Displacement-Based Seismic Capacity Assessment of Concrete Dams

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SUMMARY:

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 analyzed 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 is related to pre-defined Damage Levels (DL), while SF evaluates the structural safety margins in terms of seismic load intensity.

Keywords: Gravity Dam, Arch Dam, Displacement based approach, Seismic Safety, Nonlinear Static Analysis, Nonlinear Dynamic Analysis, Seismic Capacity

1. INTRODUCTION

In the last twenty years the seismic safety of large dams has become a subject of wide interest, mainly due to the extensive negative economic impact in case of their failure. The current state-of-the-practice approach in seismic analysis of dams is to use extensively dynamic analyses using linear or nonlinear material properties. Despite the wide variety of modeling and analysis techniques, the post-processing of the results, the safety assessment and the decision making is essentially based on stresses (i.e. forcebased approach). However, in many cases the stresses proved to be poor indicators for the damage state in structural elements and systems, especially when the response is far behind the elastic state, where the structure's capability to avoid failure depends only on the accumulated deformations, i.e. displacements. This is also in wide extend valid for dam structures, where the bulk volume of mass concrete provides high level of static indetermination (despite the brittle behavior of the mass concrete as material). Therefore the concrete dams could remain globally stable, even much after the processes of cracking and crushing have started, with the price of significant internal deformation and local failures. Although this is confirmed by the post-earthquake observations of several 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 the cases, when the seismic assessment is based on non-linear dynamic analysis, the assessment of the severity of the damages and the safety are based mainly on the accumulated inelastic zones, their concentration and propagation. At least to the authors' knowledge, currently there are no regulatory guidelines and codes, providing acceptance criteria for the allowable level of damages in case of nonlinear analyses and the recommendations are to evaluate the safety based only on engineering judgement.

These essentially "force-based" approaches complicate the assessment when analyzing dam structures for seismic loads, whose response is significantly outside the elastic range. This situation could be common case when analyzing for example seismic level MCE for old concrete dams, not designed for

seismic loads, or when evaluating the seismic risk of a dam, where the assessment of the response to extremely high seismic levels (much higher than MCE) is part of the process. Furthermore, the obtained conclusions for the dam safety could be quite conservative, which will immediately reflect in significant economic loses due to restricted serviceability (for example reduced Maximal Operational Water Level) and/or expensive strengthening, without real necessity of these measures. The mentioned limitations of the classical force-based approaches in the assessment of the post-elastic structural response is widely recognized from the earthquake engineering community, and the current trend in the seismic assessment/design of civic buildings and other industrial facilities is to shift the focus towards displacements and strains. 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 more or less unique deformed shape, irrespective of the exact value of the applied load.

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. For the purpose two case studies – Case Study 1: Gravity Dam and Case Study 2: Double Arch Dam, recently assessed for earthquake loads under the framework of commercial projects for Seismic Probabilistic Safety Assessment (SPSA) are analysed and assessed via the proposed displacement-based approach. The damage indicator in this procedure is the proposed Damage Index (DI) based on the ratio between the accumulated deformation during a seismic event (calculated via nonlinear dynamic analysis) and the deformation capacity of the dam structure (calculated via nonlinear static analyses). Further on, the calculated DIs are used to assess the significance of the accumulated damages on the dam's operational serviceability and safety. For the purpose, DI based Damage Levels (DL) and Safety Factors (SF) are developed and implemented.

2. CURRENT APPROACHES USED FOR SEISMIC ASSESSMENT

Various approaches are utilized for seismic assessment of dams, depending on their complexity, time consumption and completeness. A number of dam engineering codes and guidelines are developed from the responsible regulatory bodies and agencies, treating the subject of seismic assessment of dams. The common issue in all actual approaches is force-based load application in case of FEM analysis of the structure and stress-based control parameters for evaluation of the structural response. Generally the assessment of a dam structure is based on a multi step evaluation approach, increasing accuracy and respectively analyses time consumption with each step. The types of the actual analyses procedures together with the controlled parameters are briefly described in this section.

Response spectrum analysis

The linear-elastic response spectrum analysis is generally the first step in evaluating a concrete dam. The results of this analysis method are based on the stress screening approach and are used for rough assessment of the damage potential of the structures. The zones with excess of tensile strength are outlined and the demand-to-capacity ratio values (DCR) of the tensile stresses are estimated. The DCR value is commonly used control parameter and specific threshold values for the DCR are established in order to evaluate the necessity of subsequent analysis (USACE, 2003, 2007; FEMA, 2005).

