Applicability of Nonlinear Static Procedures for Seismic Assessment of Concrete Dams

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SUMMARY:
The focus of the current paper is the assessment of the applicability of the current Nonlinear Static Procedures for seismic assessment of large concrete dams. The classical Capacity Spectrum Method (Freeman, 1978, ATC-40, 1996) and the more recent Adaptive Capacity Spectrum Method (Casarotti et al., 2007) are applied, respectively on concrete gravity and double arch dams. The predicted seismic response under MCE is compared with the results of a set of ten dynamic analyses for different initial conditions and the same seismic intensity. Detailed numerical models of real dam structures are used as case studies. The comparison of the results obtained from NSP shows more conservative prediction of the seismic response, but still keeping good consistency with the results calculated via nonlinear dynamic analyses.

Keywords: Gravity Dam, Double Curved Arch Dam, Non-linear Static Analysis, Non-linear Dynamic Analysis, Adaptive Capacity Spectrum Method, Failure Mode, Seismic Safety, Seismic Capacity,

1. INTRODUCTION

Currently, the most widely used approach for seismic analysis and assessment of large dams is trough dynamic response history analyses of the system dam-base rock-water reservoir. The acceleration records are usually generated compatible to the site specific response spectra. For low seismic levels or when serious damages over the dam wall are not expected, the conventional modal-response history analysis is the most widely used tool. The controlled parameters of the structural response are the tensile, shear and compressive stresses. The structural safety is assessed indirectly through comparison of the controlled parameters with appropriate limits, and with engineering judgment. The main disadvantage of the linear dynamic analysis is that it considers the structure homogeneous and disrespects the presence of concentrated weaker zones at the base joint and the contraction joints. These limitations can be overcame with another widely used approach for dynamic analysis of large dams, namely to apply discrete nonlinearity for modeling the base joint and the contraction joints, while the main dam wall remains elastic. In this way more realistic stress distribution over the dam structure is produced. The structural response and safety is controlled with the same manner. However, in case of severe seismic loading, as MCE in seismic regions for example, the zones with tensile stresses above the limit can be widespread over the dam wall. Therefore, indirect assessment of the structural safety based on comparison of the obtained tensile or “cracked” zones with corresponding limit values based on engineering judgment, could lead to unrealistic conclusions. The non-linear dynamic analysis provides the most advanced tool for seismic assessment of structures subjected to severe seismic loading and is considered to gives the most realistic response prediction. The structural safety is usually assessed based on the accumulated damages over the structure. However, the non linear dynamic analysis is usually with high computational cost, when large structural model is analyzed, as in the case of large dam wall with its base rock. Furthermore, separate analyses should be performed for each seismic record if the dam seismic response should be estimated for different seismic levels (OBE, MCE, etc.). Finally, the entire procedure can be extremely time consuming.

Currently, a vast number of existing dams are located in seismic prone areas and are not specifically designed for seismic loadings, or are designed for loadings which are significantly lower than the prescribed from the latest hazard assessments. Therefore the necessity for simple, yet accurate methods for estimating the seismic demand on dam structures considering their full inelastic behavior obviously exists. The current paper focuses on the assessment of the applicability of the Nonlinear Static Procedures for accurate seismic safety assessment of large concrete dams. For the purpose, the classical Capacity Spectrum Method (CSM) proposed initially by (Freeman, 1978) and the more recent Adaptive Capacity Spectrum Method (ACSM) proposed by (Casarotti, 2007) have been implemented for the seismic assessment of two exemplary concrete dams – 60m high concrete gravity dam assessed via CSM and 130m high double arch dam assessed via ACSM. The seismic response prediction obtained via the NSP is compared with the results obtained through a set of nonlinear dynamic analyses. The comparison is performed for MCE. The Push Over analyses are based on the best-estimate (mean) values of the main input parameters, while the "dynamic" prediction is based on a set of ten dynamic analyses varying all of the significant input parameters. The sampling of the input parameters is performed using the Latin Hypercube Experimental Design (LHCED) procedure. The current paper is further development and improvement of the research presented in (Andonov, 2010).

