Nonlinear Seismic Response of Concrete Gravity Dams

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Abstract. This paper aims to present the nonlinear seismic response of concrete gravity dams considering dam-foundation interaction. For illustrative purpose, the Oued Fodda concrete gravity Dam, located in Chlef (northwestern Algeria), is selected as an example. Linear and nonlinear analyses are performed using ANSYS. The Druker-Prager model is used for dam concrete and foundation rock in nonlinear analysis. The hydrodynamic pressure of the reservoir water is modeled as added mass using the Westergaard approach. The maximum displacements and principal stresses are shown by the height of the dam. The results obtained from linear and non-linear analyses are compared with each other.

Keywords: Concrete gravity dams · Dynamic dam-foundation interaction · Nonlinear dynamic analysis · Drucker-Prager model · Finite element method

1 Introduction

Concrete gravity dams represent complex constructive systems of strategic importance. They are particularly used for electricity generation, water supply, flood control, irrigation, recreation, and other purposes. They are a fundamental part of the society's infrastructure system.

There are several factors affecting the dynamic response of concrete gravity dams to earthquake ground motions. Some of them are the interaction of the dam with the foundation rock and water in reservoir, and non-linear behavior of dam itself and its fondation. The dam-foundation interaction problem was investigated by Chopra and Chakrabarti [1], Leger and Boughoufalah [2], Nuss et al. [3], Bayraktar et al. [4], Lemos and Gomes [5], Moussaoui and Tiliouine [6], Saleh and Madabhushi [7], Lebon et al. [8], Saouma et al. [9], Hariri-Ardebili and Mirzabozorg [10], Burman et al. [11], Hariri-Ardebili and Mirzabozorg [12], and Ouzandja and Tiliouine [13].

This study investigates the nonlinear seismic response of a concrete gravity dam. The Oued Fodda Dam is considered in the numerical analyses. For this purpose,

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two-dimensional dam-foundation finite element model is used. The hydrodynamic pressure of the reservoir water is modeled utilizing the added mass concept [14]. The Druker-Prager model [15] is used for dam concrete and foundation rock in nonlinear analysis. All numerical analyses are performed using ANSYS [16]. The results obtained from linear and nonlinear analyses are compared with each other.

2 Numerical Model of Oued Fodda Concrete Gravity Dam

2.1 Material Properties

The Oued Fodda concrete gravity dam is located approximately 20 km of Oued Fodda (Chlef), in northwestern Algeria, and founded over a massive limestone known as "Koudiat Larouah". The reservoir is mainly used for irrigation purposes. The capacity of the dam is 125.5 hm^3. The maximum height "H" and base width of the dam are 101 m and 67.5 m, respectively. The dam crest is 5 m wide and the maximum height of the reservoir water is considered as 96.4 m. The dimensions of the dam-foundation system are shown in Fig. 1.

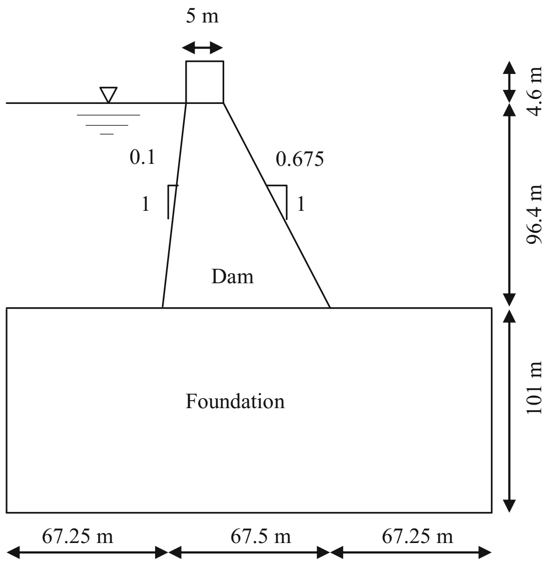

Fig. 1. Dam-foundation system

The material properties of Oued Fodda dam including its foundation are reported in Table 1 below. The Drucker-Prager model [15] is used in nonlinear analysis for concrete of the dam and foundation soil. The cohesion and the angle of internal friction of the dam body and foundation rock are assumed as to be 2.50 Mpa and 35°, respectively. The concrete of the dam has tensile strength of 1.6 MPa and compressive strength of 20 MPa.

