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EFFECT OF DAM–ROCK FOUNDATION INTERACTION MODELING ON THE MODAL RATIO-RELATED QUANTITY OF BENI BEHDEL AND `EL MEFROUCH MULTI-ARCH DAMS

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Abstract: Using the Beni Behdel dam and the El Mefrouch dam as example studies, this paper intends to clearly demonstrate how modeling of the interactions between rock foundations and dams impacts the modal behavior of these two multi-arch dams. The uniqueness of this study is that the modal behavior of each dam is represented in terms of related parameters (period, participation factor, ratio, and effective mass), and more precisely in terms of ratio (defined as the ratio between the participation factor of the mode i and the maximum participation factor), as opposed to other works that have expressed this behavior in terms of frequency. In this article, stiff rock foundation, massless rock foundation, and massed rock foundation are the three methods used to simulate dynamic interactions. The investigated dams are three-dimensionally simulated using the ANSYS finite elements code. The modeling of the rock foundation–dam interaction has an effect on the fundamental mode value, its location, and the related parameters, according to the results. Furthermore, it is found that the upstream–downstream direction is not always the most important direction for dams and that interaction modeling influences the resonance bandwidth, which affects the forecast of the resonance phenomenon.

Key words: related quantities, modal behavior, dam–rock foundation interaction, ANSYS code

1. INTRODUCTION

In the design and safety analysis of the dam structures, the dynamic dam–foundation interaction is crucial. Numerous computational techniques, such as rigid, massless, and massed foundation models, have been employed to investigate the dynamic dam–foundation interaction [5,10,16,18,20,21]. Using large foundation models is not necessary, A massless foundation model, in which only the impacts of foundation flexibility are taken into account, was put forth by Clough et al. in the 1970s [7]. This model is employed by the well-known EACD-3D [11] and ADAP-88 [12] programs, and it is viewed as a standard procedure by the U.S. Army Corps of Engineers [19]. However, using the massless foundation model has some defaults. According to Pan et al. [22], the massless foundation model could successfully replicate the seismic response of the gravity dam by adding a number of viscous dampers at the dam–foundation interface.

Models of the dam, dam–reservoir, and dam–foundation-reservoir were used by Ghaedi et al. [23] to compare the acceleration, displacement, stress, and dynamic damage of the 81.8 m high Kinta roller compacted concrete gravity dam. The results revealed that foundation flexibility had a significant impact on the seismic response of the RCC dam-reservoir-foundation system.

According to Bayraktar et al.'s [24] investigation into the impact of base-rock characteristics on the dynamic response of dam–foundation interaction systems subjected to three different earthquake input mechanisms, the rigid-base input model was found to be insufficient to accurately describe the dynamic interaction of dam-foundation systems, whereas the massless foundation input model could be used for practical analysis. The simulation results with a 90 m high concrete gravity dam supported this finding.

For instance, it is impossible to take into account how radiation damping affects energy dispersion for a far-field foundation. A. K. Chopra found in 2012 that if the foundation-rock mass and damping are ignored, stresses may be overestimated by a ratio of 2:3 [6].

When subjected to seismic disturbances, concrete dams are structures that could be excited to resonance [8,9,17]. It is common knowledge that resonance can occur if the excitation frequency is within the structural natural frequency's bandwidth. Through modal analysis, the structural natural frequency is determined.

The primary step of any structure's dynamic study is modal analysis [4,13,14]. Modal analysis reveals the structure under the study's dynamic properties. Frequencies and their related quantities are a structure's main dynamic properties. One of the crucial capabilities when utilizing the "ANSYS" finite element code is the modal analysis type [1].

2. MATERIALS AND METHODS

The uniqueness of this study lies in the expression of the modal behavior of each dam in terms of related quantities. Related quantities given by ANSYS are the modal period, the modal participation factor, effective mass, and the ratio [1–3].

