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Effect of Material Non-linearities on the Transient Dynamic Behavior of the Beni-Bahdel Dam in the Presence of the Dam-foundation Interaction

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Abstract

The current paper's goal is to investigate how dynamic interaction phenomena and material nonlinearities affect the dynamic behavior of a concrete gravity multi-arch dam in terms of maximum displacements, natural stresses, principal stresses, and Von Mises stresses when subjected to seismic excitation. Utilizing ANSYS APDL software, linear and nonlinear transient analysis using the finite element method was employed to analyze the interaction between the dam and its rock foundation. As a case study for this work, the multi-arch Beni-Bahdel dam was selected, and the seismic excitation used data from a simulated earthquake. The direct method is employed to model the interaction between the multi arch dam and the rock foundation using two approaches; the fixed base approach and the mass foundation approach. Six finite element models were performed using ANSYS code, "linear dam-fixed support", "nonlinear dam-fixed support", "linear dam-linear rock foundation" "nonlinear dam-linear rock foundation", "nonlinear dam-nonlinear rock foundation" and "linear dam-nonlinear rock foundation". The bilinear kinematic hardening model is employed to represent the nonlinearity of both dam body and rock foundation. The results obtained are compared to understand the effect of both material nonlinearities and interaction phenomenon on the dynamic behavior of the studied dam. In contrast to the nonlinearity of the rock foundation material, it is concluded that the nonlinearity of the concrete dam material has a significant impact on the behavior of the system.

Keywords

concrete arch dam, bilinear kinematic hardening model, dam–rock foundation interaction, nonlinear seismic response

1 Introduction

The prediction of the actual dynamic response of an arch dam to seismic loadings is a particularly challenging problem that depends on a number of variables, including the interaction of the dam with its foundation rock, computer modeling, particular material properties, etc.

From this perspective, a detailed analytical model should serve as the basis for a nonlinear dynamic study of arch dams under earthquake ground motions. The study of the behavior of concrete gravity dams under seismic load is an important step in the evaluation of their stability.

The knowledge of the real behavior of dams under dynamic loads is complicate because these huge structures present non-linear characteristics and are in interaction with other domain such as rock foundation and reservoir water.

Rescher [1] concluded through his research that most concrete gravity dams exhibit cracks, even under operational load conditions. Therefore, assuming linear behavior of concrete gravity dams may not be appropriate in their seismic response analysis, and a non-linear dynamic analysis should be performed for dam-foundation systems.

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The nonlinear dynamic response of concrete dams depends on their interaction with the rock foundation, and on the constitutive models considered for their materials.

The dam-rock foundation interaction is the first type of dynamic interaction. The direct method and the substructure method, depending on the simulation for the rock foundation around the dam, have always been two distinct approaches in the modeling and analysis of dynamic dam-rock foundation interaction during earthquakes.

The purpose of numerous studies has been to determine how the most of concrete gravity dams interact with their foundations [2–9]. Dam's seismic safety assessment should take into account all potential nonlinearity sources. The Drucker–Prager and the multilinear kinematic hardening models are employed by Ouzandja and Tiliouine [10] in the nonlinear analyses for concrete in the dam and rock in the foundation, respectively, the Oued Fodda concrete gravity Dam, located in Chlef, was selected as an example and linear as well as nonlinear seismic analyses were performed. The Concrete-Faced Rockfill (CFR) dam's geometrically and materially non-linear behaviors are taken into account by Kartal et al. [11] in the finite element analysis, which is performed with reliability analysis, in addition to its linear behavior. Concrete slabs and rockfill and foundation rock are both treated using the Drucker–Prager method and multi linear kinematic hardening method, respectively.

Ghorbani et al. [12] examined the effect of concrete's nonlinear behavior on the seismic performance of a double-curvature concrete dam. The Morrow Point concrete dam had been selected as the case study. The El Centro earthquake components were applied to the case study's modeling and analysis using the finite element method by taking into account the nonlinear behavior of concrete. The multilinear kinematic hardening in three dimensions was chosen for the nonlinear analysis and the stress strain model in this study. Although linear material is assumed for the foundation, both linear and nonlinear materials are considered for the dam body. Two-dimensional earthquake response of Cine RCC dam is presented Çavuşli et al. [13] considering geometrical non-linearity.

Besides, material nonlinearity is also taken into consideration in time-history analyses. Bilinear kinematic hardening and multi linear-hardening model are used in the materially non-linear analyses for concrete and foundation rock, respectively.

For different concrete slab thicknesses ranging from 30 to 100 cm thick, Kartal and Bayraktar [14] explore the non-linear response of the rockfill in a concrete-faced rockfill dam under seismic excitation. The concrete slab's materially non-linear behavior is evaluated using the Drucker-Prager model. In the material non-linear studies, rockfill and foundation rock are analyzed using the multi linear kinematic hardening model. Kartal et al. [15] used the improved Rackwitz–Fiessler method to evaluate the reliability of the concrete slab of a CFR dam. The dam's geometrically and materially non-linear behaviors are taken into account in the finite element analysis,

which is carried out in conjunction with reliability analysis, in addition to its linear behavior. The multi linear kinematic hardening approach is utilized for both rockfill and foundation rock, whereas the Drucker–Prager method is employed for concrete slabs. Kartal [16] used Drucker-Prager model for concrete slab and multi-linear kinematic hardening model for rockfill zones and foundation rock in the two-dimensional finite element model of Torul CFR dam to investigate earthquake performance of concrete slab on CFR dam comprehensively. Akkose et al. [17] studied into how reservoir water levels affected the nonlinear dynamic response of arch dams. For this reason, the Drucker–Prager model, based on the associated flow rule assumption, idealizes the nonlinear behavior of the dam concrete as elasto-plastic.

