

TOWARDS DISPLACEMENT-BASED SEISMIC ASSESSMENT OF CONCRETE DAMS

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Abstract: The current paper demonstrates the application of displacement-based procedure in the seismic safety assessment of large concrete dams. Two dam structures – double-arch and gravity, are used as case studies and analysed through conventional force-based approaches, for various Seismic Levels. Nonlinear static analyses are used for assessment of structural capacity and nonlinear dynamic analyses – to obtain the maximum response for each Seismic Level. The dams' safety is assessed totally based on displacements through displacement-based damage indicators in the form of Damage Indexes (DI) and Safety Factors (SF). The DI accounts for the accumulated inelastic deformations in the structure and are related to predefined Damage Levels (DL), while SF evaluates the structural safety margins in terms of seismic load intensity.

Introduction

The current state-of-the-practice approach in seismic analysis of dams extensively involves dynamic analyses using linear or nonlinear material models. The safety assessment and decision making procedures are essentially based on stresses (i.e. force-based approach). However, in many cases the stresses proved to be poor indicators for damage states in structural elements and systems, especially when the response is far beyond the elastic state, when the capability to avoid failure depends only on the accumulated deformations, i.e. displacements. This is fully valid also for dams. Concrete dams could remain globally stable, even long after the process of cracking has started, with the price of significant local deformation and damages. Although this is confirmed by the post-earthquake observations of large dams subjected to severe earthquake loads, the current practice in dam's earthquake engineering is still focused on "screening" for maximal stresses, zones with stresses exceeding the strength and cycles of stresses exceeding the strength. In cases of seismic assessment based on nonlinear dynamic analysis, the estimation of severity of the damages and the overall safety are based mainly on assessment of zones with concentration of inelastic deformations. Thus the classical "force-based" approaches do not provide reliable seismic safety assessment.

The displacements/strains proved to be more accurate damage predictor, since the damage state and the failure of a structural system can be always connected to approximately identical deformed shape. Furthermore, in the recent years the seismic design philosophy evolved significantly towards multi-level probabilistic structural performance criteria based on drifts/strains/displacements.

The principal objective of this paper is to demonstrate the application of a displacement-based seismic assessment procedure combining classical force-based methods for seismic analysis, with displacement-based decision making. The assessment procedure utilises a Damage Index (DI) based on the ratio between the accumulated deformations during a seismic event and the deformation capacity of the structure. Further on, the calculated DIs are used to assess the significance of the accumulated damages on the dam's operational serviceability and safety. For this purpose, DI based Damage Levels (DL) and Safety Factors (SF) are proposed and implemented.

Proposed Displacement-Based Seismic Assessment Method

The proposed assessment approach requires the definition of the "Demand" in the form of "accumulated deformation" during a seismic event and the "Capacity" in the form of

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“deformation capacity” of the structure. The presented study is based on two analysis methods – nonlinear static analyses used to determine the “Capacity” and series of nonlinear dynamic analyses for different seismic levels, used for the estimation of the “Demand” (based on the maximal displacements of the crest) for several considered seismic levels. However, the proposed approach has no limitations on the way to obtain “Capacity” and “Demand”. The capacity curve could be obtained through Incremental Dynamic Analysis (IDA) or alternatively, the entire assessment process could be based only on nonlinear static analyses complemented with the use of Capacity Spectrum Method (CSM).

Definition of the Damage Index (DI)

The application of seismic design concepts based on multi-level performance criteria requires definition and application of appropriate quantitative damage measures, since essential part of the proposed method is the use of a displacement-based DI. A number of damage indices are available in the technical literature, Cosenza&Manfredi (2000), Park (1984) and Powell&Allahabadi (1988), most of them are verified through extensive experimental campaign and include modification factors, to take into account the specific geometrical and loading conditions of RC or steel elements. Such detailed experimental results for definition of dam specific damage indices are not available. Therefore, the DI used in the current study is the noncumulative and purely deformation based index proposed initially by Powell&Allahabadi (1988). The definition of the DI requires the calculation of capacity curve of the structure under consideration and interpretation of the capacity curve results through the following equation:

$$DI_i = \frac{d_{r,i} - d_y}{d_u - d_y} \quad (1)$$

where,

$d_{r,i}$ – “response” (maximal) displacement at the controlled location for Seismic Level “i”;

d_u – displacement at the controlled location at the moment of structural failure;

d_y – displacements at the controlled location at elastic limit.

