

# EARTHQUAKE BEHAVIOR OF CONCRETE GRAVITY DAMS DURING GROUND MOTIONS

D. Ouzandja <sup>a</sup>, M. Messaad <sup>b</sup>, T. Messaad <sup>c\*</sup>

<sup>a</sup> Laboratory of Materials and Mechanics of Structures (LMMS), University of Msila, Department of Civil Engineering, Msila, Algeria,  
E-mail: [djamel.ouzandja@univ-msila.dz](mailto:djamel.ouzandja@univ-msila.dz)

<sup>b</sup> Laboratoire d'Aménagements Hydrauliques et Environnement (LAHE), University of Biskra, Department of Civil Engineering, Biskra, Algeria, E-mail: [mokhtar.messaad@univ-biskra.dz](mailto:mokhtar.messaad@univ-biskra.dz)

<sup>c\*</sup> University of Tiaret, Department of Mechanical Engineering, Tiaret, Algeria, E-mail: [taieb.messaad@univ-tiaret.dz](mailto:taieb.messaad@univ-tiaret.dz)

Received: 11.02.2023 / Accepted: 24.02.2023 / Revised: 12.03.2023 / Available online: 31.05.2023

DOI: [10.2478/jaes-2023-0013](https://doi.org/10.2478/jaes-2023-0013)

**KEYWORDS:** Concrete Gravity Dam, Earthquake Behavior, Dynamic Dam-Foundation Rock Interaction, Welded Contact, Friction Contact

## ABSTRACT:

The stability evaluation of the dams subjected to seismic excitations is really very complex as the earthquake response of the concrete gravity dam depends upon its connection joints with foundation rock. This study presents the seismic response of concrete gravity dams considering welded contact and friction contact and along dam-foundation rock interface. Friction contact is provided using contact elements. Two-dimensional finite element model of Oued Fodda concrete gravity dam, located in Chlef at the northwestern part of Algeria, is used for this purpose. Nonlinear analyses of dam-foundation rock system are performed using ANSYS software. The reservoir water is modeled as added mass using the Westergaard approach. The Druker-Prager model is employed in the nonlinear analysis for dam concrete. The surface-to-surface contact elements based on the Coulomb's friction law are used to describe the friction. These contact elements use a target surface and a contact surface to form a contact pair. According to this study, when the friction contact is considered in joints, sliding displacement of dam base occurs along the dam-foundation rock interface. The dam sliding along its foundation decreases the deformation response; principal stresses in the dam body and shear force at both the heel and toe of the dam.

## 1. INTRODUCTION

Classic approaches for evaluating the safety of gravity dams were based upon the welded contact that supposes common nodes in the dam-foundation contact interface. Therefore, it results in the same displacement and stress in the associated node situated along dam-foundation interface. However, the concrete dam and foundation rock have two different material properties; their joining presentation should be realized with different nodes at interface zone. This is usually supplied by employing friction contact at the interface which allows the modeling of dam sliding on its foundation due to presence contraction joints at dam-foundation rock interface. Several studies were carried out on the effect of conditions of contact in the interface between the concrete gravity dam and its foundation rock (Leger and Katsouli 1989; Chavez and Fenves 1995; Azm and plautre 2002; Viladkar and Al-Assady 2012). Hall et al. (1991) investigated the sliding failure of pine Flat dam during earthquake. The study illustrated that there is a permanent deformation at the base due to dam sliding. Other investigators studied the seismic sliding at the concrete gravity dam base using analytical methods (Chopra and Zhang 1991) and empirical laws (Danay and Adeghe 1993). Arabshahi and Lotfi (2008) used interface elements to present sliding at dam base. The results showed that sliding reduces seismic response of the dam.

Ouzandja and Tiliouine (2016) studied influence of friction coefficient variation at dam-foundation rock on earthquake behavior of Oued Fodda dam. The work demonstrates that the use of contact elements, which represent the friction coefficient, affects the earthquake performance of the dam. Impact of contact conditions at the dam-foundation interface on the seismic behavior of concrete gravity dams was investigated by Ouzandja (2016). Using hard and soft contact models, Wang et al. (2017) investigated the effects of contraction joints on the seismic damage behavior of Guandi gravity dam. The results showed that the contraction joints significantly influence the risk of dam fracture. Ouzandja et al. (2017) modeled the dam-reservoir interaction interface using interface elements in order to study the impact of dynamic fluid-structure interaction on response of gravity dams. Messaad et al. (2021) and Ouzandja et al. (2023) presented, respectively, the influence of foundation rock flexibility and materially dam-foundation system nonlinearity on seismic response of concrete gravity dams using welded contact model. This paper shows the effect of contact friction along the dam-foundation rock interface on the earthquake response of concrete gravity dams. The Oued Fodda dam is taken into account in the numerical analyses. For this purpose, two-dimensional finite element model of dam-foundation rock system is employed.

