PROBABILISTIC SEISMIC RISK ASSESSMENT OF CONCRETE GRAVITY DAMS

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ABSTRACT

Slovenia is located in active seismic region with a moderate seismic hazard, where strong earthquakes up to a magnitude of 7 are anticipated. It is well known that such earthquakes can cause damage of concrete gravity dams and consequently direct and indirect losses. However, question arises whether the risk for such losses associated with future earthquakes is tolerable or not? The answer on this question is not trivial, since the seismic risk assessment of structures is highly uncertain. Therefore the problem has to be treated in a probabilistic manner, which provides information for well-informed decision making. Herein the practice-oriented procedure for seismic risk assessment of structures is briefly described and demonstrated by means of an example of a concrete gravity dam. The seismic risk assessment of the investigated dam was performed in the preliminary design phase for the purpose of environmental impact assessment of such facility. In the paper an emphasis is given on the interpretation of results in order to distinguish between the results based on this study and those from intensity-based seismic performance assessment of structure, which is currently prescribed in codes and guidelines for seismic-resistant design of structures.

1. Introduction

Seismic resistance of concrete gravity dams is in general greater than that of other common types of dams or structural systems. Their massive and compact structure provides large structural stability, making an instantaneous collapse due to earthquake loading practically impossible. For example, just two of the 18 spillways of the Shih-Kang concrete gravity dam collapsed during the 1999 Chi-Chi earthquake (M=7.3) due to the extremely large fault movements [1]. Collapse of concrete gravity dams is therefore not instantaneous, which may help to mitigate a disaster of high proportions in the case of major earthquake. However, for earth gravity dams an instantaneous collapse was observed. The biggest disaster caused by dam failure probably happened in China in 1975. The collapse of earth dam Banqiao caused deaths of 26000 people and indirectly additional 145000 due to famine and epidemics. More than 6 million buildings were destroyed. The cause of collapse was erosion of the dam as a consequence of extreme weather conditions. The water spilled over the crest of the dam causing erosion and consequently collapse. Such failure mode is impossible in the case of concrete gravity dams.

Significant damage of concrete gravity dams due to earthquakes is rarely observed. Strong earthquake that may cause considerable damage to concrete gravity dams usually cause many fatalities which are not a consequence of the collapse of a dam, but are the ordinary buildings which collapse for such strong earthquakes. This happened in the case of the 2008 Sichuan earthquake. The earthquake had a magnitude of 7.9 MMS and caused the death of more than 80000 people. A number of concrete dams were built in the area and some of them were seriously damaged. Despite the formation of large cracks, none of the dams collapsed, neither a significant spill of water was observed. Therefore the victims and the damage on surrounding buildings were not caused due to failure of dams. It should be mentioned that an earthquake of such magnitude is not likely to occur in Slovenia. For example, during the 2008 Sichuan earthquake approximately a thousand times larger amount of energy was released comparing to 1998 earthquake in Posočje.

Still, earthquakes can cause damage on concrete gravity dams and consequently direct and indirect economic losses. From that point of view, seismic performance assessment and design of concrete gravity dams should be well regulated, which cannot be claimed for the case in Slovenia. According to Humar and Kryžanowski [2], the field of seismic monitoring is fairly well covered by the Rules on the monitoring of seismicity, but there are no provisions that would bind the seismicity monitoring operator to perform the analysis of results of seismic measurements and the drawing up of the assessment of dam safety.

Therefore a question arises whether the seismic risk for losses due to damage or collapse of concrete gravity dams in Slovenia is tolerable or not? Several approaches are available to assess the seismic safety of concrete gravity dams (e.g. [3]), but, in general, the assessment of seismic safety is associated with uncertainties which are of aleatoric (e.g. ground motions) or epistemic nature (lack of knowledge). Therefore the problem should be treated in a probabilistic manner.

A brief overview of simplified seismic risk assessment methodology and the description between the deterministic intensity-based assessment (or design) and probabilistic seismic risk assessment of structures is firstly presented in the paper. The methodology, which could be used in practice to assess seismic risk of existing or newly designed concrete gravity dams, is then demonstrated by means of an example of concrete gravity dam Učja.

