MODAL BEHAVIOR OF "MULTI-ARCH DAM"- "ROCK FOUNDATION" SYSTEM

COMPORTEMENT MODALE DU SYSTÈME "BARRAGE MULTI-VOÛTE"- " FONDATION ROCHEUSE "

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Abstract

In this paper, modal response of multi-arch concrete dam taking into account dam-foundation interaction effect are determined using the finite elements commercial packages ANSYS. The dam geometry is inspired from El-Mefrouch multi-arch dam situated at Tlemcen, Algeria.

Three approaches are used to model "dam-rock foundation" interaction phenomenon. The first approach is the "fixed support" model, the second is the "mass less rock-foundation" model and the third one is the "mass rock-foundation" model.

Comparison between results of different models was made to understand the effect of rock-foundation modeling on the dynamic characteristics (Modal behavior) of the dam-rock foundation system.

Keywords: Arch dam, Dam-Rock Foundation-Interaction, Modal Behavior

Résumé

Dans cet article, les réponses modales d'un barrage multi-voûte prenant en compte l'effet d'interaction barrage-fondation sont déterminées en utilisant le code en éléments finis ANSYS. La géométrie du barrage est inspirée du barrage à voûtes multiples d'El-Mefrouch situé à Tlemcen, en Algérie.

Trois approches sont utilisées pour modéliser le phénomène d'interaction "barrage-fondation". La première approche est le modèle à "base fixe", la deuxième est le modèle de "barrage avec fondation tenant en compte sa masse" et la troisième est le modèle de " barrage avec fondation sans tenir en compte sa masse".

La comparaison entre les résultats des différents modèles a permis de comprendre l'effet de la modélisation de la fondation rocheuse sur les caractéristiques dynamiques (comportement modal) du système barrage-fondation.

Mots-clés : Barrage-voûte, Interaction Barrage-fondation, Comportement modal

1-Introduction

Analysis of dam-reservoir systems is one of the main topics in earthquake engineering. Numerous researches were carried out on the dam-foundation interaction problem by many researchers Refs. [1-7].

Numerical procedures, which include the interaction between several domains having different properties: concrete dam, foundation rock, water, bottom sediments and bank of the reservoir, have been developed using the finite element method, the boundary element method and various combinations of both methods Refs. [8-11].

In the literature, there are four different modeling of the foundation soil: the standard rigid-base model, the massless-foundation model, the deconvolved-base-rock model, and the free-field dam-foundation interface model Ref. [12]. In the massless foundation model, absence of mass makes the foundation rock as a spring, i.e., only the flexibility of the foundation rock is taken into account.

As part of the comprehensive study undertaken on the dynamic response of multi-arch concrete dam where the geometry is inspired from El-Mefrouch multi-arch dam situated at Tlemcen, Algeria, in this paper, the influence of rock-foundation on the modal behavior of the dam is investigated.

Following this section, the 3D multi-arch dam with fixed base support and the 3D multi-arch dam with rock-foundation finite element models are presented in section 2. In Section 3, some related quantities used in results representation are explained. In section 4 and section 5, results of different studied finite element models are extracted, discussed, and compared. Conclusions are offered in the last section of the paper.

2-Dam–foundation rock finite element models

El Mefrouch dam is situated at Tlemcen, Algeria, it is a concrete multi-arch dam (Fig. 1) Ref. [13]. The dam geometry is defined in Tab.1. It is important to note that characteristics presented in Tab. 1 are given from El Mefrouch dam technical sheet.

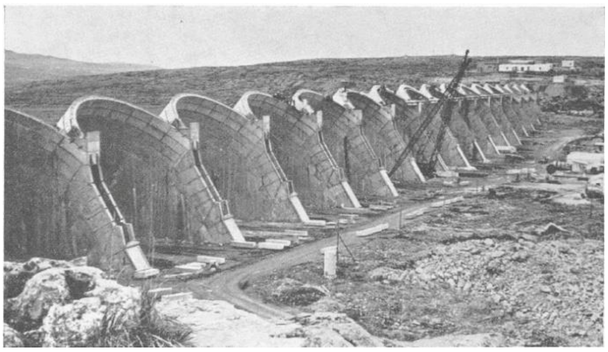

Figure 1: El Mefrouch multi-arch dam

Figure 1: Le barrage multi-voûte d'El Mefrouch

Table 1: El Mefrouch multi-arch concrete dam geometry

Tableau 1 : Géométrie du barrage multi-voûte d'El Mefrouch

Maximum height above the lowest point of the foundation	35 m
Crest width	2,30 m
Crest length	531 m
Butter thickness	2,50 m
Arch number	17
Arch thickness	0,80 m
Upstream facing slope	0,80
Downstream facing slope	0,5665