2 Research significance

Few studies on the dynamic behavior of arch dams that consider the nonlinear behavior of materials, either with or without taking into consideration soil-structure interaction, have been conducted, according to research in the literature [18]. Due to the presence of joints, the analyzed nonlinearities are primarily geometrical [10, 19–23].

The idea for the current work came from the state of the art, and it was decided to investigate the effects of material nonlinearities on the behavior of arch dams while taking into account the phenomenon of rock-dam interaction. This is a novel contribution made by the current work to the study of arch dam behavior.

This study investigates the influence of both material nonlinearities and dam-rock foundation interaction on the transient dynamic behavior of concrete gravity multi arch dam under synthetic seismic record. The multi-arch Beni-Bahdel dam was used as a case study for this work. Two approaches – the fixed base approach and the mass foundation approach – are used in combination with the direct method to model the interaction between the multi-arch dam and the rock foundation. The bilinear kinematic hardening model is employed to represent the nonlinearity of both dam body and rock foundation. Six finite element models were studied, "linear dam-fixed support", "nonlinear dam-fixed support", "linear dam-linear rock foundation", "nonlinear dam-linear rock foundation", "nonlinear dam-nonlinear rock foundation" and "linear dam-nonlinear rock foundation". The dam and rock foundation system's linear and nonlinear transient analyses were carried out using the Ansys code, where the foundation rock is assumed to be perfectly bonded with the dam and no interface contact elements are used.

3 Dam-foundation rock finite element models

Built in 1934 on Oued Tafna for a retention volume of 63 million m^3, the Beni-Bahdel dam is a dam with several cylinder arches and buttresses and is situated 25 km southwest of Tlemcen, Algeria. It was impounded in 1944. (Fig. 1). Table 1 presents the dam geometry [24].

Fig. 1 Beni-Bahdel multi-arch dam

Table 1 Beni-Bahdel multi-arch concrete dam geometry [24]

Element	Geometry entities/general information	Measures
Buttresses	The height above the ground of the foundation	57 m
	Spacing	20 m from axis to axis
	The form	Substantially triangular
	The inclination of the upstream facing	1: 0.95
	The inclination of the downstream facing	0.30
	The thickness at the top	3 m
	The thickness at the lower end	4.80 m
	The length of the ridge	220 m
Arches	Number of arches	11
	The form	The form
	Internal diameter	17.20 m
	Inclination	1: 0.95
	The thickness at the top	0.70 m
	The thickness at the lower end	

The following analyses are carried out using the finite element commercial software ANSYS to examine the impact of dam–rock foundation interaction on the dynamic response of the Beni-Bahdel multi arch dam:

First, a linear and nonlinear transient analysis of a dam with a rigid rock foundation, or without the interaction of the rock foundation and the dam, in which the rock is assumed to be infinitely rigid and the base of the dam to be clamped. There are 13926 nodes and 41598 quadratic solid elements (SOLID185) in the model (Fig. 2). SOLID185 is used for 3-D modeling of solid structures. Eight nodes having three degrees of freedom at each node (translations in the nodal x, y, and z directions) define this element [25].

Second, using the direct method in which the foundation rock is assumed to be perfectly connected with the dam and no contact elements are used, linear and nonlinear transient analysis of the dam with rock foundation system is performed. Using 3D finite element models having 97519 quadratic solid elements (SOLID185) and 27424 nodes, the dam-rock foundation system is investigated (Fig. 3).

Depending on the U-shape of the valley, the height of the dam's vaults and buttresses ranges from 18 m to 57 m.

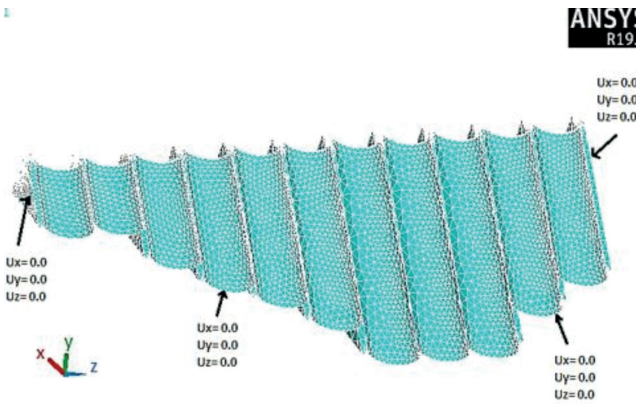

Fig. 2 Finite element model of Beni-Bahdel multi arch dam with fixed support base

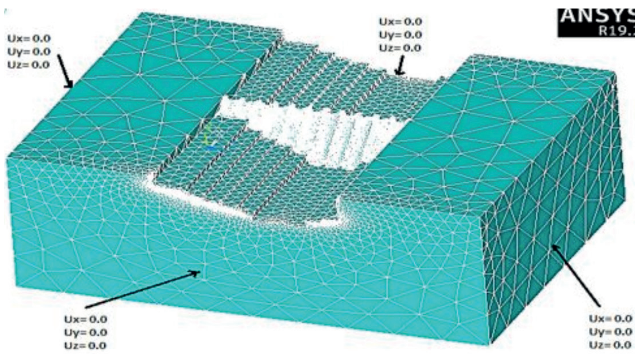

Fig. 3 Finite element model of E Beni-Bahdel multi arch dam with rigid rock foundation

Three times the height of the dam, or 171 m, is considered as the extension of the rock foundation along the three directions. These sizes are large enough that the given boundary constraints have no impact on the dam's modal responses [26].

4 Material properties

The material characteristics of the concrete multi-arch dam and the rock foundation are listed in Table 2 for the linear analysis. These characteristics are provided by a governmental organism in charge of the dam study.

