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Isogeometric analysis of the seismic response of a gravity dam: A comparison with FEM

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Abstract. Modeling and analyzing the dynamic behavior of fluid-soil-structure interaction problems are crucial in structural engineering. The solution to such coupled engineering systems is often not achievable through analytical modeling alone, and a numerical solution is necessary. Generally, the Finite Element Method (FEM) is commonly used to address such problems. However, when dealing with coupled problems with complex geometry, the finite element method may not precisely represent the geometry, leading to errors that impact solution quality. Recently, Isogeometric Analysis (IGA) has emerged as a preferred method for modeling and analyzing complex systems. In this study, IGA based on Non-Uniform Rational B-Splines (NURBS) is employed to analyze the seismic behavior of concrete gravity dams, considering fluid-structure-foundation interaction. The performance of IGA is then compared with the classical finite element solution. The computational efficiency of IGA is demonstrated through case studies involving simulations of the reservoir-foundation-dam system under seismic loading.

Keywords: finite element analysis; fluid-soil-structure interaction; gravity dam; isogeometric analysis; seismic behavior; NURBS

1. Introduction

Concrete gravity dams are strategic structures widely used for water supply, electricity production and flood control, and they are known to have a complex seismic behavior because of the interaction with the reservoir and the foundation. The construction of large dams with complex geometry in high seismicity zones makes the analysis more complex and requires accurate and efficient numerical models.

Several works carried out by different authors have been devoted to the simulation of the seismic behavior of concrete dams using the classical finite element method (FEM) with the consideration of different parameters that can impact their dynamic behavior. Altunisik and Sesli (2015) investigated the effect of hydrodynamic pressures on the dam, aiming to simulate realistic seismic behavior. They employed various modeling approaches for water pressure such as Westergaard, Lagrange and Euler. The dynamic characteristics and seismic response of the dam were analyzed using ANSYS software and compared to each other. Ouzandja and Tiliouine (2015)

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used the FEM with ANSYS software to investigate the effect of base sliding on the seismic response of the Oued Fodda gravity dam, the hydrodynamic pressure was modeled as added mass using Westergaard principle. Varughese and Nikithan (2016) investigated the static and dynamic behavior of the dam-reservoir-foundation system using ANSYS software. The dam and foundation were modeled with the 2D element in plane strains, specifically “PLANE 42,” and the reservoir was represented by the fluid acoustic element “FLUID 29,” considering fluid-structure coupling. The fundamental period of concrete dams was determined based on modal analysis and the seismic response of the dam was assessed in terms of peak displacements and stresses. Sevim (2018) examined the impact of geometrical dimensions on the seismic response of concrete gravity dams, considering five different base width-to-dam height (L/H) ratios ranging from 0.25 to 1.25. The study utilized ANSYS software, taking into account the interaction between the dam, reservoir, and foundation. The seismic response of the models was analyzed by presenting natural frequencies, mode shapes, displacements, and principal stresses. In their study, Altunisik *et al*. (2018) developed engineering software to evaluate the structural response of a laboratory-constructed concrete arch dam utilizing spectrum analysis under an empty reservoir condition, considering soil-structure interaction and a fixed foundation. Numerical results obtained through the finite element method were then compared with experimental measurements to demonstrate the accuracy of the model. Mandal and Maity (2019) conducted a seismic analysis of a concrete gravity dam, taking into account soil-structure-fluid interaction. They utilized a displacement-based plane strain finite element formulation for the dam and foundation domain, and a pressure-based finite element formulation for the fluid domain. A direct coupling method was adopted to incorporate the interaction effects among the dam, foundation, and reservoir domain, aiming to obtain the dynamic responses of the dam. Ouzandja *et al*. (2017) investigated the three-dimensional seismic response of Oued Fodda gravity dam using the finite element method with ANSYS code, considering the full coupling system of dam-reservoir-foundation.

Considering the mentioned references, it is undeniable that the Finite Element Method (FEM) remains a robust and widely used approach for modeling the behavior of gravity dams. However, many researchers emphasize that its application on imprecise geometry can lead to calculation errors, ultimately affecting the quality of the solution. Recently, isogeometric analysis (IGA) has emerged as a method of choice in modeling and analysis of complex systems. Hughes *et al*. (2005) developed the mathematical foundations of IGA using the Non Uniform Rational B-Spline (NURBS) functions to overcome these shortcomings and improve the classical finite element method. Cottrell *et al*. (2009) demonstrated the interoperability between computer aided design and FEM analysis by performing numerical simulations and concluded that the use of IGA allows a gain in computational time due to the time required to convert the geometric model to the numerical model. Since then, IGA has been widely studied and successfully introduced in many areas of mechanics. It has been successfully applied to structural vibrations, fluid-structure interaction, fluid modelling and optimization problems. Lin *et al*. (2012) integrated the benefits of IGA and the scaled boundary finite element method (SBFEM) to analyze the interaction problem of the reservoir-soil-dam, where IGA is used to model the dam structure, while scaled isogeometric analysis (SBIGA) is applied to represent the semi-infinite fluid domain of the reservoir and the unbounded elastic domain of the dam foundation. The results demonstrate that the proposed approach is highly accurate and requires fewer nodes compared to widely used conventional finite element and boundary element methods. Maghsoodi *et al*. (2014) employed the isogeometric method to model the flow in dam failure analysis using the Lagrangian approach. The free surface profile and pressure values obtained with the isogeometric method at different times were compared with a meshless method, demonstrating the capability of the proposed method in solving the moving fluid with moving boundaries. Shahrbanozadeh *et al*. (2015) used IGA to solve the Laplace equation using NURBS basis function to approximate the anisotropic saturated porous media of the dam foundation field and the geometry. The results show satisfactory agreement with the experimental measurements and an improvement in convergence and accuracy. Fakhye *et al*. (2016) investigated the dynamic behavior of a gravity dam model using IGA. Initially, IGA was applied to study the free vibration behavior of a two-dimensional dam model. Subsequently, the dynamic response of the structure subjected to time-varying loads was obtained using the Central Difference Method (CDM). Numerical tests were performed to demonstrate applicability, and potential future applications were discussed. Ma *et al*. (2016) performed a numerical implementation of the spatial elastoplastic damage model of concrete using IGA. The comparison between the simulation results and the experimental data shows that the use of the elastoplastic damage model within the IGA framework is proven to be practical in accurately reflecting the material properties of concrete. Amin Abbasi and Barani (2018) used IGA to assess the hydrodynamic pressure of an arch dam, considering the fluid-structure interaction. The results were compared with those of the analytical and finite element methods, and the calculated root mean square error (RMSE) confirms the accuracy of the isogeometric method.