2. SHORT OVERVIEW OF THE NONLINEAR STATIC PROCEDURE

2.1. An overview

The method is based on the assumption that the post elastic response of the structure due to seismic excitation can be derived by series of static analyses under monotonically increasing lateral loading, with structural stiffness updated on every step. Further, the structural capacity can be represented graphically by plotting the base shear versus the top displacement and compared with the demand. There are basic steps of the NSP – calculation the capacity, calculation the demand and checking the performance. The capacity calculation is essential part from the NSP and is independent from the sub-method used for interpretation the demand and performance. Broadly speaking, the capacity is represented by a capacity curve which is the lateral displacement as a function of the base shear. Usually the top node, when planar structure is considered, or the masses center, in case of spatial models, is chosen as representative. As to the load vector, it is a function of the storey masses and the assumed acceleration profile, and can be single-mode or multi-mode load vector. In the first case, the capacity curve is a product of a single vector with constant or varying profile. In the second case, capacity curves are generated independently due to load vectors representing few main modes and then combined to obtain the maximum structural response.

2.2. Load Vector

Regarding the assumed acceleration profile of the load vector, the following cases are most popular:

- Single concentrated force – applicable for one storey buildings or for structures with sufficient mass concentration on one level, as portal crane frames.
- Uniform- constant acceleration along the height
- Triangular – linearly increasing from the base to the roof.
- Code distribution – in proportion to the standard code procedures for equivalent static forces, varying from triangular to parabolic, depending on the fundamental mode.
- First mode – corresponding to the fundamental mode.
- Adaptive – as the first mode, but continuously updating the load pattern in respect to the non-uniform softening of the structure.
- SRSS – in function of the storey shear forces from Linear Dynamic Analysis.

2.3. Solution of the SDOF system

The static non-linear procedures propose close-form relations between the target displacement and a set of governing parameters in one of the two general forms:

$$\delta_t = C_0.C_1.C_2.C_3.\left(Sa(T_0, \beta_0)\frac{T_{ef}^2}{4\pi^2}.g \right) \tag{2.1}$$

or

$$\delta_t = Sa(T_{eff}, \beta_{eff})\frac{T_{eff}^2}{4\pi^2}.g \tag{2.2}$$

The first approach, eq. (2.1), is called Displacement Modification Technique, since the target displacement is obtained by modification of the maximum displacement of the elastic system (in brackets) by the factors C_i to account for yielding (C_1), cyclic stiffness and strength degradation (C_2) and the amplification of the maximum displacement due in-cycle strength degradation (C_3).
The second approach, eq. (2.2), is called Equivalent Linearization Technique, since the original system is substituted with linear system, which has natural period T_{eff} and damping ratio β_{eff}. The two systems are equivalent with respect to the maximum displacement (target displacement). Usually, the pseudo-acceleration response spectrum $Sa(T, \beta_{eff})$ is obtained from the 5%-damped spectrum $Sa(T, \beta_0)$ using reduction factor with values depending on β_{eff}. The Equivalent Linearization Technique requires an iterative procedure since the energy dissipation (β_{eff}) increases with increasing the inelastic deformations, i.e. with increasing the ductility μ, which is not known in advance.

The expressed general forms of the static non-linear procedures are implemented in the two most widely used NSP methods for seismic assessment - Capacity Spectrum Method and Displacement Coefficient Method.

2.3.1. Capacity Spectrum Method
The capacity spectrum method (Freeman, 1978) relay on the Equivalent Linearization Technique (eq. (2.2)) and is based on direct graphical comparison of the capacity with the demand, by crossing the capacity curve with the reduced elastic response spectrum converted in spectral coordinates. The crossing point is called performance point and gives the actual state of the structural response under the considered earthquake. The method is implemented in ATC-40 (ATC-40, 1996), where guidelines for the calculation of the spectral reduction factors based on (β_{eff}) are provided.

2.3.2. Displacement Coefficient Method
The Displacement Coefficient Method (DCM) relay on the Displacement Modification Technique (Eq.(2.1)). The displacement coefficient method is based on statistical analysis of the results of time history analysis of single degree of freedom models of different types and is implemented in FEMA 356 (FEMA356, 2000), where guidelines for calculation of the modification factors Ci are given. The method provides a direct numerical process for calculating the displacement demand without to convert the capacity curve to spectral coordinates.

