Dynamic analysis of a vaulted dam

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Abstract:

Introduction/purpose: The dynamic analysis of a seismic response of a concrete vault dam is a complex problem in which the representation of the behavior of the material requires some form of a nonlinear model, especially if the concrete is subjected to a significant stress load of the ground. In the case of large movements of the latter, large cracks may form in some areas *of the dam, especially at the base of the dam and near sudden changes in geometry.*

Methods: This analysis was based on a numerical simulation of the dynamic effect. This work was carried out using the finite element method with the ANSYS 12.1 program. The dam was modelled in two dimensions. Four types of analysis were performed: static analysis, modal analysis, seismic analysis under excitation of two accelerograms (Asnam 1980 and Boumerdes 2003), and spectral analysis.

Results: This analysis showed the vulnerability of the Brezina dam to the Boumerdes earthquake with high stresses at the base of the structure.

Conclusions: Based on this study, it was concluded that if the Brezina dam suffers an earthquake of a greater intensity than that of Boumerdes, this will cause structural damage and cracks that will compromise the dam's watertightness as well as its durability.

Key words: dynamic behavior, finite element method, cracking, dam, spectral analysis.

Introduction

Water resources are incredibly important for promoting agricultural economic development worldwide. Hydraulic structures, such as dams, intake towers, and piles, are considered special structures that require a significant safety margin under both normal and critical conditions such as major earthquakes.

The evaluation of the seismic safety of a concrete gravity dam is one of the main subjects of design and construction, as well as other basic safety checks such as dam stability in its foundations and a high overflow velocity of a dam. The reservoir - dam interaction can be an important factor influencing the response of concrete dams. When a reservoir - dam system is subjected to a strong earthquake, its behavior is likely to be influenced.

The procedures for a seismic analysis of structures are often approached with simplifying assumptions. Among the most important is the one which assumes that the seismic signal is uniform. In the seismic analysis of structures, (Datta, 2010) explained the fundamentals of seismology that all structural engineers must know. Progress has been made (Der Kiureghian, 1981), which led to a specific application to linear structures using the response spectrum of soil motion. Different phenomena contributing to the spatio-temporal variability of the seismic signal have been grouped together, with four distinct effects (Der Kuirghian, 1996).

The first interaction model between the dam and the reservoir was developed by Westergaard (1933), who presented a solution for the two-dimensional pressure distributions on the upstream face of the dam due to seismic excitation. He assumed that the water is incompressible and the dam is rigid. Zienkiewicz & Bettes (1978) studied the problems of the dam reservoir in a coupled manner taking into account the flexibility of the dam. Fenves & Chopra (1987) presented a simplified approach for the analysis of concrete gravity dams under earthquake actions.

Jablonski & Humar (1990) explained the application of the constant boundary element method in the three-dimensional boundary element reservoir model for the seismic analysis of arch dams and gravity. A comparison of computer codes for a dam analysis was conducted by Singhal (1991) using EADG, PAS IV, as well as the ADINA software. The analysis of the severity of an earthquake on dam-reservoir systems using Eulerian and Lagrangian approaches was conducted by Calayir et al. (1996). Guan & Moore (1997) developed new techniques for modeling the reservoir-dam interaction and the dam foundation. Chopra & Gupta (1981) investigated the effects of the hydrodynamic interaction and the foundations on the seismic response of a concrete gravity dam. A hybrid numerical procedure is proposed for the dynamic frequency response of earth dams resting on a multilayered base. De Araújo & Awruch (1998) used the probabilistic finite element method for the analysis of a concrete gravity dam. Ghaemian & Ghobarah (1999) studied the nonlinear seismic response of concrete gravity dams considering the interaction between the dam and the reservoir. The dynamic analysis of the soil-structure interaction using the finite element-boundary coupling method has been studied by Yazdchi et al. (1999). The dynamic analysis of concrete arch dams by an ideal-coupled modal approach has been studied by Aftabi Sani & Lotfi (2010). A parametric study on the fluid-structure interaction problem was conducted by Maity & Bhattacharyya (2003). An evaluation of the effectiveness of the equations developed to determine the response of the fundamental mode of weight-bearing dams was carried out by Miguel & Bouaanani (2010). In their study, an iterative scheme in dynamic analysis and a complicated boundary condition were used. Küçükarslan et al. (2005) studied the transient analysis of the dam-reservoir interaction, including the effects of the reservoir bottom by coupling the finite element method in the infinite fluid domain and in the solid domain. A comparison of stochastic and deterministic dynamic responses of gravity dam-reservoir systems using finite fluid elements was conducted by Bayraktar et al. (2005). Asteris & Tzamtzis (2003) used a smeared crack analysis model based on a non-linear fracture mechanics crack propagation criterion to study dam cracking and response.

The experimental and numerical seismic surveys of the Three Gorges Dam were conducted by Li et al. (2005). Millán et al. (2007) demonstrated the effects of the reservoir geometry on the seismic response of gravity dams. In this paper, a boundary element method (BEM) model in the frequency domain is used to study the influence of the reservoir dam geometry on the hydrodynamic response. Bayraktar et al. (2010) studied the effect of the reservoir length on the seismic performance of gravity dams to near- and far-fault ground motions. Samii & Lotfi (2007) compared coupled and decoupled modal approaches in the seismic analysis of concrete gravity dams in the time domain. Ross et al. (2008) studied the treatment of the fluid-structure acoustic interaction using localized Lagrange multipliers. Li et al. (2008) developed a semi-analytical solution for the absorption characteristics of a reservoir bottom dam retention system. Bilici et al. (2009) studied the stochastic dynamic response of the dam-reservoir-foundation system to spatial variations in earthquake ground motions. Wang et al. (2021) studied influences on the seismic response of a gravity dam with different foundation and reservoir modeling assumptions. Xu et al. (2024) studied a time series modeling approach for damage monitoring of a concrete dam under seismic effects.

The analysis aims to study the dynamic behaviour of the dam under seismic excitation and the detection of anomalies in stresses and displacements that can be harmful to the structure. Practical conclusions are also drawn from the results obtained using different numerical strategies.

Dynamic analysis has a great importance in the design of dams with respect to seismic excitations. Several mathematical concepts govern the dynamic behavior.

Fluid equation

$$\nabla^2 P = \frac{1}{C^2}\,\ddot{P} \tag{1}$$

where ∇^2 is the Laplacian operator in two dimensions, (C) is the speed of sound in the water, and the points represent the derivative with respect to time. Equation (1), with appropriate boundary conditions, fully defines the hydrodynamic aspects of the problem.

Finite element analysis execution

The water domain is discretised as a finite element assembly, assuming that the pressure is the nodal unknown. By using the Galerkin method, the discretised form of equation (1) is obtained as:

$$[E]\{\ddot{P}\} + [A]\{\dot{P}\} + \left([G] + \frac{\zeta C}{H}[A]\right)\{p\} = -\rho f [S]\{a\} \qquad (2)$$

where {p} represents the vector of nodal pressures for the water domain. The expressions for the matrices [E], [A], [G], and [S] can be found in Maity & Bhattacharyya (1999).

$$[E] = \frac{1}{c^2}\sum\int_{\Omega}[N]^T[N]\; d\Omega + \frac{1}{g}\sum\int_{\Gamma_f}[N]^T[N]\; d\Gamma \qquad (3)$$

$$[A] = \frac{1}{c}\sum\int_{\Gamma_f}[N]^T[N]\; d\Gamma \qquad (4)$$

$$[G] = \sum\int_{\omega}\left(\frac{\partial}{\partial_x}[N]^T\frac{\partial}{\partial_x}[N] + \frac{\partial}{\partial_y}[N]^T\frac{\partial}{\partial_y}[N]\right) d\Omega \qquad (5)$$

$$[S] = \sum\int_{\Gamma_s}[N]^T[T][N_s]\; d\Gamma \qquad (6)$$

In the equations above, (3-6) Γ and Ω represent the surface and the volume of the reservoir, respectively. The indices f, s, r, and t represent the free surface, the solid-fluid interface, the bed-reservoir interface, and the truncated surface, respectively.