Zhang *et al*. (2019) proposed a new approach based on the fusion of isogeometric analysis and heuristic optimization algorithms (GA, MIGA, ASA) for the performance analysis of a new type of RCC gravity dam using the functional gradient partition structure (FGPS), to improve the overall dam performance. Xu *et al*. (2019) proposed a new and efficient 2D damage-plasticity model within the IGA framework for geometrically nonlinear damage analysis of concrete. The numerical results computed by the model are compared with the experimental data of three benchmark problems of plain concrete (three-point and four-point bending single-notched beams and four-point bending double-notched beam) to illustrate the geometrical flexibility, accuracy and robustness of the proposed approach. Lahdiri and Kadri (2022) explored the free vibration frequencies of three-directional functionally graded materials in imperfect plates. The investigation considered various plate geometries with two types of porosity (even and uneven) and different material configurations. To address this, an efficient computational method was developed and implemented in the Matlab environment. The method utilized three-dimensional modeling, and the isogeometric method was employed to discretize the structure based on NURBS (Nonuniform Rational B-spline) basis functions. The obtained results were validated through comparison with results obtained by different authors in the literature.

This paper deals with the use of the IGA approach to analyze the seismic behavior of the Oued Fodda concrete gravity dam, located at Chlef in northern Algeria, taking into account the reservoir-dam-foundation interaction. The analysis is carried out for a 2D problem using the MATLAB code and compared with that obtained by the classical finite element method using Ansys. Three cases are considered: 1) empty reservoir, 2) full reservoir and 3) full reservoir with consideration of the dam-flexible foundation interaction. In all cases, the system was subjected to the Boumerdes (2003) earthquake loading.

2. Isogeometric analysis

Hughes *et al*. (2005) first introduced a new numerical method for solving the governing equations of engineering problems, commonly known as Isogeometric Analysis (IGA), which is based on NURBS to describe the geometry directly in the analysis framework without making geometric approximations as in FEM. Furthermore, coupling CAD and analysis solvers into a unified framework reduces issues related to geometry and mesh, thus significantly minimizing the computational cost (Hughes *et al*. 2008, Cottrell *et al*. 2009, Evans *et al*. 2009, and Thai *et al*. 2012). Due to the accurate representation of geometric features and higher order continuity, the IGA technology has been applied in many fields by various researchers, e.g. in elsatodynamics (Cottrell *et al*. 2006, Hughes *et al*. 2008, Thai *et al*. 2012, Reali. 2006, Evans *et al*. 2009, Auricchio *et al*. 2012), in elastostatics (Simpson *et al*. 2012, 2013), in fluid mechanics (Bazilevs and 2010, Gomez *et al*. 2010, Nielsen *et al*. 2011), in fluid-structure interaction (Bazilevs *et al*. 2006, 2008, 2009, 2012). Due to the widespread application of IGA technology in many fields, efforts have been made to implement this method on several supports, de Falco *et al*. (2011) free and open source search tools GeoPDEs which serve as a starting tool for IGA users, compatible with Octave and Matlab for isogeometric analysis of PDEs have been developed. Recently, Dalcin *et al*. (2016), presented a code framework PetIGA based on PETSc (Portable Extensible Toolkit for Scientific Computation), to achieve the high-performance with the IGA of PDEs. Also, there are implementations for commercial software such as Abaqus and Ls-dyna (Hartmann *et al*. 2011, Duval *et al*. 2015 and Lai *et al*. 2017). However, the method cannot be directly applied to commercial software as with conventional finite elements, and its use is still limited to the scientific community.