\* Corresponding author: Taieb Messaad, E-mail: [taieb.messaad@univ-tiaret.dz](mailto:taieb.messaad@univ-tiaret.dz)

The hydrodynamic pressure of the reservoir water is modeled utilizing the added mass concept (Westergaard 1933). In the nonlinear analysis, the Drucker-Prager model (Drucker and Prager 1952) is used for dam concrete. Welded and friction contact are considered in the joints along dam-foundation rock interface. Surface-to-surface contact elements based on the Coulomb's friction law are used to describe friction using ANSYS software (2013).

## 2. SURFACE-TO-SURFACE CONTACT ELEMENTS

To model a contact problem, we first must identify the parts to be analyzed for their possible interaction. If one of the interactions is at a point, the corresponding component of our model is a node. If one of the interactions is at a surface, the corresponding component of our model is an element: either a beam, shell, or solid element. The finite element model recognizes possible contact pairs by the presence of specific contact elements. These contact elements are overlaid on the parts of the model that are being analyzed for interaction. There are various contact elements. The surface-to-surface contact elements based on the Coulomb's friction law are used to describe the friction. These contact elements use a target surface and a contact surface to form a contact pair (Figure 1).

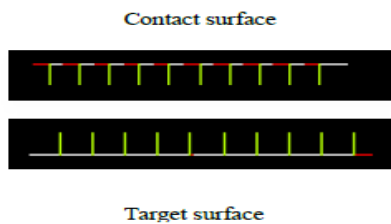


Figure 1. Target and contact surface elements

## 3. OUED FODDA CONCRETE GRAVITY DAM-FOUNDATION SYSTEM

### 3.1 Material properties

The selected dam in this study is located approximately 20 km of Oued Fodda (Chlef), in northwestern Algeria, 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<sup>3</sup>. 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 geometry of the dam-foundation rock system is shown in Figure 2.

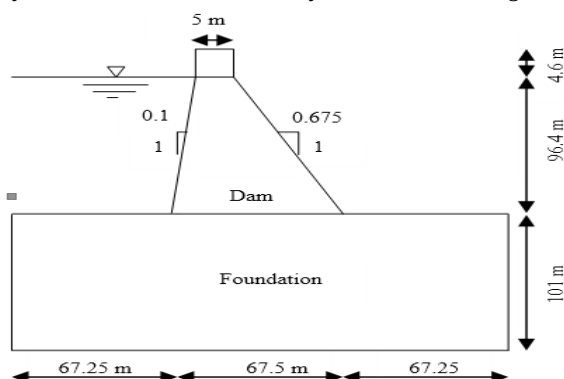


Figure 2. Geometry of dam-foundation rock system

The material properties for both the concrete gravity dam and foundation rock are reported in Table 1 below. The cohesion and the angle of internal friction of dam concrete requis in nonlinear response according to the Drucker-Prager model (Drucker and Prager 1952) are taken as 2.50 Mpa and 35°, respectively.

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

Table 1. Material properties of Oued Fodda gravity dam

### 3.2 Finite element modeling of dam-foundation rock system

This study considers two-dimensional finite element model of Oued Fodda concrete gravity dam (Figure 3). In this model, if the height of the dam is indicated as "H", the foundation rock is extended as "H" in the gravity direction. Besides, foundation rock is extended as "2H" in the width direction. The effect of hydrodynamic pressure is incorporated in the analysis by the added mass concept proposed by Westergaard (1933). The solid finite elements (Plane 82) are used to model the dam and the foundation rock; the structural mass finite elements (Mass 21) are used to model reservoir water. In the finite element model, dam body has 240, and foundation rock has 260 solid finite elements. Besides, reservoir water has 20 structural mass finite elements. 10 contact-target element pairs are employed to model the joints along dam-foundation rock interface. The surface-to-surface contact elements based on the Coulomb's friction law are used to describe the friction. These contact elements use a target surface (Targe169) and a contact surface (Conta172) to form a contact pair.