The participation factor for a given excitation is given as [1,3]:

$$P_{\mathrm{f\,i}} = \{\varphi\}_i^T \, [M] \, \{D\} \tag{1}$$

where:
$P_{\mathrm{f\,i}}$: Participation factor for the ith mode.
$\{D\}$: vector describing the excitation direction
$\{\varphi\}_i$: Normalized eigenvector
$\{\varphi\}_i^T$: Normalized eigenvector transpose.
$[M]$: Structural mass (global structural mass)

The effective mass in a given direction is defined as:

$$M_{\mathrm{e\,i}} = \frac{{P_{\mathrm{f\,i}}}^2}{\{\varphi\}_i^T [M] \{\varphi\}_i} \tag{2}$$

$M_{\mathrm{e\,i}}$: The effective mass for the ith mode
with:

$$\{\varphi\}_i^T [M] \{\varphi\}_i = 1 \tag{3}$$

It is important to note that in ANSYS code the frequencies are normalized by default with respect to the mass, but it is also possible to normalize it with respect to the unity.

The modal ratio is defined as:

$$\mathrm{Ratio} = \frac{P_{\mathrm{f\,i}}}{P_{\mathrm{f\,i\ max}}} \tag{4}$$

$P_{\mathrm{f\,i\ max}}$: The maximal participation factor.

All related quantities presented above depend on the excitation direction (Eqs. 1, 2, 3 and 4).

Numerous studies have found that the phenomena of soil–structure interaction had an impact on the modal behavior of the structure. The rigid foundation model, the massless foundation model, and the massed foundation model are three approaches to modeling the soil–structure interaction phenomenon that have been described in the literature.

This article examines the effects of the rock–dam interaction phenomenon on the modal-related quantities of the two multi-arch dam study cases, with an emphasis on the ratio-related quantities. The two dams are the El Mefrouch arch dam and the multi-arch dam of Beni Behdel.

The originality of this work lies in the fact that, unlike earlier works that have expressed this behavior in terms of frequency, it expresses the modal behavior of each dam in terms of related quantities (period, participation factor, ratio, and effective mass), and more specifically, in terms of ratio (defined as the ratio between the participation factor of the mode I and the maximum participation factor).

Three finite element dam–foundation soil models are presented in Section 2. Sections 3 and 4 give the results of the modal analysis [14]. In the final section, the conclusions are drawn.

2.1. Dam–foundation rock finite element models

The two dams that are the subject of the current study and their finite element models are presented in this section.

The first case study is the Beni Bahdel multi arch dam in Algeria, which is 25 km to the southwest of Tlemcen. It was constructed in 1934 on the Oued Tafna for a retention volume of 63 million m3, and it was impounded in 1944 (see Fig. 1). The detailed geometry is given in Tab. 1.

Fig. 1. Beni Bahdel multi-arch dam [27]

Tab. 1. Geometry of the Beni Bahdel dam [25]

Element	Dimensions	The measures
Foothills	Height above ground level of the foundation	57 m
	Spacing	20 m d'axe en axe
	The shape	Sensiblement triangulaire
	The slope of the upstream face	1 :0.95
	Slope of the downstream face	0.30
	Thickness at the top	3 m
	Thickness at the lower end	4.80 m
Arches	The length of the ridge	220 m
	Number of arches	11
	The shape	Circular cylinder
	Inside diameter	17.20 m
	Inclination	1 : 0.95
	Thickness at top	0.70 m
	Thickness at the lower end	1.30 m

The second case study is El Mefrouch multi arch dam, which is made up of 17 concrete arches and is located in the same area as the first dam in Tlemcen, Algeria (Fig. 2). The dam on the wadi El Nachef started to be built at the end of 1952. It was placed into service in 1963 and has a 15 million m3 capacity. A detailed geometry is given in Tab. 2.

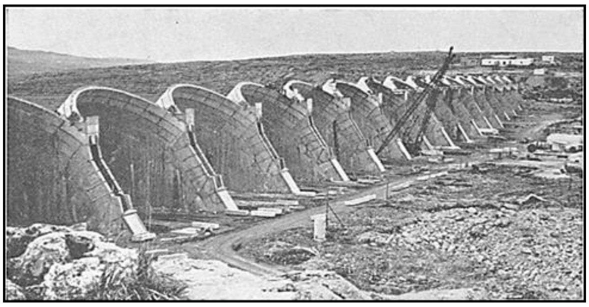

Fig. 2. El Mefrouch multi-arch dam [26]

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Tab. 2. Geometry of El Mefrouch multi-arch dam [27]

Element	The measures
Maximum height above lowest point of foundation	35 m
Capping height (N.G.A)	1,125.00 m
Exceptional high water mark (N.G.A)	1,124.50 m
Normal impoundment elevation	1,122.00 m
Surface area of the reservoir at normal water level	189.35 ha
Safety embankment above the normal reservoir	2.80 m
Width at crest (service bridge)	2.30 m
Thickness of the buttresses at the base	2.50 m
Thickness of the vaults	0,80 m
Slopes of the upstream face	0,80
Downstream face slopes	0.5665
Volume of the reservoir	14,993 hm3
Regulated annual volume	14 hm3/year
Maximum depth	19 m

3. ANALYSES AND RESULTS

The following analyses are carried out using the finite element commercial program ANSYS to examine the effects of rock foundation–dam interaction on the modal response of the studied multi-arch dams.