Table 1. Material properties of Oued Fodda concrete gravity dam

Material	Material properties		
	Modulus of elasticity (MPa)	Poisson's ratio	Mass density (kg/m^3)
Dam	24600	0.20	2640
Foundation	20000	0.33	2000

2.2 Finite Element Model of Dam-Foundation System

The dam-foundation system is investigated using the two-dimensional finite element model shown in Fig. 2. The dynamic effect of the reservoir during the analysis is modeled by the Westergaard approach [14] based on the added mass concept. This finite element model is created using software ANSYS [16].

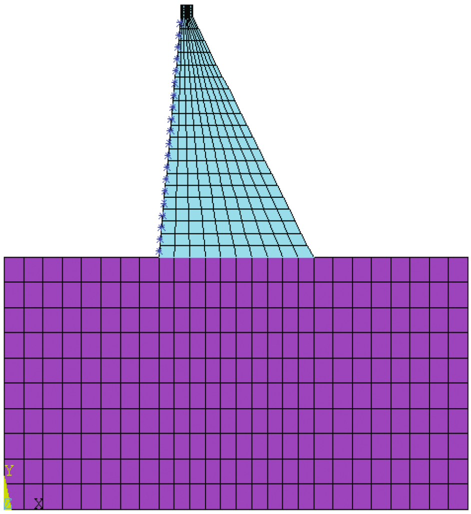

Fig. 2. Finite element discretization of dam-foundation system

A two-dimensional (2D) finite element model with 500 plane solid elements (PLANE 82) is used to model the dam and the foundation. A finite element model with 20 structural masses (Mass21) is used to model the reservoir water. The solid elements used in the analysis have eight nodes and 2 × 2 integration points. Solid element matrices are computed using the Gauss numerical integration technique [17].

3 Numerical Results and Discussion

This study investigates the seismic response of Oued Fodda concrete gravity dam considering barrage-foundation interation. For this purpose, the horizontal component of the 1980 El Asnam earthquake acceleration scaled by factor of 2.5 is utilized in analyses (Fig. 3). In 1980, El Asnam Province has already been shaken by the strong earthquake (M7). Unfortunately, we only have a record of a replica of this earthquake with peak ground acceleration (PGA) 0.132 g. Consequently, we chose the record of replica earthquake with a scaling factor of 2.5 to obtain an earthquake acceleration record with PGA 0.33 g, nearly equal to PGA of record of the strong earthquake (M7) which occurred in 1980. The linear and nonlinear time history analyses are performed using ANSYS [16]. The maximum horizontal displacements in upstream direction and the maximum principal stresses in the dam along its height are presented.

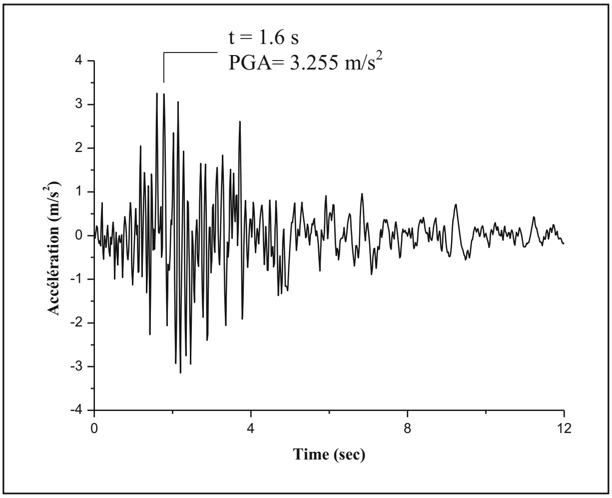

Fig. 3. Time history of horizontal acceleration for 1980 El Asnam earthquake record scaled by factor of 2.5

3.1 Displacements

The Fig. 4 represents the maximum horizontal displacements of dam in upstream direction obtained from linear and nonlinear transient analyses.