2. Overview of simplified seismic risk assessment of structures

The seismic risk assessment is a complex problem, which combines seismic hazard analysis, structural vulnerability and socioeconomic impacts of earthquakes. Each analysis is associated with many uncertainties. Therefore, the problem of seismic risk assessment can be effectively solved by using probabilistic methods, since only this approach guarantee systematic incorporation of uncertainties, which arise from the input data of the built environment and from the seismic hazard, damage, and loss models. The result of evaluation of seismic risk is the probability of certain damage to structures and the risk, which in general can be expressed as expected number of people injured, or by direct and indirect financial losses.

In the simplified approach, the seismic risk is communicated by the mean annual frequency of exceeding designated limits state. The reciprocal of the mean annual frequency of limit-state exceedance is the mean return period (or simply the return period) of the limit state, e.g. the return period for concrete crack in the concrete gravity dams due to earthquakes. A probabilistic framework seismic design and assessment of structures, which can also be applied to concrete gravity dams, was proposed by Cornell et al. [4]. Authors have shown that in the case if seismic hazard is idealized in the form

$$\tilde{H}(a_g) = k_0 \cdot (a_g)^{-k} \tag{1}$$

where k_0 is the intercept point and k is the slope of the hazard curve expressed in log-domain, and if the relationship between the intensity measure (e.g. maximum peak ground acceleration) and the demand (e.g. displacement) is idealized with the power form,

$$\tilde{D}(a_g) = a \cdot (a_g)^{b} \tag{2}$$

which have parameters *a* and *b,* then the mean annual frequency of exceeding a limit state can be expressed in closed form

$$P_f = \tilde{H}(a_g^{\tilde{C}}) \cdot \exp\left[\frac{1}{2}\beta_H^2 + \frac{k^2}{2b^2}\left(\beta_{DR}^2 + \beta_{CR}^2 + \beta_{DU}^2 + \beta_{CU}^2\right)\right] = \tilde{H}(a_g^{\tilde{C}}) \cdot C_f \tag{3}$$

where $\tilde{H}(a_g^{\tilde{C}})$ is the median value of the hazard function at the seismic intensity $a_g^{\tilde{C}}$, which causes damage associated with a designated limit state, β_H is dispersion in log-domain for seismic hazard, β_{DR} in β_{CR} are the dispersion measures for randomness in the demand and capacity, and β_{DU} in β_{CU} are the dispersion measures for uncertainty in the demand and the capacity associated with the limit state of interest. For a practical application, the dispersion measures β have to be predetermined based on parametric studies for typical structural systems. These values can then be defined in regulatory guide.

Risk-based assessment is possible if, seismic response analysis and seismic hazard is obtained for a multiple levels of peak ground accelerations. Detailed seismic hazard analysis has to be made for a region where the structure is located. In Slovenia, there is a lack of data regarding the seismic hazard analysis for a multiple levels of return period. However, for a practical application the approximate hazard curve (Eq.(1)) can be obtained from the hazard maps for two return period, e.g. for 1000 and 10000 years. Based on such simplifications, seismic response analyses of a structure becomes a key component of the proposed simplified risk assessment in order to assess the relationship between the peak ground acceleration and the median demand associated with the capacity. Since limit states are often defined on the basis of structural damage, the nonlinear methods and models should be used to estimate $a_g^{\tilde{C}}$.

The proposed approach for assessment of concrete gravity dams is therefore based on simulations of seismic response of such structures, which should be as realistic as possible. The result is the mean annual frequency (reciprocal of return period) of exceeding designated limit state which can be directly compared with the tolerable return period for a limit state, such as cracking of concrete, sliding of dam for a given threshold value, or others limit state of interest.

The proposed risk-based assessment is different in comparison to the traditional intensity-based design or assessment. Traditionally, the design seismic action is defined for a certain return period of earthquake, and the analyst have to perform a series of design check, which incorporate a certain level safety factor. It is argued that the proposed simplified seismic risk assessment has advantages in comparison to traditional intensity-based assessment, since the proposed procedure allows well-informed decision making, which cannot be claimed in the case of intensity-based assessment, since the factors of safety are implicitly embedded in the methodology.