Linear modal analysis without rock foundation of both multi-arch dams, which means that the bases of both multi-arch dams are clamped.

Linear modal evaluation of the dam and rock foundation system. Here, two studies are conducted with regard to the mass of the rock foundation; the first analysis takes into account the mass of the rock foundation, and the second study ignores it.

Fig. 3 sketches the finite element simulation of the multi-arch Beni Bahdel dam without rock foundation. A total of 41,598 quadratic solid elements (SOLID185) and 13,926 nodes are used in the model. The model base is blocked in the three directions x, y, and z to simulate the absence of Beni Bahdel multi-arch dam-–rock foundation interaction phenomenon.

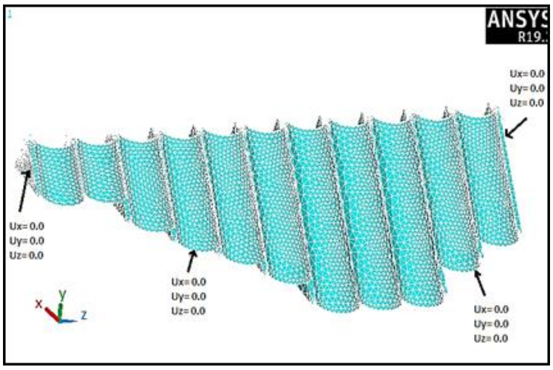

Fig. 3. ANSYS Finite element model of Beni Bahdel multi-arch dam with rigid rock foundation

Sketches for Fig. 4 Finite element model for the Beni Bahdel multi-arch dam–rock foundation. The model has 27,424 nodes and 97,519 quadratic solid elements (SOLID185). As boundary conditions, the three directions of x, y, and z are blocked on the model base.

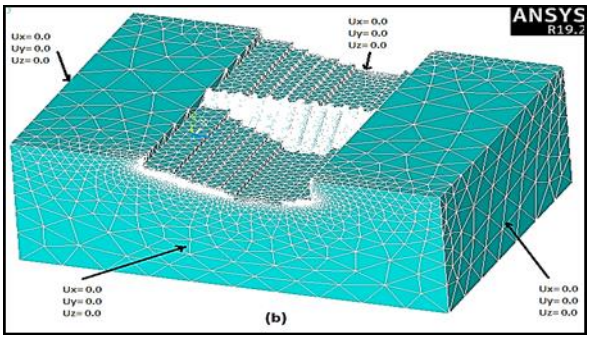

Fig. 4. Finite element model of Beni Bahdel multi-arch dam–rock foundation system

Fig. 5 depicts the El Mefrouch arch dam with rigid rock foundation as a finite element model in ANSYS. The model contains 19,619 nodes and 55,819 quadratic solid components (SOLID185). The model base is constrained in the x, y, and z axes to simulate the rigid rock foundation.

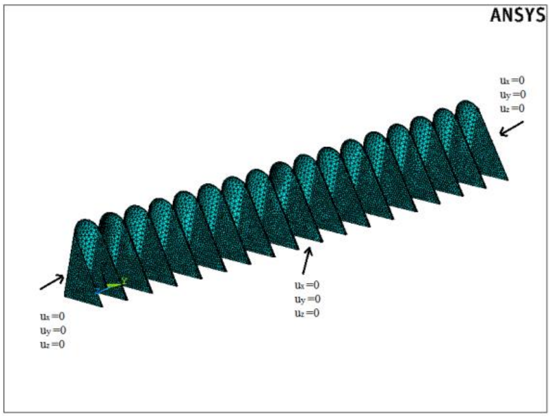

Fig. 5. ANSYS Finite element model of El Mefrouch multi-arch dam with rigid rock foundation

Sketches from Fig. 6 El Mefrouch finite element model system for multi-arch dams with rock foundations. The model has 43,108 nodes and 178,047 quadratic solid elements (SOLID185). It is crucial to remember that the model's base is fixed in the x, y, and z directions.