2.1 B-spline

The b-splines are built from a set of parametric curve splines, the b-spline shape functions are built from the node vector, which is a growing node vector such as $\Xi = \{\xi_1, \xi_2, \ldots, \xi_{n+p+1}\}$ where $\xi_i \in \mathbb{R}$ is the i^{th} knot, p is the order of the shape functions (Cottrell *et al*. 2009, Piegl and Tiller 1996), n is the number of the shape functions. The basis functions of the b-spline are calculated by the Cox-De Boor recurrence formula (COX 1971, De Boor 1972), given by:
for $p = 0$

$$N_{i,0}(\xi) = \begin{cases} 1 & if\ \xi_i \le \xi < \xi_{i+1} \\ 0 & otherwise \end{cases} \tag{1}$$

for $p > 1$

$$N_{i,p} = \frac{\xi - \xi_i}{\xi_{i+p} - \xi_i} N_{i,p-1}(\xi) + \frac{\xi_{i+p+1} - \xi}{\xi_{i+p+1} - \xi_{i+1}} N_{i+1,p-1}(\xi) \tag{2}$$

2.2 NURBS

IGA technology uses two mesh definitions: the control mesh and the physical mesh. Control points define the control mesh and the control mesh interpolates the control points. The unknowns of the solved problem are the degrees of freedom at the control points. Cottrell *et al*. (2009). The NURBS are a generalization of the B-splines and allow an exact representation of the geometry, the B-spline shape functions are multiplied by weights and divided by the sum of the shape functions multiplied by the weights (Les and Wayne 1997). The NURBS shape functions for the curves are given by:

$$R_i^p = \frac{N_{i,p}(\xi)w_i}{\sum_{\hat{\imath}=1}^{n} N_{\hat{\imath},p}(\xi)w_{\hat{\imath}}} \tag{1}$$

the NURBS curve is a linear combination of the NURBS basis function and the control points and is given by:

$$C(\xi) = \sum_{i=1}^{n} R_i^p(\xi)\mathrm{B}_i \tag{4}$$

The NURBS shape functions for the surface are given by:

$$R_{i,j}^{p,q}(\xi,\eta) = \frac{N_{i,p}(\xi)M_{j,q}(\eta)w_{i,j}}{\sum_{\hat{\imath}=1}^{n}\sum_{\hat{\jmath}=1}^{m} N_{\hat{\imath},p}(\xi)M_{\hat{\jmath},q}W_{i,j}} \tag{5}$$

The NURBS surface is a bilinear combination of the NURBS basis function and the control points and are given by:

$$S(\xi,\eta) = \sum_{\hat{\imath}=1}^{n}\sum_{\hat{\jmath}=1}^{m} R_{\hat{\imath},p}(\xi)M_{\hat{\jmath},q}(\eta)\,\mathrm{B}_{i,j} \tag{6}$$

3. Mathematical formulation of the seismic response of dam-reservoir-foundation system using isogeometric approach

3.1 Modelling of dam and foundation

The dam and foundation are modeled with an elastodynamic model. The governing equations in indicial form are given by relation Eq. (7) below:

$$\sigma_{ij,j} + f_i - \rho\ddot{u}_i = 0 \quad in \quad \Omega \tag{7}$$

The boundary condition is given by:

$$\sigma_{ij}n_j = pn_i \quad in \quad \Gamma_1$$
$$\sigma_{ij}n_j = 0 \quad in \quad \Gamma_f$$
$$u_i = 0 \quad in \quad \Gamma_s$$

The weak form is obtained by applying the principle of variational methods as follows:

$$\int_\Omega \delta\,\varepsilon_{ij}\sigma_{ij}d\Omega + \int_\Omega \delta\,u_i\rho\ddot{u}_i d\Omega = \int_{\Gamma 1} \delta\,u_i p n_i d\Gamma 1 + \int_\Omega \delta\,u_i f_i d\Omega \tag{8}$$

where ε_{ij} is the deformation tensor, σ_{ij} is stress tensor, ρ is the density, p is the water pressure on the dam, f_i is the body force and Ω is the considered, Γ1 is the contact boundary between the reservoir and the dam, Γf , the downstream side of the dam, and the indices 'S' and 'D' referring to soil and dam, respectively, u and n represent displacement and the normal vector.

To derive the matrix formulation of the problem, the IGA approach was used to approximate the displacements according to the relation:

$$u = N_s U \tag{9}$$

where N_s is the NURBS shape functions, U is the vector of the control points.

Finally, the equation of motion becomes.

$$M\ddot{U} + C\dot{U} + KU = QP - P_{eff} \tag{10}$$

where M, C, K are the mass, damping and stiffness matrices, QP is the hydrodynamic force and Q is the coupling matrix. The damping matrix is assumed linear viscous given by the proportion of mass and stiffness by the Rayleigh relationship:

$$C = \alpha M + \beta K \tag{11}$$

where α and β are given parameters depending on the damping factor, which is equal to 5% according to Chakrabarti and Chopra (1973) P_{eff} is the vector of the load due to the ground acceleration and is given by:

$$P_{eff} = -MI\ddot{u_g} \tag{12}$$

$\ddot{u_g}$ is the ground acceleration, I is the vector giving the direction of loading which is equal to one in the loading direction and zero in the other.