Differential equations governing the coupled structure of a dam

The dam-reservoir interaction is represented by two coupled second-order differential equations. The equations for the structure and the reservoir can be written in the following form:

$$[N]\{\ddot{U}\} + [C]\{\dot{U}\} + [N]\{U\} = \{f_1\} - [M]\{\ddot{U}_{gh}\} - [M]\{\ddot{U}_{gv}\} + [Q]\{P_h(t)\} \qquad (7)$$

$$[G]\{\ddot{P}_h\} + [C'']\{\dot{P}_h\}[K'']\{P_h\} = \{f_2\} - \rho[M]^T\{\ddot{U}\} \qquad (8)$$

The point represents the time derivative. The structure of the dam is analysed using the plane deformation formulation with a side reservoir. By the analysis of the structural system using the plane deformation formulation, the elementary stiffness matrices are obtained:

$$[K^e] = \int_{\Omega} [B\quad]^T [D][B]\, d\Omega \tag{9}$$

The elementary mass matrix with ρ_s is the density.

$$[M^e] = \int_{\Omega} [B^T]\quad \rho_s [N]\, d\Omega \tag{10}$$

Damping matrix

The global damping matrix is calculated using the following expression since Rayleigh damping is taken into account:

$$[C] = a[M] + b[K] \tag{11}$$

According to the theory of modal analysis, the structure of the dam can be simplified as a multi-degree of freedom system, and its equation of motion control is equation (7). In free vibration analysis, we need to solve the eigenvalue equation given below:

$$([K] - \omega^2 [M])\,\{u\} = 0 \tag{12}$$

Dynamic analysis

The dynamic analysis method is mainly based on two methods, depending on the idealisation of the dam body, namely, the method of distributed or continuous masses and the method of discrete or grouped masses. The first method forms the dynamic stiffness matrix of the structure, which includes the elastic and inertial forces acting on the structure during vibration, and determines the natural frequency and mode of the dam by solving the frequency equation, (7) (Clough & Penzien, 1975).

The second method of calculating the static stiffness matrix of the structure reduces the natural frequencies and mode shapes using standard eigenvalue solutions (Bathe & Wilson, 1987). Chopra (1995), in his book *Dynamics of Structures,* has also developed theories and applications to seismic engineering.

Description and modeling of the dam

The Brezina Dam (El-Bayadh-Algeria) is a gravity dam, a concrete arch dam. It is built on a rocky foundation (limestone) and has a total height of 63 m. The arc length at the top is 153 m, with a maximum arc radius of 67.80 m. The maximum thickness is 41.33 m, and the thickness at the crest is 3 m as shown in Figure 1. These mechanical and physical properties are as follows: Young's modulus E = 26.6 GPa; Poisson's ratio v = 0.2; and density γ = 2.5 t/m3. There are also the mechanical and physical properties of the foundation (rock) and the fluid, which are, respectively, Young's modulus E = 14 GPa; Poisson's ratio n = 0.3; density Mv = 2.7 t/m3, and Young's modulus E = 20.7x106 GPa; density Mv = 1 t/m3.

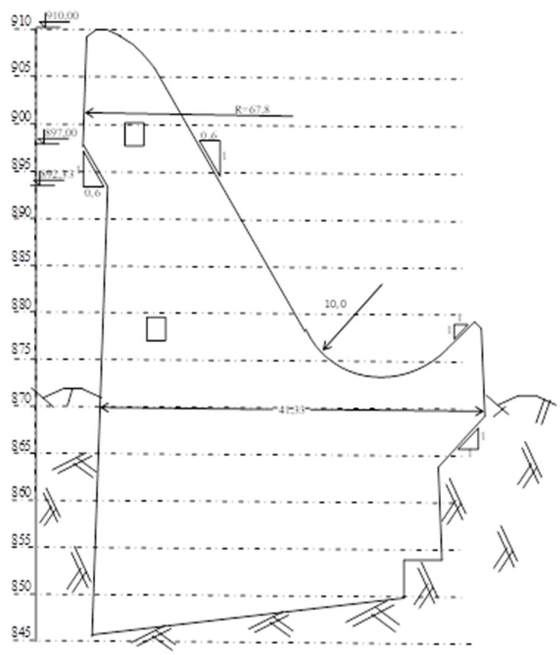

Figure 1 – Cross section and the dimensional parameters of the dam

ANSYS is a versatile finite element analysis software; it allows testing of product prototypes in a virtual environment before manufacturing them. It also identifies weaknesses and improves them. In our modeling, we used two types of finite elements: Fluid29 and Plane42; the resulting mesh included 4,790 nodes and 1,974 elements, as shown in Figure 2.

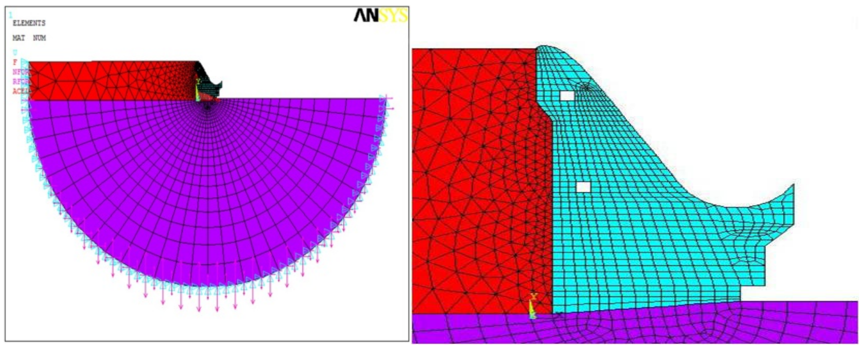

Figure 2 – Model of the Dam - Fluid - Foundation system with ANSYS

Analysis and interpretation

Static analysis

Static stresses are caused by the hydrostatic pressure and the dead weight of the dam, which is automatically distributed towards the center of gravity, while the sign convention is respected when entering the pressure and assuming that the tank is full. The results are presented in Table 1 and Figure 3.

This shows the distribution of static stresses in the dam body. These stresses reach the maximum and minimum values in the lower part. Figures 4 and 5 show the distribution of the normal (X, Y and XY) and main (S1, S3 and Tmax) stresses in the lower part of the structure. It can be seen that these stresses vary from upstream and downstream of tension to compression.

Table 1 – Results (minimum and maximum) of the various static constraints

	Sx (MPa)	Sy (MPa)	Sxy (MPa)	S1 (MPa)	S3 (MPa)	Tmax (MPa)
MAX	0.47556	0.30071	0.90254	0.64125	0.13501	0.38813
MIN	-2.3767	-3.499	0.23755	-1.4314	-4.0006	-2.716