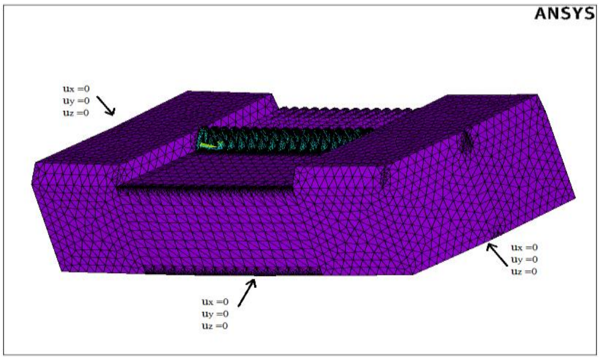

Fig. 6. ANSYS Finite element model of El Mefrouch multi-arch dam–rock foundation system

For both examples under study, it is assumed that the foundation rock's length and width, measured along the global x, y, and z axes, respectively, exceed 2.5 H, where H is the level of the reservoir. These sizes are big enough that the modal responses of the investigated dams are unaffected by the boundary conditions that are used. To ensure a proper representation of the foundation rock, it is customary to take the factor of 2.5; for example, see Ref. [15].

The materials characteristics for the Beni Behdel and El Mefrouch arch dams, as well as their rock base foundation, are provided in Tabs. 3 and 4.

Tab. 3. Material properties of Beni Behdel multi-arch dam and its rock foundation

Material	Young's modulus (N/m2)	Poisson coefficient	Density (kg/m3)
Beni Behdel concrete dam	3 E+10	0.2	2,500
Foundation rock	3.25 E+10	0.3	2,600

Tab. 4. Material properties of El Mefrouch multi-arch dam and its rock foundation

Material	Young's modulus (N/m2)	Poisson coefficient	Density (kg/m3)
El Mefrouch concrete dam	2.85 E+10	0.2	2,500
Foundation rock	6.22 E+9	0.25	2,100

3.1. Modal behavior of multi-arch dams without rock foundation modeling

Without accounting for the rock foundation–dam interaction phenomenon, this section discusses the modal responses of the two analyzed dam examples.

Block Lanczos is used to extract the modal responses (ANSYS v19). The first natural mode number frequencies, the associated frequency, period, participation factor Pfi, its ratio to the maximum participation factor, and effective mass are the related quantities discussed in this article. It is important to note that ANSYS finite element code gives modal results in the three directions of x, y, and z.

The "x" axis represents the upstream–downstream direction in both of the multi-arch dam study cases, while the "y" and "z" axes represent the transverse and vertical directions, respectively.

For Beni Behdel multi-arch dam without interaction phenomenon modeling (multi-arch dam clamped at its base), the related quantities of the first eigenmodes are listed in Tabs. 5–7 in the x, y, and z directions, respectively.

The dam frequencies (and consequently the dam periods) are evident in Tabs. 5–7 to be independent of the motion directions; the same frequencies are in the x, y, and z directions; the only parameters that change are the participation factors, which affect the ratio and effective mass.

The most dominating mode, or the fundamental mode, is the one that involves the most mass. This mode is described in ANSYS code as the mode with a modal ratio quantity of "one" (1) for the direction taken into consideration [3].

The fundamental mode of the Beni Behdel multi-arch dam is mode number 12 in the x direction (see Tab. 5), mode number 1 in the y direction (see Tab. 4), but mode number 35 in the z direction (see Tab. 7).

Tab. 5. First frequencies in x direction for Beni Behdel multi-arch dam with rigid rock foundation

Mode	Frequency	Period	Participation Factor	Ratio	Effective Mass
1	5.02949	0.19883	–5.2983	0.000849	28.0719
2	5.51075	0.18146	–254.05	0.040704	64,540.1
.	.	.	.	.	.
12	12.2534	0.81610E -01	6,241.3	1.000000	0.389537 E + 08
13	12.6866	0.78824E -01	–15.382	0.002465	236.621

Tab. 6. First frequencies in y direction for Beni Behdel multi-arch dam with rigid rock foundation