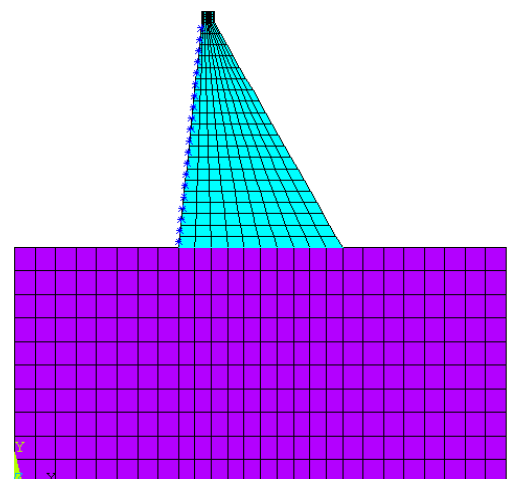


Figure 3. Finite element modeling of dam-foundation rock system

#### 4. NONLINEAR SEISMIC RESPONSE OF OUED FODDA DAM

This study investigates the seismic response of Oued Fodda concrete gravity dam considering base sliding. For this purpose, the 2003 boumerdes earthquake horizontal component with peak ground acceleration (PGA) 0.34 g (Figure 4) is utilized in analyses. Nonlinear time-history analyses are performed using ANSYS (2013). The horizontal displacements and principal stress components in dam body are presented in both welded contact model and friction contact model.

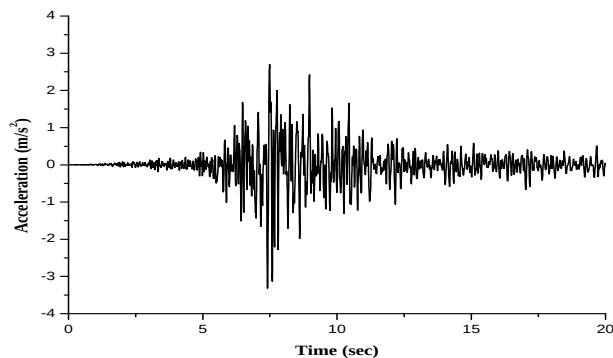


Figure 4. Time history of horizontal component of the 2003 boumerdes earthquake

##### 4.1 Displacements

The envelopes of maximum horizontal displacement of the dam are presented in Figure 5 for welded and friction contact models. Horizontal displacements obtained from friction contact model are slightly smaller than ones obtained from welded contact model. It can be seen in Figure 5(b) that dam can slide along its foundation having the motion of rigid body in its response. When friction contact is applied at dam-foundation rock interface, sliding phenomenon of dam base is occurred, which is resulted from shear failure.

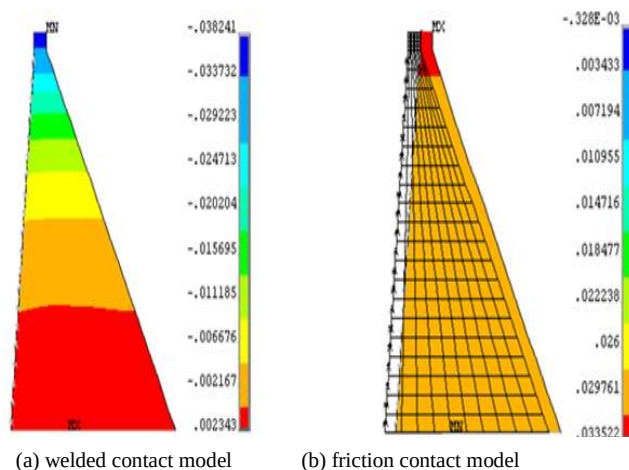


Figure 5. Maximum horizontal displacement envelopes of the dam (Unit: m)

dam crest for both two models. The horizontal displacement at the crest decreases from 3.82 cm for welded contact model to 3.35 cm for friction contact model. On the other hand, the time history of sliding displacement at the dam heel is depicted in Figure 7. The sliding displacement at the heel is negligible (0.32 cm) for welded contact model, while this is 3.23 cm for friction contact model due to existence of contraction joints along dam-foundation rock interface decreasing the contact zone rigidity.