3. Example of application

3.1 Description of the dam and design parameters

The proposed methodology is demonstrated by means of an example of concrete gravity dam (Figure 1). The dam was investigated for a purpose of the environmental impact assessment [5]. Herein it is shown how the risk can be communicated to the stakeholders if seismic performance assessment is based on the probabilistic approach. For a comparison reasons, the results of performance assessment using intensity-based approach are also presented.

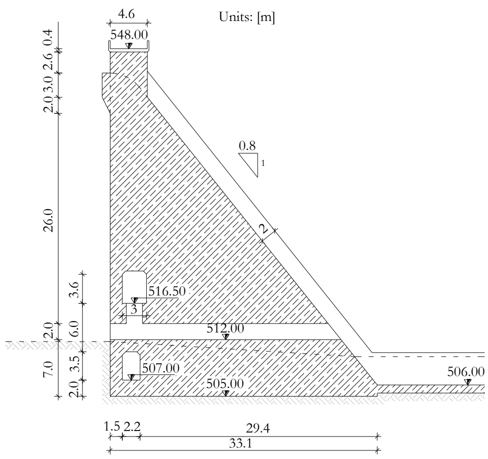

Figure 1: Cross-section of the dam.

In preliminary design phase the concrete C20/25 [6] was assumed. The corresponding median compressive and tensile strengths was equal to, respectively, 28 MPa and 2.2 MPa. Based on the site investigations it was assumed that the concrete gravity dams, which was a subject of investigation, has a foundation on the rock with elastic modulus and Poisson ratio equal to E=5000 MPa and 0.2, respectively [7]. The earthquake load was simulated by three generated accelerograms in horizontal and vertical directions, which were modified to match the target Eurcode's acceleration spectra for soil type A (rock). Generated ground motions were based on recorded ground motion from the Friuli (1976) and Montenegro (1979) earthquakes. The seismic hazard was defined with a mean seismic hazard curve (Figure 2) [8].

Other actions on dam, which were considered in the evaluation, were self-weight, hydrostatic pressure at the upstream face and uplift pressure at the bottom of the dam.

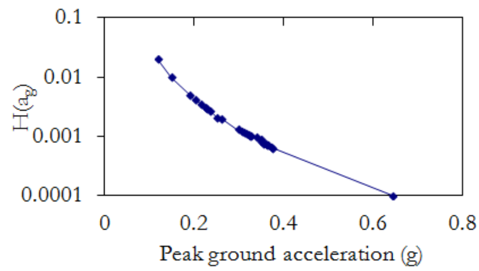

Figure 2: Seismic hazard curve.

A simple 2D nonlinear structural model was created for the purpose of preliminary design. It consisted of elastic shell elements and soil springs in vertical and horizontal directions to simulate soil-structure interaction [9]. The vertical springs carried loads only in compression, whereas the nonlinear horizontal springs were used to simulate slip of dam due to ground shaking. The coefficient of friction between dam and underlying rock was assumed 1.0 [10-12]. Two types of boundary conditions were assumed in order to achieve the worst case scenario for simulation of slipping and overturning of the dam. Such approach was used since the detailed cross-section of the dam was not known in preliminary design phase. In the first case, the dam was restrained only with the horizontal springs of which resistance against slipping were modelled by the friction force. The second boundary conditions were used to simulate deeper toe of the dam, which prevents slipping but consequently increase the risk for uplifting. In this model the dam was restrained at dam toe against slipping.

In both models the uplift pressure at the upstream face was assumed equal to the hydrostatic water pressure at the bottom of the reservoir. The uplift pressure was reduced below injection gallery to one-third of the maximum value, and dropped to zero at the downstream side of the dam. The mass was calculated taking into account the mass of the dam and additional mass at the upstream face due to dynamic effect of the reservoir in according to Westergaard [13,14].

The seismic performance assessment was evaluated for the limit state of concrete cracking, slip and overturning. These limit states were controlled using approximate threshold quantities associated with each limit state. It was assumed that the limit state of concrete cracking was violated if tensile strength of concrete was exceeded at about 10% of the area of selected horizontal cut of the cross-section. The threshold slip of dam was assumed at 10 cm of horizontal slip of dam. Three criteria were used for definition of the third limit state (overturning): (1) maximum vertical movement of the dam at the upstream bottom corner exceeded 5 cm, (2) the uplift of the entire dam observed during the seismic analysis, and (3) exceedance of the strength of the concrete observed at the major part of the selected section.