Mode	Frequency	Period	Participation Factor	Ratio	Effective Mass
1	5.02949	0.19883	7,771.8	1.000000	0.604002 E + 08
2	5.51075	0.18146	76.410	0.009832	5,838.50

Tab. 7. First 10 frequencies in z direction for Beni Behdel multi-arch dam with rigid rock foundation

Mode	Frequency	Period	Participation Factor	Ratio	Effective Mass
1	5.02949	0.19883	–6.9136	0.000981	47.7980
2	5.51075	0.18146	–34.644	0.004918	1200.18
.	.	.	.	.	.
35	21.6018	0.46292E -01	7,044.2	1.000000	0.496214 E + 08

The ratio value of the Beni Behdel arch dam with rigid rock foundation is presented in Fig. 7 as a function of the analysis directions. This image makes it evident that ratio values are more significant in the x and y directions than in the vertical direction, or z. This indicates that the range of frequencies that capture significant mass values is larger in the x and y directions than in the vertical direction, or z.

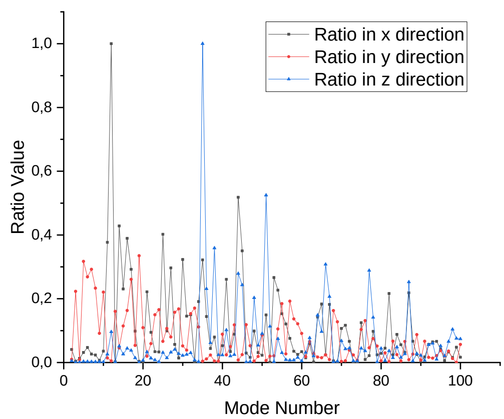

Fig. 7. Effect of analysis direction on the ratio value for Beni Behdel arch dam with rigid rock foundation

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To avoid resonance phenomena, it is crucial to consider the fundamental mode seriously as a dynamic property. According to modal analyses, the dam is more susceptible in both the transverse and upstream–downstream directions, so for dams, the upstream–downstream direction is not already the most unfavorable direction. Instead, it is necessary to study the dynamic behavior of the Beni Behdel multi-arch dam due to excitation in both the transverse and upstream-downstream directions (x and y).

Without taking interaction phenomenon into account, the same analysis is done for the El Mefrouch multi-arch dam. The first frequencies and their associated values in the x, y, and z directions are summarized in Tabs. 6–8, respectively.

It is clear from Tabs. 8–10 that the dam-related quantities depend on the motion directions.

The fundamental mode of El Mefrouch multi arch dam in x direction is the mode number 17 (see Tab. 8), in y direction is the mode number 16 (see Tab. 9); however, in z direction is the mode number 79 (see Tab. 10).

Tab. 8. First 10 frequencies in x direction for El Mefrouch multi-arch dam with rigid rock foundation

Mode	Frequency	Period	Participation factor	Ratio	Effective mass
1	7.31985	0.13661	–5.3568	0.001338	28.6951
2	7.38362	0.13543	–2.2185	0.000554	4.92174
.					
17	9.51602	0.10509	4,004.5	1.000000	0.160358 E + 08

Tab. 9. First 10 frequencies in y direction for El Mefrouch multi-arch dam with rigid rock foundation

Mode	Frequency	Period	Participation factor	Ratio	Effective mass
1	7.31985	0.13661	–0.90156	0.000153	0.812807
2	7.38362	0.13543	50.952	0.008656	2,596.14
.	.	.	.	.	.
16	8.76738	0.11406	5,886.5	1.000000	0.346507 E + 08

Tab. 10. First frequencies in z direction for El Mefrouch multi-arch dam with rigid rock foundation

Mode	Frequency	Period	Participation factor	Ratio	Effective mass
1	7.31985	0.13661	–2.4075	0.000548	5.79619
2	7.38362	0.13543	–1.5863	0.000361	2.51631
.	.	.	.	.	.
79	25.2994	0.39527E -01	4,392.2	1.000000	0.192910 E + 08