2.4. Limitations of the current approaches in respect to dam structures

The available procedures for seismic design and assessment based on non-linear static analyses are generally developed for relatively compact buildings in mind and can not be directly applied to other kind of structural systems, as long or irregular buildings, bridges, dams and etc. In the majority of current assessment methods, the displacement of a physical location is sort of 'manipulated' to convert the curve in a SDOF equivalent by means of a modal transformation.
The dam structural topology implies several significant differences compared to "classical" building structures. The mass of the structure is concentrated predominantly in the lower portion of the dam. Therefore the classical load vectors (1^{st} mode, triangular, etc.) based on the assumption for uniform mass distribution in height are not suitable for applications in dams, since they significantly overestimate the response of the upper part of the dam modifying the failure mode and the response. The use of uniform acceleration profile (solely mass proportional) has also limitations, since it totally

underestimate the dynamic behavior of the dam, usually concentrated in the upper part. The classical NSPs use the top displacement as a parameter describing the structural response – building of a capacity curve and obtaining of a performance point. Tracing of a single physical location of the crest could lead to misleading conclusions, since the crest displacement profile is highly non-uniform, with displacements significantly higher in the central portion of the crest.

3. MODIFICATION OF THE AVAILIABLE NSP'S FOR DAMS

The definition of appropriate load vector and the selection of correct location for tracing the displacement are critical points for reliable application of NSPs. Due to the significant difference between dams and buildings as structural systems, the conventional NSPs should not be applied directly in seismic assessment of dams and some modifications are necessary.

3.1. Definition of the load vector

The current paper proposes the use of 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. The mass proportional (uniform acceleration profile) load vector takes into account the specific mass distribution over the dam and neglecting the dynamic response – the inertial forces at each node are proportional solely to the mass associated with this node. The acceleration proportional load profile adds the contribution of the dam dynamic response to the generation of the inertial forces. Each load vector is scaled to correspond to 50% modal participating mass, thus jointly giving 100% modal participating mass.

3.2. Calculation of the equivalent SDOF system response

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 (especially at arch dams). 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 (ATC-40, 1996) 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, 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 implied by the dam structural topology.

4. EVALUATION OF THE PROPOSED APPROACH

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 m^3. 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.

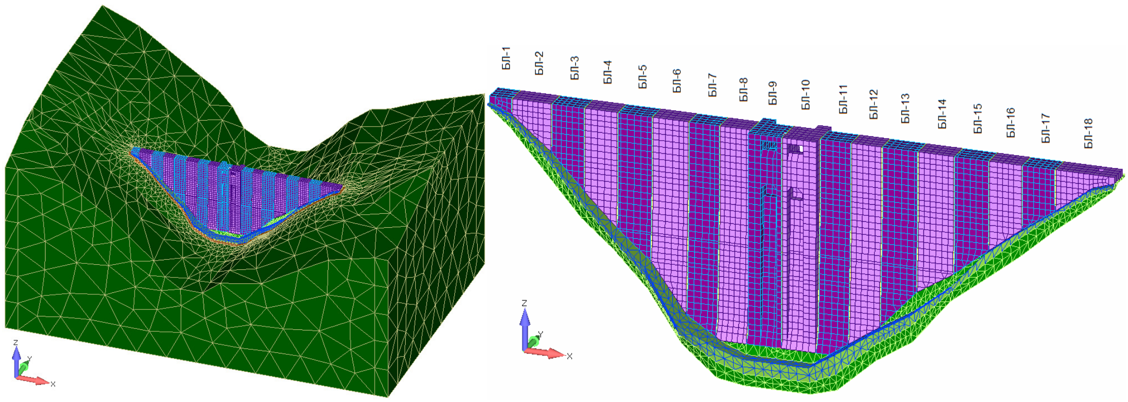

Figure 4.1. Numerical model of the gravity dam and the surrounding rock foundation

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 even after cracking and opening of the joints. The base joint is presented by layer of finite elements with decreased dynamic tensile strength. The model of the dam wall and its surrounding rock foundation is presented in Fig. 4.2.

