DYNAMIC BEHAVIOR ANALYSIS OF CONCRETE GRAVITY DAMS
ANALYSE DU COMPORTEMENT DYNAMIQUE DES BARRAGES-POIDS EN BÉTON

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ABSTRACT
The stability evaluation of the dams subjected to seismic loads is really very complex. One of the most important problems in evaluation of dynamic behavior of concrete gravity dams is soil-structure interaction phenomenon. In this paper, we study the effect of soil-structure interaction (SSI) on dynamic behavior of concrete gravity dams. For this purpose, two finite element models using ANSYS software are created. The first model represents the dam alone fixed at its base (dam without SSI). The second model represents the dam-foundation rock system (dam with SSI). Oued Fodda concrete gravity dam, located in the north west of Algeria, is chosen in the present study. Reservoir water is modeled using Westergaard approach. According to finite element analyses, numerical results show that taking into account of interaction soil-structure in the model increase more stresses and displacements in the dam body. Therefore, the dynamic soil-structure interaction phenomenon plays an important role in accurately estimating the concrete gravity dam behavior.
Keywords: Concrete Gravity dams, Soil-Structure Interaction, Dynamic Behavior, Finite Element Method

RÉSUMÉ
L'évaluation de la stabilité des barrages soumis à des charges sismiques est très complexe. L'un des problèmes les plus importants dans l'évaluation du comportement dynamique des barrage-poids en béton est le phénomène d'interaction sol-structure. Dans ce travail, nous étudions l'effet de l'interaction sol-structure (ISS) sur le comportement dynamique des barrage-poids en béton. Pour cela, deux modèles d'éléments finis en utilisant le code de calcul ANSYS sont créés. Le premier modèle représente le barrage seul fixe à sa base (barrage sans ISS). Le deuxième modèle représente le système barrage-fondation (barrage avec ISS). Le barrage-poids en béton de Oued Fodda, situé au nord-ouest de l'Algérie, est choisi dans la présente étude. L'eau du réservoir est modélisée en utilisant l'approche de Westergaard. Selon les analyses par éléments finis, les résultats numériques montrent que la prise en compte de l'interaction sol-structure dans le modèle augmente les contraintes et les déplacements dans le corps du barrage. Par conséquent, le phénomène d'interaction dynamique sol-structure joue un rôle important dans l'estimation précise du comportement du barrage-poids en béton.
Mots-clés: barrage-poids en béton, interaction sol-structure, comportement dynamique, méthode des éléments finis

1. INTRODUCTION

Dams have contributed to the development of civilization for a long time. They will continue to keep their importance in satisfying the ever increasing demand for power,
irrigation and drinking water, the protection of man, property and environment from catastrophic floods, and in regulating the flow of rivers.
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 [1-7]. Hence it becomes imperative to consider the effect of soil-structure interaction for heavy structures such as concrete gravity dams.
Wolf [8] first presented the direct method of soil-structure interaction analysis. Using this method the soil region near the structure along with the structure is modeled directly and the idealized soil-structure system was analyzed in a single step. An excellent amount of work on dam-reservoir-foundation interaction in the frequency domain has been carried out by Chopra et al. [9]. However, frequency domain based methods are difficult to understand compared to the time domain based methods. Also, incorporation of nonlinear material behavior will be a prohibitive task for frequency domain based methods. The time domain based methods do not suffer from such limitations. Rizos and Wang [10] developed a partitioned method for soil-structure interaction analysis in the time domain through a staggered solution method using both FEM and BEM.
A time domain transient analysis of a concrete gravity dam and its foundation has been carried out in a coupled manner using finite element technique and the effect of soil-structure Interaction (SSI) has been incorporated using a simplified direct method [11]. Ouzandja and Tiliouine [12] presented the effects dam-foundation contact conditions on seismic performance of concrete gravity dams.
This study investigates the effect of dynamic soil-structure interaction (SSI) on dynamic behavior of concrete gravity dams. Oued Fodda concrete gravity dam, located in Chlef, Algeria, is chosen in this study.