The simplest and most used mode is the bilinear kinematic hardening model, as shown in Fig. 4. Von Mises yield criterion and the related flow rule are used in this model. Throughout all loading phases, the elastic range remains constant.

The Young's modulus (*E*) for stresses below the yield stress (*fy*) and the Young's modulus (*E*) for stresses above the yield stress is the tangent modulus needed to update the element stiffness matrix [13].

For both the concrete dam and the rock foundation, the bi-linear model is employed to express the nonlinear behavior. The "linear dam-fixed support", "nonlinear dam-fixed support", "linear dam-linear rock foundation", "linear dam-nonlinear rock foundation", "nonlinear dam-linear rock foundation" and "nonlinear dam-nonlinear rock foundation" are six finite element models that were investigated.

5 Seismic response of Beni-Bahdel arch dam

Beni-Bahdel multi-arch dam's dynamic behavior is assessed using a synthetic seismic signal with 15-second duration. It is significant to highlight that the spatial variability of the earthquake record is not taken into consideration in this article because the earthquake record is applied uniformly at each model base. In Fig. 5.

The horizontal component of the earthquake's acceleration has a maximum ground acceleration (PGA) of approximately 1.962 g. ANSYS finite element code is used to perform the time history analysis [2]. For the two models without and with dam-rock foundation interaction, as well as for both linear and nonlinear behaviors, the numerical analyses present the maximum horizontal displacements in the upstream face and the maximum horizontal, vertical, and Von Mises stresses along the dam height.

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

Material	Young's modulus (N/m^2)	Poisson's ratio	Density (kg/m^3)
Concrete dam	3 E+10	0.2	2500
Foundation rock (sandstone)	3.25 E+10	0.3	2600

6 Transient analysis results and discussion

6.1 Horizontal displacement of Beni-Bahdel multi arch dam with rigid rock foundation (without interaction phenomenon)

Fig. 6 illustrates the time variation of the horizontal displacement at the crest of a dam without a rock foundation (a dam with fixed support at the base) for two different material behaviors: linear ("linear dam-fixed support")

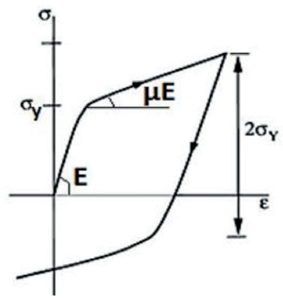

Fig. 4 Stress-Strain behavior of bilinear kinematic hardening model for Bauschinger effect [8]

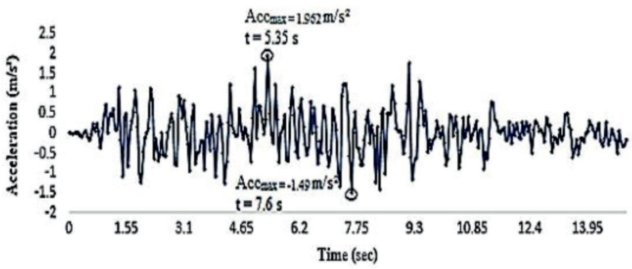

Fig. 5 Acceleration records for an artificial seismic signal

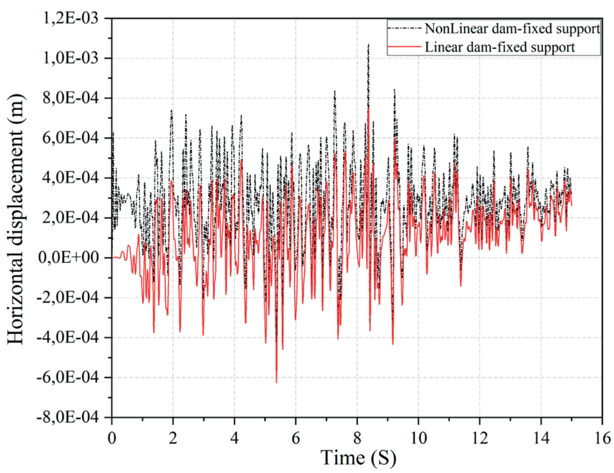

Fig. 6 Linear and nonlinear horizontal displacement at the crest of the dam without rock foundation (dam with fixed support at the base)

and nonlinear ("nonlinear dam-fixed support"). In nonlinear behavior, the horizontal displacement increases from 7.51E-04 m for linear behavior to 1.07E-03 m, which represents an increase in the magnitude of the crest displacement of nearly 42%.

For the case of Beni-Bahdel multi-arch dam with fixed support, the maximum horizontal displacement at the end of the load seismic along the dam height in the upstream face for both concrete material behavior models (linear and nonlinear behaviors) are presented in Fig. 7. The maximum horizontal displacement at the crest reaches 2.62 E-04 m and 3.19 E-04 m respectively for linear and nonlinear behavior. The displacement is more pronounced in the case of nonlinear behavior of dam than in the case of the linear behavior. The similar conclusion was reached by Ghorbani et al. [12] for the concrete Morrow Point dam with massless rock foundation. For the linear concrete dam behavior, the displacement at the dam crest was 3.85 cm, but it increased to 4.01 cm for the nonlinear dam behavior.

6.2 Horizontal displacement of Beni-Bahdel multi arch dam with rock foundation interaction modeling

Fig. 8 depicts the time evolution of the horizontal displacement at the crest of the multi-arch Beni-Bahdel dam with a rock foundation for the four cases: "linear dam-linear rock foundation", "linear dam-nonlinear rock foundation", "nonlinear dam-nonlinear rock foundation."

According to Fig. 8, the "nonlinear dam-nonlinear rock foundation" situation results in the greatest horizontal time history displacement at the dam crest.

The Maximum crest horizontal displacement of Beni-Bahdel multi arch dam with rock foundation interaction modeling is summarized in Table 3.