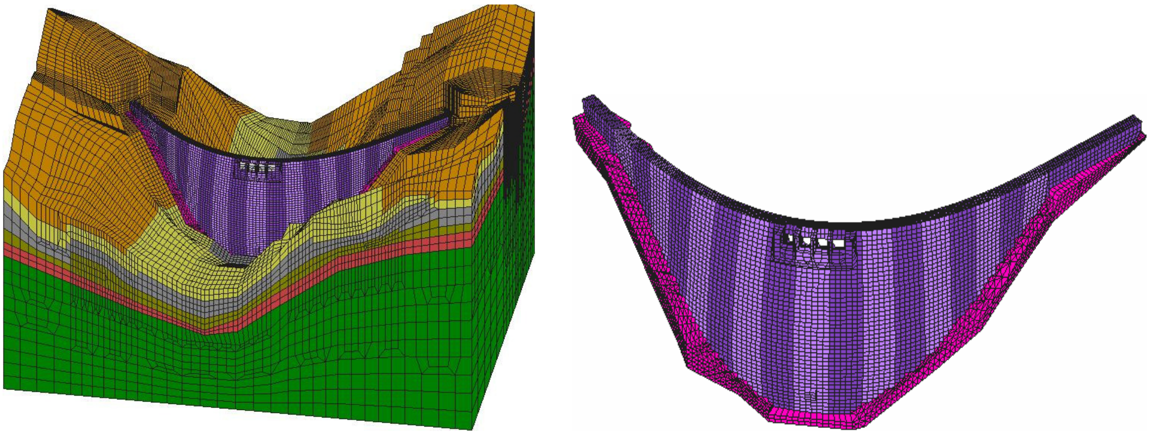

Figure 4.2. Numerical model of the double arch dam and the surrounding rock foundation

4.2. Numerical Analyses

For both structures (gravity and arch dam) a set of ten nonlinear dynamic analyses for seismic level MCE are performed, named D-1 to D-10. For every analysis a set of three statistically independent accelerograms are used. The analyses include statistically independent variations of material properties (density, compressive and tensile strength, elastic modulus, Poisson ratio), Rayleigh damping coefficients, temperature regime, water level in the reservoir, etc. The variations are based on mean values and standard deviations, obtained from field investigations and monitoring. For variables without empiric data (for example Rayleigh damping) engineering judgement is applied. The input parameters for each dynamic analysis are estimated based on the Latin Hypercube Experimental Design (LHCED) procedure.

Hydrodynamic pressure is modelled with added horizontal masses at upstream face of the dam. The added masses are calculated for different water levels with a procedure, implemented in current Bulgarian seismic code and based on the classical Westergaard equations. Elastic analysis with reservoir modelled with fluid finite elements was also performed to check the calculation of added mass. For the dynamic analyses standard implicit Hilber-Hughes method for direct integration was used. The time step of the analyses is 0,005s. Nonlinear behaviour of concrete is modelled with Ottosen constitutive model (SOLVIA, 2003). Crack formation and propagation is based on the smeared crack approach. The iteration method is BFGS combined with energy convergence criteria.

Six nonlinear static (pushover) analyses are performed for the gravity dam. The analyses use three different loads – monotonic load in downstream direction, monotonic load in downstream direction and cyclic load. Summer and winter temperature regimes are considered as initial conditions. For the arch dams, two analyses are performed with summer temperature, one in upstream and one in downstream direction.

5. SEISMIC CAPACITY ASSESSMENT

5.1. Structural response prediction via NSP

5.1.1. Gravity Dam

The results from the performed pushover analyses are shown on Fig.6. The capacity curves are derived based on the relative base shear and displacements, i.e. the initial values due to the permanent loading are extracted. The target displacements from the analyses with winter temperature are higher, i.e. higher level of inelastic response. This is due to the fact that the contraction joints between the blocks tends to open at winter temperatures, which reduces the effect of interaction between the blocks and lead to reduced “global” stiffness and larger displacements over the central blocks of the structure. Thus, the damages from the winter temperature will also be greater from the ones with summer temperature which can be observed at Fig. 9