For this purpose, two studied finite element models: dam alone without ISS and dam with ISS were employed in analyses using the ANSYS software [13]. The effect of hydrodynamic pressure is considered according to added mass technique originally proposed by Westergaard [14].

2. FINITE ELEMENT MODELS OF SYSTEM DAM-FOUNDATION ROCK

The concrete gravity dam Oued Fodda is located in the north west of Algeria. The geometry of the Oued Fodda dam is illustrated in the Fig. 1. The dam-foundation system is investigated using two finite element models. The first model represents the dam alone neglecting the soil-structure interaction effect and assuming that the structure is fixed at its base (Fig. 2). The second model represents the dam-foundation interaction system (Fig. 3). The effect of hydrodynamic pressure is considered according to added mass technique originally proposed by Westergaard [14]. These finite elements models are created using software ANSYS [13].

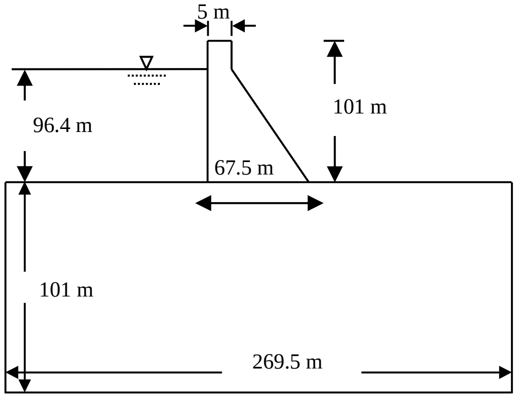


Fig. 1. Dam-foundation rock system.
Système barrage-fondation rocheuse.

A two-dimensional (2D) finite element model with 937 nodes and 308 plane solid elements (PLANE 82) is used to model Oued Fodda dam alone (Fig. 2). A two-dimensional (2D) finite element model with 4795 nodes and 1532 plane solid elements (PLANE 82) is used to model dam-foundation rock system (Fig. 3).

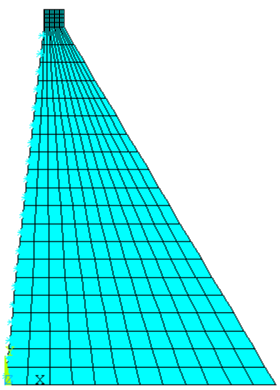


Fig. 2. Finite element model of dam alone.
Modèle d'éléments finis du barrage seul.

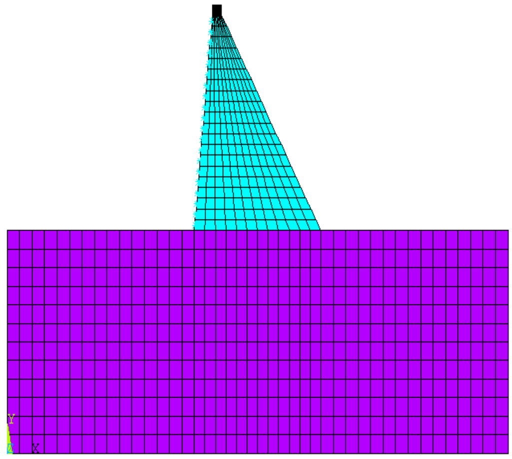


Fig. 3. Finite element model of dam-foundation rock system.
Modèle d'éléments finis du système barrage-fondation.

The material properties of Oued Fodda dam including its foundation are reported in Table 1 below.

Table 1: Material properties of the dam and foundation rock.
Propriétés des matériaux du barrage et de la fondation rocheuse.

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

3. DYNAMIC ANALYSIS AND RESULTS

3. 1. MODAL ANALYSIS

The five lowest natural frequencies of Oued Fodda dam without SSI and Oued Fodda dam with SSI are presented in Table 2.

Table 2: First five natural frequencies of the dam without SSI and dam with SSI.
Cinq premières fréquences naturelles du barrage sans ISS et du barrage avec ISS.

Mode	Frequency (Hz)	
	Dam alone	Dam-foundation system
1	3.286	2.561
2	7.882	5.610
3	10.027	6.106
4	13.670	8.134
5	20.273	10.567

Table 2 shows that frequencies are very important in model without SSI; these vary between 3.286 Hz and 20.273 Hz, which implies that the dam is very rigid. It is obvious that the dam is fixed at its base.