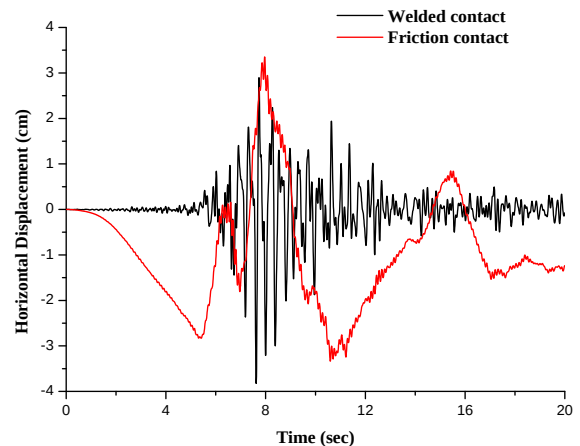


Figure 6. Time history of horizontal displacement at dam crest for welded and friction contact models

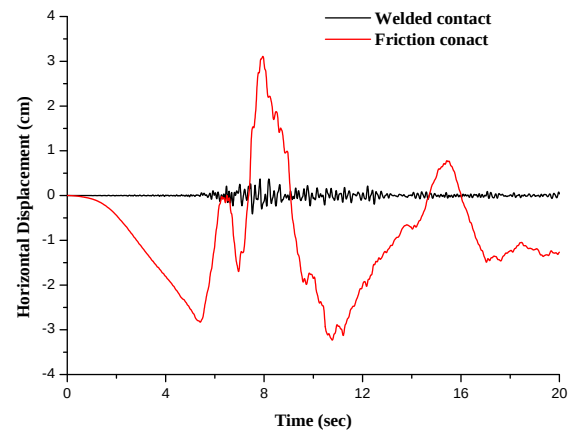


Figure 7. Time history of sliding displacement at dam heel for welded and friction contact models

##### 4.2 Stresses

The envelopes of maximum principal stresses of the dam are shown in Figs. 8 and 9 for welded and friction contact models.

As can be seen, principal tensile and compressive stresses obtained from friction contact model are smaller than ones obtained from welded contact model.

Figure 6 represents the time history of horizontal displacement at the

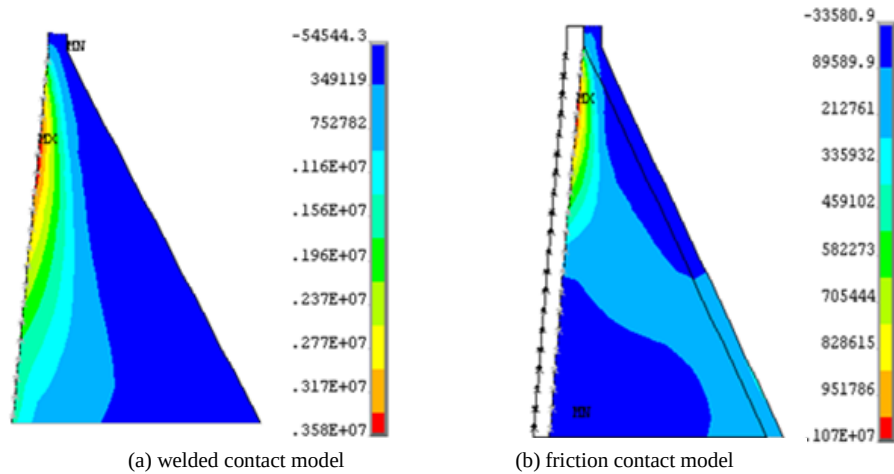


Figure 8. Maximum principal tensile stress envelopes of the dam (Unit: Pa)

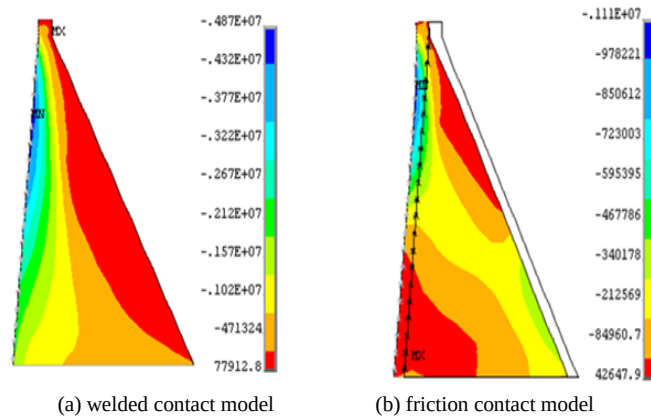


Figure 9. Maximum principal compressive stress envelopes of the dam (Unit: Pa)

Figure 10 illustrates the time history of principal stresses at the dam heel for both two models. Principal tensile and compressive stresses reduce

from 2742.73 and -2828.33  $\text{KN/m}^2$  for welded contact model to 505.08 and -566.04  $\text{KN/m}^2$  for friction contact model.