The crest of the dam is assumed as controlled location for the present study. The Damage Index represents ratio between accumulated nonlinear deformations (damage) to the deformation capacity of the structure, where 0 means fully elastic behaviour and 1 – near collapse conditions. Values above 1 will correspond to structural failure. More advanced DI definitions will require extensive experimental research to define the appropriate modification factors/coefficients. Graphical representation of the DI definition is given in Fig. 1.

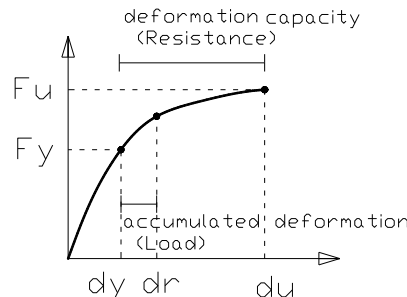


Figure 1. Graphical representation of the Damage Index definition

Definition of Damage Levels (DL)

Despite safety is still the main goal, the current trends in seismic design are towards setting multilevel structural performance goals, i.e. definition of acceptable damage levels under different seismic loading. The dam engineering community is also familiar with the multilevel seismic design concept since several seismic levels are usually considered in a large dam design, Wieland (2012). Some recent research works, Andonov (2012b) and Zhong (2012), are attempting to adapt the seismic performance-based design principles developed for

conventional buildings for application in dam design/assessment. The current study is based on five Damage Levels (DL) correlated with specific DI values. The Damage Levels (DL) are qualitatively defined based on the expected consequences on the dam operability, the retrofiting costs and structural safety. An accurate correlation between DIs and DLs will require extensive documental survey of the response of dams subjected to real strong earthquakes, or a large number of analytical simulations or both. Such information is not currently available and there is also relatively limited information in the technical literature about the correlation of DIs and DLs for conventional buildings. However, interesting and valuable analysis, Powell&Allahabadi (1988), of real buildings damaged by earthquakes in Japan and USA has shown the following relations: for $DI > 1$ structural collapse occurred; for the case of $0,4 < DI < 1$ structural collapse is avoided, but the damages are not repairable; for $DI < 0,4$ the structure is repairable. Such observations for dam structures are not available. Since the current paper is focused on promoting performance-based design principles in dam seismic engineering rather than establishing standards, the correlation between DIs and DLs are adapted for dams based on engineering judgment and experience, as follows: **DL0** – totally elastic structural response; **DL1** – superficial cracking to initial structural damages; minor inelastic structural response; **DL2** – initial to moderate structural damages; moderate inelastic structural response; possibility for significant cracks in the structure; **DL3** – moderate to heavy structural damages; significant inelastic structural response; possibility for cracks passing through the whole dam cross section; **DL4** – heavy structural damages to total failure; heavy inelastic structural response and possibility for loss of structural integrity; Correlation between the Damage Indexes and the Damage Levels is proposed in Table 1.

Table 1. Correlation between Damage Levels and Damage Indexes

Damage Levels	DL0	DL1	DL2	DL3	DL4
Damage Indexes	0,0	< 0,1	0,1 – 0,25	0,25 – 0,5	0,5 -1,0

The definition of Damage Levels adds an element of performance - based engineering to the proposed procedure. Based on adaptation of current guidelines and regulations, Wieland (2012), several performance goals for the dam seismic response can be defined: no damages or loss of service (DL0) under OBE (Operational Basis Earthquake), slight to moderate damages (DL2) under DBE (Design Basis Earthquake) and heavy damages without affecting the structural safety (DL3) under MCE/SEE (Maximum Credible Earthquake / Safety Evaluation Earthquake)

Definition of Safety Factors (SF)