3.2. DYNAMIC RESPONSE OF OUED FODDA DAM

The dynamic behavior of Oued Fodda concrete gravity dam was evaluated using horizontal component of 2003 boumerdes earthquake during 20 s. The peak ground acceleration (PGA) of the horizontal component of the earthquake acceleration is 0.34 g (Fig. 4). Time history analysis is performed using ANSYS software [13]. In the numerical analyses, the maximum horizontal displacements in upstream direction and the maximum horizontal, vertical and shear stresses in the dam along its height are presented for models without and with SSI.

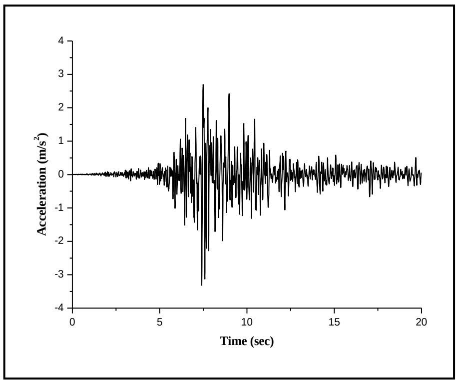


Fig. 4. Acceleration records of 2003 boumerdes earthquake.
Enregistrement de l'accélération du séisme de Boumerdes (2003).

3.2.1. HORIZONTAL DISPLACEMENTS

The Fig. 5 represents the maximum horizontal displacements of dam in upstream direction obtained from transient analyses for model without SSI and model with SSI.

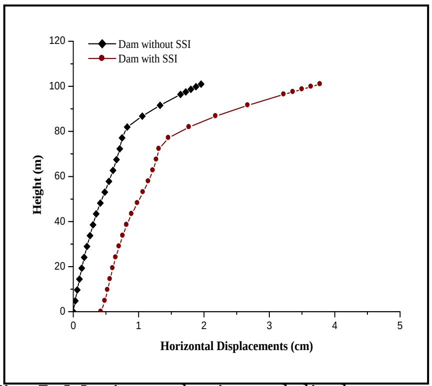


Fig. 5. Maximum horizontal displacements in upstream direction for model without SSI and model with SSI.
Déplacements horizontaux maximaux en direction amont pour le modèle sans ISS et modèle avec ISS.

The time history of horizontal displacement at the crest of dam is presented in Fig. 6 for both models without and with SSI. The horizontal displacement at crest increases from 1.96 cm for dam without SSI to 3.78 cm for dam with SSI. This indicates that there is about 93% rise in the magnitude of the crest displacement in model with ISS. The Figs. 7 and 8 show the maximum horizontal displacement contours at the crest of dam for model without SSI and model with SSI.

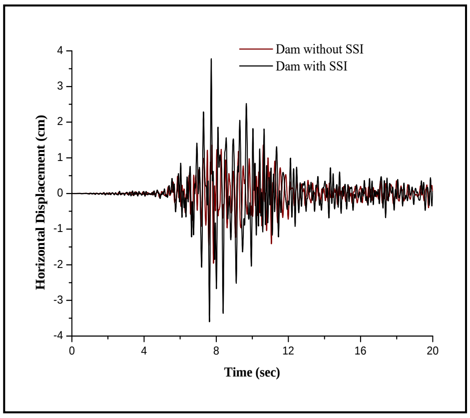


Fig. 6. Time history of horizontal displacement at crest of dam for model without SSI and model with SSI.
Déplacement horizontal en fonction du temps à la crête du barrage pour le modèle sans ISS et modèle avec ISS.