The horizontal displacement rises from 7.67E-03 m for the "linear dam-linear rock foundation" case to 3.06 E-02 m for the "nonlinear dam-linear rock foundation" behavior to 3.47 E-02 m for the nonlinear dam-nonlinear rock foundation behavior, but 7.64 E-03 is found for the linear dam-nonlinear rock foundation case.

Fig. 9 illustrates the maximum horizontal displacement at the end of the seismic load along the dam's upstream face for the four previously studied cases. For the cases of "linear dam-linear rock foundation", "linear dam-nonlinear rock foundation", "nonlinear dam-nonlinear rock foundation", and "nonlinear dam-linear rock foundation", respectively, the maximum horizontal displacement reaches -2.37 E-04 m, -1.92 E-04, 1.27 E-02 m, and 3.09E-02.

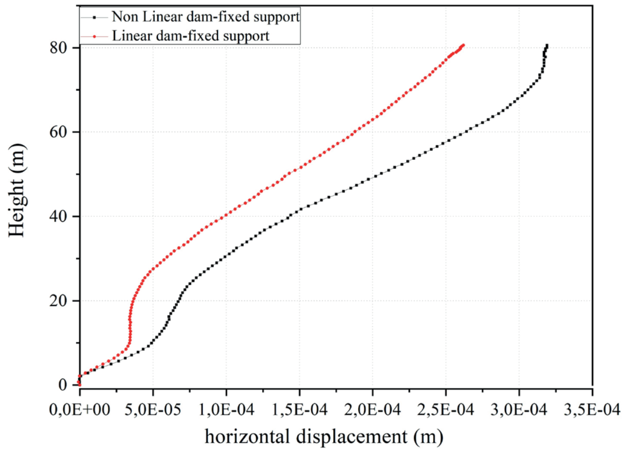

Fig. 7 Maximum linear and nonlinear horizontal displacements along the dam height upstream face for the case of dam with rigid rock foundation (without interaction phenomenon)

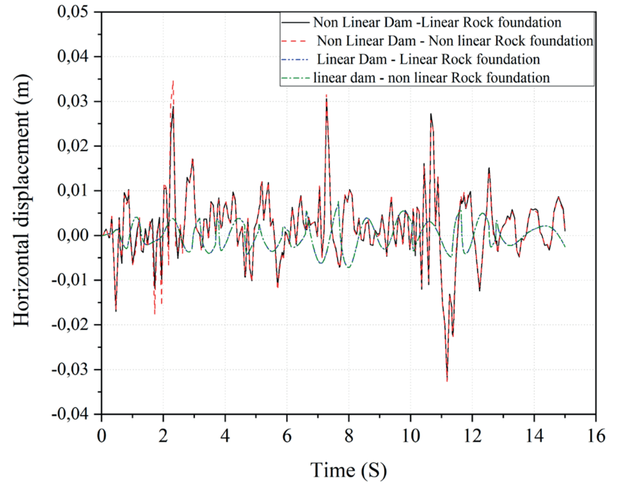

Fig. 8 The maximum horizontal time history displacement at the dam crest for the four studied cases

Table 3 Maximum crest Horizontal displacement of Beni-Bahdel multi arch dam with rock foundation interaction modeling

Case study	Maximum horizontal displacement (m)
linear dam-linear rock foundation	7.67E-03
nonlinear dam-linear rock foundation	3.06E-02
nonlinear dam - nonlinear rock foundation	3.47 E-02
linear dam - nonlinear rock foundation	7.64 E-03

The comparison of the behavior of both Beni-Bahdel dam models without and with interaction phenomenon (comparing Fig. 6 with Fig. 8 and Fig. 7 and Fig. 9) is summarized in Table 4.

The horizontal displacement at the crest in linear behavior (linear dam - fixed support) case increases from 7.51E-04 for the case of the dam without interaction phenomenon

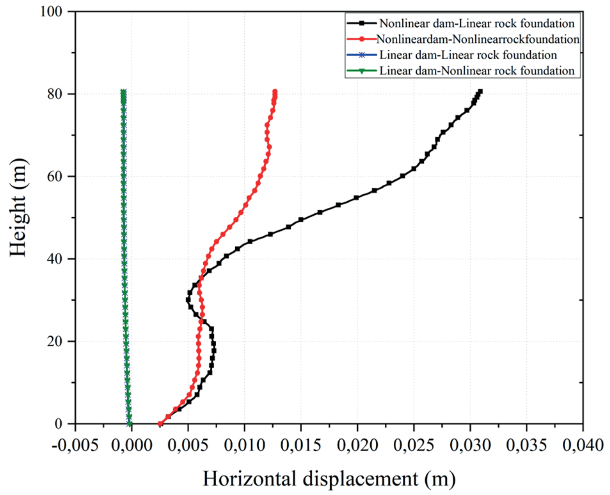

Fig. 9 Maximum horizontal displacements along the dam height upstream face for the case of dam with rock foundation interaction

Table 4 Maximum horizontal displacements at the end of the seismic load along the dam's upstream face for the case of dam with rock foundation interaction

Case study	horizontal displacement at the crest (m)	the maximum horizontal displacement at the end of the seismic load along the dam's upstream face
linear dam - fixed support	7.51E-04	2.62E-04
linear dam-linear rock foundation	7.67E-03	-7.16E-04
linear Dam-Nonlinear rock foundation	7.64E-03	-1.92 E-04
nonlinear dam - fixed support	1.07 E-03	3.19 E-04
Non-linear Dam-Linear rock foundation	3.06E-02	1.27E-02
Non-linear Dam-Non-linear rock foundation	3.47E-02	3.09E-02

to 7.67E-03 for the case of the dam with interaction (linear dam-linear rock foundation), it is an increase of 921%. This means that taking into account dam-rock foundation interaction phenomenon leads to an increase in the system horizontal displacement [6, 7].