Linear dynamic procedure

The liner dynamic procedures are widely used in the engineering practice as they combine accurate dynamic behaviour and average analysis time consumption (FEMA, 2005, USACE, 2003, 2007 FERC, 1999, 2002). In this procedure again linear elastic materials are applied but the structural response is performed in the time domain. The interpretation of the results again includes comparison of stress-based parameters to their allowable values. The controlled parameters include DCRs, cumulative inelastic duration (Ghanaat, 2004) and spatial extent of overstressed regions.

Assessment of the overall damage state of the structure could be carried out through critical principal stresses or concurrent principal stresses at the time of maximum stress, as these parameters serve to identify the location and extent of overstressed regions at specific time steps and in this case sound

engineering judgement is necessary for prediction of eventual nonlinear behaviour of the structure.

Nonlinear dynamic procedures

The nonlinear analysis is considered as the most precise method for seismic response assessment of structures as well as the most time consuming. Different approaches are available using nonlinearities representing the damaged response of the structure in case of strong ground motions. Typical application of nonlinearities is discrete ones applied in the modelling, for example the base joint and the contraction joints, while the main dam wall remains elastic. Another procedure for damaged response assessment of a dam structure is a multi step analysis procedure where the structural zones with exceeded tensile strength in linear analyses are replaced with contact elements or nonlinear elements in a limited area. Furthermore, totally non-linear dynamic analysis can be performed taking directly into account the non-linear material behaviour of the mass concrete, the base and contraction joints, as well of the soil/rock medium if necessary.

Nonlinear static procedures (Pushover analysis)

Despite, widely used in seismic assessment of buildings, there are no available recommendations in the current guidelines and standards, regarding the implementation of nonlinear static procedures in the seismic assessment of dams. Although the so called pushover analysis is initially intended for structures easily represented by SDOF system, the method can be applied to practically all kinds of structures if the load pattern is correctly obtained and the response locations is suitably selected. Several recent research activities deal with the application of non-linear static procedures for dam seismic assessment (Andonov, 2010; Andonov et al., 2012).

Limitations of the current approaches and motivation for the current study

Currently many regulatory bodies has no acceptance criteria for the allowable level of damage in case of nonlinear analyses as the they are subject to numerous assumptions and in these cases the damaged state should be evaluated only based on engineering judgement (FERC, 1999). The severity of the damage states is based mainly on the accumulated inelastic deformations at the critical zones, their concentration and propagation. The current approaches do not provide also information about the formation of the failure modes, and do not provide recommendations how to estimate the remaining seismic capacity after the accumulation of significant inelastic deformations.

3. PROPOSED DISPLACEMENT – BASED SEISMIC CAPACITY ASSESSMENT

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 "deformation capacity" of the structure. The presented study is based on two analysis methods – nonlinear static analyses used to determine the "Capacity" (based on the deformations corresponding to the elastic limit of the structure and its ultimate capacity) and various nonlinear dynamic analyses for different seismic levels, used for the estimation of the "Demand" (based on the maximal displacements of the crest) for the several considered seismic levels. However, the proposed approach has no limitations on the way to obtain the "Capacity" and the "Demand". The capacity curve needed for the implementation of the proposed assessment approach could be successfully obtained through Incremental Dynamic Analysis (IDA) and thus to skip the necessity to use Nonlinear Static Procedures (NSP). Alternatively, the entire assessment process could be based only on nonlinear static analyses complemented with the use of Capacity Spectrum Method (CSM) to obtain the "Demand" for each considered seismic event described with its response spectrum.

Essential part of the proposed seismic assessment method is the use of displacement-based Damage Index. The definition of the DI requires the calculation of the capacity curve of the structure under consideration. The DI is calculated by the interpretation of the capacity curve results through the following equation:

$$DI_i = \frac{d_{r,i} - d_y}{d_u - d_y} \tag{3.1}$$

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 and can vary between 0 and 1, where 0 means fully elastic behavior and 1 -complete destruction. Graphical representation of the DI definition is given in Fig. 3.1.



Figure 3.1. Graphical representation of the Damage Index definition

Five Damage Levels (DL), are defined and are correlated with specific DI values, based on engineering judgment. Short description of the Damage Levels is presented below and proposed correlation between the Damage Indexes and the Damage Levels is presented in Table 3.1. The purpose of the damage levels is to be used in the serviceability assessment and the post-earthquake actions planning.