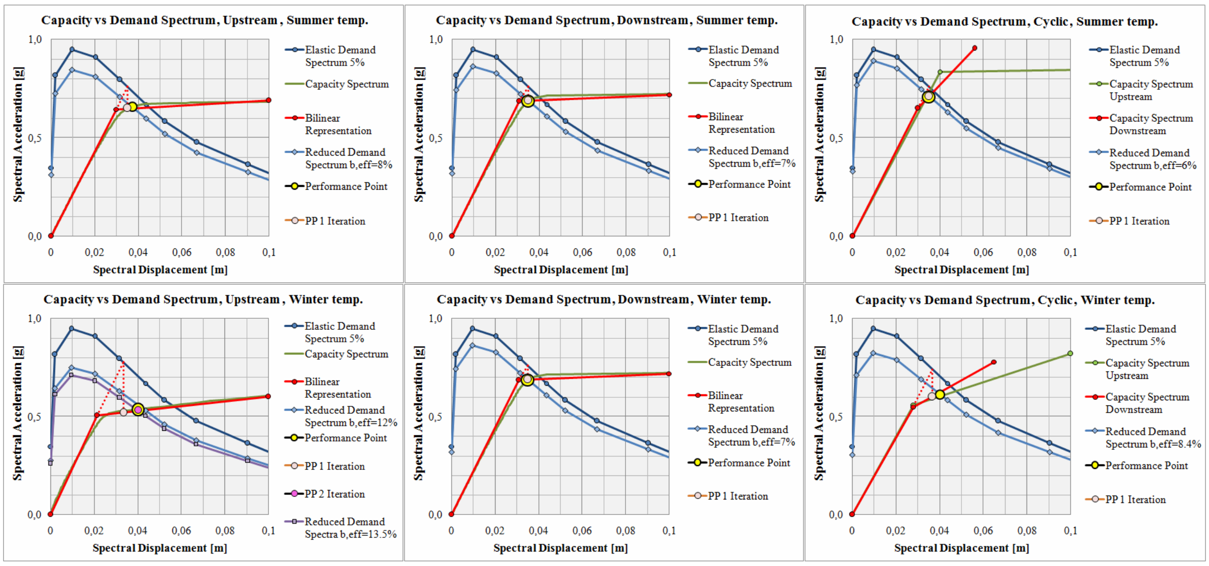

Figure 6. Representation of capacity and demand in ADRS format.

5.1.2. Double Arch Dam

The results from the performed pushover analyses are shown on Fig.7. The capacity curves are derived based on the relative base shear and displacements, i.e. the initial values due to the permanent loading are extracted. The obtained capacity curves illustrate the typical non-symmetric response of arch dams in transversal direction. The structure is much stiffer in downstream direction, due to the curved shape of the wall, however the failure mode in upstream direction is more ductile. Since the performance point from the analysis at downstream direction is close to the yielding point of the system, the structure should undergo the excitation will less damages than the one at upstream direction.

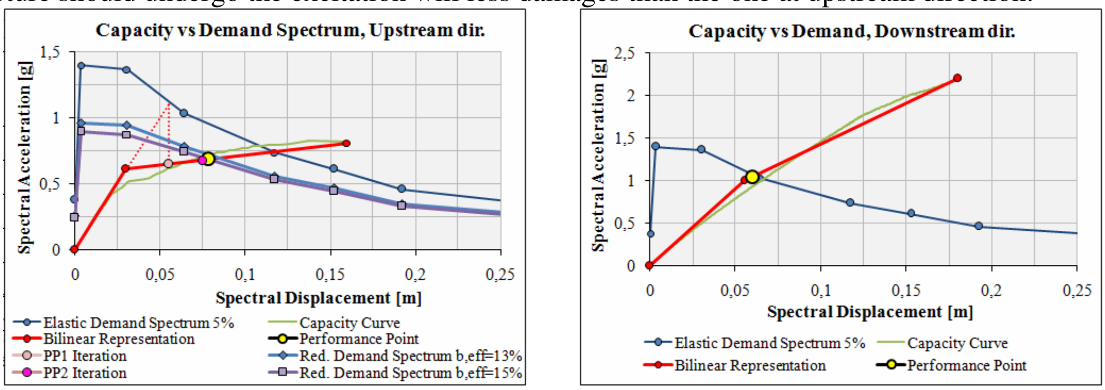

Figure 7. Representation of capacity and demand in ADRS format.

5.2. Comparison and analysis of the results

5.2.1. Gravity Dam

The comparison of the capacity curves of the dam obtained through nonlinear dynamic and static analyses is shown on Fig. 8, right. The “dynamic” capacity curves are obtained through the so called Incremental Dynamic Analysis (IDA). The comparison of the accumulated damages for MCE calculated through non-linear dynamic and static analyses are presented on Fig.9. The displacement profiles of the central block of the dam are compared on Fig.10.