The last step from the assessment process is the definition of Safety Factors (SF) to be used for quantitative assessment of the seismic safety and as input for seismic risk studies. Since the seismic hazard is mainly expressed in accelerations, i.e. “force-based approach”, the proposed SFs are based on the ratio between the base shear “at failure” F_u and the maximal base shear from any particular nonlinear dynamic analysis corresponding to particular seismic level. The following approach is used: 1) The capacity curve is bi-linearized with coordinates $0,0; d_y, F_y$ and d_u, F_u ; 2) The SF for particular crest displacement is calculated by equation (2) in case of elastic response and by equation (3) in case of inelastic response:

$$SF_i = \frac{F_u}{F_y \cdot \left(\frac{d_{r,i}}{d_y} \right)} \quad (2)$$

$$SF_i = \frac{F_u}{F_y + (F_u - F_y) \cdot \left(\frac{d_{r,i} - d_y}{d_u - d_y} \right)} = \frac{F_u}{F_y + (F_u - F_y) \cdot DI_i} \quad (3)$$

where,

- DI_i – Damage Index for given analysis “i” (Seismic Level “i”);
- $d_{r,i}$ – response (maximum) crest displacement for given analysis “i” (Seismic Level “i”);
- d_u – crest displacement at structural failure;
- d_y – crest displacement at elastic limit;
- F_u – base shear at structural failure;
- F_y – base shear at elastic limit.

The so defined SF is based on manipulation (displacement based) of the capacity curve using the values of the calculated DIs, instead to directly calculate ratio between the ultimate and the response base shear. The reason for this is to avoid spurious (unrealistically high) values of the base shear due to the spatial response of the dam structure. The minimum possible value of the defined SF is 1 (near collapse conditions) and there is no limitation of the maximum value.

Range of applicability of the proposed approach

The proposed assessment approach should give consistent results until the dam structure is relatively “homogeneous”, i.e. there are no local failures and/or disconnected parts which will drastically change the deformed shape of the structure. The failure mode corresponding to DI and SF approaching one is exceeding of the shear capacity along a horizontal failure plane. With increasing of the lateral loading the depth of the cracking zone increases too, and thus the compressed zone of the cross sections is continuously reduced. The “failure” will be formed when this stress redistribution provokes sliding of the upper disconnected part of the dam along the failure/crack plane. A number of analytical, Iliev et al (2012) and Wieland&Malla (2000) and experimental studies of this phenomenon showed that dams with fully disconnected upper parts can still resist significant seismic forces. Therefore the proposed here approach possess certain level of conservatism, since reaching $DI=1$ and $SF=1$ will correspond practically to “prior failure” conditions and not to physical collapse of the structure. Realistic assessment of the dam structural response under more damaged conditions require change of the analysis approach from “smeared nonlinearity” to “discrete nonlinearity” and modelling and simulation of the dynamic response of the detached part of the dam, Iliev et al (2012) and Wieland&Malla (2000).

Case studies

Although the purpose of the current study is to demonstrate the proposed displacement-based seismic capacity assessment, all aspects of the investigation as input data, modelling and analyses are presented without any simplifying assumptions. This comes from the fact that the current investigation represents selected data from two actual seismic assessments projects of two different types of dams described in more details in Andonov et al (2013).

Description of the dam structures and the numerical models

The model of Case Study 1: Gravity Dam is presented in Fig. 2.

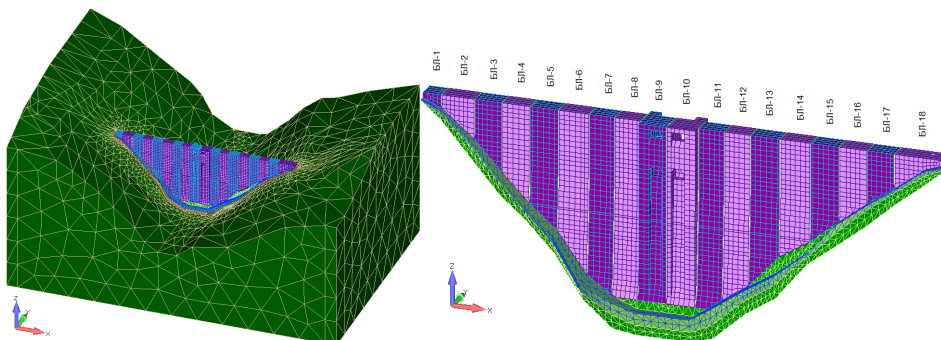


Figure 2. Numerical model of the gravity dam and the surrounding rock foundation

The selected dam is a concrete gravity dam composed of 18 separate blocks. The approximate geometrical properties of the dam are: total crest length – 200 m; maximum height – 70 m; width of crest – 7 m; maximum width of base – 60 m; total volume of mass concrete – around 200 000 m³. The spillway is situated in the two central blocks of the dam. The grouting curtain is located under the injection gallery at the upstream part of the dam and its depth varies between 18 and 50 meters.