The Fig. 5 shows the time history of horizontal displacement at the crest of dam in linear and nonlinear analyses. The maximum horizontal crest displacements are equal to 4.10 and 3.54 cm, respectively, in linear and nonlinear analyses. However, it should be recognized that the use of nonlinear material models at the foundation and dam could increase or decrease the displacements depending on ground motion characteristics, surrounding foundation properties and the dam mechanical properties [18, 19].

3.2 Stresses

The Figs. 6 and 7 represent the principal tensile and compression stress distributions along the dam height.

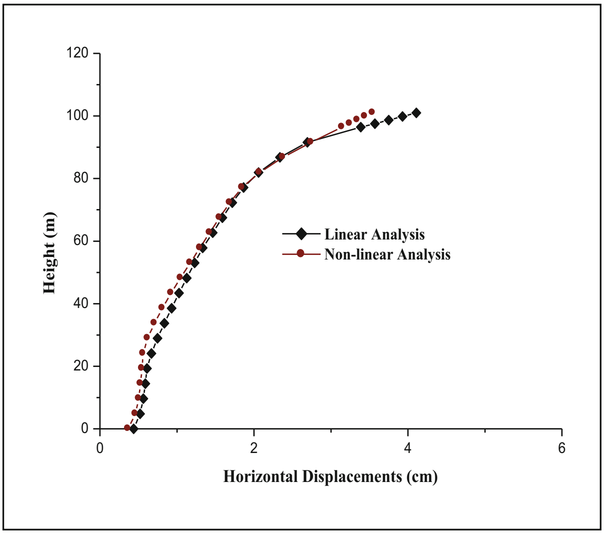

Fig. 4. Maximum horizontal displacements in upstream direction according to linear and nonlinear analyses

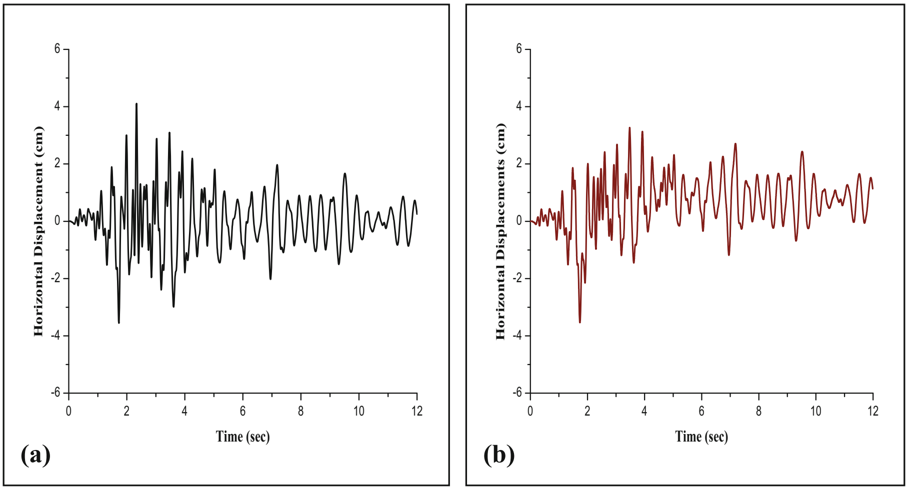

Fig. 5. Time history of horizontal displacement at crest of dam: (a) linear analysis and (b) nonlinear analysis

The maximum values of principal tensile and stresses were observed to be 7683.90 and 2347.09 kN/m^2, respectively, in linear and nonlinear analyses. The maximum values of principal compression stress were observed to be −6376.90 and −2513.83 kN/m^2, respectively, in linear and nonlinear analyses. Therefore, in nonlinear analysis, a decrease of 70 and 60%, respectively, in the magnitude of principal tensile and compression stresses were noticed.