3.2 Seismic performance assessment according to intensity-based approach

The dam was analyzed using deterministic intensity-based approach for an earthquake with return period of 475 years. Corresponding peak ground acceleration amounted to 0.25 g and 0.225 g in horizontal and vertical direction, respectively. The results of nonlinear dynamic analysis for the three ground motions are presented in Figures 3–5. It can be observed that there is no danger for exceeding the threshold associated with overturning of the dam (Figure 3), but in the case of design earthquake with return period of 475 years the dam can slip up to around 5 cm (max. 4.9 cm, Figure 4). The principal stresses did not exceed the estimated tensile strength of the concrete (Figure 5). This means that cracking of concrete is not expected in the case of the earthquake with return period of 475 years.

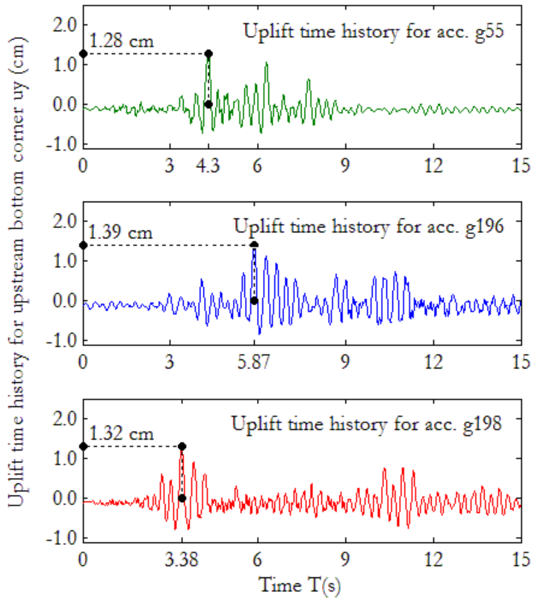

Figure 3. Time histories and maximum values of vertical displacements at the bottom of the upstream side of the dam for the three accelerograms (g55, g196 in g198).

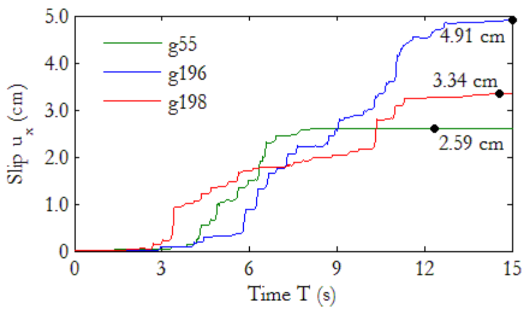

Figure 4. Time histories and maximum values of slip of the dam for different accelerograms (g55, g196 in g198).

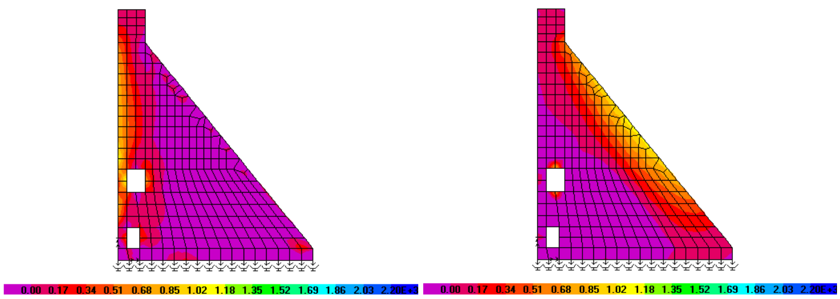

Figure 5: Maximum principle tensile stresses (MPa) at a) the upstream and b) the downstream face by taking into account the horizontal and the vertical component of the accelerogram g196 associated with the 475 year return period.