The dam model is consisted of nearly 70 000 and the rock foundation model from around 30 000 solid elements. Average size of the solid element of the dam structure is around 2m. The hydro dynamic water pressure is evaluated through added masses based on the Westergaard approach.

The size of the rock foundation model is assumed one dam's height in all three directions around the dam structure and presented as massless medium. The contact between the separate blocks is modelled by finite elements with negligible tensile strength and adjusted material properties, providing on one hand possibility for cantilever behaviour of the separate blocks in case of open contraction joints and on another – frictional interaction in case of closed joints. The base joint is modelled as a layer of finite elements with decreased dynamic tensile strength. The model of Case Study 2: Doble Arch Dam is presented in Fig. 3.

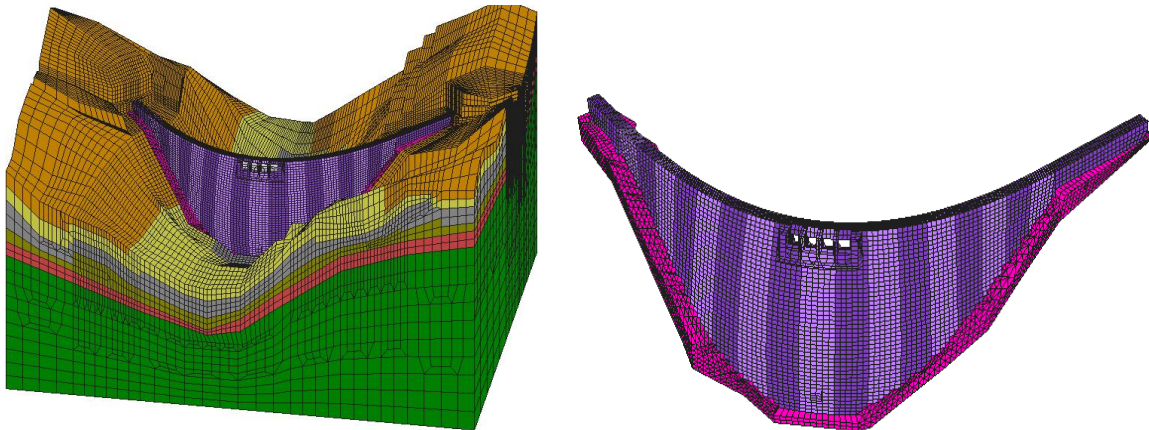


Figure 3 Numerical model of the double arch dam and the surrounding rock foundation

The dam consisted of 17 separately erected 20-meter-wide cantilever blocks. The contraction joints are originally designed with series of shear key locks on both surfaces of each block, ensuring uniformly distributed shear force transmission between the blocks. A spillway with four divisions is situated in the middle part of the crest. The general geometrical properties of the dam are: total crest length – 460 m; crest length (curved part) – 340 m; maximum height – 130 m; maximum width of crest – 9 m; maximum width of base – 26 m; total volume of mass concrete – around 400000m³. The total model of the double-arch dam includes 83000 solid finite elements. The model consists of 8 layers of elements along the dam's width. The average solid element size of the dam wall model is 3m.

The hydro dynamic water pressure is evaluated through the Westergaard method. The size of the rock foundation model is assumed one dam's height in all three directions around the dam structure and presented as massless medium. More precise modelling is focused on the connection between the dam and the rock foundation and fine mesh is applied for this zone. Some weakened and weathered zones of the rock foundation that are substituted by concrete plugs in the design of the dam are reflected in the FE model. The contraction joints are modelled by a thin layer of solid finite elements between each adjacent block, with decreased dynamic tensile strength and with adapted material properties to ensure the shear stress transfer capabilities of the joint elements even after cracking and opening of the joints. The base joint is presented by layer of finite elements with decreased dynamic tensile strength. More detailed description of the structural model and the modelling concept can be found in Varbanov et al. (2012).