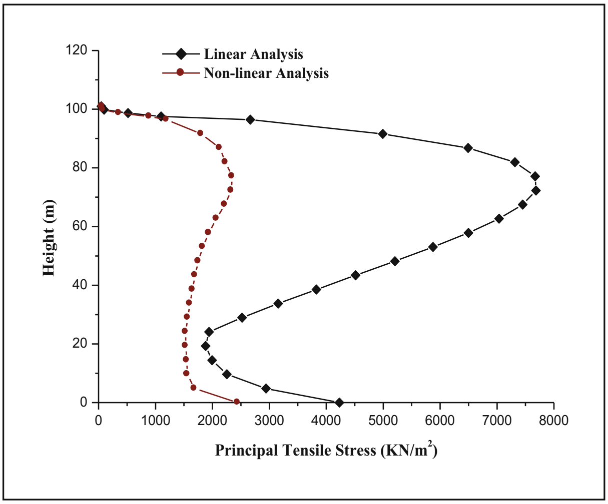

Fig. 6. Maximum principal tensile stresses along dam height according to linear and nonlinear analyses

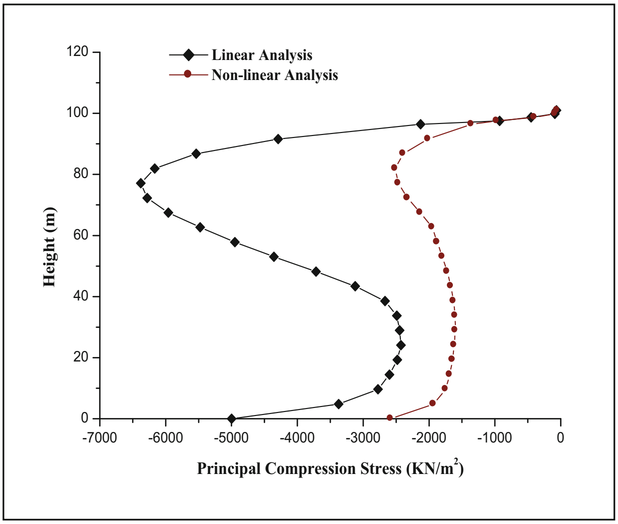

Fig. 7. Maximum principal compression stresses along dam height according to linear and nonlinear analyses.

When comparing linear and nonlinear analyses, a substantial decrease in the distribution of principal tensile and compression stresses due to material nonlinearity effects can be observed from Figs. 6 and 7. Table 2 below shows the maximum principal stress values at heel of the dam using both linear and nonlinear analyses.

It is observed that material nonlinearity of the foundation rock and dam decreases the principal stresses at heel of the dam when compared to the case when foundation

Table 2. Maximum principal stress values at heel of the dam in linear and nonlinear analyses

Principal stresses	Linear analysis	Nonlinear analysis
Principal tensile stress (kN/m^2)	4229.046	2443.51
Principal compression stress (kN/m^2)	−4998.51	−2581.37

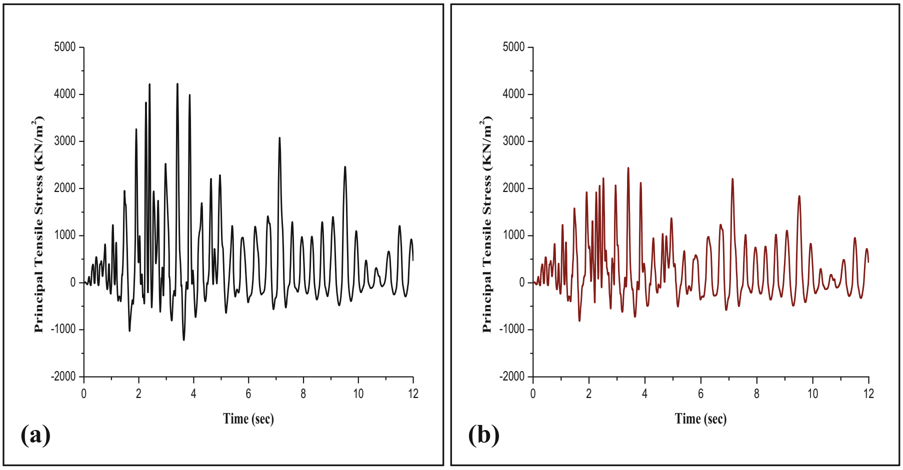

Fig. 8. Time history of principal tensile stress at heel of dam: (a) linear analysis and (b) nonlinear analysis