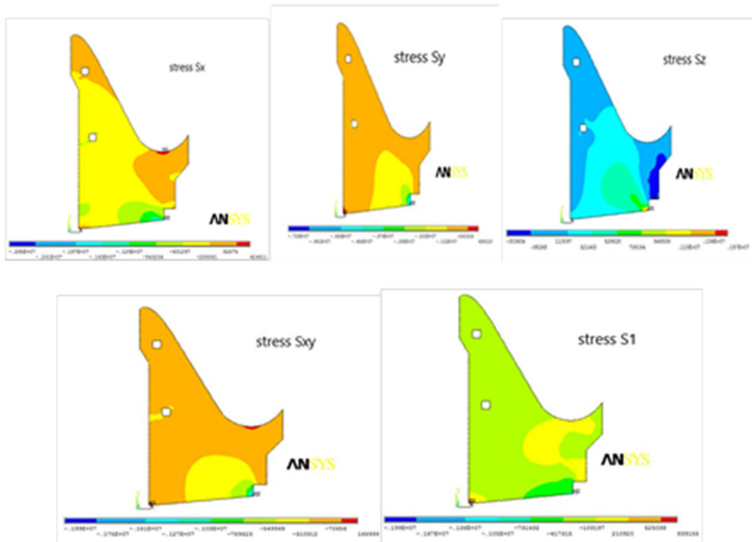

Figure 3 – Mapping the distribution of static stresses in the dam

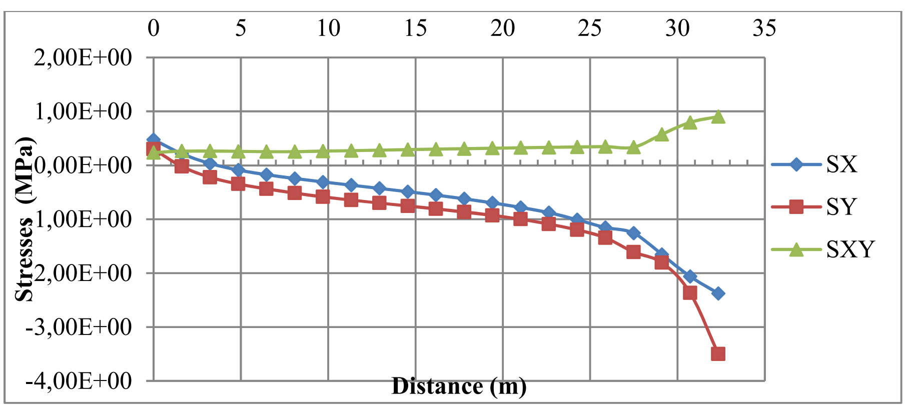

Figure 4 – Normal stresses in the directions X, Y and XY

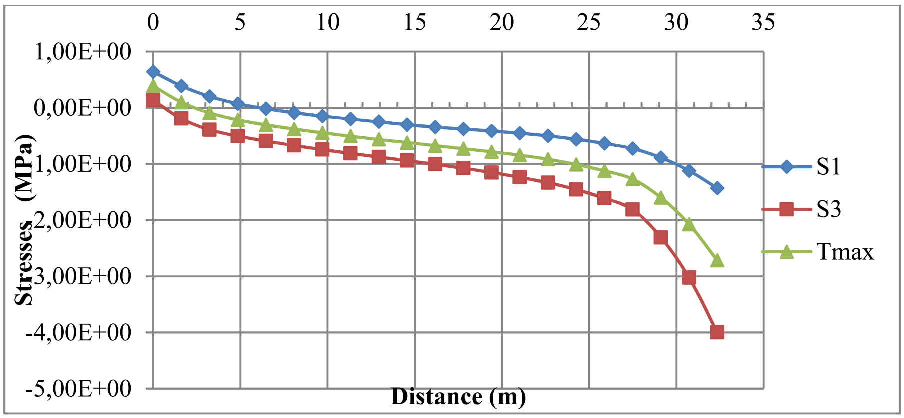

Figure 5 – Principal stresses in the directions S1, S3 and Tmax

Modal analysis

The principle of the modal method is to find, for each mode of vibration, the maximum value of the effect of seismic forces in the structure, which is represented by the calculated response spectrum. Prior to dynamic analysis, the natural frequency of the dam in the case of an empty reservoir is determined by modal analysis. The analysis is performed in the modal mode. All degrees of freedom at the base of the rock substrate and the peripheral equipment are restricted.

The value of the damping coefficient considered is 5% - the results of the analysis are shown in Table 2.

Table 2 – Results obtained for different vibration modes

Mode	Frequency [Hz]	Period [s]	Participation factor	Coefficient	Effective mass	Mass fraction	Total mass
1	4.332	0.231	1.44×10^3	1.000	2.08×10^6	0.604	0.594
2	9.729	0.103	-8.11×10^2	0.562	6.58×10^5	0.795	0.188
3	11.029	0.091	-5.81×10^2	0.403	3.38×10^5	0.892	0.096
4	18.917	0.053	6.09×10^2	0.422	3.71×10^5	1.000	0.106
5	23.073	0.043	-1.80×10^1	0.012	3.25×10^2	1.000	0.000
Sum	/	/	/	/	3.45 x 106	/	0.985

The deformations obtained for each vibration mode are presented in Figure 6.

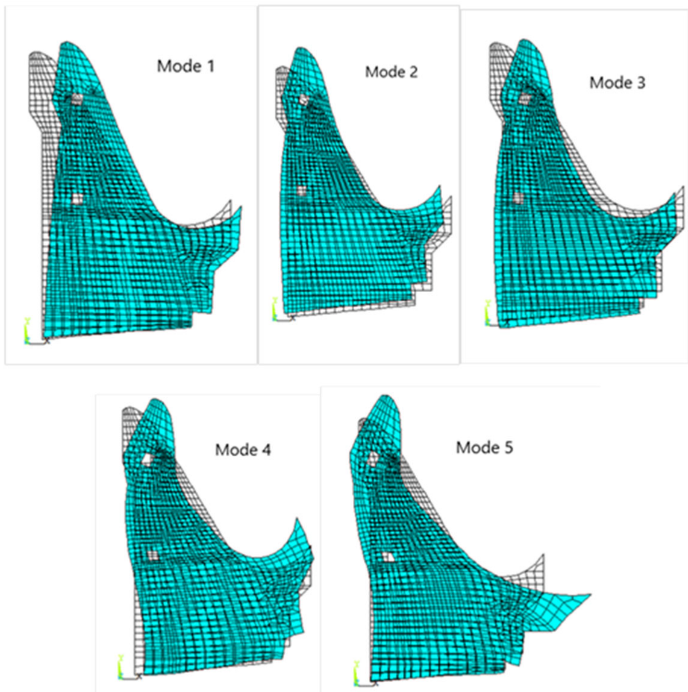

Figure 6 – Deformations of each vibration mode

Dynamic analysis by accelerograms

At this stage of the analysis, the two most destructive earthquakes recorded in Algeria have been selected, namely the Asnan earthquake and the Boumeldes earthquake. The accelerograms and the characteristics of these two earthquakes are presented in Table 3 and shown in Figure 7.

Table 3 – Characteristics of the two earthquakes

Earthquake name	Location	Date	PGA (g)	Magnitude
Asnam	15 km east of Al Asnam (CHELF) Béni Rached	10 /10/1980	0.034	7.3
Boumerdes	04 Km from the coast between Zemmouri and Boumerdes	21/05/2003	0.338	6.4

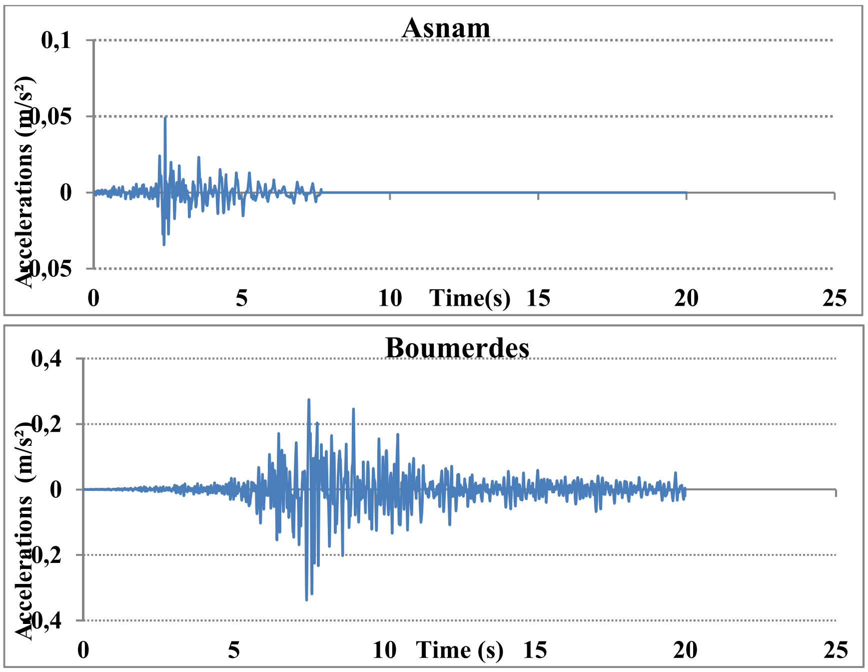

Figure 7 – Accelerograms of the two earthquakes

Results of the displacements at the top of the dam

The movement of the dam crest under the excitation of the two earthquakes is shown in Figure 8. The comparison of the two figures shows that the excitation generated by the Boumerdes earthquake has a significant effect on the movement of the dam crest.