3.3 Risk-based seismic performance assessment

In the risk-based seismic performance assessment of the dam (Section 2), the nonlinear dynamic analysis should be performed for multiple levels of ground motion intensity in order to estimate $a_g^{\tilde{C}}$ (see Section 2).The threshold peak ground acceleration was assessed for the three limit states (Figures 6-9), which represents an input for estimation of the mean return period of the three limit states. Since only three ground motions were used in the analysis, $a_g^{\tilde{C}}$ was estimated on the basis of maximum seismic demand. The smallest threshold peak ground acceleration which caused slip of 10 cm was observed at peak ground acceleration of 0.30 g (Figure 6). The limit state of cracking of the concrete was estimate at the peak ground acceleration of around 0.5 g (Figure 7). The criteria of vertical displacement at the upstream side of the dam or by uplifting the entire dam for a moment during the nonlinear dynamic analysis (Figure 8 and 9) controlled the limit state of overturning of the dam. However, the smallest possibility was assessed for exceeding the concrete compressive strength, which was estimated to occur for peak ground acceleration of 1.0 g. At that level of acceleration, a failure of an upper part of the dam or severe damage of its toes may be expected (Figure 10).

Mean annual frequencies (MAFs) of limit-state exceedance were estimated by means of Eq. (3). Dispersions β_H=0.3, β_{DR}=0.4, β_{DU}=0.25 and β_{CR}=β_{CU}=0.15 were assumed based on previous study [15]. The parameter *k* was determined from the mean seismic hazard curve taking into account two return periods. The first return period corresponded to the limit-state acceleration, whereas the second corresponded to 25% of this acceleration.

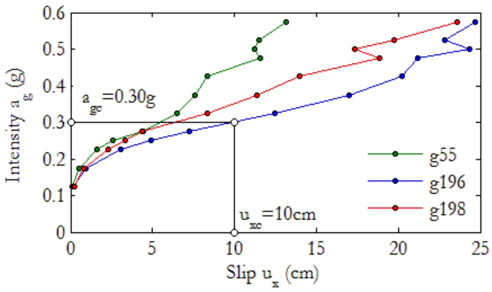

Figure 6. Relationship between peak ground acceleration and slip of the dam for the three accelerogram.

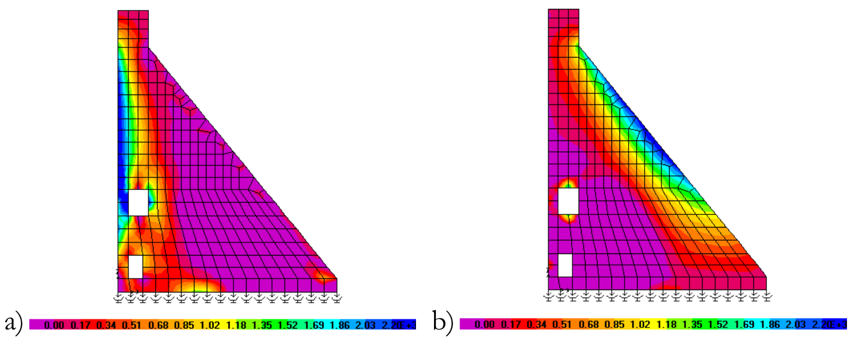

Figure 7: Maximum principle tensile stresses (MPa) at a) the upstream and b) the downstream face of the dam by taking into account the horizontal and the vertical component of the accelerogram g55, which was scaled to peak ground acceleration of 0.5 g.

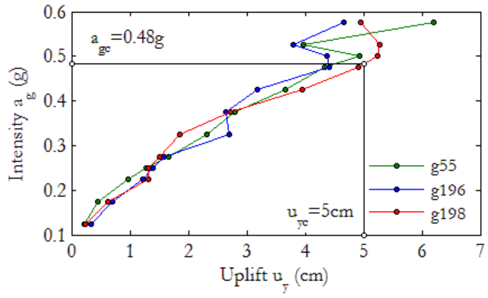

Figure 8. Relationship between the peak ground acceleration and the maximum uplift at the bottom of the upstream side of the dam.

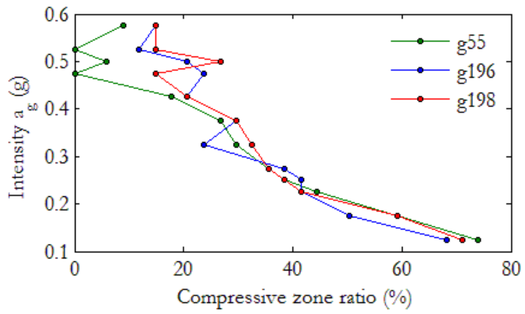

Figure 9. Relationship between the peak ground acceleration and the proportion of the length at the bottom side of the dam in compression.