3.2 Modelling of fluid

The fluid is modeled by an acoustic model. The formulation in terms of pressure is given by:

$$\Delta p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \tag{13}$$

The pressure is approximated using NURBS shape functions Nf:

$$p = N_f P \tag{14}$$

Which allows to present the system in the following matrix form:

$$M_f \ddot{P} + C_f \dot{P} + K_f P = -\rho Q^T \ddot{U} \tag{15}$$

where M_f, C_f, K_f, Q are the mass matrix, the damping, the rigidity of the fluid and the matrix of interaction respectively:

$$M_f = \int_{\Omega_f} N_f^T \frac{1}{C^2} N_f d\Omega_f \tag{16}$$

$$C_f = \int_{\Gamma_3} N_f^T \frac{1}{C} N_f d\Gamma_3 \tag{17}$$

$$K_f = \int_{\Omega_f} \nabla N_f^T \nabla_f d\Omega_f \tag{18}$$

$$Q = -\int_{\Gamma_1} N_s^T n N_f d\Gamma_1 \tag{19}$$

Table 1 Review of all the optimization techniques used by the researchers for solving design optimization problem of RC structures

	Step 1
1	Preparation of the geometry.
2	Discretization into an isogeometric element.
3	For each element **i** in the current patch **j.**
a	Evaluation of b-spline shape functions Eqs (1) - (2).
b	Rationalization of b-spline shape functions to NURBS shape functions Eq (5).
c	Calculate elementary matrices $\mathbf{K^e}$, $\mathbf{M^e}$, $\mathbf{K^e_f}$ Eqs (16) - (17) - (18) - (19).
4	Repeat **a**, **b** and **c** for each patch
5	Assembly of **matrices** $\mathbf{K}$, $\mathbf{M}$, $\mathbf{K_f}$, $\mathbf{M_f}$, $\mathbf{C_f}$, $\mathbf{Q}$.
6	Evaluation of the matrix **C** Eq (11).
7	Rewrite Eqs (10) - (15) as Eq (20).
8	Evaluation of the global load vector Eq (12).
	Step 2
1	Calculate integration coefficient for the Newmark's method.
2	Calculate $\overline{\mathbf{K}}$ $\overline{\mathbf{P}}$
3	Solve $\overline{\mathbf{K}}$u= $\overline{\mathbf{P}}$

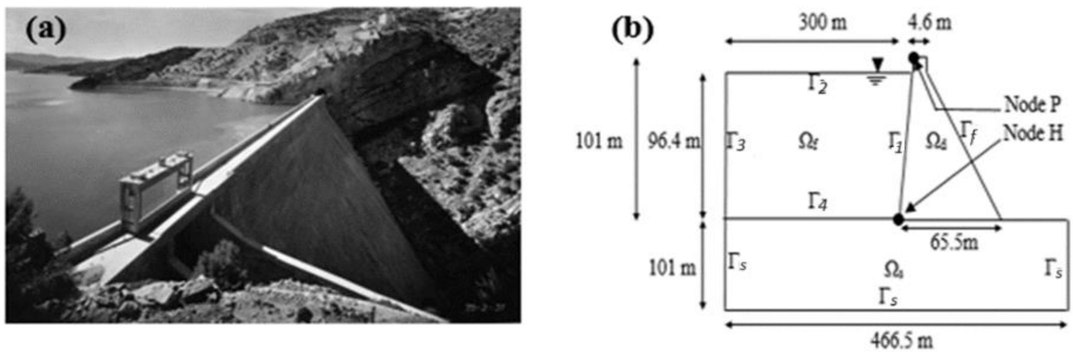


Fig. 1 Oued Fodda dam: (a) Overall view, (b) geometric model

C is the velocity of sound in the water equals to 1440 m/s, ∇ is the gradient operator, the density $\rho = 1000\ kg/m^3$ and n is the normal vector.

3.3 Coupling system

Eqs ((10)-(15) are coupled in a single system with a mixed displacement-pressure formulation (U, P). Ledoux and El Hami (2017) and given by:

$$\begin{bmatrix} M & 0 \\ \rho Q^T & M_f \end{bmatrix} \begin{Bmatrix} \ddot{U} \\ \ddot{P} \end{Bmatrix} + \begin{bmatrix} C & 0 \\ 0 & C_f \end{bmatrix} \begin{Bmatrix} \dot{U} \\ \dot{P} \end{Bmatrix} + \begin{bmatrix} K & -Q \\ 0 & K_f \end{bmatrix} \begin{Bmatrix} U \\ P \end{Bmatrix} = \begin{Bmatrix} P_{eff} \\ 0 \end{Bmatrix} \tag{20}$$

The system is non-symmetrical but is easily made symmetric.

Table 2 The material properties

	Material properties		
	Modulus of Elasticity (MPa)	Poisson's Ratio	Mass density (kg/m^3)
Dam	24600	0.2	2640
Foundation	20000	0.33	2000

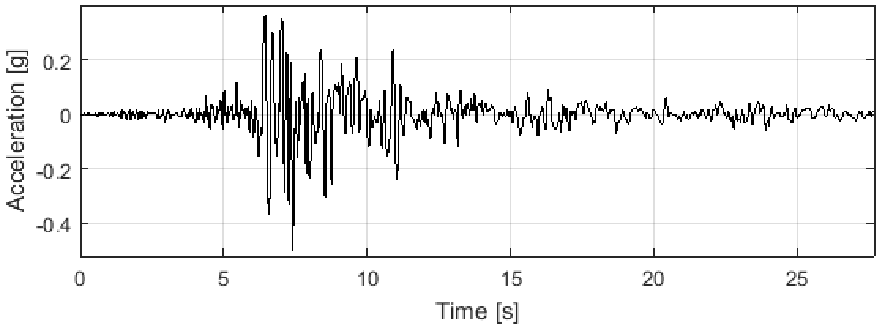


Fig. 2 Acceleration records of Boumerdes earthquake at dare El Beida station (CGS 2003)