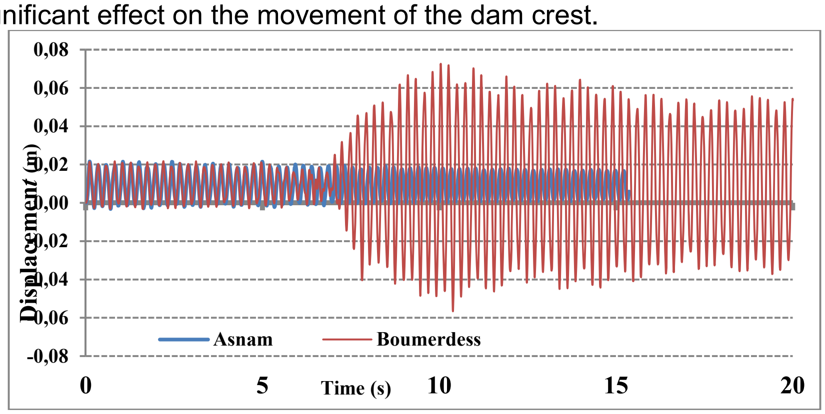

Figure 8 – Displacement to the ridge (top) of the dam under the excitation of the two earthquakes

Results of the acceleration at the top of the dam

The accelerations at the top of the dam under the excitation of the two earthquakes are illustrated in Figure 9.

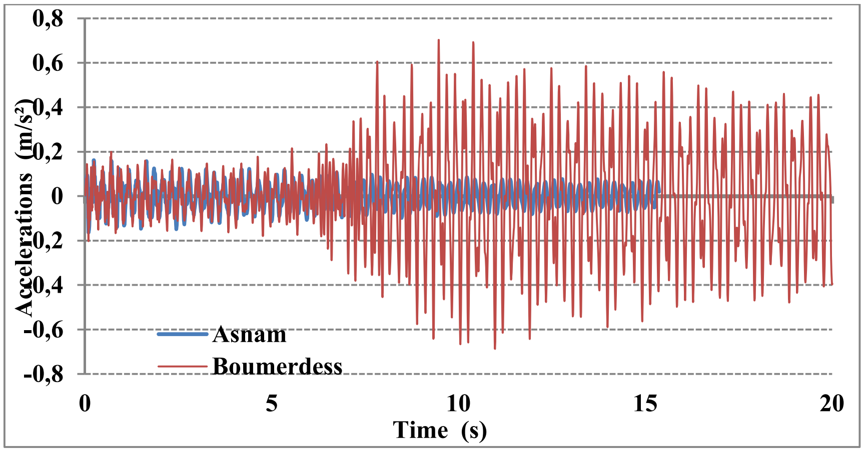

Figure 9 – Acceleration at the crest (top) of the dam under the excitation of the two earthquakes

Distribution of the principal stresses (S1) at the base as a function of time

The distributions of the main stresses at the base of the dam over time are shown in Figures 10, 11, and 12.

These figures illustrate the variation of stresses along the upstream, central, and downstream sections of the dam during two earthquakes. In particular, the tensile stresses exceed the compressive stresses in the upstream section, while both stresses decrease significantly in the central section.

Conversely, in the downstream section, compressive stresses dominate and exceed tensile stresses.

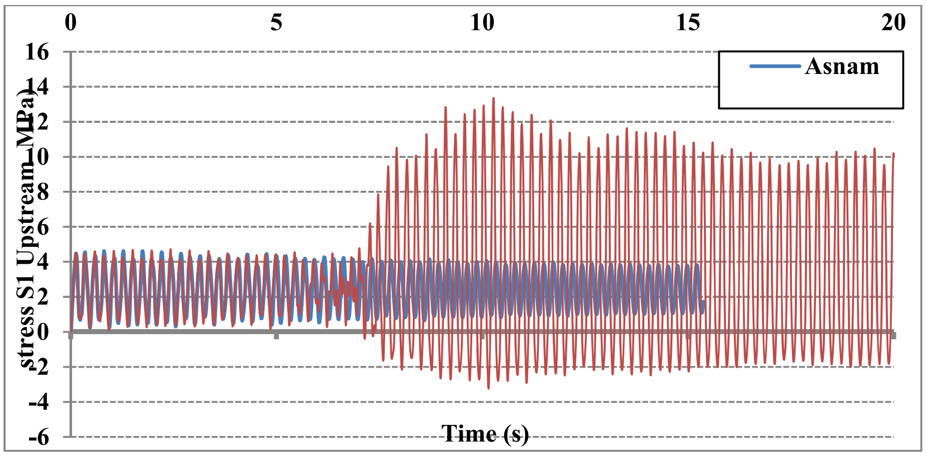

Figure 10 – Principal stresses S1 at the basis of the dam upstream for the two earthquakes

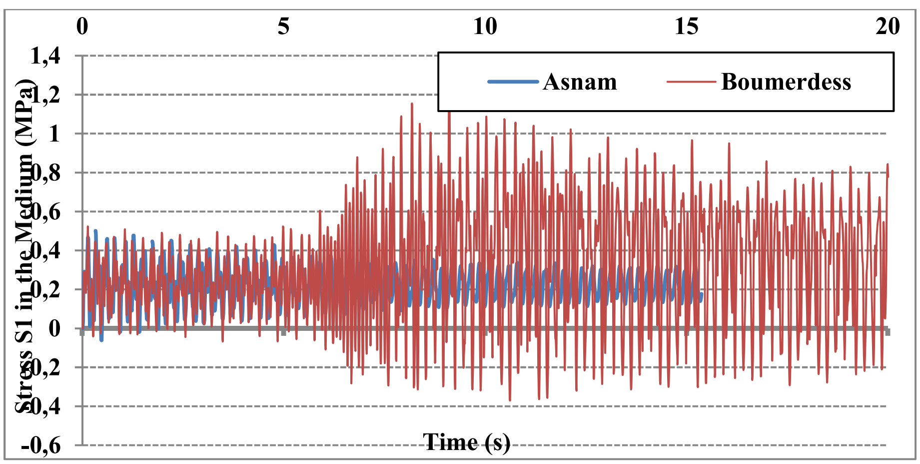

Figure 11 – Principal stresses S1 at the basis of the dam in the middle for the two earthquakes

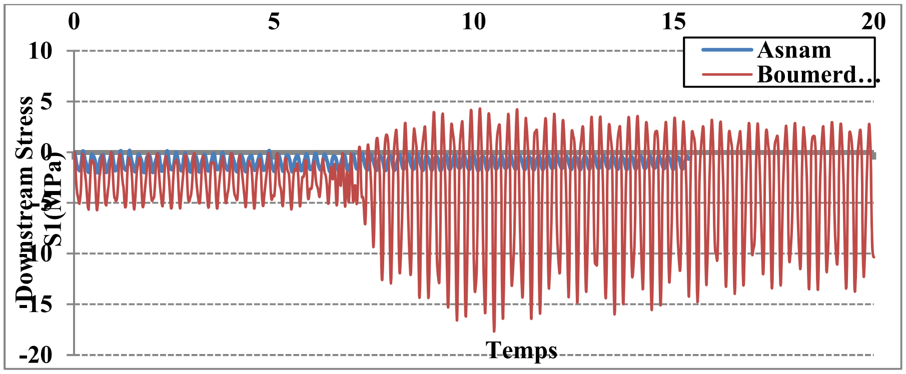

Figure 12 – Principal stresses S1 at the basis of the downstream dam for the two earthquakes

Table 4 shows the maximum displacements and accelerations at the crest and the principal stresses S1 at the base (upstream, intermediate and downstream) recorded for the two earthquakes.