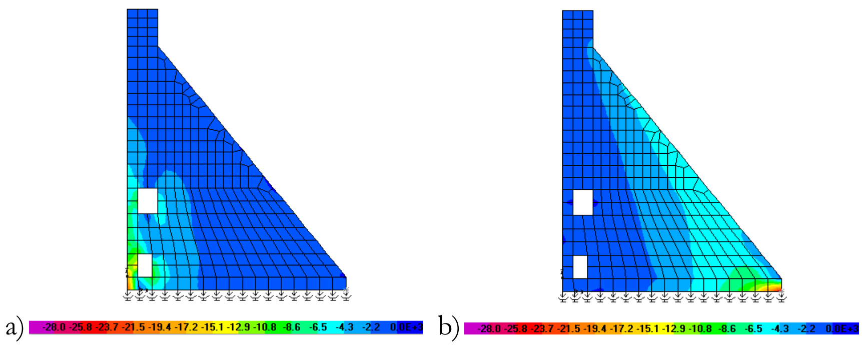

Figure 10: Maximum principle compressive stresses (MPa) at a) the upstream corner and b) the downstream corner in the bottom part of the dam. Stresses are presented for accelerogram g55 and peak ground acceleration 1.0 g.

The MAFs of limit-state exceedance are presented in the Table 1. The first four columns in the table represent the parameters required in Eq. (3), whereas the last two columns represent the results expressed in terms of MAF and return periods of limit-state exceedance. In the case if dam would not be prevented against slipping (Model 1) it is expected that slip of about 10 cm can occur in average once per 370 years. Quite smaller seismic risk was estimated for the limit state of cracking of concrete. The expected return period of cracking of concrete was estimated to be 1200 years. The most unfavourable situation, i.e. the failure of a certain part of the dam was estimated to occur on average once in 10000 years.

Table 1. Input parameters (Eq. (3)) and results of risk-based seismic performance assessment of the dam.

$a_g^{\tilde{C}}$	$H\ a_g^{\tilde{C}\%}$	k	C_f	P_f	$T_{R,LS}$ (years)
0.35	$8.09 \cdot 10^{-4}$	2.94	3.3	$2.69 \cdot 10^{-}$	370
0.5	$2.37 \cdot 10^{-4}$	3.01	3.5	$8.33 \cdot 10^{-}$	1200
1	$2.16 \cdot 10^{-5}$	3.30	4.5	$9.72 \cdot 10^{-}$	10000

4. Summary

The objective of this paper was to show the difference between the common intensity-based and the risk-based approach for seismic performance assessment/design of the concrete gravity dam. The decision-making according to intensity-based approach is always conditional to the so-called design earthquake, which has a certain occurrence rate. For example, it was shown that the limit value of the slip was not exceeded for an earthquake with return period of 475 years. The decision would be that the dam is safe against the slip. However, such decision is misleading, since according to the intensity-based assessment it is not known what would happen in the case of stronger earthquake or even in the case of an unfavourable earthquake with smaller intensity in comparison to that of the design earthquake. From that point of view, the intensity-based approach is not sufficient for seismic performance assessment and design of critical infrastructures. It is argued that critical infrastructures should be designed using at least the simplified risk-based approach, which was in this paper demonstrated by means of seismic performance assessment of the concrete gravity dam.

The risk-based approach provides information regarding the probabilities of unfavourable consequences of natural hazards such as earthquakes, which is an advantage in comparison to the intensity-based approach. Therefore the decision model is based on the comparison between the calculated probability of collapse and the tolerable probability of collapse. Probabilistic Model Code [16] defines that, under high consequences of the collapse, which can also be expected in the case of collapse of the dam, and high cost input to prevent the collapse, the tolerable annual probability of collapse (or failure in operability) would be 10^{-4}. The same probability is defined by ASCE 43-05 (ASCE, 2005) for the structure classified in the third category. This suggests that the level of safety of the investigated dam against the failure is sufficient.