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;

Damage Levels DL0 DL1 DL2 DL3						
Damage Indexes	0.0	< 0.1	0.1 – 0.25	0.25 – 0.5	0.5 -1.0	

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The dam response to seismic loads obtained from the dynamic analyses is related to particular Damage Levels through the calculated DIs for each considered seismic event.

The last step from the assessment process is the definition of Safety Factors (SF), which can 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 seismic 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 (3.2) in case of elastic response and by equation (3.3) in case of inelastic response:

$$SF_{i} = \frac{F_{u}}{F_{y}\left(\frac{d_{r,i}}{d_{y}}\right)}$$
(3.2)

$$SF_{i} = \frac{F_{u}}{F_{y} + (F_{u} - F_{y}) \left(\frac{d_{r,i} - d_{y}}{d_{u} - d_{y}}\right)} = \frac{F_{u}}{F_{y} + (F_{u} - F_{y}).DI_{i}}$$
(3.3)

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;
- dy crest displacement at elastic limit;
- F_u base shear at structural failure;

 F_y – base shear at elastic limit.

4. CASE STUDIES

Although the purpose of the current study is to demonstrate of the proposed displacement-based seismic capacity assessment, all aspects of the investigation as input data, modelling, analyses are presented without any simplifying assumptions. This is due to the fact that the current investigation represents selected data from two actual seismic assessments projects of two different types of dams. The proposed displacement-based seismic assessment was included in these projects as additional tool to the standard code-based practices, for the purpose of better understanding and evaluation of results from the performed dynamic analyses.

4.1. Description of the dam structures and numerical models

4.1.1. Case Study 1: Gravity Dam

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.



Figure 4.1. Numerical model of the gravity dam and the surrounding rock foundation

The dam model is consisted of nearly 70 000 mainly prismatic solid elements and the rock foundation model – around 30 000 tetrahedral solid elements. Average size of the solid element of the dam structure is around 2m. The modeling of the rock foundation is assumed to be one dam's height in all

three directions around the dam structure and presented as massless medium. The contact between the separate blocks is modeled by finite elements with negligible tensile strength and adjusted material properties, which provide on one hand possibility for cantilever behavior of the separate blocks in case of open contraction joints and on another – frictional interaction in case of closed joints. The base joint is modeled as a layer of finite elements with decreased dynamic tensile strength. The model of the dam wall and its surrounding rock foundation is presented in Fig. 4.1.

4.1.2. Case Study 2: Double Arch Dam

The dam is consisted of 17 separately erected 20-meter-wide cantilever blocks. The contraction joints are 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 400000m^3 .

The total model of the double-arch dam includes 83000 solid finite elements. The modeling of the rock foundation is assumed to be one dam's height in all three directions around the dam structure and presented as massless medium. More precise modeling 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 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 contraction joints are modeled 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 with decreased dynamic tensile strength. The model of the dam wall and its surrounding rock foundation is presented in Fig. 4.2.



Figure 4.2. Numerical model of the double arch dam and the surrounding rock foundation

4.2. Numerical Analyses

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 seismic hazard assessment studies for the corresponding dam site and their characteristics are presented in Table 4.1.

Table 4.1. Seismic levels and respective and respective Return Periods and Peak Ground Accelerations

Seismic	Return Period	PGA
Level	(years)	(g)
A	100	0.05-0.1

В	475	0.12-0.17
C (OBE)	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 every analysis a set of three statistically independent accelerograms are used. The analyses include nonlinear concrete constitutive model and statistically independent variations of material properties (density, compressive and tensile strength, elastic modulus, Poisson ratio), Rayleigh damping coefficients, thermal stressed and strained state based on transient analysis, hydrostatic and hydrodynamic pressure. The variations are based on mean values and standard deviations, obtained from field investigations and laboratory tests. For variables without empiric data (for example Rayleigh damping) engineering judgement is applied.

The pushover analyses, used for calculation of the deformation capacity of the structure are performed including the temperature effects as initial conditions. For the gravity dam summer and winter average temperature values are selected, having major influence on the thermal structural response. Six nonlinear static analyses are performed for the gravity dam for maximum and minimum temperatures using three different loads – 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 for each cycle is used. For the arch dam, two pushover unidirectional analyses are performed with summer temperature, one in upstream and one in downstream direction.