Numerical Analyses

Initial Conditions

The initial stress-strain state of the two dams for the seismic analyses is based on self weight, hydrostatic pressure and thermal-stress analysis. The hydrostatic pressure is applied as element pressure, normal to the outer face of all upstream dam elements. Uplift pressure is applied at the bottom surface elements of the model taking into account the piezometric measurements. The transient temperature analysis is based on the annual temperature curves for the air and various water layers in depth obtained from the available monitoring data for the dams' region. The dam structural response to the initial conditions is verified through comparison of the measured and the analytical data for crest displacement Iliev et al. (2012).

Nonlinear Dynamic Analysis

For both structures (gravity and arch dam) a number of nonlinear dynamic analyses for various seismic levels are performed to calculate the "demand" in the form of maximal crest displacement. The selected seismic levels are based on results from site specific PSHA (Probabilistic Seismic Hazard Assessment) studies for the corresponding dam sites. The range of the peak ground acceleration for each seismic level are presented in Table 2.

Table 2. Seismic levels and respective Return Periods and Peak Ground Accelerations

Seismic Level	Return Period (years)	PGA (g)
A (OBE)	100	0,05-0,1
B	475	0,12-0,17
C (DBE)	1000	0,2-0,25
D (MCE)	10 000	0,35-0,4
E	100 000	0,5-0,6
F	1 000 000	0,8-0,9

For each seismic level a set of ten dynamic analyses are performed with different input parameters based on statistically independent variations of material properties (density, compressive and tensile strength, elastic modulus, Poisson ratio), damping coefficients, temperature regime, hydrostatic and hydrodynamic pressure. The variations are based on mean values and standard deviations, obtained from field investigations and laboratory tests. Engineering judgement is applied for variables without available empiric data (for example damping). For every analysis a set of three statistically independent accelerograms are used. For all analyses the dam is modelled via nonlinear concrete constitutive models with mechanical properties based on field and laboratory obtained data.

Nonlinear Static Analysis

The pushover analyses, used for calculation of the deformation capacity of the structure are also performed including the initial conditions from gravity, hydrostatic and temperature loads. Summer and winter average temperatures of air and water are selected, having major influence on the thermal structural response and therefore the initial condition for the dynamic structural capacity. For the gravity dam three different load types were applied – unidirectional load in upstream direction, unidirectional load in downstream direction and cyclic load. For the cyclic pushover analyses a load function with increasing amplitudes until failure is detected in one of the directions. For the arch dam, two pushover unidirectional analyses are performed using the summer temperature regime, one in upstream and one in downstream direction.

The definition of appropriate load vector and the selection of correct location for tracing the displacement are critical points for reliable application of NSPs. The current investigation uses a hybrid load vector based on the combination of mass proportional and acceleration proportional loading. The latter is computed proportionally to the displacement pattern of the dam obtained through response spectrum analysis based on the significant modes. Each

load vector is scaled to correspond to 50% modal participating mass, thus jointly forming 100% of modal participating mass. More detailed information, regarding load vector composition and its applicability for nonlinear static analyses of dams, is presented in Andonov (2010) and Andonov (2012a).

The displacement at the controlled response location is another critical parameter, since it is directly connected with the post-processing of the results of the NSP and the seismic safety assessment. The dam structural topology implies non-uniform displacement pattern, both in height and in transversal direction at crest level. This could be additionally affected by presence of different irregularities in the dam structure. Therefore, a capacity curve based on physical node displacement could be heavily affected from local effects and not necessarily to describe the exact global structural response. The critical point here is the decision on the significance of eventual local failure modes on the global dam safety. In the current study, the Capacity Spectrum Method is used for the seismic response assessment of Case Study 1: Gravity dam, using the crest displacement of the central block as controlled location. The Adaptive Capacity Spectrum Method, Casarotti&Pinho (2007) is used for the seismic response assessment of Case Study 2: Double Arch Dam, using a build-up system displacement instead of focusing on a particular physical location. The necessity for the use of the more advanced ACSM is to overcome the limitations of the conventional NSPs due to the non-uniform crest displacement pattern in transversal direction.

Seismic Assessment through the proposed method

Calculation of the capacity curve and definition of the ultimate and cracking displacements

The failure modes and the corresponding damage distribution for Case Study 1: Gravity Dam in upstream and downstream directions for summer and winter temperature regimes are presented in Fig. 4. The capacity curves, in upstream and downstream directions for the studied gravity dam, are shown on Fig.5. The mean values of the “cracking” and the “ultimate” displacements d_y and d_u , used for the calculation of the DIs and SFs, are computed based on the whole set of six pushover analyses.