The risk-based design also offers many possibilities for communicating risk to the stakeholders. For example, the estimated return period of exceedance of limit value of slip was 370 years. Assuming that the occurrence of such event is independent of time and that the probability of more than one occurrence in very short interval is negligible it can be shown that there is around 13% and 24% probability that the slip of 10 cm will be exceeded, respectively, in the period of 50 and 100 years. Such level of risk cannot be simply ignored. Therefore, the results of risk-based assessment should represent a good basis for well-informed decision-making associated with development of earthquake preparedness and mitigation measures, which are in the interest of each resilient society.

5. References

[1] KUNG, C.-S., NI, W.-P., CHIANG, Y.-J., 2001. Damage and rehabilitation work of Shih-Kang dam. *Seismic fault-induced Failures*, 33-48.

[2] HUMAR, N., KRYŽANOWSKI, A., 2011. Dam safety in Slovenia. Proceedings of International Symposium on Dams – Recent experiences on Research, Design, Construction and Service, Skopje.

[3] LUPIO, A., CALLARI, C., 2011. The Role of Probabilistic Methods in Evaluating the Seismic Risk of Concrete Dams. *In*: M. DOLŠEK, ed. *Protection of Built Environment against Earthquakes*, Springer.

[4] CORNELL, C.A., JALAYER, F., HAMBURGER, R.O., FOUTCH, D.A., 2002. Probabilistic basis for 2000 SAC Federal Emergency Management Agency Steel Moment Frame Guidelines. *Journal of Structural Engineering ASCE*; 128(4), 526-533.

[5] DOLŠEK, M., FAJFAR, P., REJEC, K., CELAREC, D., 2009. Ocena potresnega tveganja za pregrado HE Učja. *Technical report (in Slovenian)*. Ljubljana: Faculty of Civil and Geodetic Engineering, Institute so structural engineering, earthquake engineering and constuction IT, 72 pages, Subscriber: SENG d.o.o., Nova Gorica.

[6] SIST EN 1992-1-1:2005/A101, 2005. Evrocode 2: Design of concrete structures Part 1-1: General rules and rules for buildings.

[7] IBE, 2008. HE UČJA Nova gradnja – Idejna zasnova z elementi idejnega projekta. *Technical report (in Slovenian)*, Ljubljana, Subscriber: SENG d.o.o., Nova Gorica.

[8] FAJFAR P., LAPAJNE J, 1998. Strokovne podlage za določanje potresne obtežbe za slovenski predstandard EC8 – II. Faza, *Technical report of R&D project (in Slovenian)*, Ljubljana.

[9] CSI, 2006. SAP2000 – Structural analysis program. Computers and Structures Inc., Berkeley, California.

[10] [CHOPRA AK, ZHANG L, 1991. Earthquake-Induced base sliding of concrete gravity dams. *Journal of Structural Eningeering*, 117(12), 3698-3719.

[11] CHAWEZ, J.W., FENVES, G.L., 1995. Earthquake response of concrete gravity dams including base sliding. *Journal of Structural Engineering ASCE*, 121(5), 865-875.

[12] KAZEMI, M.R., 2004. Reliability based analysis and design of anchor retrofitted concrete gravity dams. *Proceedings of 13th World Conference on Earthquake Engineering*, Vancouver, Canada, P.No. 645.

[13] FERC, 1999. Engineering Guidelines for the Evaluation of Hydropower Projects – Chapter 11 – Arch Dams, Federal Energy Regulatory Commission, Washington DC, October 1999.

[14] WESTERGAARD, H.M., 1932. Water pressures on dams during earthquakes. Transactions Paper No. 1835, American Society of Civil Engineers.

[15] DOLŠEK, M., FAJFAR, P., 2007. Simplified probabilistic seismic performance assessment of plan-asymmetric buildings. *Earthquake Engineering and Structural Dynamics*, 36:2021-2041.

[16] JCSS, 2001. Probabilistic Model Code, Joint Committee of Structural Safety, Available from: http://www.jcss.ethz.ch/JCSSPublications/PMC/PMC.html [Accessed November 2009].

[17] ASCE, 2005. Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities, *ASCE Standard ASCE/SEI 43-05*. American Societiy of Civil Engineers.