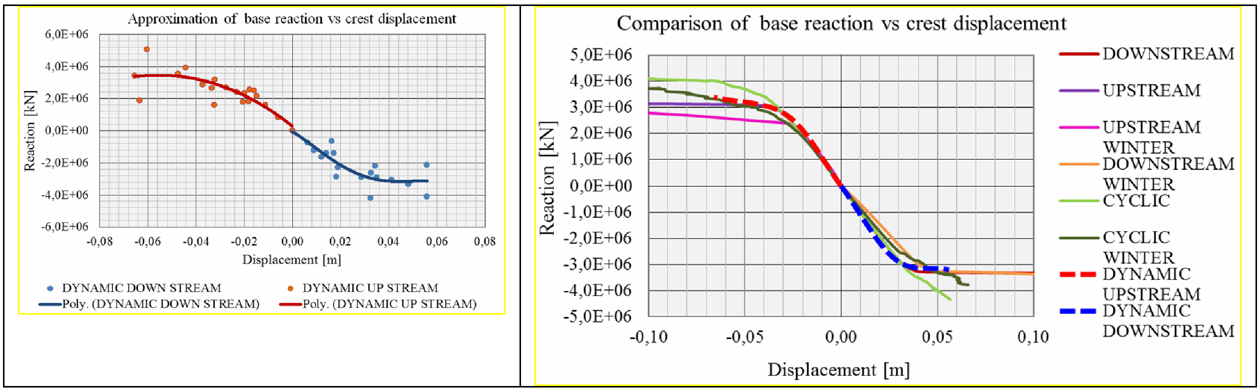

Figure 8. Capacity curves from the dynamic analyses (left) and comparison of the capacity curves obtained from the nonlinear static and dynamic analyses (right).

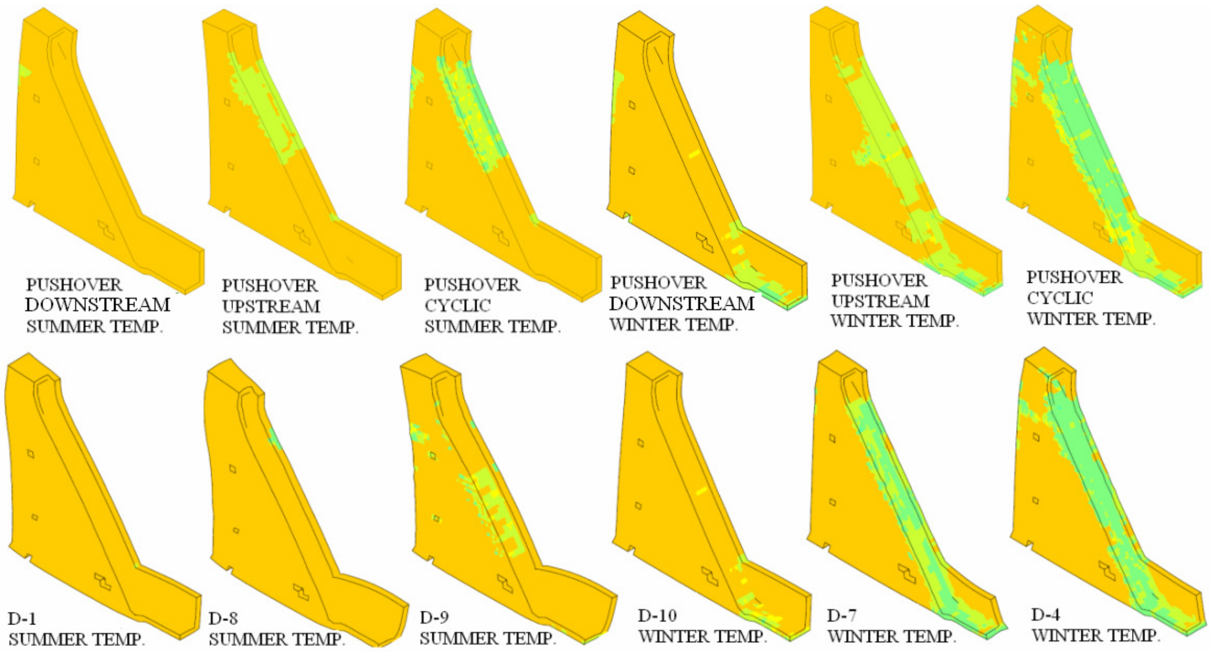

Figure 9. Accumulated damages from static (up) and dynamic(bottom) analyses.