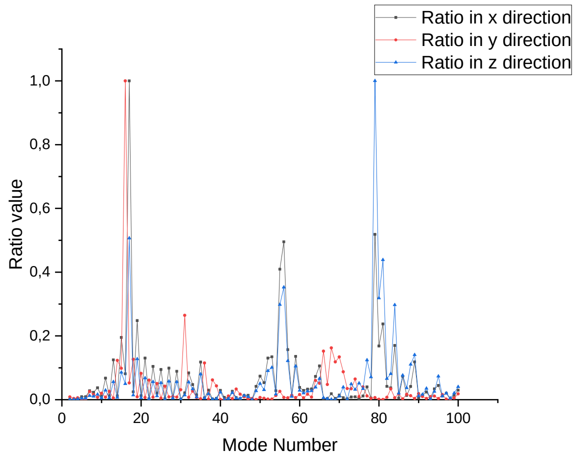

Fig. 8. Effect of analysis direction on the ratio value of El Mefrouch arch dam with rigid rock foundation

According to Fig. 8, the number of modes with a significant ratio value is more significant in the x and y directions than the z directions. This is because the El Mefrouch dam ratio value is more prominent in the x and y directions than the z directions.

The upstream–downstream direction is not already the most unfavorable direction for dams, according to El Mefrouch modal analyses, which also show that this dam is more sensitive in the transverse and upstream–downstream directions. Instead, it is essential to examine the El Mefrouch multi-arch dam's dynamic behavior as a result of excitation in both the transverse and upstream–downstream directions (x and y).

3.2. Modal behavior of multi-arch dams with rock foundation modeling (taking into account interaction phenomenon)

The interaction phenomenon is taken into account for both multi-arch dam cases in the section that follows. The massless rock foundation model and the mass-rock foundation model are the two models that are used for dynamic interaction modeling.

The effects of the Beni Behdel multi-arch-rock foundation interaction modeling on the ratio value in the x, y, and z directions are shown in Figs. 9–11, respectively. These graphs demonstrate how the fundamental frequencies shift as a result of the rock foundation modeling; this shift is particularly pronounced in the vertical direction (z-axis).

The ratio values are also modified by the dam–rock foundation interaction models. This means that accounting for the presence of the rock foundation modifies the participation factor of each mode, which in turn modifies the dynamic properties of the dam.

Figs. 12–14 show the impact of El Mefrouch multi-arch and rock foundation interaction modeling on the ratio value in the x, y, and z directions, respectively. These figures also demonstrate how the rock foundation modeling affects the shifting of fundamental frequencies.

As for the Beni Behdel arch dam, the El Mefrouch arch dam's fundamental mode shifting is more pronounced in the vertical direction z than in the other two directions. This is because the entire system (dam with rock foundation) is more sensitive to changes in mass and stiffness in the z direction (gravity direction) than in the other two directions (knowing that adding foundation to the dam leads only to a decrease in the system stiffness for the case of dam with massless rock foundation and to a decrease in

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stiffness and increase in the mass for the case of dam with mass rock foundation).

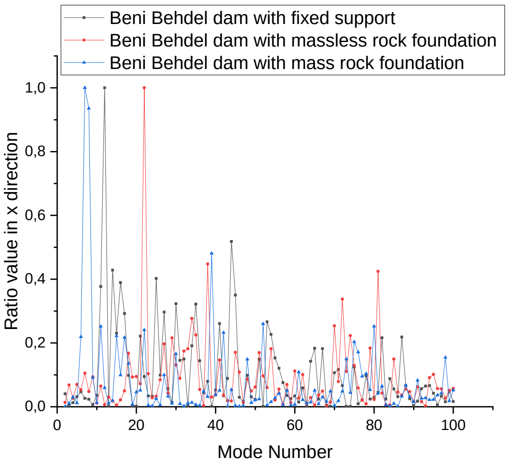

Fig. 9. Effect of Beni Behdel arch dam–rock foundation interaction modeling on the ratio value in x direction

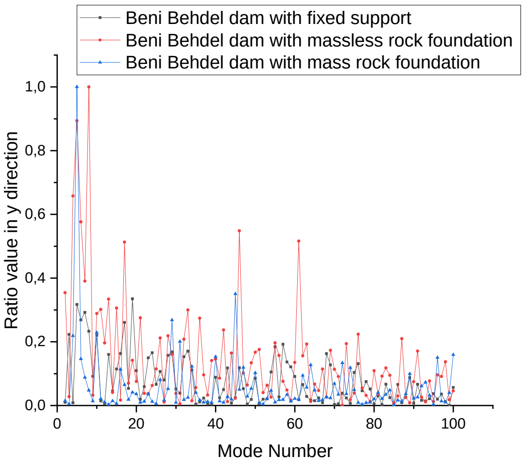

Fig. 10. Effect of Beni Behdel arch dam–rock foundation interaction modeling on the ratio value in y direction

