- Other scenarios with high probability for realization are the exceeding the tension strength of the concrete or the exceeding the tension zone length. Examine them one after another they are not able to cost the serious dam failure. But they are dangerous for the dam stability if they act simultaneously, however if they are considered to act together, their probability is reduced significantly and is in acceptable limits.

6.2 Sensitivity analysis

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

The influence of the model uncertainties on the values of the global seismic risk can be assessed by varying of the number of the particular LHCED combination of system parameter 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. From the other side the greater number of realizations reflects in the minimization of the standard deviation of the result and leads to more favourable results for the seismic risk. The number of realization 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 (tensile strength, cohesion and angle of internal friction) 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 the probable failure scenarios for DAM3 are shown in Table 3.

### Table 3 Seismic risk (total probabilities of occurrence per year) - sensitivity analysis

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Seismic risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
</tr>
<tr>
<td>1. Damages due to the exceedance of the allowable tensile stresses in of the upstream side of the wall;</td>
<td>1.89E-5</td>
</tr>
<tr>
<td>2. Failure due to the sliding of the right supporting block</td>
<td>1.63E-5</td>
</tr>
<tr>
<td>3. Failure due to the sliding of the left supporting block</td>
<td>1.33E-5</td>
</tr>
<tr>
<td>4. Damages due to the occurrence of critical crack</td>
<td>9.28E-6</td>
</tr>
</tbody>
</table>

6.3 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. The measures for seismic upgrading to enhance the dam global stability have to implemented or the exploitation water level in the dam reservoir shall be lowered.

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