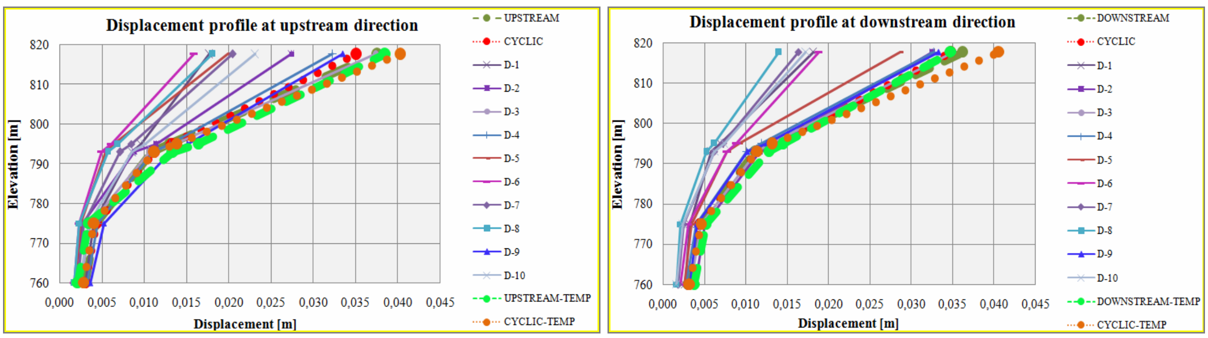

Figure 10. Comparison of displacement profiles between static and dynamic analyses

5.2.2. Double Arch Dam

Good coincidence between the “static” and the “dynamic” results in downstream direction is observed, while in upstream direction the Push Over analysis underestimates the response. One of the possible reasons for this could be that the idealized horizontal loading in upstream direction produces “opening” of the wall and disconnection of the arch action. The arch dam is transformed into a system of separate cantilevers, which has significantly lower lateral stiffness than the arch dam. During the dynamic analysis, the loading is in the form of continuously changing its principal direction in the 3D space acceleration vector, and such idealised upstream lateral loading can not be produced. However, both approaches predict higher elastic capacity and brittle failure in downstream direction (the length of the initial curve slope).

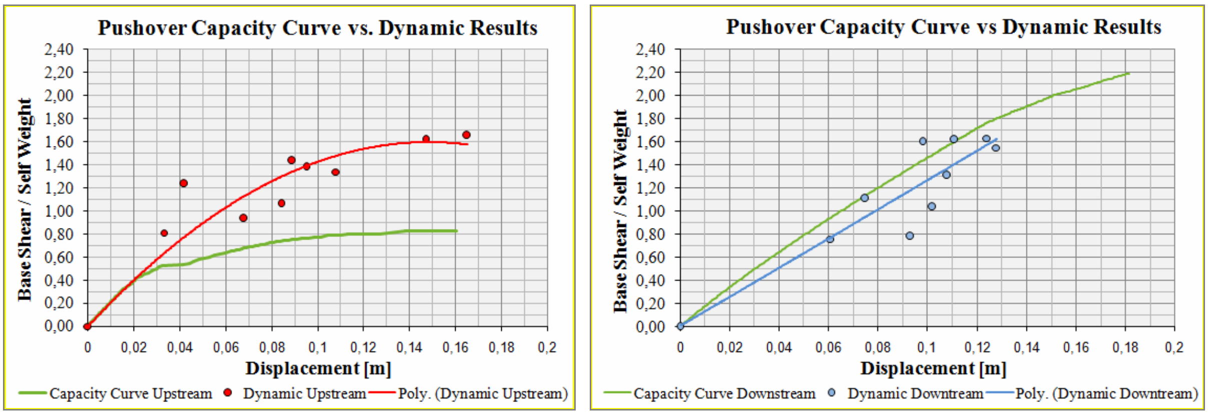

Figure 11. Approximation of lateral load from dynamic analyses D-1 to D-10.