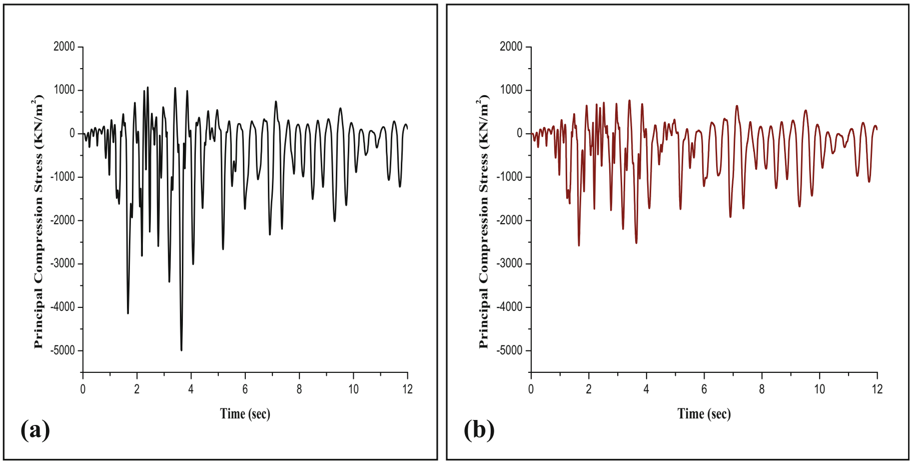

Fig. 9. Time history of principal compressive stress at heel of dam: (a) linear analysis and (b) nonlinear analysis

and dam material are considered to be linear. Therefore, foundation and dam nonlinearity could decrease the stress values in the dam body depending upon the ground motion characteristics [18, 19].

The Figs. 8 and 9 show the time history of principal tensile and compression stresses at heel of dam in linear and non-linear analyses. In linear analysis, the principal tensile and compression stresses at heel are 4229.05 and −4998.51 kN/m^2, respectively, while these reduce to 2443.51 and −2581.37 kN/m^2, respectively, in nonlinear analysis. Therefore, in nonlinear analysis, a decrease of 42 and 48%, respectively, in the magnitude of principal tensile and compression stresses were noticed.

4 Conclusions

This paper presents the non-linear seismic response of concrete gravity dams consedering dam-foundation interaction. For illustrative purpose, the Oued Fodda concrete gravity Dam, located in Chlef (northwestern Algeria), is selected as an example. Linear and nonlinear analyses are performed using ANSYS. The Druker-Prager model is used for dam concrete and foundation rock in nonlinear analysis.

From the numerical results obtained in the study, the following conclusions can be drawn:

1. Linear analysis of the dam shows high tensile stresses at the heel and top of the dam. Therefore, the upper and heel regions of the dam are the most severely stressed zones, hence one may expect the appearance of cracks around these parts.
2. When the material nonlinearity of dam-foundation system is considered, the horizontal displacements and principal stresses decrease compared to the linear case.
3. Nonlinear analysis of dam-fondation system leads to low values of displacement at the crest and stresses at the heel and near the neck region of dam.
4. In nonlinear analysis, the tensile stresses at the heel reduce but no such reduction is observed at the top of the dam. Upper and lower parts of the dam are still susceptible to cracking in this case.

It is clear that the consideration of material nonlinearity of the dam-foundation system affects the response (displacements and stresses) compared to the case when the dam-foundation system is assumed to be linear. However, the foundation and dam nonlinearity may increase or decrease the response parameters depending on ground motion characteristics, surrounding foundation properties and the structure mechanical properties. Thus, it is important to carry out the nonlinear analysis of foundation-dam interaction system to achieve more reliable results of dam behavior.

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