To investigate the effects of rock foundation-dam interaction on the modal response of the multi arch dam object of the study, the following analyses are performed using the finite element commercial package, ANSYS:

(1) Linear modal analysis of dam without rock foundation so without rock foundation-dam interaction effect, which means that the rock is infinitely rigid, and hence its modulus of elasticity is infinite and the dam base is clamped. The model exhibit55819 quadratic solid elements (SOLID185) and 19619 nodes

(2) Linear modal analysis of the rock foundation-dam system rock foundation-dam system is investigated using two 3D finite element models. The first model is the "massless rock foundation-Dam" model, represents the dam and the adjacent soil but the rock foundation mass is neglected. The foundation rock is clamped at its base, the second model is "mass rock foundation-Dam" model is similar to the first one except that the mass of the rock is taken into account. The two models exhibit 178047 quadratic solid elements (SOLID185) and 43108 nodes.

The length and width of the foundation soil, along the global X, Y and Z-axis, respectively, are taken to be 200 m. These sizes are sufficiently large so that the applied boundary conditions do not affect the modal responses of the dam. The size of 200 m is more than to 2.5 times the dam's height. Taking the factor of 2.5 is a common practice to assure a good representation of the foundation rock, see for instance Refs. [10, 14, 15].

The material properties for both the concrete multi-arch dam and rock foundation are given in Tab. 2. A governmental organism in charge of the dam study provides these characteristics. Table 2 summarizes material properties of the multi-arch dam and the rock foundation. A governmental organism in charge of the dam study provides these characteristics.

Table 2: Material properties of the multi-arch dam and its rock foundation

Tableau 2 : Caractéristiques des matériaux du barrage multi- voûte et de sa fondation

Material	Young's Modulus (N/m2)	Poisson's ratio	Density (kg/m3)
Concrete dam	28.5e+09	0.2	2500
Foundation soil	6.22e+09	0.25	2100

Mapped meshing is chosen for this study Ref. [16]. The finesse of the mesh has been determined after doing a convergence analysis in the study of both static and modal responses. To study convergence analysis, three meshing cases using SOLID185 have been proposed for the case of dam with fixed support; meshing 1 which correspond to a coarse meshing at 100%, meshing 2 which correspond to a meshing refined at 2% and meshing 3 which correspond to a refined meshing at 100%. Table 3 summarizes the first ten frequencies for the three meshing cases chosen.

Table 3: the first ten frequencies for the three meshing cases chosen

Tableau 3 : Les dix premières fréquences pour les trois cas de maillage choisis

Mode	Mesh 1	Mesh 2	Mesh 3
1	2,12112	2,42329	2,42330
2	2,15208	2,45159	2,45159
3	2,27013	2,67042	2,67043
4	2,55123	2,67745	2,67745
5	2,59008	2,72505	2,72507
6	2,63445	2,74455	2,74465
7	2,69665	2,77949	2,77959
8	2,71111	2,81788	2,81708
9	3,11567	3,42669	3,42659
10	3,26798	3,59169	3,59179

It is clear from Tab. 3 that the results for the case of meshing 2 and meshing 3 are practically the same. Table 4 summarizes the maximum static displacement at the dam crest for the three meshing cases.

Table 4: Maximum dam crest static displacements for the three meshing cases

Tableau 4: Les déplacements maximum en crête du barrage pour les trois cas de maillage.

Meshing case	Meshing 1	Meshing 2	Meshing 3
Maximum crest displacement (m)	0.358E-1	0.4212E-1	0.4212E-1

From Tab. 3 et Tab.4 it is clear that the case of meshing 2 and meshing 3 give practically the same results in term of frequencies and maximum crest static displacement respectively, for these reason the meshing case "meshing 2" is chosen for this study in order to save both computing time and memory space. It is important to note that the same principle of choice of mesh fineness was applied for the dam with foundation rock.

Figure 2 sketches the dam with mapped meshing 2 chosen in this study.