Comparison between the response predicted by the complex dynamic analyses and the ACSM is given on Fig.12 by means of graphical comparison between the deformed shapes of the crest under MCE. The "deformed shape" from each dynamic analysis is actually an envelope of the maximum radial displacements of each block during the entire response. The Push Over analysis is based on best-estimate (mean) values of the input parameters. It can be assumed that the deformed shapes from these several dynamic analyses bound the most probable one during real earthquake. The five dynamic analyses with the closest to the mean values input parameters are selected for the comparison.

According to the obtained results the ACSM gives good prediction of the deformed shape in downstream direction, but slightly underestimate the displacements in the central portion of the crest. Regarding the response in upstream direction, the ACSM based prediction overestimate the displacements in the central part of the crest and underestimate these one in the quarter points. However, the main reason for the higher displacements in the quarter points from the dynamic analyses is the seismic loading and the response in longitudinal direction, which produces the so called "buckling mode". The overestimation of the displacement in the central part of the crest is due to the idealized unidirectional lateral loading, which when acting in upstream direction produces "opening" of the arch and earlier (compared to the dynamic loadings) disconnection of the arch action, i.e. softer structure. The inertial forces in downstream direction activate the "arch" action of the dam, i.e. the response is less non-linear and naturally better predicted. The underestimation of the displacements in the central crest section is due to the fact that the dynamic analyses are cyclic, while the static implies monotonically increasing loading in one direction. The cracking over the downstream surface during the dynamic analyses produces structural softening which reflect in higher displacements from the dynamic analyses.

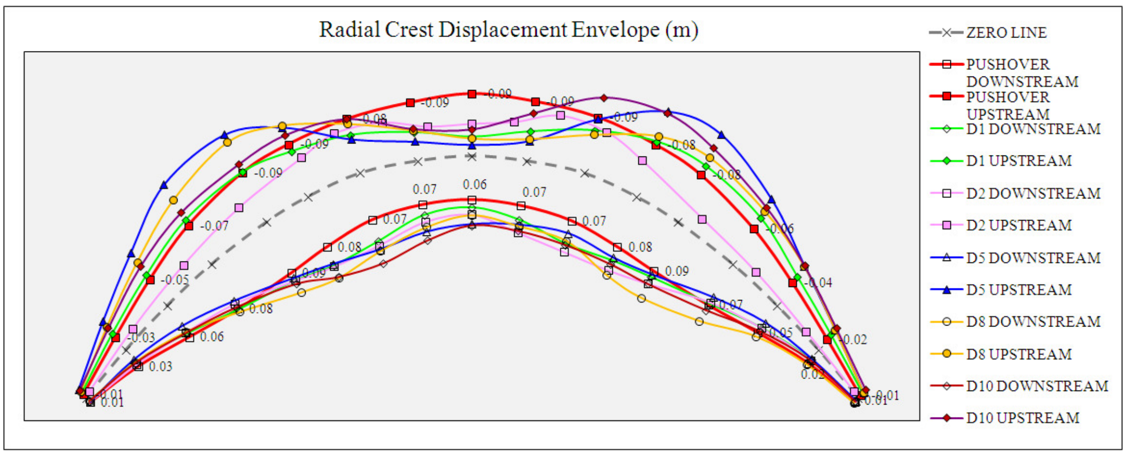

Figure 12. Envelope of crest displacements

6. CONCLUSIONS

The current paper provides an assessment of the use and the applicability of Nonlinear Static Procedures for seismic assessment of large concrete dams. The classical Capacity Spectrum Method (Freeman, 1978, ATC-40, 1996) and the more recent Adaptive Capacity Spectrum Method (Casarotti et al., 2007) are applied, respectively on concrete gravity and double arch dams. The predicted seismic response under MCE is compared with the results of a set of ten dynamic analyses for different initial conditions and the same seismic intensity. Detailed numerical of real dam structures are used as case studies. The comparison of the results obtained from NSP shows more conservative prediction of the seismic response, but still keeping good consistency with the results calculated via nonlinear dynamic analyses.

The provided adequate for practical needs response prediction and the slight conservatism, together with the method simplicity and sufficiently lower time cost verify the NSP as adequate additional tool for preliminary or simplified seismic assessment of dams subjected to high seismic loadings, including from the scale of MCE.

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