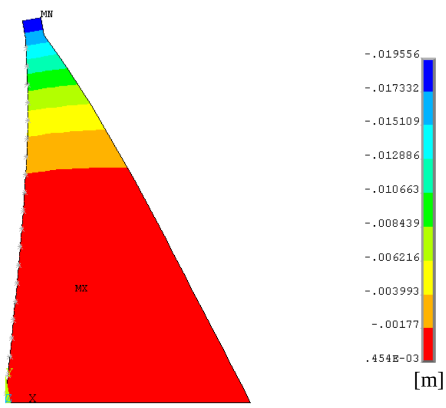
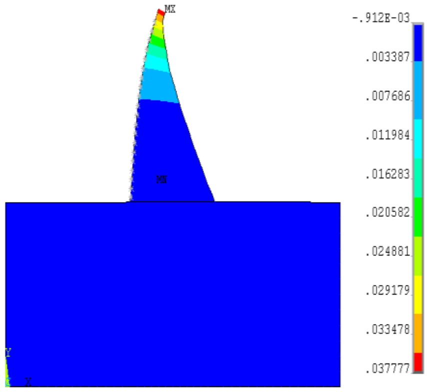


Fig.7. Maximum horizontal displacement contours of dam for model without SSI.
Contours du déplacement horizontal maximal du barrage pour le modèle sans ISS.



[m]

Fig.8. Maximum horizontal displacement contours of dam for model with SSI.
Contours du déplacement horizontal maximal du barrage pour le modèle avec ISS.

3.2.2. STRESSES

The Figs. 9, 10 and 11 show the horizontal and vertical as well as shear stress distributions along the dam height for both models without and with SSI.

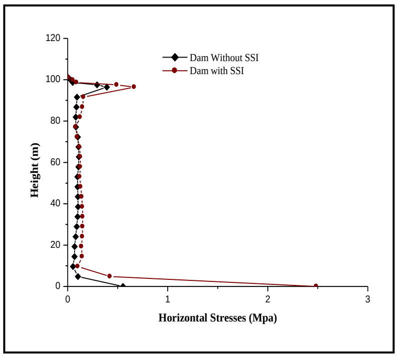


Fig. 9. Distribution of horizontal stresses along dam height for model without SSI and model with SSI.
Distribution des contraintes horizontales le long de la hauteur du barrage pour le modèle sans ISS et modèle avec ISS.

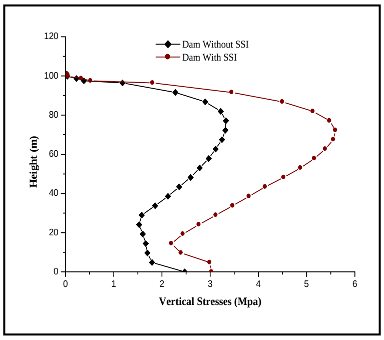


Fig. 10. Distribution of vertical stresses along dam height for model without SSI and model with SSI.

Distribution des contraintes verticales le long de la hauteur du barrage pour le modèle sans ISS et modèle avec ISS.

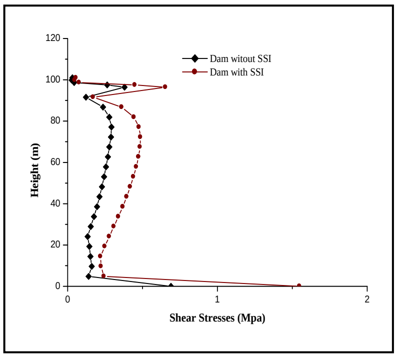


Fig. 11. Distribution of shear stresses along dam height for model without SSI and model with SSI.
Distribution des contraintes de cisaillement le long de la hauteur du barrage pour le modèle sans ISS et modèle avec ISS.

The maximum values of horizontal, vertical and shear stresses were noticed to be 0.29 and 3.33 and 0.38 Mpa, respectively, for model without SSI. The maximum values of horizontal, vertical and shear stresses were noticed to be 0.66, 5.60 and 0.65 Mpa, respectively, for model with SSI. Therefore, for model with SSI, an indecrease of 128, 68 and 71 %, respectively, in the magnitude of horizontal, vertical and shear stresses.
Table 3 below shows the maximum horizontal, vertical and shear stress values at heel of the dam for both models without and with SSI.

Table 3: Maximum stress values at heel of the dam for models without and with SSI.
Valeurs de contraintes maximales au pied du barrage pour le modèle sans ISS et modèle avec ISS.