Table 4 – Comparison of the results of the deferent characteristics under the effect of the excitations of the two earthquakes

	Displacement (m)	Acceleration (m/s^2)	Stresses S1 en Amant MPa	Stresses S1 au Milieu MPa	stresses S1 en Aval MPa
Asnam	2.16×10^{-02}	0.1617515	4.61263648	0.50066706	0.16896932
Boumerdes	7.26×10^{-02}	0.7032191	13.3658454	1.26142696	4.31357794

Comparing the different results in Table 4 shows that all the results obtained under the excitation of the Boumerdes earthquake are much more significant than those of the Asnam earthquake.

The tensile stresses are mainly concentrated upstream of the dam and greatly exceed the tensile strength limit of the concrete f_t= 2.35MPa, causing cracks at the base of the dam.

Spectral analysis

The spectral method is an approximate technique for evaluating the peak response of a structure based on the peak response of each modal oscillator read from the vibration spectrum of the excitation.

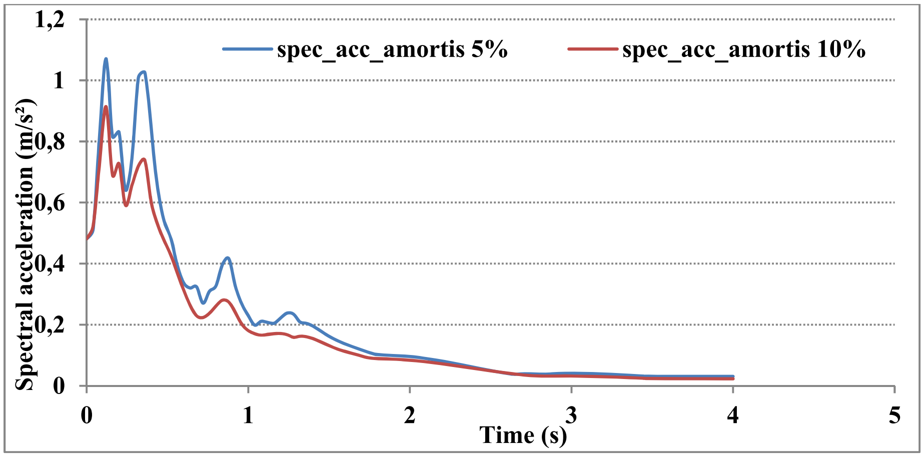

Figure 13 – Response spectra with 5% and 10% damping (Asnam earthquake)

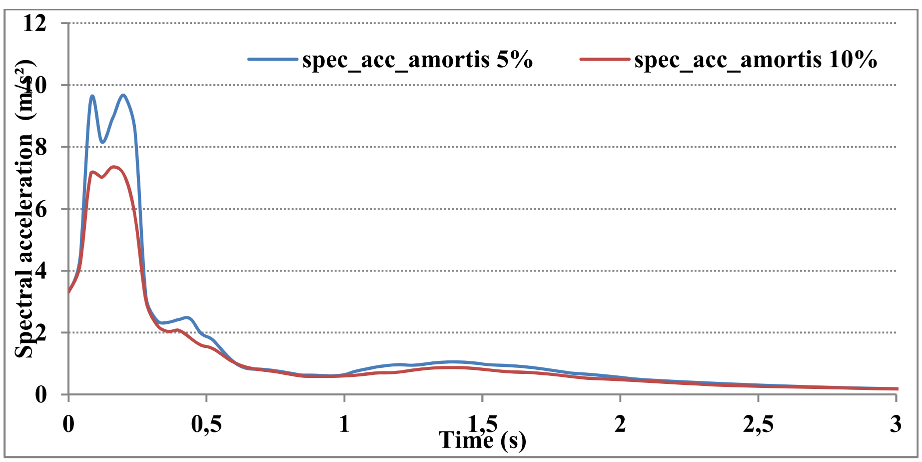

Figure 14 – Response spectra with 5% and 10% damping (Boumerdes earthquake)

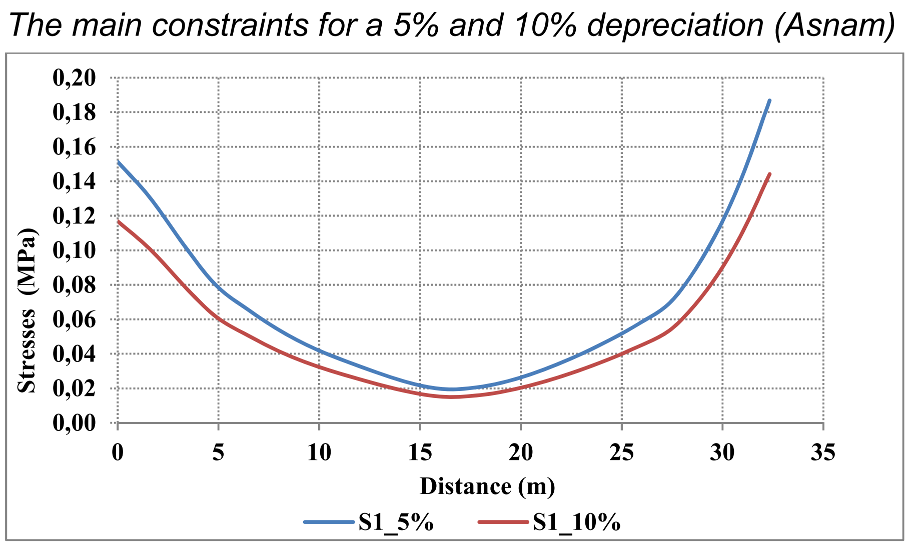

Figure 15 – Principal stresses S1 at the basis for the Asnam earthquake damped at 5% and 10%

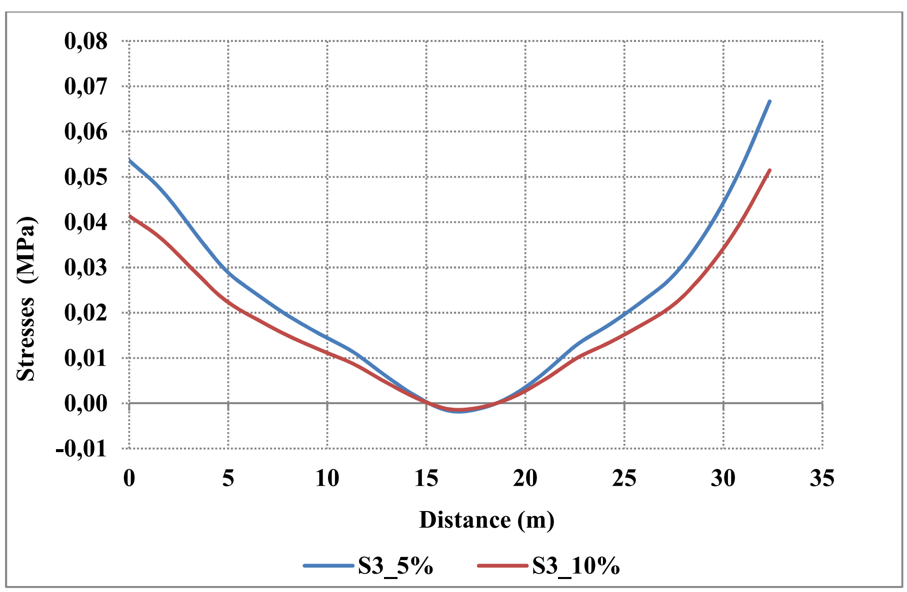

Figure 16 – Principal stresses S3 at the basis for the Asnam earthquake damped at 5% and 10%