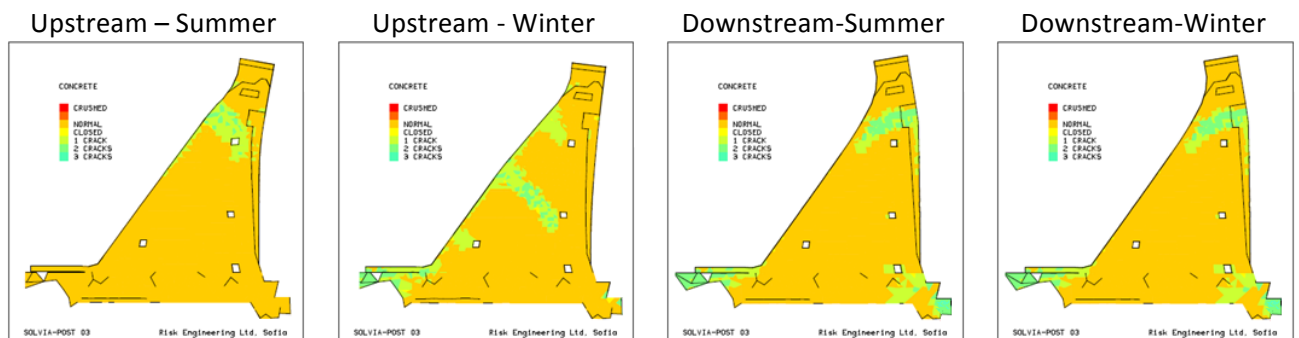


Figure 4. Damage distribution at failure – Case Study 1: Gravity Dam

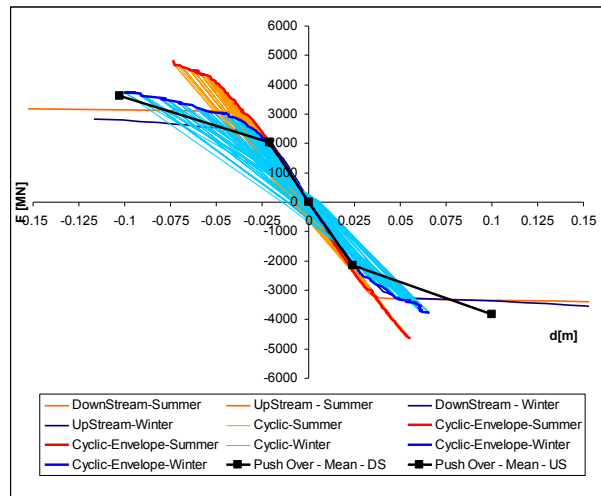


Figure 5. Capacity curves – Case Study 1: gravity dam

As can be seen from the results on Fig.4, the temperature regime influences the failure mode in upstream direction. The main reason for this is that the temperature loading provide volumetric changes of each block and therefore influence on the contact condition between the blocks. Under summer temperature, the concrete extension lead to full interaction between the blocks, therefore the less deformable peripheral blocks support the more deformable and higher central blocks in the resistance of the seismic force. The cracks are accumulated at the upper, most deformable, portion of the dam. From other side, the opening of the contraction gaps during winter temperature regime lead to lower contact interaction in the upper part of the blocks and to more “independent” seismic response of each block. Therefore, the cracking of the central blocks is concentrated on lower level. The temperature regime, do not influence the failure mode in downstream direction.

The capacity curves in upstream and downstream direction of the studied double arch dam are shown in Fig.6. The failure modes and the corresponding damage distribution in upstream and downstream directions are presented in Fig. 6. a) and b). As can be seen from Fig.6 the seismic capacity in upstream direction is much lower due to the structural typology of arch dams.