In the absence of interaction, the concrete dam's nonlinearity causes the maximum horizontal displacement at the crest to increase. Concrete dam nonlinear behavior also increases the maximum horizontal displacement at the crest for the case of linear rock foundation behavior when the interaction is considered.

When the interaction is considered, concrete dam nonlinear behavior increases the maximum horizontal displacement at the crest for the case of nonlinear rock foundation behavior. However, when concrete dam behaves linearly, the maximum horizontal displacement at the crest is slightly decreases due to the nonlinear behavior of the rock foundation.

The maximum horizontal displacement at the crest is reduced for nonlinear concrete dam behavior due to rock foundation nonlinearity behavior. It can be concluded that while rock foundation nonlinearity behavior minimizes maximum horizontal displacement at the crest, concrete dam nonlinearity behavior increases it.

6.3 Stresses of Beni-Bahdel multi arch dam with rigid rock foundation (without interaction phenomenon)

Fig. 10, Fig. 11, and Fig. 12 show, respectively, the horizontal normal stresses (in an upstream-downstream direction), vertical normal stresses, and Von Mises stress distributions along the Beni-Bahdel dam's upstream face height

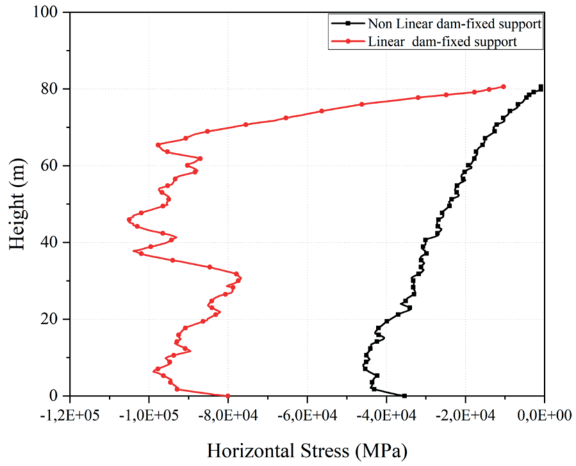

Fig. 10 Horizontal normal stresses distribution along the dam upstream height for the case of dam with fixed support (dam without interaction phenomenon)

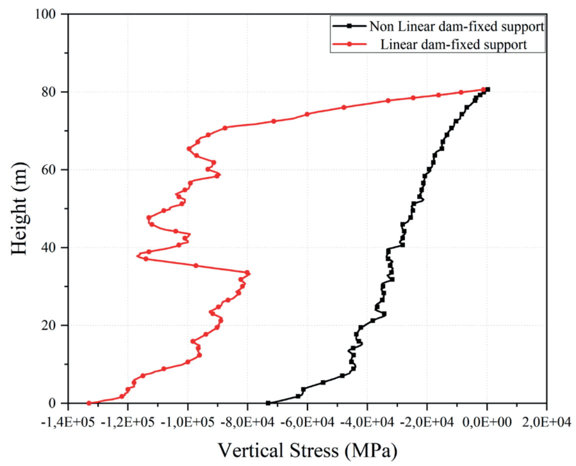

Fig. 11 Vertical normal stresses distribution along the dam upstream height for the case of dam with fixed support (dam without interaction phenomenon)

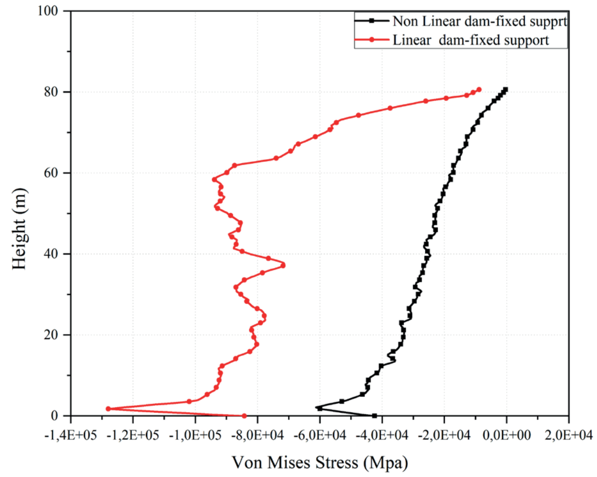

Fig. 12 Von mises stress distribution along the dam upstream height for the case of dam with fixed support (dam without interaction phenomenon)

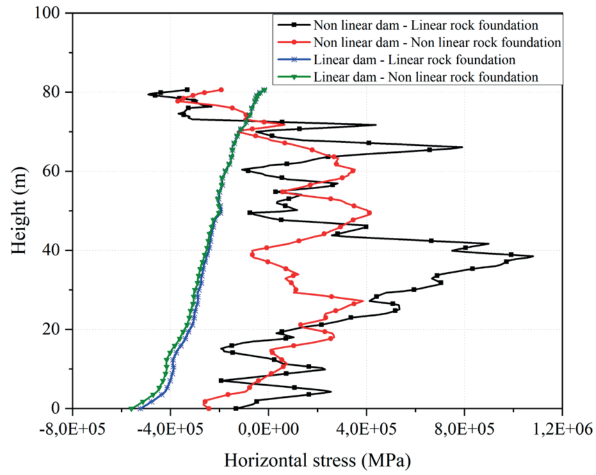

Fig. 13 Horizontal normal stresses distribution along the dam upstream face height for the case of dam with Rock foundation (dam with interaction phenomenon)

for the case of the dam with a rigid rock foundation (without the interaction phenomenon) for both material linearities behavior.