Table 3 Modes of vibration for the case of dam with full reservoir

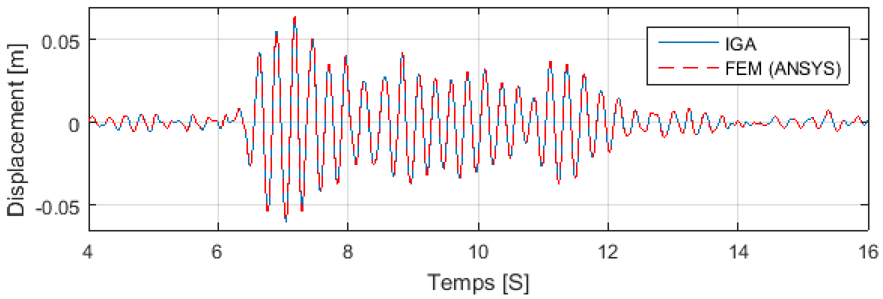
	IGA	FEM (ANSYS)
mode	Frequency (Hz)	Frequency (Hz)
1	3.0362	3.0112
2	4.1155	4.0991
3	5.2381	5.2165
4	6.9301	6.8454
5	8.3169	7.8851

3.4 Routine of resolution for dynamic multi-patch

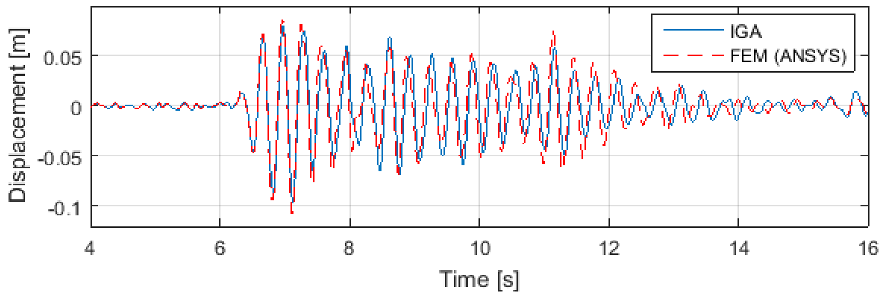
One of the differences between finite element and isogeometric analysis is the notion of the patch. In the classical finite element geometry is directly divided into elements, but in isogeometric it's divided into patches and then into elements. For simple geometry, a single patch is sufficient, but for complex geometry or multi-physical studies it is necessary to go through a multi-patch representation, this requires a loop on the patches and then a loop on the elements, compared to the finite elements, which is in fact a loop only on the elements. In Table 1, a routine of resolution is given in the case of a dynamic multi-patch study using the Newmark's integration method. In our case three patches were used, one for the fluid, another for the soil and the last one for the dam.

4. Numerical examples

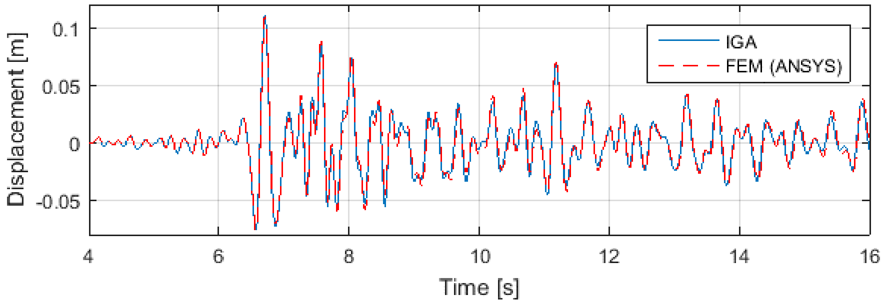
To demonstrate the efficiency of the method in the study of complex problem, the Oued Fodda dam located at Chlef in northern Algeria is taken as a numerical example, with a total crest height



(a)



(b)



(c)

Fig. 3 Horizontal displacement of the node P, (a) Dam, (b) Dam-reservoir interaction, (c) Dam-reservoir- flexible foundation interaction.

of 101 m and a width of 65.5 m, the maximum reservoir filling height is 96.4 m, see Fig. 1.

The properties of the material are summarized in Table 2.

The dam is subjected to the Boumerdes earthquake 2003 recorded at the Dar el Beida station in northern Algeria with the peak ground acceleration $of\ u_{g_{max}} = 0.5012g$.

To solve the problem, the displacement field is used for the discretization of the dam and the foundation with two degrees of freedom and the pressure field for the fluid of the reservoir at each control point using NURBS of order p=2.

5. Result and discussion

To show the advantage of the isogeometric approach, the obtained results by a developed computer code under MATLAB are compared to the results of the commercial code ANSYS