4. CONCLUSION

This paper presents the effect of soil-structure interaction phenomenon on dynamic behavior of concrete gravity dams. For this purpose, two finite element models: dam alone without SSI and dam with SSI are conducted to simulate the behavior of concrete gravity dams. The Oued Fodda concrete gravity dam is selected as an example in this study.
From the numerical results obtained in the study, the following conclusions can be drawn:

Stresses	Model without SSI	Model with SSI
Horizontal stress (Mpa)	0.55	2.49
Vertical stress (Mpa)	2.47	3.03
Shear stress (Mpa)	0.69	1.55

- The numerical results show that the displacements and stresses increase in the dam body for model with SSI compared to model without SSI.
- Dynamic analysis of the dam show high stresses at the heel as well as the top of the dam for both models without and with SSI.
- It is also observed in model with SSI that 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.
- When the soil-structure interaction phenomenon is taken into account in the analysis, the shear force increases in the base, which can lead to instability of the dam.

It is obvious that taking into account of soil-structure interaction phenomenon in the dynamic behavior analysis of concrete gravity dams affects greatly the response parameters. Hence, it is becomes imperative to carry out the soil-structure interaction analysis for massive structures such as concrete gravity dams.

REFERENCES

[1] Leger, P. and Boughoufalah, M. Earthquake input mechanisms for time domain analysis of dam-foundation systems. Eng. Struct., 11, 37-46 (1989).
[2] Bayraktar, A., Hancer, E. and Akkose, M. Influence of base-rock characteristics on the stochastic dynamic response of dam-reservoir-foundation systems. J. Engineering Structures, 27: 1498-1508 (2005).
[3] Moussaoui, S.E. and Tiliouine, B. Analyse du comportement dynamique des barrages poids compte tenu de l'interaction fluide-sol-structures. In 1st International Conference on
[4] Sustainable Built Environment Infrastructures in Developing Countries, ENSET, Oran, (Algeria), October 12-14, 2009.
[5] Saleh, S. and Madabhushi, S. P. G. Response of concrete dams on rigid and soil foundations under earthquake loading. Earthquake Tsunami, 4, No.3, 251-268 (2010).
[6] Saouma, V., Miura, F., Lebon, G. and Yagome, Y. A simplified 3D model for soil-structure interaction with radiation damping and free field input. Bull. Earthquake Eng., 9, No.5, 1387-1402 (2011).
[7] Ouzandja, D. and Tiliouine, B. Analyse de la réponse sismique des barrages-poids en béton compte tenu de la flexibilité de la fondation. In: 1st International Seminar: Risks and Civil Engineering, Batna, Algeria, 2012.
[8] Hariri-Ardebili, M.A. and Mirzabozorg, H. A comparative study of the seismic stability of coupled arch dam-foundation-reservoir systems using infinite elements and viscous boundary models. International Journal of Structural Stability and Dynamic 13(6), 1350032-1--350032-24 (2013).
[9] Wolf, J.P. Dynamic soil-structure interaction, Englewood Cliffs, NJ: Prentice Hall (1985).
[10] Chopra, A. K. and Chakrabarti, P. Earthquake analysis of concrete gravity dams including dam-water-foundation rock interaction. Earthquake Eng. Struct. Dynam., 9, 363-383 (1981).
[11] Rizos, D.C., & Wang, Z. Coupled BEM-FEM solutions for direct time domain soil-structure interaction analysis", Engineering Analysis with Boundary Elements, 26, 877-888 (2002).
[12] Burman, A., Nayak, P., Agrawal, P. and Maity, D. Coupled gravity dam-foundation analysis using a simplified direct method of soil-structure interaction. Soil Dynam. Earthquake Eng., 34, 62-68 (2012).
[13] Ouzandja, D. and Tiliouine, B. Effects of dam-foundation contact conditions on Seismic Performance of Concrete Gravity Dams. Arabian Journal for Science and Engineering, Vol. 40(11), pp 3047-3056 (2015).
[14] ANSYS. Theory user's manual. Swanson Analysis Systems Inc., Houston, PA, USA (2009).
[15] Westergaard, H.M. Water pressures on dams during earthquake. Trans. ASCE 98, 418-433 (1933).