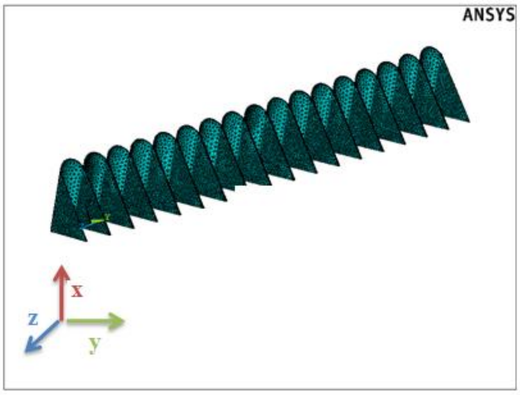

Figure 2: Finite element model of multi-arch dam with fixed support base (meshing case 2)

Figure 2: Modèle en élément finis du barrage multi-voûte à base encastrée (maillage cas 2)

3-Definition of some parameters used in the modal analysis and given by Ansys code

3.1- Participation factor

The participation factor for a given excitation is given as :

$$P_{f\,i} = \{\phi\}_i^T [M]\{D\} \quad (1)$$

Where:

$P_{f\,i}$: Participation factor for the ith mode.

$\{D\}$: vector describing the excitation direction

$\{\phi\}_i$: Normalized Eigenvector

$\{\phi\}_i^T$: Normalized Eigenvector transpose.

3.2- Effective mass

The effective mass in a given direction is defined by:

$$M_{e\,i} = \frac{P_{f\,i}^{\ 2}}{\{\phi\}_i^T [M]\{\phi\}_i} \quad (2)$$

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

With :

$$\{\phi\}_i^T [M]\{\phi\}_i = 1 \quad (3)$$

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.

3.3-Ratio

The ratio is defined as :

$$Ratio = \frac{P_{f\,i}}{P_{f\,i\ max}} \quad (4)$$

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

4-Modal Analysis Results of multi-arch dam with fixed support

This section covers modal responses Refs. [17 &18] of the dam object of this study without taking into account rock foundation-dam interaction phenomenon. The modal responses are calculated using the Block Lanczos method Ref. [16]. Reported quantities are the first natural mode frequencies and the corresponding Frequency, period, participation factor P_{fi}, its ratio to the maximum participation factor, Ratio and effective mass, Mei.

It is important to note that Ansys finite element code gives modal results in x, y and z direction. For the present studied model, x axis corresponds to the vertical direction however y axis corresponds to the upstream-downstream sens (Fig.2 and Fig.3). Table 5, Tab. 6 and Tab. 7 list these quantities for the multi-arch dam alone (multi-arch dam clamped at its base) in x, y and z direction respectively.

Table 5: First ten frequencies in x direction for the case of multi-arch dam with fixed support

Tableau 5: Les premières dix fréquences suivant la direction x pour le cas du barrage multi- voûte à base fixe

Mode Number	Frequency (Hz)	Période (second)	Participation factor (Pfi)	Ratio	Effective Mass (Mei) (kg)
1	2,423	0,412	325,29	0,129	105813
2	2,451	0,407	-272,75	0,108	74390,3
3	2,670	0,374	20,28	0,008	411,29
4	2,677	0,373	51,658	0,020	2668,52
5	2,725	0,366	34,846	0,013	1214,24
6	2,744	0,364	39,446	0,015	1555,97
7	2,779	0,359	53,368	0,021	2848,13
8	2,817	0,354	19,253	0,007	370,683
9	3,426	0,291	1193,1	0,473	1,42E+06
10	3,591	0,278	1219,3	0,483	1,49E+06

Table 6: First ten frequencies in y direction for the case of multi-arch dam with fixed support

Tableau 6: Les premières dix fréquences suivant la direction y pour le cas du barrage multi- voûte à base fixe

Mode Number	Frequency (Hz)	Période (second)	Participation factor (Pfi)	Ratio	Effective Mass (Mei) (kg)
1	2,423	0,412	1082,3	0,417	1,17E+06
2	2,451	0,407	1119,9	0,432	1,25E+06
3	2,670	0,374	1076,2	0,415	1,16E+06
4	2,677	0,373	1088,8	0,420	1,19E+06
5	2,725	0,366	1077,9	0,416	1,16E+06
6	2,744	0,364	1084,8	0,418	1,18E+06
7	2,779	0,359	1056,5	0,407	1,12E+06
8	2,817	0,354	1052,1	0,406	1,11E+06
9	3,426	0,291	92,54	0,035	8563,68
10	3,591	0,278	347,77	0,134	120942