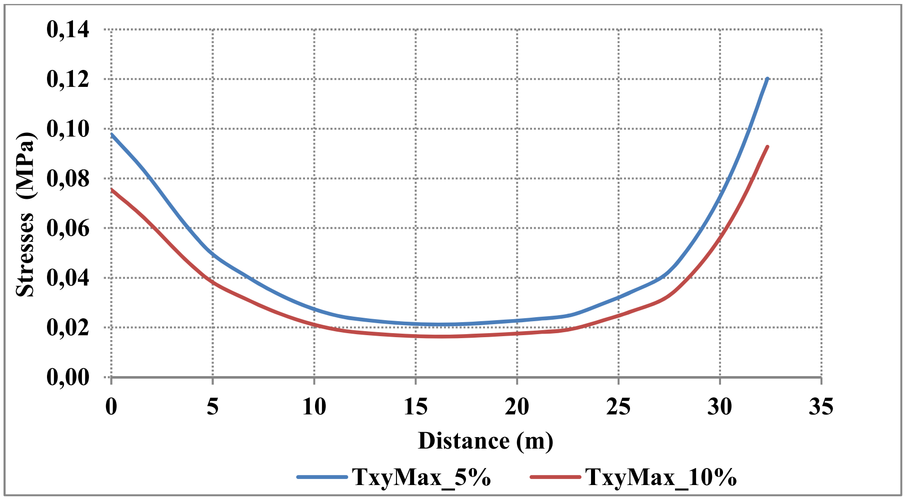

Figure 17 – Principal stresses TMax at the basis for the Asnam earthquake damped at 5% and 10%

Table 5 – Results under the excitation of the Asnam earthquake damped at 5% and 10%

	S1		S3		Tmax		Dépl max (m)	
	5%	10%	5%	10%	5%	10%	5%	10%
Max	0.18686	0.14421	0.06666	0.051446	0.1202	0.092764	$8.43 \cdot 10^{-04}$	$6.51 \cdot 10^{-04}$
Min	0.019478	0.01503	-0.00168	-0.00129	0.02116	0.016330		

According to Figures 15, 16, and 17, damping has an opposite effect on the principal stresses. Damping significantly reduces the stresses upstream and downstream, but in the central section, the damping effect is weak for the stresses S1 and TMax, and negligible for the stress S3. These results are reported in Table 5.

When comparing the stress S1 with 5% and 10% damping, it can be seen that at 10% damping the stress is reduced by 0.043 MPa compared with a reduction of 5%, while for displacements the reduction is 1.92 x 10-4 m.

The main constraints for a 5% and 10% depreciation (Boumerdes)

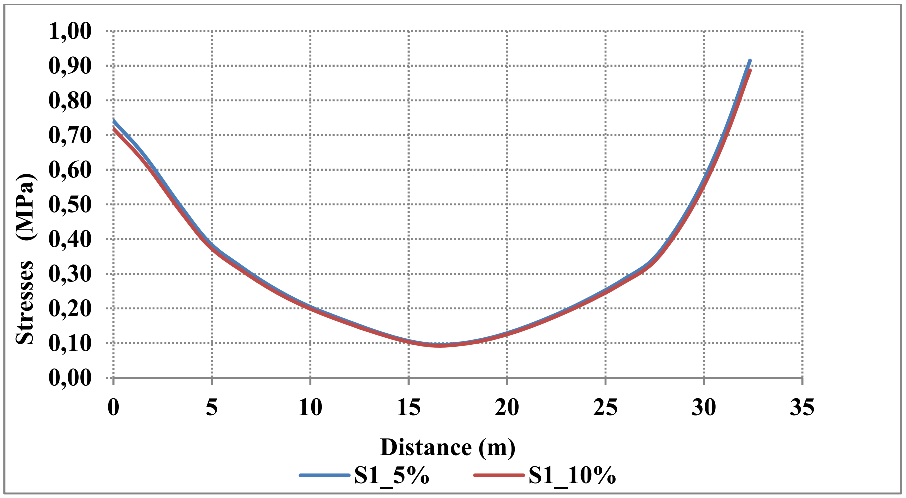

Figure 18 – Principal stresses S1 at the basis for the Boumerdes earthquake damped at 5% and 10%

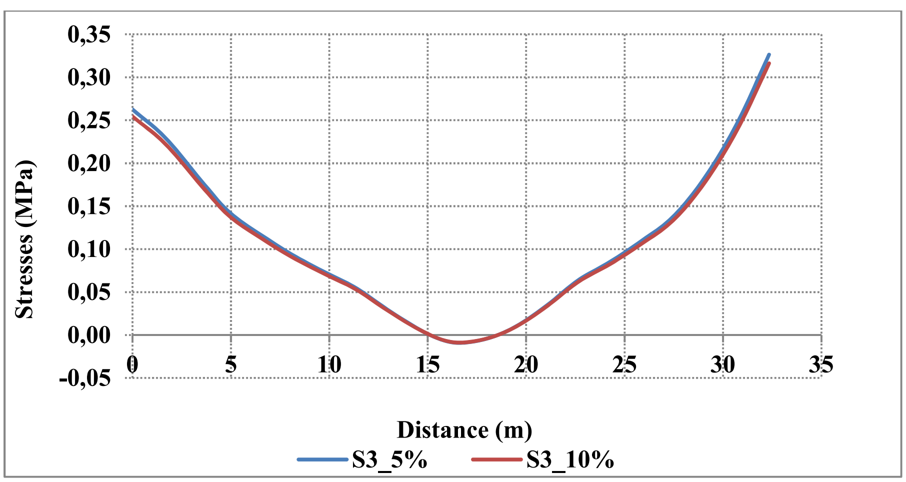

Figure 19 – Principal stresses S3 at the basis for the Boumerdes earthquake damped at 5% and 10%

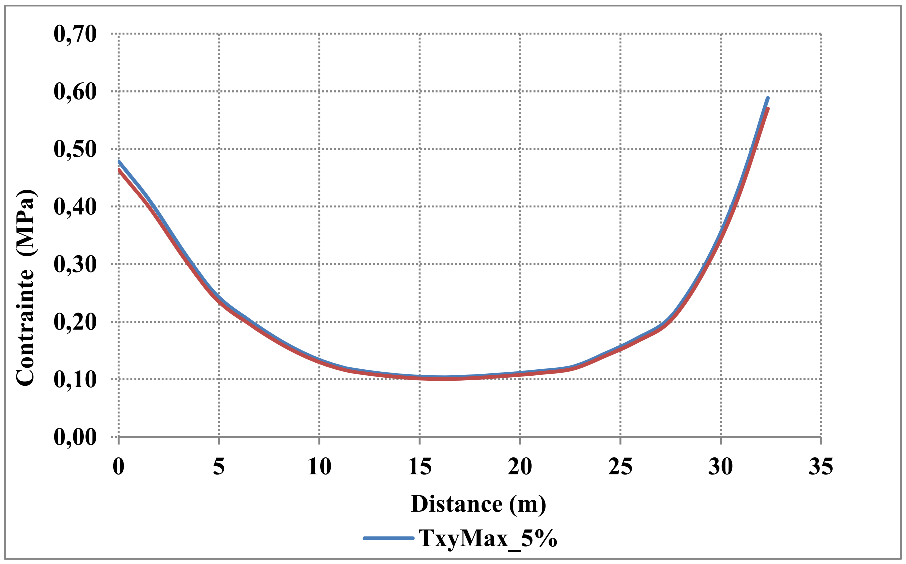

Figure 20 – Principal stresses TMax at the basis for the Boumerdes earthquake damped at 5% and 10%

Table 6 – Results under the excitation of the Boumerdes earthquake damped at 5% and 10%

	S1		S3		Tmax		Depl max (m)	
	5%	10%	5%	10%	5%	10%	5%	10%
Max	0,91489	0,8866	0,32637	0,31628	0,58852	0,57032	4.13×10^{-03}	4.00×10^{-03}
Min	0,095366	0,092417	-0,0082377	-0,007983	0,1036037	0,1004		

Similar to the Asnam earthquake and based on Figures 18, 19 and 20, it can be seen that damping has an opposite effect on the principal stress. The damping reduces the stresses in the upstream and downstream directions, but in the centre the damping effect on the three stresses is negligible. The same results are shown in Table 7. If the stresses S1 for 5% and 10% damping are compared, it can be seen that the difference is small, 0.028 MPa, whereas for displacement the reduction is still insignificant.