In the present study the total load vector, applied to the dam structures, is combination of two independent sub vectors – mass-proportional load vector and "1^{-st}-mode-proportional load vector". The first one represents the mass distribution, while the second vector accounts for contribution of the first mode of vibration of the structures. Each sub vector composes 50% of the total load vector applied to a structure. More detailed information regarding load vector composition and its applicability for nonlinear static analyses of dams could be found in (Andonov 2010, Andonov et al, 2012).

5. SEISMIC SAFETY ASSESSMENT THROUGH THE PROPOSED METHOD

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



5.1.1. Case Study 1: Gravity Dam

Figure 5.1. Damage distribution at failure – Case Study 1: Gravity Dam

The failure modes and the corresponding damage distribution in upstream and downstream directions for summer and winter temperature regimes are presented in Fig. 5.1. The capacity curves, in upstream and downstream directions for the studied gravity dam, are shown on Fig.5.2. 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 six analyses.



Figure 5.2. Capacity curves - Case Study 1: gravity dam

5.1.2. Case Study 2: Double Arch Dam

The capacity curves in upstream and downstream direction of the studied double arch dam are shown in Fig.5.3. The failure modes and the corresponding damage distribution in upstream and downstream directions are presented in Fig. 5.3. a) and b).



Figure 5.3. Capacity curves for Case Study 2: double arch dam. Damage distribution at failure: a) upstream direction and b) downstream direction

5.2. Calculated Damage Indexes for the considered Seismic Levels

5.2.1. Case Study 1: Gravity Dam

The obtained damage indexes for the six considered seismic levels are presented in Table 5.1. The obtained Damage Indexes represent the range between the minimum and maximum values obtained from each set of analyses for each seismic level.

Table 3.1. Damage indexes for the considered Seisinic Levels – Case Study 1. gravity dam								
Seismic Levels	Level A	Level B	Level C (OBE)	Level D (MCE)	Level E	Level F		
Damage Indexes - upstream	0	0	0	0.0 - 0.14	0.13-0.31	0.41-0.55		
Damage Indexes - downstream	0	0	0	0.0-0.17	0.11-0.30	0.48-0.54		

 Table 5.1. Damage Indexes for the considered Seismic Levels – Case Study 1: gravity dam

5.2.2. Case Study 2: Double Arch Dam

The obtained damage indexes for the six considered seismic levels are presented in Table 5.2. The

values of the obtained Damage Indexes represent the mean values obtained from each set of analyses for each seismic level.

Seismic Levels	Level A	Level B	Level C (OBE)	Level D (MCE)	Level E	Level F
Damage Indexes - upstream	0	0	0.003	0.2253	0.4	0.75
Damage Indexes - downstream	0	0	0.003	0.1816	0.36	0.58

Table 5.2. Damage Indexes for the considered Seismic Levels - Case Study 2: double arch dam

5.3. 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 of 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.

5.2.1. Gravity Dam

The correlation between the investigated Seismic Levels and the corresponding Damage Levels and Safety Factors for Case Study 1: gravity dam is presented in Table 5.3. The presented DLs give the range of the obtained values. The presented Safety Factors are the lowest obtained for each seismic level.

Table 5.3. Correlation between the investigated Seismic Levels and the corresponding Damage Levels and Safety Factors – Case Study 1: gravity dam

Seismic Levels	Level A	Level B	Level C (OBE)	Level D (MCE)	Level E	Level F
Damage Levels	DL0	DL0	DL0	DL1-DL2	DL2-DL3	DL4
Safety Factors	7.22	3.89	2.92	2.03	1.52	1.27

5.2.2. Double Arch Dam

The correlation between the investigated Seismic Levels and the corresponding Damage Levels and Safety Factors for Case Study 2: double arch dam is presented in Table 5.4. The presented damage levels are the mean values from the performed analyses. The safety factors for upstream and downstream directions are presented to stress on the strongly non-symmetrical response of arch dams.

 Table 5.4. Correlation between the investigated Seismic Levels and the corresponding Damage Levels and Safety Factors – Case Study 2: double arch dam

Seismic Levels	Level A	Level B	Level C (OBE)	Level D (MCE)	Level E	Level F
Damage Levels	DL0	DL0	DL0	DL2	DL3	DL4
Safety Factors -	2.78	2.09	1.37	1.26	1.19	1.09
upstream						
Safety Factors -	5.04	3.03	2.12	1.81	1.54	1.30
downstream						

6. CONCLUSIONS

In the recent years the design/assessment for seismic resistance has been undergoing a critical reappraisal, with the emphasis changing from "strength" to "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, at least to the authors' knowledge, 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 which provide 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.

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