Table 7 : First ten frequencies in z direction for the case of multi-arch dam with fixed support

Tableau 7 : Les premières dix fréquences suivant la direction z pour le cas du barrage multi- voûte à base fixe

Mode Number	Frequency (Hz)	Période (second)	Participation factor (Pfi)	Ratio	Effective Mass (Mei) (kg)
1	2,423	0,412	264,4	0,101	69909,2
2	2,451	0,407	-214,16	0,082	45865,1
3	2,670	0,374	17,315	0,007	299,825
4	2,677	0,373	49,985	0,019	2498,48
5	2,725	0,366	28,322	0,011	802,155
6	2,744	0,364	52,81	0,020	2788,91
7	2,779	0,359	46,815	0,018	2191,6
8	2,817	0,354	38,077	0,014	1449,83
9	3,426	0,291	737,82	0,282	544374
10	3,591	0,278	675,74	0,258	456624

Examining the above modes presented in Tab.5, Tab. 6 and Tab. 7 and their related quantities, it is clear that the multi-arch dam object of the present study is more sensitive in “y” direction compared to the two other directions. The related quantities (Pfi, Ratio, Mei), for example the effective masse taken by each mode is more pronounced in y direction than in the two other directions, which is obvious because this is the direction characterized by weak inertia.

Also, it can be notice that these related quantities are also much important in x direction than in z direction, these can be explained by the fact that in z direction (vertical direction) the multi-arch dam resist by its one weight which make it more stable via deformations.

Figure 3 plots the effect of analysis directions on natural mode frequency ratio of the dam with fixed support. Knowing that a Ratio value of one (unit) corresponds to the fundamental mode. The fundamental mode is defined as the mode that takes the maximum mass of the system.

The fundamental mode is a very important dynamic characteristic which must be taken seriously to ovoid resonance phenomenon.

Figure 3 shows shift of fundamental mode passing from x-axis to y axis to the z one for the case of dam with fixed support. In x direction the fundamental mode is the mode number 15 (with frequency value equal to 4,103 Hz) however in y and z direction the fundamental mode is number 30 (with frequency value equal to 8,258Hz) and 76 (with frequency value equal to 19,5759 Hz) respectively.

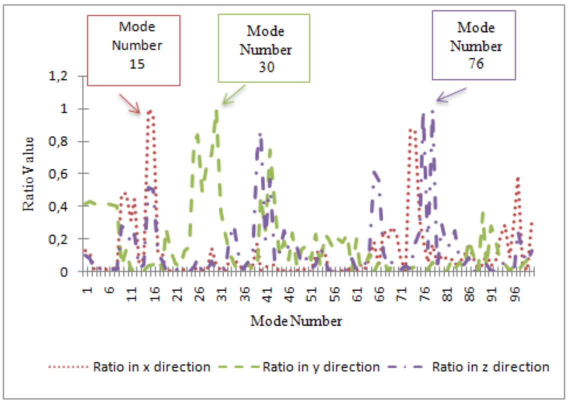

Figure 3: Effect of analysis direction on natural mode frequency ratio value of the dam with fixed support

Figure 3: Effet de la direction d'analyse sur la valeur du rapport de fréquence de mode propre pour le cas du barrage à base fixe

It is also to note that from Fig.3, for the case of dam with fixed base support the margin of shift of fundamental mode with respect to three direction axes is remarkable.

5-Modal Analysis Results of multi-arch dam with rock foundation base

In the following section; we are interested on results in y direction which is the direction characterized by the low inertia value.

5.1-Dam with massless rock foundation

Figure 4 plots the effect of analysis direction on the ratio value of natural frequencies and shows the shift of the fundamental mode passing from one axis to other.

Figure 4 shows shift of fundamental mode passing from one axe to other for the case of dam with massless rock foundation. In x direction the fundamental mode is the mode number 49 (with frequency value equal to 22,3961Hz) however in y and z direction the fundamental mode is number 17 (with frequency value equal to 11,6072Hz) and 9 (with frequency value equal to 10,1541Hz) respectively.