For the "Linear dam - Fixed support" example, the maximum values of the horizontal, vertical, and Von Mises stresses are -105390, -132990, and -128130MPa, respectively. For the "Non-Linear dam - Fixed support" example, these stresses are modified to -45914, -73123, and -61305 MPa; this results in a reduction in the horizontal, vertical, and Von Mises stresses of approximately 56%, 45%, and 52%, respectively. So, as results the nonlinear concrete dam behavior decreases the above-mentioned stresses.

6.4 Stresses of Beni-Bahdel multi arch dam with rock foundation interaction modeling

Fig. 13, Fig. 14 and Fig. 15 show, respectively, horizontal normal stresses (in an upstream-downstream direction), the vertical normal stresses and Von Mises stresses distribution along the dam's upstream face height for the case of a dam with a rock foundation, i.e., for the case where the interaction phenomenon is taken into consideration.

Table 5 summarizes the maximum horizontal normal stresses (in an upstream-downstream direction), the maximum vertical normal stresses and the maximum Von Mises stresses along the dam's upstream face height for the case of a dam with a rock foundation.

Nonlinear rock foundation behavior causes a decrease in maximal and vertical horizontal stress but an increase in von Mises stress for linear concrete dam behavior.

Nonlinear rock foundation behavior reduces the maximal and vertical horizontal stress as well as the Von Mises stress for nonlinear concrete dam behavior.

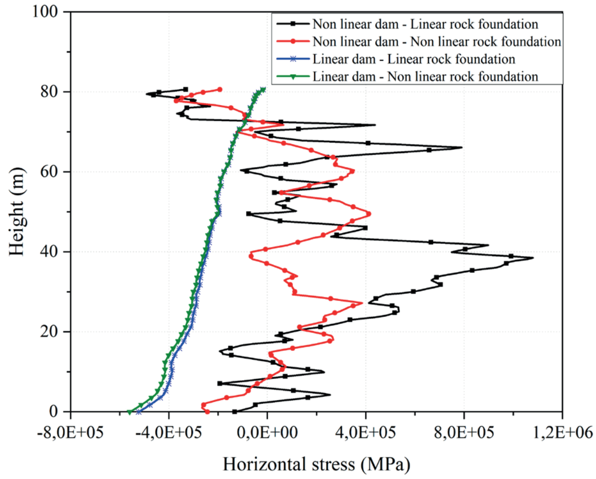

Fig. 14 Vertical normal stresses distribution along the dam upstream face height for the case of dam with Rock foundation (dam with interaction phenomenon)

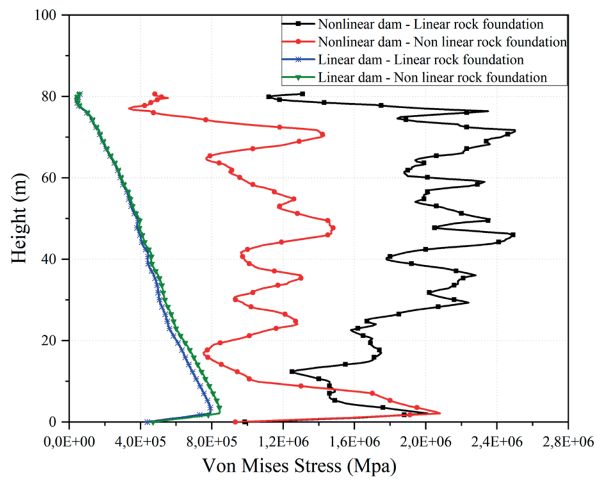

Fig. 15 Von Mises stresses distribution along the dam upstream face height for the case of dam with Rock foundation (dam with interaction phenomenon)

Table 5 The maximum horizontal normal stresses (in an upstream-downstream direction), the maximum vertical normal stresses and the maximum Von Mises stresses along the dam's upstream face height for the case of a dam with a rock foundation

Case study	Parameter	Value (MPa)
Linear dam- linear rock foundation	Maximum horizontal stress	-17873
	Maximum vertical stress	20408
	Von Mises stresses	792450
Linear dam-nonlinear rock foundation	Maximum horizontal stress	-17317
	Maximum vertical stress	18306
	Von Mises stresses	844200
Nonlinear dam- linear rock foundation	Maximum horizontal stress	1080300
	Maximum vertical stress	1354600
	Von Mises stresses	2501900
Nonlinear dam- nonlinear rock foundation	Maximum horizontal stress	414660
	Maximum vertical stress	464670
	Von Mises stresses	2083800

Table 6 Maximum horizontal, vertical and Von Mises stresses at heel of the dam for all studied cases

case	Horizontal stresses (MPa)	Vertical stresses (MPa)	Von Mises stresses (MPa)
linear dam-fixed support	-80061	-132990	170520
Non-linear dam-fixed support	-35421	-73123	86692
linear dam - linear rock foundation	-523290	-260990	437400
linear dam – Non-linear rock foundation	-559720	-271780	469830
Non-linear dam - linear rock foundation	-132850	-86952	985110
Non-linear dam - Non-linear rock foundation	-243850	-133640	931510

Table 6 below summarizes the maximum horizontal, vertical and Von Mises stress values at the heel of the dam for the different studied cases.

It is clear from Table 6 that the model experiences more stresses as a result of the addition of a rock foundation.

The nonlinearity of the rock foundation material has a significant impact if the behavior of the concrete dam material is nonlinear, but it has no effect if the behavior of the concrete dam is linear. We found very little difference in results between "linear dam-linear rock foundation" case and "linear dam-non linear rock foundation" case.

The heel's horizontal and vertical stresses both increase as a result of the rock foundation's nonlinear behavior, while the heel's Von Mises stress decreases.