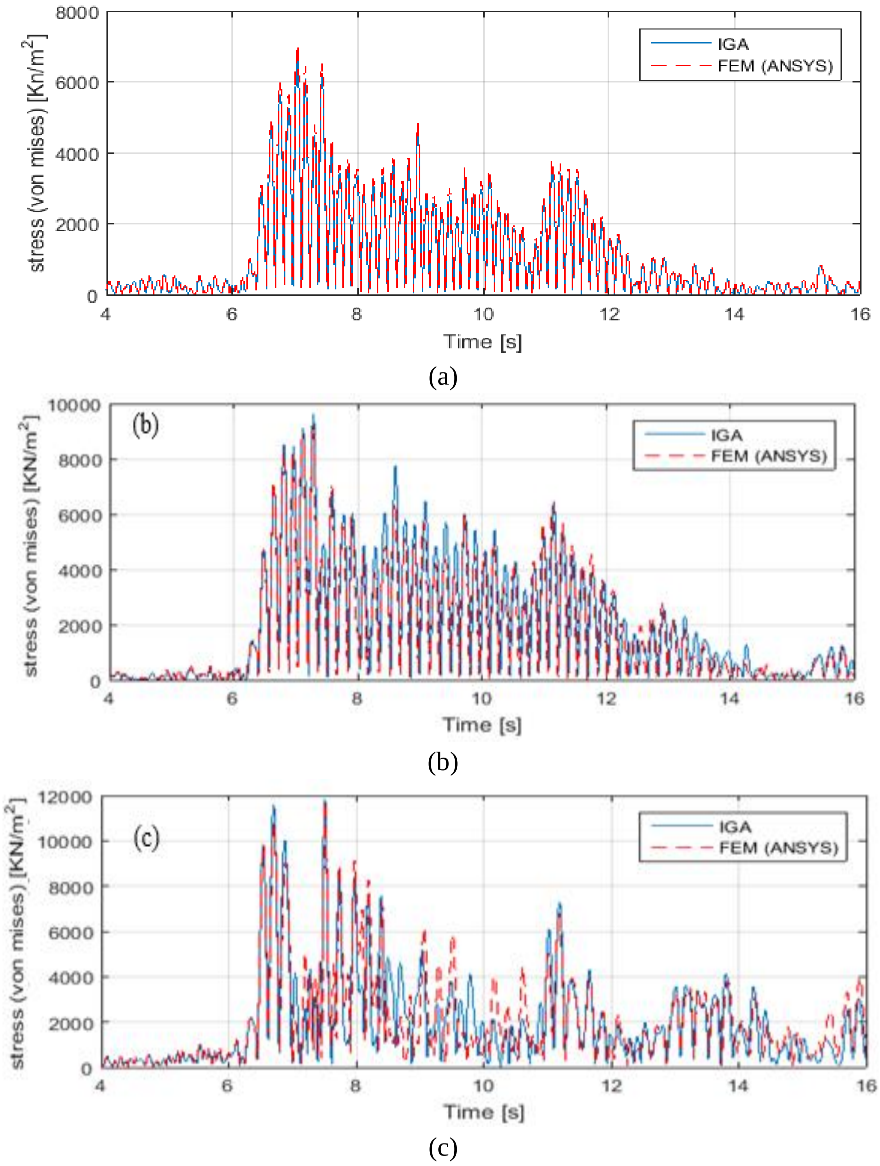
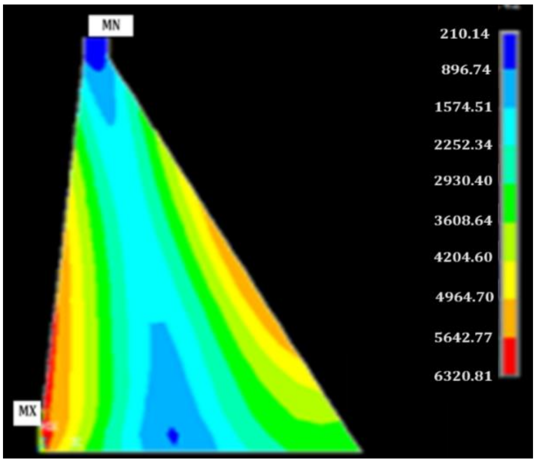


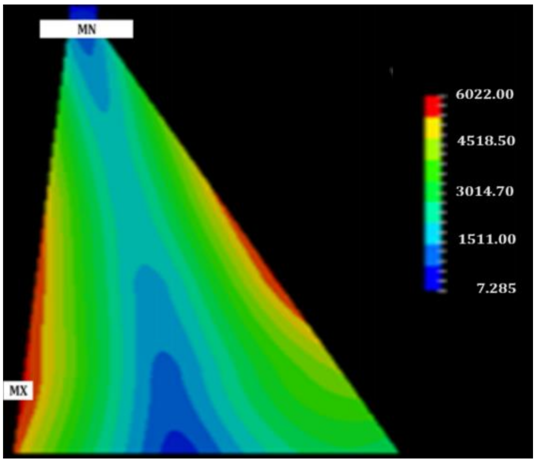
Fig. 4 Von Mises stresses at the node Hm, (a) Dam, (b) Dam-reservoir interaction, (c) Dam-reservoir-flexible foundation interaction

Multiphysics using 2D elements with 4 nodes “plane 182” for the dam and the foundation and 2D acoustic element “FLUID29” with 3 degrees of freedom (two displacements and one pressure) for the fluid of the reservoir. To solve the problem, the Newmark’s method with the parameters $\alpha = 1/2$ and $\beta = 1/4$ and time step of 0.005s are used.