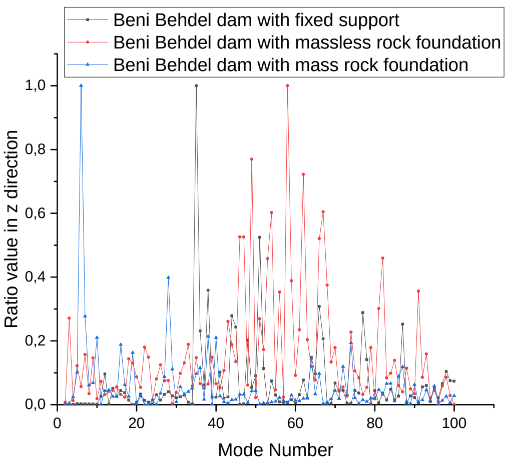

Fig. 11. Effect of Beni Behdel arch dam–rock foundation interaction modeling on the ratio value in z direction

Recall that the ratio value is the division of participation factor of mode "i" by the maximum participation factor. The rock foundation modeling has an impact on this ratio value-related quantity, which also has an impact on the prediction of resonance bandwidth and the resonance phenomenon in general.

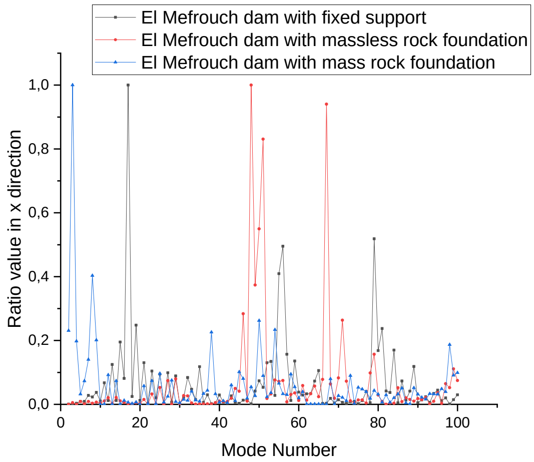

Fig. 12. Effect of El Mefrouch multi-arch rock foundation interaction modeling on the ratio value in x direction

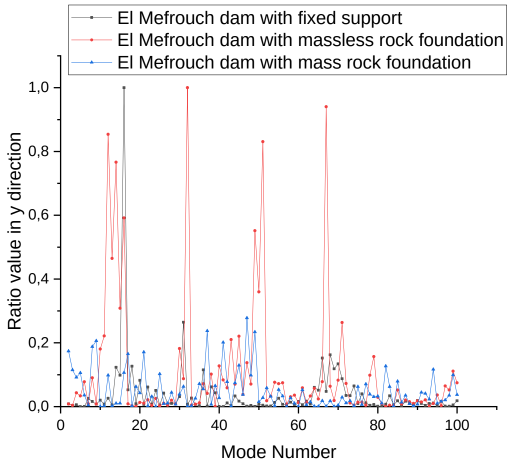

Fig. 13. Effect of El Mefrouch multi-arch rock foundation interaction modeling on the ratio value in y direction

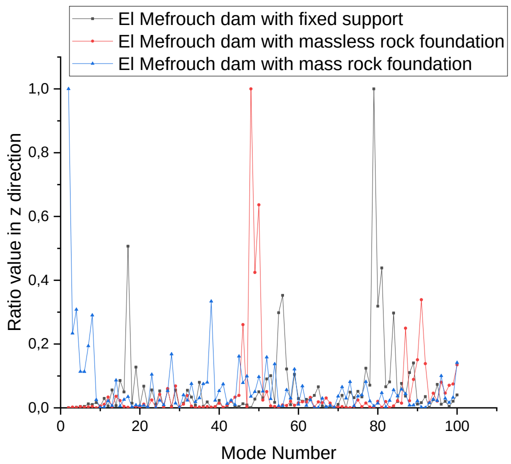

Fig. 14. Effect of El Mefrouch multi-arch rock foundation interaction modeling on the ratio value in z direction

It is concluded that for the two researched arch dams, the studied direction and the interaction phenomenon modeling have an impact on the modal participation factor and, as a result, the ratio-related quantity value.