Conclusion

The main objective of this paper is to provide a scientific and analytical contribution on the internal constraints of arch dams, in order to better understand the complexity of the engineer's task when designing dams.

Indeed, this analysis shows that, contrary to what has been said, dams have certain displacements and no part of the superstructure is immune to the risk of failure; therefore, engineers must find feasible technical solutions.

Static analysis has shown that stresses vary from tension to compression over the entire surface of the dam. Concentrations of tension constraints are observed at the upstream base, while compression constraints are observed downstream. Whether tension or compression, the constraints remain low compared to the tolerated limits.

As for modal analysis, it allowed us to identify the natural modes of the structure. We considered the first five (5) eigenmodes, where we observed that the first two modes are the most important because their frequency is low. It is known that when the frequency is low, there is a risk of collapse.

After static and modal analyses comes dynamic analysis which is carried out under the excitation of two earthquakes, namely Boumerdes and Asnam, to get an idea of the dynamic behaviour (tension, compression and displacement) of the dam at the top.

The Boumerdes earthquake generated significant tensile stresses upstream and downstream, exceeding the ultimate tensile stress, whereas the tensile stress in the Asnam earthquake only exceeded the ultimate tensile stress upstream.

It should be noted that the values obtained under the excitation of the Boumerdes earthquake are larger than those of the Asnam earthquake. For example, the principal stress S1 of the upstream Boumerdes earthquake is almost three (3) times greater than that of the Asnam earthquake. Although the magnitude of the Asnam earthquake was greater than that of the Boumerdes earthquake, these results are probably due to the acceleration time.

Overall, this study concludes that if the Brezina dam is affected by an earthquake of a greater intensity than that of Boumerdes, there will be structural damage and cracks that will affect the watertightness and durability of the dam.

References

Aftabi Sani, A. & Lotfi, V. 2010. Dynamic analysis of concrete arch dams by ideal-coupled modal approach. *Engineering Structures*, 32(5), pp.1377-1383. Available at: https://doi.org/10.1016/j.engstruct.2010.01.016.

Asteris, P.G. & Tzamtzis, A.D. 2003. Nonlinear Seismic Response Analysis of Realistic Gravity Dam-Reservoir Systems. *International Journal of Nonlinear Sciences and Numerical Simulation*, 4(4), pp.329-338. Available at: https://doi.org/10.1515/IJNSNS.2003.4.4.329.

Bathe, K.-J. & Wilson, E.L. 1976. *Numerical methods in finite element analysis (Prentice-Hall civil engineering and engineering mechanics series).* Prentice-Hall. ISBN: 978-0136271901.

Bayraktar, A., Hançer, E. & Dumanoğlu, A.A. 2005. Comparison of stochastic and deterministic dynamic responses of gravity dam–reservoir systems using fluid finite elements. *Finite Elements in Analysis and Design*, 41(14), pp.1365-1376. Available at: https://doi.org/10.1016/j.finel.2005.02.004.

Bayraktar, A., Türker, T., Akköse, M. & Ateş, Ş. 2010. The effect of reservoir length on seismic performance of gravity dams to near- and far-fault ground motions. *Natural Hazards*, 52, pp.257-275. Available at: https://doi.org/10.1007/s11069-009-9368-1.

Bilici, Y., Bayraktar, A., Soyluk, K., Haciefendioğlu, K., Ateş, Ş. & Adanur, S. 2009. Stochastic dynamic response of dam-reservoir-foundation systems to spatially varying earthquake ground motions. *Soil Dynamics and Earthquake Engineering*, 29(3), pp.444-458. Available at: https://doi.org/10.1016/j.soildyn.2008.05.001.

Calayir, Y., Dumanoğlu, A.A., & Bayraktar, A. 1996. Earthquake analysis of gravity dam-reservoir systems using the eulerian and lagrangian approaches. *Computers & Structures*, 59(5), pp.877-890. Available at: https://doi.org/10.1016/0045-7949(95)00309-6.

Chopra, A.K. 1995. *Dynamics of structures: Theory and applications to earthquake engineering*. Englewood Cliffs, NJ, USA: Prentice Hall. ISBN: 0-13-855214-2.

Chopra, A.K. & Gupta, S. 1981. Hydrodynamic and Foundation Interaction Effects in Earthquake Response of a Concrete Gravity Dam. *Journal of the Structural Division,* 107(8), pp.1399-1412. Available at: https://doi.org/10.1061/JSDEAG.0005756.

Clough, R.W. & Penzien, J. 1975. *Dynamics of Structures*. McGraw-Hill College. ISBN: 978-0070113923.

de Araújo, J.M. & Awruch, A.M. 1998. Probabilistic finite element analysis of concrete gravity dams. *Advances in Engineering Software*, 29(2), pp.97-104. Available at: https://doi.org/10.1016/S0965-9978(98)00052-0.

Datta, T.K. 2010. *Seismic Analysis of Structures*. Wiley. ISBN: 978-0-470-82462-7.

Der Kiureghian, A. 1981. Seismic Risk Analysis of Structural System. *Journal of Engineering Mechanics*, 107(6), pp.1133-1153. Available at: https://doi.org/10.1061/JMCEA3.0002772.

Der Kiureghian, A. 1996. Structural reliability methods for seismic safety assessment: a review. *Engineering Structure*, 18(6), pp.412-424. Available at: https://doi.org/10.1016/0141-0296(95)00005-4.

Fenves, G. & Chopra, A.K. 1987. Simplified Earthquake Analysis of Concrete Gravity Dams. *Journal of Structural Engineering*, 113(8), pp.1688-708. Available at: https://doi.org/10.1061/(ASCE)0733-9445(1987)113:8(1688).

Ghaemian, M. & Ghobarah, A. 1999. Nonlinear seismic response of concrete gravity dams with dam–reservoir interaction. *Engineering Structures*, 21(4), pp.306-315. Available at: https://doi.org/10.1016/S0141-0296(97)00208-3.

Guan, F. & Moore, I.D. 1997. New techniques for modelling reservoir-dam and foundation-dam interaction. *Soil Dynamics and Earthquake Engineering*, 16(4), pp.285-293. Available at: https://doi.org/10.1016/S0267-7261(96)00044-9.

Jablonski, A.M. & Humar, J.L. 1990 . Three-dimensional boundary element reservoir model for seismic analysis of arch and gravity dams. *Earthquake Engineering & Structural Dynamics*,19(3), pp.359-376. Available at: https://doi.org/10.1002/eqe.4290190306.

Küçükarslan, S., Coşkun, S.B. & Taşkın, B. 2005. Transient analysis of dam–reservoir interaction including the reservoir bottom effects. *Journal of Fluids and Structures*, 20(8), pp.1073-1084. Available at: https://doi.org/10.1016/j.jfluidstructs.2005.05.004.

Li, S.-m., Li, H. & Li, A.-m. 2008. A Semi-Analytical Solution for Characteristics of a Dam-Reservoir System with Absorptive Reservoir Bottom. *Journal of Hydrodynamics*, 20, pp.727-734. Available at: https://doi.org/10.1016/S1001-6058(09)60008-1.

Li, Q.S., Li, Z.N., Li, G.Q., Meng, J.F. & Tang, J. 2005. Experimental and numerical seismic investigations of the Three Gorges Dam. *Engineering Structures*, 27(4), pp.501-513. Available at: https://doi.org/10.1016/j.engstruct.2004.11.009.