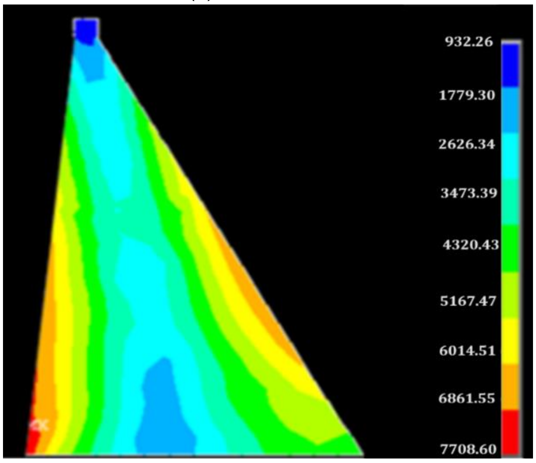
First, we compared the natural vibrations of the studied system of the two approaches. As shown in Table 3, the values of natural vibration frequencies obtained by IGA are very close to the values obtained by FEM. The error between the results does not exceed 1% generally. These



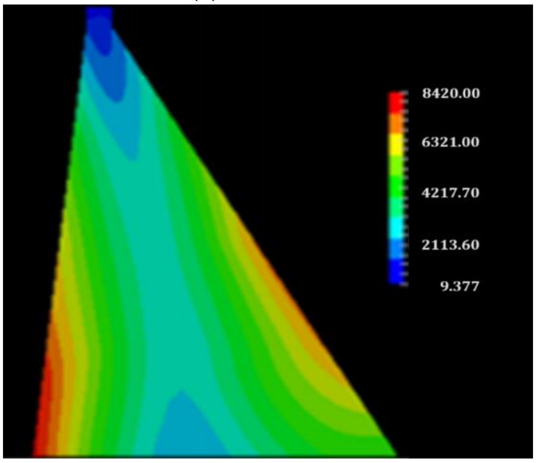
(a) dam – FEM



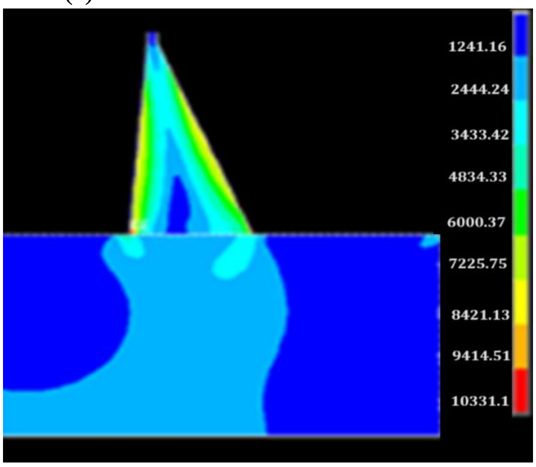
(b) dam – IGA



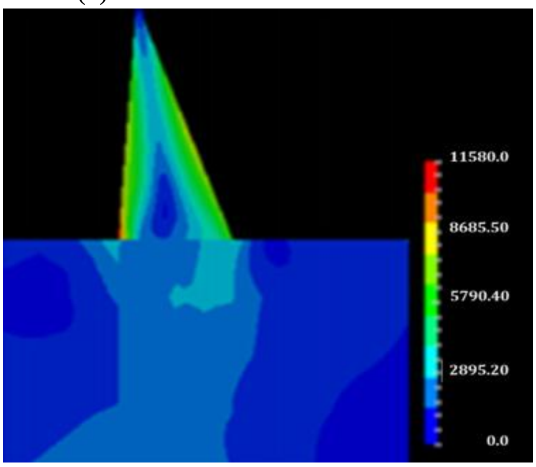
(c) dam-reservoir interaction – FEM



(d) dam-reservoir interaction – IGA



(e) Dam-reservoir-flexible foundation interaction: FEM



(f) dam-reservoir-flexible foundation interaction: IGA

Fig. 5 Von Mises stress contours correspondent to the maximum horizontal displacement

Table 4 Computation time

	IGA			FEM (ANSYS)		
	N_{el}	Control Points	Time (min)	N_{el}	Nodes	Time (min)
Dam only	50	182	0.43	49	69	2.89
Dam and fluid	1400	2200	4.67	1422	1513	15.44
Dam, fluid and soil	3750	7803	25.288	3724	3866	54.22