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The effects of the rock–foundation interaction phenomenon on the modal frequencies of Beni Behdel and El Mefrouch multi-arch dams are depicted in Figs. 15 and 16, respectively.

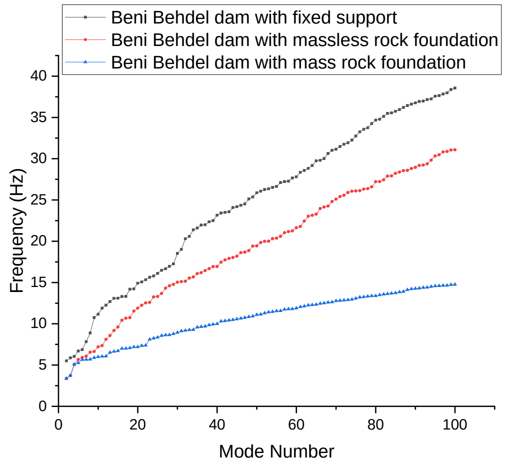

Fig. 15. Dam–rock foundation interaction modeling effect on the modal frequencies of Beni Behdel multi-arch dam

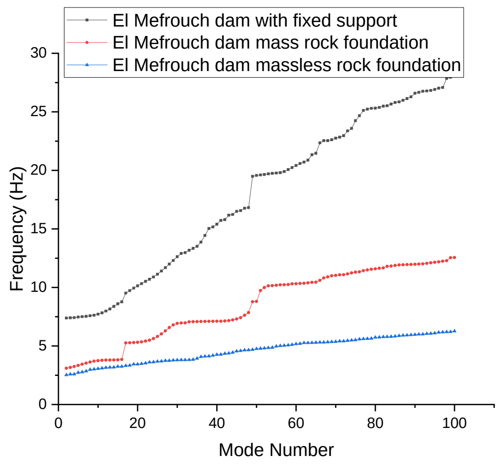

Fig. 16. Dam–rock foundation interaction modeling effect on the modal frequencies of El Mefrouch multi-arch dam

Figs. 15 and 16 make it very evident that adding in the foundation rock reduces system frequencies, especially if the rock is modeled as a mass rock foundation. Both the Oued Taht dam [16] and the Brezina concrete arch dam [3] yield the same results. The system becomes more flexible as a result of the addition of foundation, which also increases the system's mass and, as a result, its period.

The interaction modeling-induced changes in natural frequencies have an impact on the resonance bandwidth, which has an impact on the resonance phenomena prediction.

It is deemed more acceptable to take into account the foundation presence in the modeling since changing the natural frequency values as a result of interaction modeling affects the dam's dynamic response (transient response).

4. CONCLUSIONS

To explore the modal behavior of the multi-arch dams Beni Behdel and El Mefrouch and to account for their interaction with the rock–foundation medium, the present work models the dams using the 3D finite element code ANSYS. The output of a modal analysis is presented as frequencies and related quantities (participation factor, ratio, and effective mass). The following was discovered through this investigation:

– The ANSYS finite element code can provide the analyzed system's modal characteristics in three directions (x, y, and z).
– Due to the varied inertia in the three directions, the two examined arch dams' modal behavior in terms of participation factor, and consequently ratio and effective mass, differs for each direction.
– Rock foundation–dam interaction modeling affects the behavior of the dam in terms of frequency which is a curial dynamic characteristic to take into consideration for several analysis types (spectrum analysis, transient analysis).
– Rock foundation modeling modifies the fundamental mode's position as well as frequency values (knowing that the fundamental mode is the mode which takes the maximum of mass).
– The interaction modeling-induced changes in natural frequencies have an impact on the resonance bandwidth, which has an impact on the resonance phenomena prediction.
– It is thought to be more acceptable to take into account the foundation presence in the modeling because changing the values of the natural frequencies as a result of interaction modeling changes the dynamic response of the dam (transient response).
– The fundamental mode must be taken carefully as a dynamic attribute in order to prevent resonance phenomenon.
– According to modal analyses, the upstream–downstream direction is not already the most unfavorable direction for dams because, for example, the two previous studied dams are more sensitive in both the transverse and upstream–downstream directions. Rather, it is required to examine these studied dams's dynamic behavior as a result of excitation in both the transverse and upstream–downstream directions (x and y).

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