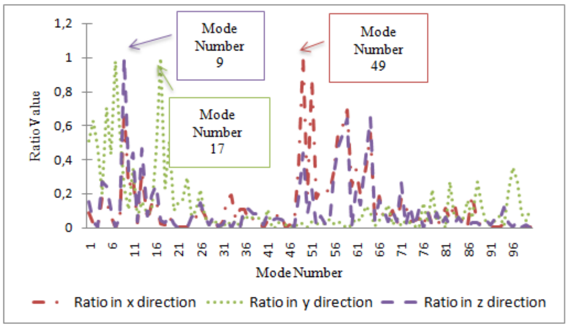

Figure 4: Effect of analysis direction on natural mode frequency ratio value of the dam with massless rock foundation

Figure 4 : Effet de la direction d'analyse sur la valeur du rapport de fréquence de mode propre pour le cas du barrage avec fondation sans masse

It is important to note that from Fig.4, for the case of dam massless rock foundation the margin of shift of fundamental mode with respect to three direction axis is less remarkable compared with the case of dam with fixed support base. This is can be explained by the fact that adding rock to dam model make the system more flexible, although in this case (dam with massless rock foundation), le rock foundation participates in the all system behavior only by its stiffness because its mass is neglected and consequently its inertia effect is absent.

5.2-Dam with mass rock foundation

As Fig. 3 and Fig. 4, Fig. 5 plots the effect of analysis direction on the ratio value of natural frequencies and shows the shift of the fundamental mode passing from one axis to other but for the case of multi-arch dam with mass rock foundation. The shift of fundamental mode passing from one axe to other is also presented in Fig.5. In x direction the fundamental mode is the mode number 4 (with frequency value equal to 2,652 Hz) however in y and z direction the fundamental mode is number 1 (with frequency value equal to 2,3211Hz) and 3 (with frequency value equal to 2,58841Hz) respectively

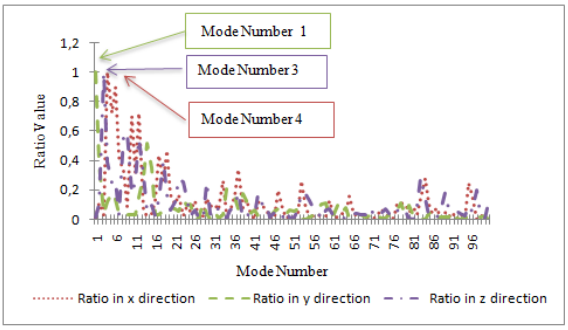

Figure 5: Effect of analysis direction on natural mode frequency ratio of the dam with mass rock foundation

Figure5: Effet de la direction d'analyse sur la valeur du rapport de fréquence de mode propre pour le cas du barrage avec fondation en tenant compte de sa masse

However, from Fig. 5, for the case of dam with mass rock foundation the margin of shift of fundamental mode with respect to three direction axes is negligible compared with that for both cases of dam with fixed support base and dam with massless rock foundation model. In this case the rock foundation participates in the all system behavior by is stiffness and by its inertia since the rock mass is taken into account. So, the system dam-rock foundation works uniformly in the three directions.

5.3-Multi-arch dam-rock foundation interaction effect on the modal behavior of the model

Figure 6 shows the effect of rock-foundation interaction phenomenon on the modal behavior of the multi-arch dam. It is important to note that three cases are studied; dam with fixed support which means without rock-foundation interaction effect, dam with foundation rock but neglecting its mass which means neglecting the inertial component of the interaction phenomenon and finally dam with foundation rock taking into account its mass which means taking into account the two interaction components the inertial and the kinematic one. Table 6 summarizes the first thirty frequencies for the three studied cases in y direction since it is downstream-upstream direction.

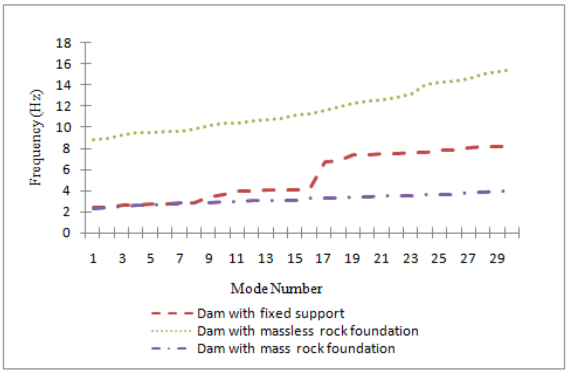

Figure 6 : Effect of multi-arch dam –rock foundation interaction phenomenon on the modal behavior of the system