6.5 Principal stresses of Beni-Bahdel multi arch dam with rigid rock foundation (without interaction phenomenon)

Fig. 16, Fig. 17 and Fig. 18 depict the maximum principal stresses that occurred in the Beni-Bahdel dam's upstream face height for the case of the dam with a rigid rock foundation (without the interaction phenomenon) and for both material linearity's behavior, Table 7 provides a summary of the findings.

Table 7 shows that the principal stresses were reduced when the nonlinear behavior of the dam material was taken into account for the dam with fixed support; Ghorbani et al. [12] came to the same result about the concrete Morrow Point dam with massless rock foundation.

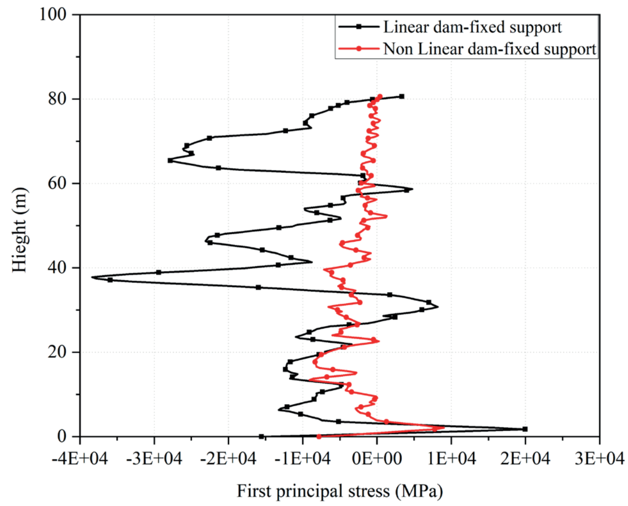

Fig. 16 First principal stress distribution along the dam upstream face height for the case of dam with fixed support

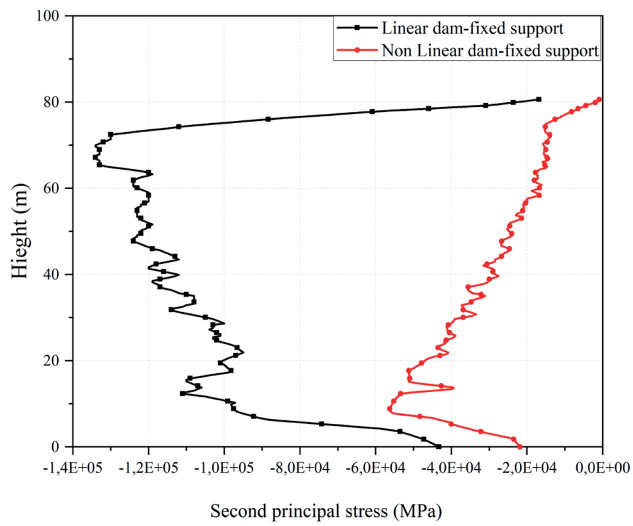

Fig. 17 second principal stress distribution along the dam upstream face height for the case of dam with fixed support

6.6 Principal stresses of Beni-Bahdel multi arch dam with rock foundation interaction modeling

The results of the maximum principal stresses for the second model (dam with rock foundation interaction) are shown in Fig. 19 and Fig. 20 and Fig. 21 for the four cases of "linear dam - linear rock foundation," "non-linear dam - linear rock foundation," "non-linear dam - non-linear rock foundation," and "linear dam - non-linear rock foundation."

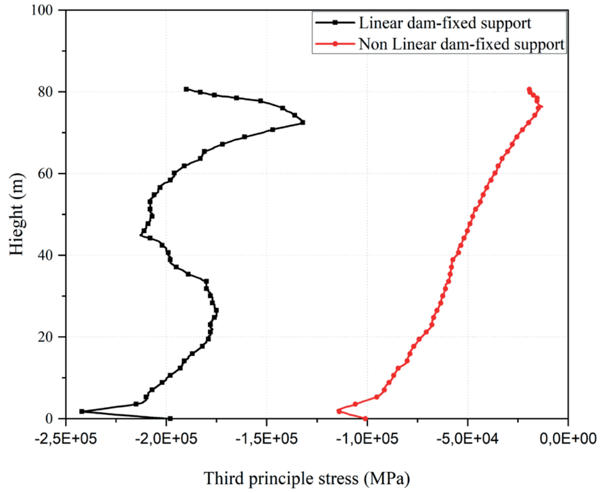

Fig. 18 Third principal stress distribution along the dam upstream face height for the case of dam with fixed support

Table 7 Maximum First, second and third principal stresses for the case of the dam with fixed support

Case	First principal stress (MPa)	Second principal stress (MPa)	Third principal stress (MPa)
Linear	-38380	-133920	-242020
Non-linear	-9111.8	-56282	-114940
Discount percentage	76%	58%	53%

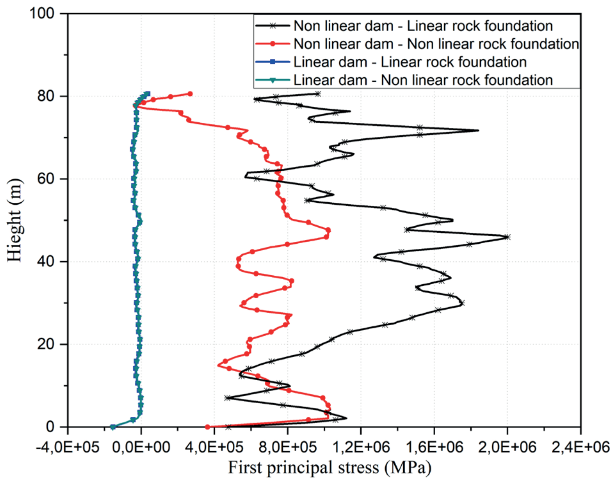

Fig. 19 First principal stress distribution along the dam upstream face height for the case of dam with Rock foundation (dam with interaction phenomenon)