Maity, D. & Bhattacharyya, S.K. 1999. Time-domain analysis of infinite reservoir by finite element method using a novel far-boundary condition. *Finite Elements in Analysis and Design*, 32(2), pp.85-96. Available at: https://doi.org/10.1016/S0168-874X(98)00077-8.

Maity, D. & Bhattacharyya, S.K. 2003. A parametric study on fluid–structure interaction problems. *Journal of Sound and Vibration*, 263(4), pp.917-935. Available at: https://doi.org/10.1016/S0022-460X(02)01079-9.

Miguel, B. & Bouaanani, N. 2010. Simplified evaluation of the vibration period and seismic response of gravity dam water systems . Engineering Structures, 32(8), pp.2488-2502. Available at: https://doi.org/10.1016/j.engstruct.2010.04.025

Millán, M.A., Young, Y.L. & Prévost, J.H. 2007. The effects of reservoir geometry on the seismic response of gravity dams. *Earthquake Engineering And*

Structural Dynamics, 36(11), pp.1441-1459. Available at: https://doi.org/10.1002/eqe.688.

Ross, M.R., Felippa, C.A., Park, K.C. & Sprague, M.A. 2008. Treatment of acoustic fluid–structure interaction by localized Lagrange multipliers: Formulation. *Computer Methods in Applied Mechanics and Engineering*, 197(33-40), pp.3057-3079. Available at: https://doi.org/10.1016/j.cma.2008.02.017

Samii, A. & Lotfi, V. 2007. Comparison of coupled and decoupled modal approaches in seismic analysis of concrete gravity dams in time domain. *Finite Elements in Analysis and Design*, 43(13), pp.1003-1012. Available at: https://doi.org/10.1016/j.finel.2007.06.015.

Singhal, A.C. 1991. Comparison of computer codes for seismic analysis of dams. *Computers & Structures*, 38(1), pp.107-112. Available at: https://doi.org/10.1016/0045-7949(91)90128-9.

Wang, C., Zhang, H ., Zhang, Y., Guo, L ., Wang, Y. & Thira Htun, T.T. 2021 Influences on the Seismic Response of a Gravity Dam with Different Foundation and Reservoir Modeling Assumptions. *Water*, 13(21), art.number:3072 . Available at: https://doi.org/10.3390/w13213072.

Westergaard, H.M. 1933. Water Pressures on Dams during Earthquakes. *Transactions of the American Society of Civil Engineers*, 98(2), pp.418-472. Available at: https://doi.org/10.1061/TACEAT.0004496.

Xu, Y., Shao, C., Zheng, S., Li, X., Gu, H. & Zheng, D. 2024. A time series modeling approach for damage monitoring of concrete dam under seismic effects. *Structures,* 59, art.number:105656. Available at: https://doi.org/10.1016/j.istruc.2023.105656.

Yazdchi, M., Khalili, N. & Valliappan, S. 1999. Dynamic soil-structure interaction analysis via coupled finite-element-boundary-element method. *Soil Dynamics and Earthquake Engineering*, 18(7), pp.499-517. Available at: https://doi.org/10.1016/S0267-7261(99)00019-6.

Zienkiewicz, O.C. & Bettes, P. 1978. Fluid-structure dynamic interaction and wave forces. An introduction to numerical treatment. *International Journal for Numerical Methods in Engineering*, 13(1), pp.1-16. Available at: https://doi.org/10.1002/nme.1620130102.

Análisis dinámico de una presa abovedada

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CAMPO: ingeniería mecánica, materiales
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: El análisis dinámico de la respuesta sísmica de una presa de bóveda de hormigón es un problema complejo en el que la representación del comportamiento del material requiere alguna forma de modelo no lineal, especialmente si el hormigón está sometido a una carga de tensión significativa del suelo. En el caso de grandes movimientos de estos últimos, se pueden formar grandes grietas en algunas zonas de la presa, especialmente en la base de la presa y cambios casi repentinos en la geometría

Métodos: Este análisis se basó en una simulación numérica del efecto dinámico. Este trabajo se realizó mediante el método de elementos finitos con el programa ANSYS 12.1. La presa fue modelada en dos dimensiones. Se realizaron cuatro tipos de análisis: análisis estático, análisis modal, análisis sísmico bajo excitación de dos acelerogramos (Asnam 1980 y Boumerdes 2003) y análisis espectral.

Resultados: Este análisis mostró la vulnerabilidad de la presa de Brezina al terremoto de Boumerdes con altas tensiones en la base de la estructura.

Conclusión: A partir de este estudio se concluyó que, si la presa de Brezina sufre un terremoto de mayor intensidad que el de Boumerdes, éste provocará daños estructurales y grietas que comprometerán la estanqueidad de la presa, así como su durabilidad.

Palabras claves: comportamiento dinámico, método de elementos finitos, fisuración, presa, análisis espectral.

Динамический анализ арочной плотины

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РУБРИКА ГРНТИ: 55.01.77 Методы исследования и моделирования. Математические и кибернетические методы,
67.09.33 Бетоны. Железобетон. Строительные растворы, смеси, составы,
70.17.29 Плотины водохозяйственные и мелиоративные
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Динамический анализ сейсмической реакции бетонной арочной плотины представляет сложную задачу, в которой представление поведения материала требует некоторой формы нелинейной модели, особенно если бетонный фундамент подвергается большой нагрузке. В случае массивных сдвигов грунта на плотине могут образоваться крупные трещины, особенно у ее основания, а также вблизи внезапных изменений геометрии.

Методы: В статье проведен анализ, основанный на численном моделировании динамического воздействия. С помощью программы ANSYS 12.1 применен метод конечных элементов. Плотина была смоделирована в двух измерениях. Были выполнены четыре типа анализа: статический анализ, модальный анализ, сейсмический анализ при возбуждении двух акселерограмм (Аснам, 1980 и Бумердес, 2003) и спектральный анализ.

Результаты: Анализ показал уязвимость плотины Брезина при землетрясении в Бумердесе из-за высокой нагрузки на фундамент сооружения.

Выводы: На основании данного исследования был сделан вывод, что при землетрясении большей интенсивности, чем в Бумердесе плотина Брезина могла бы сильно пострадать. Такое землетрясение могло привести к структурным повреждениям и появлению трещин, которые поставят под угрозу водонепроницаемость плотины, а также ее долгосрочность.

Ключевые слова: динамическое поведение, метод конечных элементов, трещинообразование, плотина, спектральный анализ.

Динамичка анализа лучне бране

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ОБЛАСТ: машинство, материјали
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални нуачни рад

Сажетак:

Увод/циљ: Динамичка анализа сеизмичког одговора лучне бране од бетона представља сложен проблем где представљање понашања материјала захтева неки облик нелинеарног модела, нарочито ако је бетон изложен великом оптерећењу темељне површине. У случајевима када долази до масивних померања тла, велике прслине могу да се формирају на брани, нарочито у њеној основи, као и у близини изненадних промена у геометрији.

Методе: Ова анализа је заснована на нумеричкој симулацији динамичког одговора. Рад се заснива на коришћењу методе коначних елемената помоћу програма ANSYS 12.1. Брана је моделована у две димензије. Коришћене су четири врсте анализа: статичка анализа, модална анализа, сеизмичка анализа са побудом два акцелерограма (Аснам 1980 и Бумердес 2003) и спектрална анализа.

Резултати: Ова анализа указала је на рањивост бране Брезина од земљотреса јачине оног у Бумердесу са великим оптерећењима на темељ структуре.

Закључци: На основу ове студије закључено је да би земљотрес веће јачине од оног у Бумердесу изазвао структурна оштећења и прслине на брани Брезина који би угрозили њену водонепропусност и трајност.

Кључне речи: динамичко понашање, метод коначних елемената, формирање прслина, брана, спектрална анализа.

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