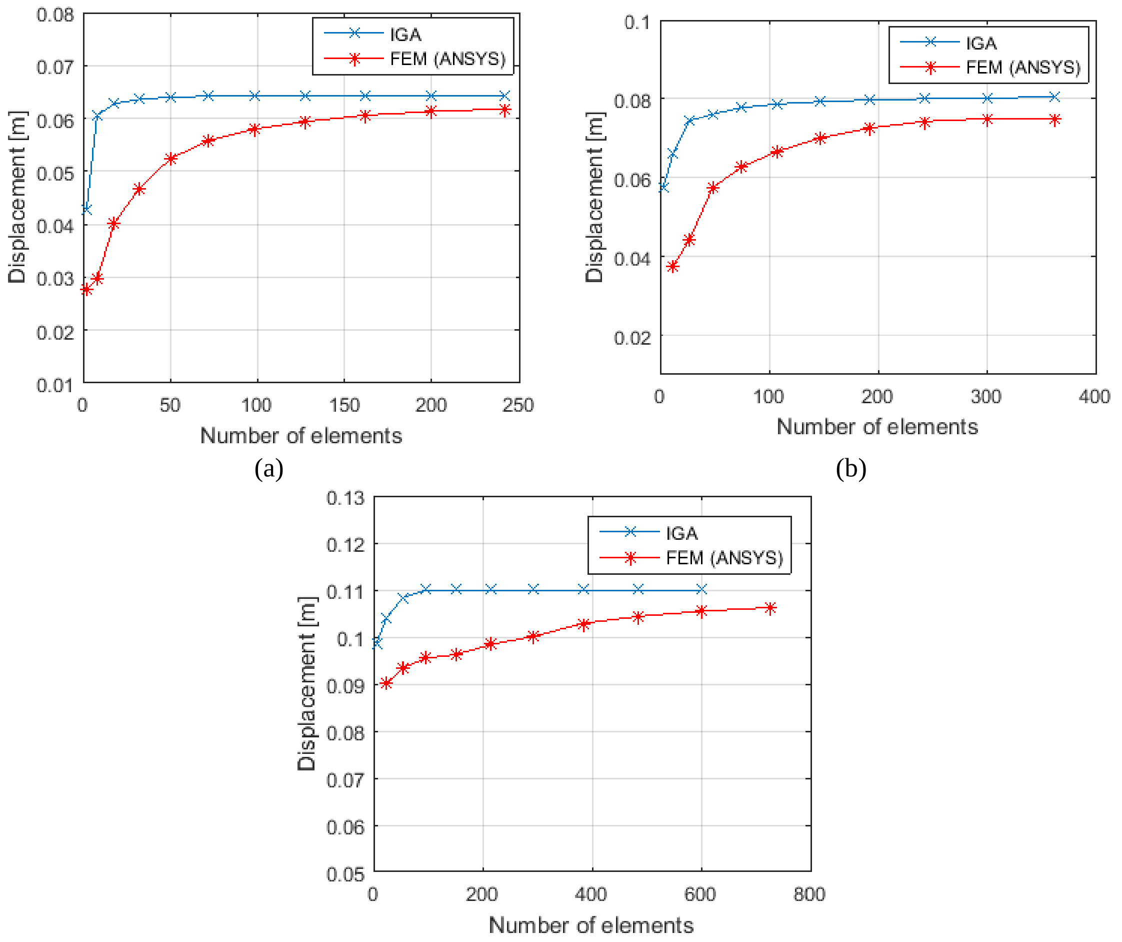


Fig. 6 Convergence according to the number of elements

results show clearly that NURBS are also a good tool for vibration analysis for complex systems as shown by Cottrell *et al*. (2006) for simple ones.

To have a global view of the applicability of the IGA to complex dynamic problems, the problem of the forced vibrations was investigated by considering three case studies. The Fig. 3 Below show the displacements of the node P located at the crest of the dam. It is found that the displacements are practically identical except for the case of the full reservoir dam where there is a very small phase shift due to the slight extension of vibration periods obtained by IGA due to the inherent higher-order continuity and accurate representation of geometric features in IGA, as demonstrated by Bazelevs *et al*. (2008), where they showed that this technique has proven advantageous for problems related to fluids and fluid-structure interaction, leading to an improvement in the accuracy of the obtained results.

The stress response was calculated for the point H located at the dam heel on the upstream side. The Von Mises stresses obtained using the isogeometric analyses are compared to those obtained by FEM (ANSYS).

The Fig. 4 ((a), (b), (c)) shows the variation of the Von Mises stresses versus time at the node H located at the dam heel of the dam on the upstream side. As can be seen from the curves of the Fig 4, The maximum stress values obtained by IGA are slightly higher than those obtained using ANSYS, which can be explained by the utilization of higher continuity and exact representation of geometry in isogeometric analysis (IGA).To appreciate the quality of obtained results by the IGA compared to those of the FEM, we have represented the distribution of the Von Mises stresses at t= 6.975s in Fig. 5. By matching these images, we notice the distribution of Von Mises stresses are quite identical for the two considered approaches.

To show the superiority of the IGA, the computation time of seismic response using the classical finite element method (FEM) and IGA were compared. The results presented in Table 3. Show that the use of isogeometric approach allows a considerable saving in computation time, which can reach 50% of the time, required by FEM which in good agreement with Cottrell *et al*. (2009) even when it comes to complicated problems.

On other side, a parametric study was carried out to show the influence of the number of elements on the solution. The analysis of the obtained results represented by the Fig. 6 (a)-(b)-(c) allows to say. That the displacement curves for the case of IGA reach the plateau quickly in comparison with the curves obtained by FEM. So, we conclude that IGA converges faster and does not require a fine mesh which has a positive impact on the cost of solution.

6. Conclusions

The paper is dedicated to exploring the potential application of Isogeometric Analysis (IGA) as an alternative approach to the classical Finite Element Method (FEM) for studying the dynamic behavior of concrete gravity dams, taking into consideration the interactions of foundation-dam and reservoir-dam. To achieve this goal, NURBS (Non-Uniform Rational B-Spline) basis functions are employed as approximation functions for displacement and pressure fields, as well as for representing the geometry. The dam and soil foundation are modeled using an elastodynamic approach, while an acoustic model is adopted for the fluid in the reservoir.

As an illustrative numerical example, the study considers the Oued Fodda gravity dam. Three cases are examined to demonstrate the applicability of IGA, including: (a) the dam, (b) the dam-reservoir interaction with a rigid foundation, and (c) the dam-reservoir-flexible foundation interaction. The obtained results highlight the efficiency of the isogeometric method in terms of result quality and reliability.

The comparison of the seismic response, calculated using IGA, reveals good agreement with the classic finite element method obtained by ANSYS. These results also demonstrate the superiority of IGA, particularly in terms of computation time and memory space usage, as illustrated in Fig. 6. A significant improvement is observed compared to the finite element method.

In summary, isogeometric analysis (IGA) offers enhanced accuracy, particularly in coupled problems, owing to its higher continuity and exact geometry representation. These features make isogeometric analysis a valuable tool for studying complex multi-physics phenomena.

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