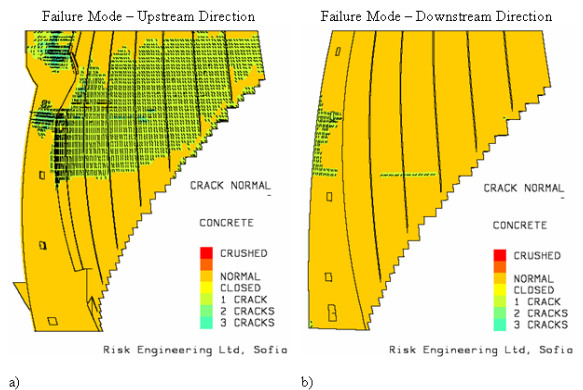
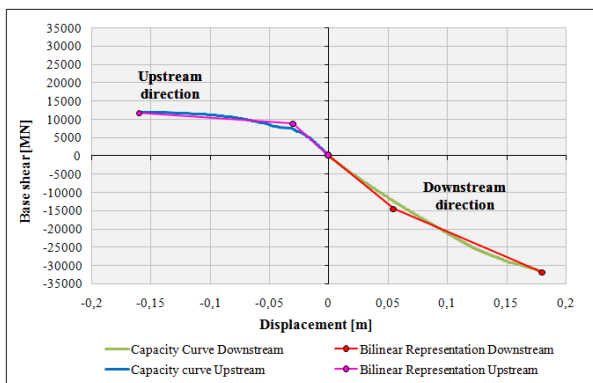


Figure 6. Capacity curves for Case Study 2: double arch dam. Damage distribution at failure: a) upstream direction and b) downstream direction

Calculated Damage Indexes for the considered Seismic Levels

The Damage Indexes obtained from the nonlinear dynamic analyses for the considered six seismic levels are presented in Table 3. The minimum and maximum values of DI for each seismic level represent the range of the parameter obtained from the set of nonlinear analyses.

Table 3. Damage Indexes for the considered Seismic Levels

Seismic Levels	Level A (OBE)	Level B	Level C (DBE)	Level D (MCE)	Level E	Level F
Case Study 1: Gravity Dam						
DI – upstream	0	0	0	0,0 – 0,14	0,13-0,31	0,41-0,55
DI - downstream	0	0	0	0,0-0,17	0,11-0,30	0,48-0,54
Case Study 2: Double Arch Dam						
DI - upstream	0	0	0,003	0,23	0,4	0,75
DI – downstream	0	0	0,003	0,18	0,36	0,58

Seismic Assessment based on the obtained Damage Indexes

The essence and the biggest advantage of the proposed method is the ability to provide quantitative assessment of the damage state, the corresponding operational serviceability and finally the seismic safety of the dam structure. The damage states and the corresponding operational serviceability are assessed through the calculated Damage Indexes, while the dam safety is assessed through the obtained Safety Factors.

The correlation between the investigated Seismic Levels and the corresponding Damage Levels and Safety Factors is presented in Table 4. The presented DLs are based on the calculated Damage Indexes and demonstrate the expected overall damaged state for the relevant seismic level. The presented Safety Factors for Case Study 1: Gravity Dam are the lowest obtained from the set of dynamic nonlinear analyses for each seismic level including both upstream and downstream directions. The safety factors for Case Study 2: Double Arch Dam in upstream and downstream directions are presented separately in order to stress on the significantly non-symmetrical response of arch dams

Table 4. Correlation between the investigated Seismic Levels and the corresponding Damage Levels and Safety Factors – Case Study 1: Gravity dam

Seismic Levels	Level A(OBE)	Level B	Level C (DBE)	Level D (MCE)	Level E	Level F
Case Study 1: Gravity Dam						
Damage Levels	DL0	DL0	DL0	DL1-DL2	DL2-DL3	DL4
Safety Factors	7,22	3,89	2,92	2,03	1,52	1,27
Case Study 2: Double Arch Dam						
Damage Levels	DL0	DL0	DL0	DL2	DL3	DL4
Safety Factors - upstream	2,78	2,09	1,37	1,26	1,19	1,09
Safety Factors - downstream	5,04	3,03	2,12	1,81	1,54	1,30

Conclusion

In the recent years the design/assessment for seismic resistance has been undergoing a critical reappraisal, with the emphasis changing from “strength” towards “performance”. As a result a number of methods for displacement-based assessment of buildings are developed, or are currently under development, mainly for building structures. However the seismic assessment approaches implemented in the regulatory documents related to dams’ seismic safety are still essentially “stress/force” based. The current paper describes the basic elements of a newly proposed approach for displacement-based seismic assessment of concrete dams. The approach is based on the calculation of displacement based Damage Indexes and Safety Factors providing quantitative assessment of the damage intensity and the seismic safety. The proposed DIs and SFs can be used for further post-processing of the results as calculation of fragility curves, assessment of the seismic risk and finally for decision making in programs for post-earthquake actions. The proposed assessment approach is based on the implementation of nonlinear static and dynamic analyses, though the entire procedure itself could be performed using only NSP or NDP.