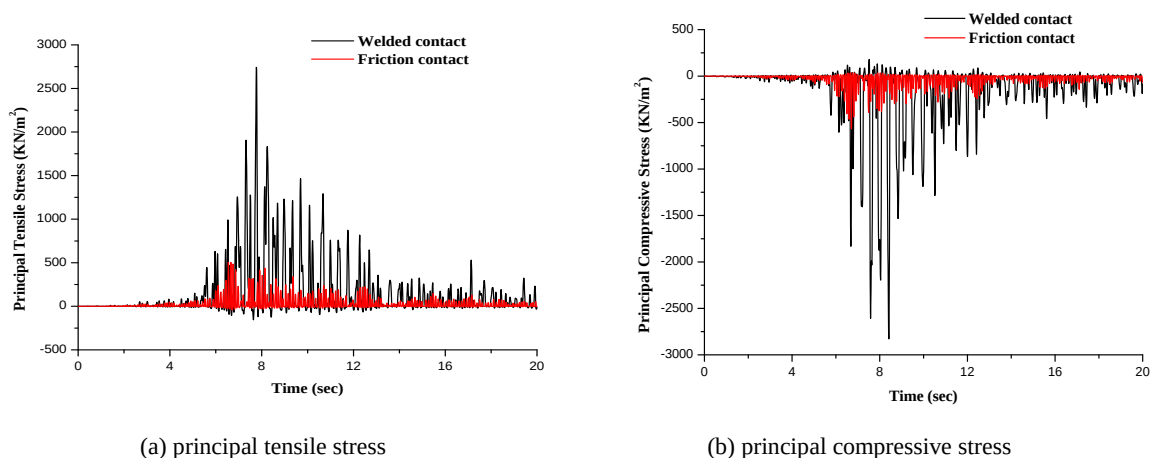


Figure 10. Time history of principal stresses at dam heel (Unit: Pa)

The time history of shear stress at the heel and toe of the dam is presented in Figures 11 and 12 for both two models. Shear stress at the heel and toe is 328.28 and 1044.92  $\text{KN/m}^2$ , respectively, for welded contact model, while this reduces to 70.94 and 159.92  $\text{KN/m}^2$ , respectively, for friction

contact model. Generally, friction contact, which allows dam sliding at dam-foundation rock, decreases significantly the principal stresses in the dam and shear force at the heel and toe of the dam.

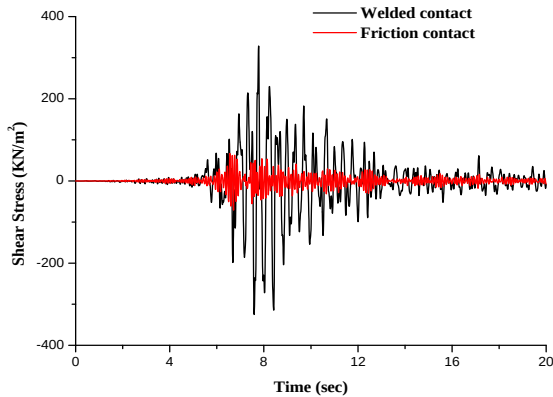


Figure 11. Time history of shear stress at dam heel

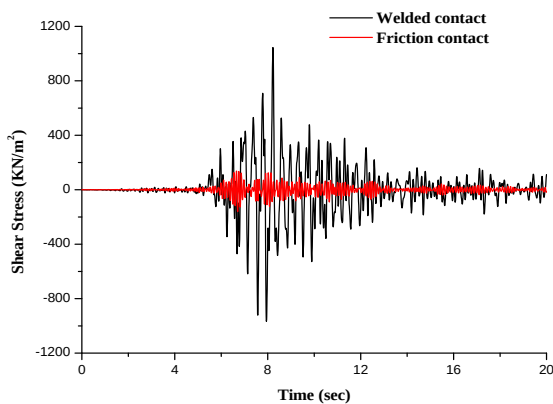


Fig. 12. Time history of shear stress at dam toe

## 5. CONCLUSIONS

This work presents the seismic response analysis of concrete gravity dams considering base sliding.