Figure 6 : Effet de phénomène d'interaction barrage multi voûte-fondation sur la réponse modale du système

Table 6: The first thirty frequencies of the studied dam for the three studied cases

Tableau 6: Les premières trente fréquences du barrage étudié pour les trois cas d'étude

Mode Number	Dam with fixed support	Dam with massless rock foundation	Dam with mass rock foundation
1	2,42329	8,87422	2,3211
2	2,45159	8,99725	2,46758
3	2,67042	9,28035	2,58841
4	2,67745	9,53801	2,65258
5	2,72505	9,57461	2,67903
6	2,74455	9,6109	2,74214
7	2,77949	9,64105	2,84013
8	2,81788	9,83492	2,88282
9	3,42669	10,1541	2,91919
10	3,59169	10,4107	2,93188
11	3,97993	10,4671	3,00763
12	3,99899	10,5942	3,05284
13	4,02189	10,7331	3,10894
14	4,04312	10,9096	3,11703
15	4,103	11,1469	3,14104
16	4,16221	11,322	3,27994
17	6,76022	11,6072	3,32231
18	6,80256	11,91	3,36425
19	7,37438	12,3079	3,39918
20	7,39683	12,4998	3,41424
21	7,47603	12,6715	3,48675
22	7,49117	12,7937	3,50263
23	7,55379	13,1193	3,54312
24	7,64547	14,0596	3,61073
25	7,76689	14,2472	3,61733
26	7,82523	14,366	3,65283
27	8,00906	14,5765	3,80732
28	8,1694	14,9902	3,88051
29	8,19183	15,214	3,93389
30	8,25884	15,4823	3,97074

It's clear from Fig. 6 that taking into account the foundation rock decreases the system frequencies furthermore if the foundation rock is modelized as mass rock foundation. The same results are found for Brezina concrete arch dam Ref. [14] and for Oued that dam Ref. [19]. Adding foundation soil to the structure returns the system more flexible and increases its mass and consequently its period increase.

According to Tab. 6 and Fig. 7, it can be noted that rock foundation modeling change not only frequencies values but also the positioning of the fundamental mode (remembering that the fundamental mode is the mode which takes the maximum of mass).For the fixed support case, the fundamental mode is the mode number thirteen (30), if the foundation rock is added without taking into account its mass the fundamental mode shifts to the mode number seventeen (17) and to mode number one (1) if the foundation rock mass is taken into account.

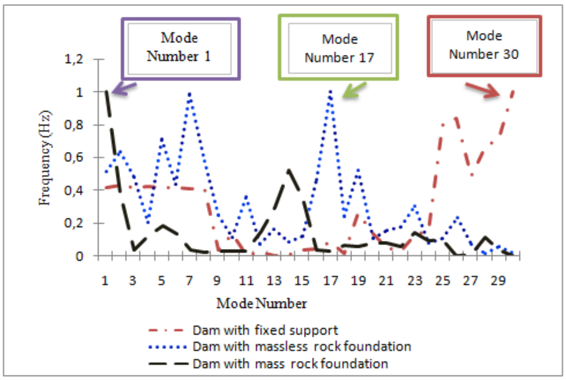

Figure 7: Effect of multi-arch –rock foundation interaction phenomenon on the natural system frequencies modes

Figure7 : Effet du phénomène d'interaction barrage multi-voûte /fondation sur les fréquences propres du système.

Results are in perfect agreement with those of El Bayadh dam Ref. [14] and Oued Taht dam Ref. [19].

6- Conclusion

In the present article, a multi-arch dam is modeled using finite element code Ansys, to understand its modal behavior taking into account its interaction with the rock-foundation domain.

Modal Analysis allows concluding what follows:

1) Ansys is a good finite elements code for Dam-rock interaction modeling, it gives the modal behavior of the system in three directions (x, y and z);

2) The system modal behavior is different for the three directions; this is due to the difference of inertia in the three directions.

3) Rock foundation – dam interaction modeling change the dam frequency, knowing that the frequency is a dynamic characteristic to take into account for different analyses kinds (spectrum analysis, transient analysis….)

4) Rock foundation modeling change not only frequencies values but also the positioning of the fundamental mode (knowing that the fundamental mode is the mode which takes the maximum of mass)

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