REFERENCES

- ATC-40. (1996). Seismic Evaluation and Retrofit of Concrete Buildings, Applied Technology Consul.
- Andonov, A., Iliev, A. and Apostolov, K., (2013), Towards Displacement-Based Seismic Assessment of Concrete Dams using Nonlinear Static and Dynamic Analyses”, Structural Engineering International, Special Issue on “Advances in Design for Seismic Action”, SEI 2/2013, IABSE, ETH Zurich, Switzerland
- Andonov, A. (2010). An Application of the Adaptive Capacity Spectrum Method for Seismic Assessment of Concrete Dams. Proceedings of the 14th European Conference on Earthquake Engineering. Ohrid. Macedonia.
- Andonov, A., Iliev, A, Andreev, S. (2012a). Applicability of Nonlinear Static Procedures for Seismic Assessment of Concrete Dams. Proceedings of the 15th World Conference on Earthquake Engineering. Lisbon. Portugal.
- Andonov, A., Apostolov, K. (2012b). Displacement-Based Seismic Capacity Assessment of Concrete Dams. Proceedings of the 15th World Conference on Earthquake Engineering. Lisbon. Portugal.
- Casarotti, Ch., Pinho, R. (2007). An adaptive capacity spectrum method for assessment of bridges subjected to earthquake action. Bulletin of Earthquake Engineering. 5:3, 377-390.
- Cosenza, E., Manfredi, G. (2000). Damage Indices and Damage Measures. Progress in Structural Engineering and Materials. 2: 50-59.
- Volume 2, Issue 1
- F.E.M.A. (2005). Earthquake Analyses and Design of Dams, FEMA-65.
- F.E.R.C. (1999). Engineering Guidelines for the Evaluation of Hydropower Projects, Chapter 11-Arch Dams. Federal Energy Regulatory Commission, Division of Dam Safety and Inspection, Washington.
- F.E.R.C. (2002). Engineering Guidelines for the Evaluation of Hydropower Projects, Chapter 3 - Gravity dams. Washington, USA.
- Freeman, S.A. (1978). Prediction of Response of Concrete Buildings to Severe Earthquake Motion. ACI SP-55, P.589-605
- Ghanaat, Y., (2004) Failure modes approach to safety evaluation of dams. Proc. 13-th World Conference on Earthquake Engineering, Vancouver, Canada.
- Iliev, A., et al. (2012) Seismic Evaluation and Post-earthquake Safety Assessment of Gravity Dam based on Numerical Simulation. Proceedings of the 15th World Conference on Earthquake Engineering. Lisbon. Portugal
- Malla, S. and Wieland, M. (2003). Simple model for safety assessment of cracked concrete dams subjected to strong ground motions. Proc. 21-st ICOLD Congress, Montreal, Canada, 151-165.
- Park YJ. (1984). Seismic damage analysis and damage-limiting design of RC structures. PhD Thesis. Department of Civil Engineering, University of Illinois, Urbana, IL.
- Powell, G.H. and R. Allahabadi, (1988), “Seismic damage prediction by deterministic methods: concepts and procedures,” Earthquake Eng. Struct. Dyn., Vol. 16, pp 719-734.
- SOLVIA. (2003). SOLVIA Finite Element System. User manual. SOLVIA Engineering AB, Vasteras, Sweden.
- Varbanov, G., Kostov, M., Andonov, A., Apostolov, K., Iliev, A., (2012), Seismic Risk Assessment of Large Dams”, Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal.
- Wieland, M. and Malla, S. (2000). Earthquake safety of an arch-gravity dam with a horizontal crack in the upper portion of the dam. Proc. 12-th World Conference on Earthquake Engineering, Auckland, New Zealand.
- Wieland, M. (2012). Seismic Design and Performance Criteria for Large Storage Dams. Proc. 15-th World Conference on Earthquake Engineering, Lisbon, Portugal.
- Zhong, H. et al. (2012). Seismic Vulnerability Analysis of a Gravity Dam Based on Typical Failure Modes. Proc. 15-th World Conference on Earthquake Engineering, Lisbon, Portugal.