The Oued Fodda dam is taken in the numerical analyses. The Druker-Prager model is employed for dam concrete in nonlinear response. Welded and friction contact are considered in the joints along dam-foundation rock interface. Surface-to-surface contact elements based on the Coulomb's friction law are used to describe friction.

The results of analyses show a reduction in the deformation response, principal stresses and shear force at the heel and toe of the dam when the dam is able to slide along dam- foundation rock interface.

The dam sliding can be verified by providing the maximum friction stress at the dam base. Therefore, it is noted that the dam comports much better if it is permitted to slide moderately along its foundation as sliding displacement decreases the stresses in the dam body.

## References

- ANSYS (2013) Theory user's manual. Swanson Analysis Systems Inc., Houston, USA.
- Arabshahi, H., V. Lotfi (2008) Earthquake response of concrete gravity dams including dam-foundation interface nonlinearities. *Eng. Struct.* 30(11): 3065-3073.
- Azmi, M., P. Paultre (2002) Three-dimensional analysis of concrete dams including contraction joint nonlinearity. *Engineering Structures* 24: 757-771.
- Chopra, A.K., L. Zhang (1991) Earthquake-induced base sliding of concrete gravity dams. *J. Struct. Eng.* 117(12): 3698-3719.
- Chavez, J.W., G.L. Fenves (1995) Earthquake analysis of concrete gravity dams including base sliding. *J. Struct. Eng.* ASCE 121(5): 865-875.
- Danay, A., L.N. Adeghe (1993) Seismic induced slip of concrete gravity dams. *J. Struct. Eng.* 119(1): 108-129.
- Drucker, D.C., W. Prager (1952) Soil mechanics and plastic analysis of limit design. *Q. Appl. Math.* 10(2):157-165.
- Hall, J.F., M.J. Dowling, B. El-Aidi (1991) Defensive design of concrete gravity dams. Report no. EERL 91-02. Earthquake Engineering Research Center, University of California, Berkeley, USA.
- Leger, P., M. Katsouli (1989) Seismic stability of concrete gravity dams. *Earthq. Eng. Struct. Dyn.* 18(6): 889-902.
- Messaad, M., Bourezane, M., Latrache, M., Berrabah, A. T., & Ouzendja, D. (2021). Three-dimensional seismic analysis of concrete gravity dams considering foundation flexibility. *Mechanics and Mechanical Engineering*, 25(1), 88-98.
- Ouzandja, D., B. Tiliouine (2015). Effects of dam-foundation contact conditions on seismic performance of concrete gravity dams. *Arab. J. Sci. Eng.* 40(11): 3047-3056.
- Ouzandja, D. (2016). Effets des conditions de contact à l'interface barrage-fondation sur la performance sismique des barrages-poids en béton (Doctoral dissertation, Alger, Ecole Nationale Polytechnique).
- Ouzandja, D., Tiliouine, B., Belharizi, M. and Kadri, M. (2017), "Three-dimensional nonlinear seismic response of Oued Fodda concrete gravity dam considering contact elements at dam-reservoir interaction interface", *Asian Journal of Civil Engineering (bhrc)*, 18(6), 977-992.
- Ouzandja, D., Messaad, M., Berrabah, A. T., & Belhrizi, M. (2023). Impact of material nonlinearity of dam-foundation rock system on seismic performance of concrete gravity dams. *Journal of Theoretical and Applied Mechanics*, 49-63.

Viladkar, M.N., A.M.S. Al-Assady (2012) Nonlinear analysis of pine flat dam including base sliding and separation. Proceedings of the 15th World Conference on Earthquake Engineering (15 WCEE), Lisbon, Portugal.

Wang, G., Wang, Y., Lu, W., Yu, M. and Wang, C. (2017), "Deterministic 3D seismic damage analysis of Guandi concrete gravity dam: A case study", Engineering Structures 148, 263-276; <https://doi.org/10.1016/j.engstruct.2017.06.060>

Westergaard, H.M. (1933) Water pressures on dams during earthquake. Trans. ASCE 98: 418-433.