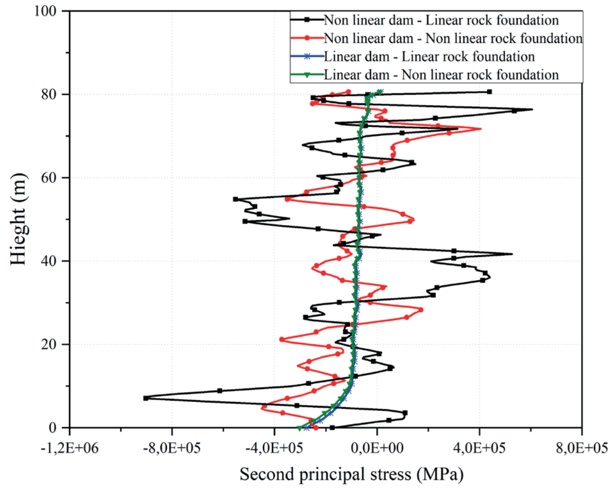

Fig. 20 Second principal stress distribution along the dam upstream face height for the case of dam with Rock foundation (dam with interaction phenomenon)

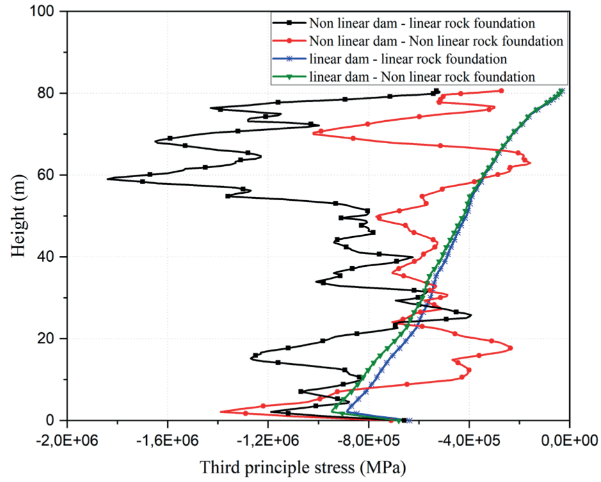

Fig. 21 Third principal stress distribution along the dam upstream face height for the case of dam with Rock foundation (dam with interaction phenomenon)

The maximum three principal stresses for the case of the dam with a rock foundation are shown in Table 8. It can be shown that the nonlinearity of the rock foundation material has little effect on the principal stresses if the behavior of the dam material is linear; on the other hand, if the behavior of the dam material is nonlinear, the nonlinearity of the rock foundation material causes a reduction in the principal stresses.

7 Conclusions

This work examines the effects of material nonlinearities and the interaction between the concrete gravity multi-arch dam and its rock foundation on the transient dynamic behavior under synthetic seismic data. The Beni-Bahdel multi-arch dam was selected as the case subject for this

Table 8 Maximum First, second and Third principal stresses for the case of the dam with rock foundation

Case	First principal stress (MPa)	second principal stress (MPa)	Third principal stress (MPa)
Linear dam – linear rock foundation	37780	-275870	-887210
Linear dam – Non-linear rock foundation	28978	-303480	-947420
Non-linear dam – linear rock foundation	2002100	-904180	-1835700
Non-linear dam – non-linear rock foundation	1032500	-451010	-1387200

study. The nonlinearity of both the dam body and the rock foundation is described by the bilinear kinematic hardening model. The "linear dam-fixed support," "nonlinear dam-fixed support," "linear dam-linear rock foundation," "linear dam-nonlinear rock foundation", "nonlinear dam-linear rock foundation," and "nonlinear dam- nonlinear rock foundation" are six finite element models that were investigated. Assuming that the foundation rock and the dam are perfectly bonded, linear and nonlinear transient analyses of the dam with rock foundation system were carried out using the Ansys code. No interfaces or contact elements were used in these analyses.

The following conclusions are made based on the results discussed above:

For the case of Beni-Bahdel dam with fixed support, the displacement is more evident when a concrete dam behaves nonlinearly than when it behaves linearly. However, the nonlinear concrete dam behavior decreases the horizontal, vertical and Von Mises stresses.

The system maximum crest horizontal displacement increases as a result of accounting for the interaction between the dam and the rock foundation.

For the case of Beni-Bahdel dam-rock foundation interaction, concrete dam nonlinearity behavior increases maximum horizontal displacement at the crest, whereas rock foundation nonlinearity decreases this displacement.

The maximum values of the horizontal, vertical, and Von Mises stresses along the dam's upstream height are reduced by the nonlinear concrete dam behavior in the case of dams with fixed supports.

While linear concrete dam behavior results in an increase in von Mises stress, nonlinear rock foundation behavior results in a decrease in maximal and vertical horizontal stress.

The maximal and vertical horizontal stresses as well as the Von Mises stress for nonlinear concrete dam behavior are reduced by nonlinear rock foundation behavior.

If the behavior of the concrete dam material is nonlinear, the nonlinearity of the rock foundation material has a considerable impact, but it has no effect if the behavior of the concrete dam is linear.

Due to the nonlinear behavior of the rock foundation, the Von Mises stress of the heel increases while the horizontal and vertical stresses both increases.

If the behavior of the dam material is linear, the nonlinearity of the rock foundation material has little impact on the principal stresses; however, if the behavior of the dam material is nonlinear, the nonlinearity of the rock foundation material results in a reduction in the principal stresses.

The nonlinearity of the concrete dam material has an important effect on the behavior of the system compared with the nonlinearity of the rock foundation material effect.

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