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Seismic analysis of Souk Tlata dam behaviour using finite element simulation

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Abstract. In this study, earthquake resistance of Souk Tlata earth dam was examined. It corresponds to a preliminary investigation of the behaviour of the dam under earthquake loading with a dominant frequency close to the fundamental frequency of the dam. The dam was modeled with plane-strain finite elements using Plaxis-2D program. The behaviour of both the fill and core of the dam is described using the simple non associated Mohr-Coulomb criterion. The development of the safety factors as a function of the displacement of the dam crest dam reveals that the static stability of the dam under conditions of drawdown is not assured. Dynamic analyses are conducted under a real earthquake motion, which corresponds to the main shock of May 21, 2003 in Algeria. The results show that the seismic loading, with peak acceleration exceeding 0.10g, induces significant settlement at the crest of the dam and substantial displacement in the upper part of the rip-rap in the upstream side.

Key words: Earth dam, finite element analysis, safety factor, earthquake loading, settlement at crest.

1. Introduction

Earth or rockfill dams that predominate for some 65 % of dams are the archetype of embankment dams (ICOLD, 2019). Their resistance is provided by natural soil-type materials available nearby. The design and construction of these structures have evolved significantly over the past century, and has gone from a relatively simple construction of homogeneous dikes or embankment dams composed of two zones at the beginning of the 20th century, to extremely complex earth or rockfill dams. The height of theses dams is continually increasing also, with many dams being more than 200 m high and even reaching 300 m like Nurek dam (300 m) and Rogun dam (335 m) in Tajikistan(ICOLD, 2019). Many of them are located in areas with a number of large-scale, high-intensity active faults and have been damaged during strong earthquakes and even broken in some serious cases. Ambraseys (1960) reviewed 58 dams damaged in 24 earthquakes and suggested that inertial forces and pore-pressure had the greatest effect on the structure. Wood (1973) showed that when the frequency at which the seismic power of the input motions approaches the fundamental frequency of the unrestrained backfill, dynamic amplification becomes an important factor, which is not considered in engineering approaches that assess the embankment dam stability. Seed et al. (1978) and Seed (1979) reported that the seismic performance of embankment dams has been good in general. They noted that well-built compacted embankment dam can withstand moderate earthquake shaking, with peak acceleration of 0.2 g and more with no detrimental effects. Harder et al. (1998) summarized more than 20 case histories of earth and rockfill dams experienced earthquakes and presented the relationship of peak crest accelerations against peak ground accelerations. Youd and Idriss, (2001), Wang (2007), Chen et al. (2009), Holzer et al. (2010), Huang and Jiang (2010), Cao et al. (2011), Hou et al. (2011) and Liu et al. (2016) have shown that medium–strong earthquakes (Mw 5.5–6.5) will not cause fissures in earth dams, but do cause sand liquefaction over large areas. Dakoulas (2012) reported that the seismic response of an earth or rockfill dam depends on a large number of factors, such as the quality of rockfill compaction, the dam geometry, the narrowness of the canyon, the irregularity of the abutments, the flexibility of the canyon rock, the ground motion intensity and its frequency characteristics, spatial variability of the seismic motion. Internal erosion and seepage problems increased leakage through cracks resulting from differential settlements and different dynamic responses of various parts of the dam following the earthquake. Shear failure of the dam caused by the movement of a fault crossing the foundation is also indicated. Only settlements of the crest and landslides may be computed. For internal erosion, a modeling of the phenomena is not easy because of the random mechanisms of particle flow and transport. Yu et al. (2012) summarized 43 case histories and 18 numerical analyses of earth and rockfill dam behaviour during earthquake, focusing on the characteristics of seismic response and found that the narrowness of canyon, seismic motion input, angle of incidence, shear modulus of rockfill, and dam height have moderate effects on the value of the peak crest acceleration. In addition, they concluded that both case histories and numerical analyses show that seismic measures for high embankment dams should focus on the mid-top area of the dam. Chen et al. (2014) analyzed a total of 670 earth dams damaged by the Wenchuan earthquake and found that fissures in the dams were one of the most important causes of damage. Kong et al. (2018) considered relative settlement ratios of 0.4%, 0.7%, and 1% of the dam crest as the assessment limitation and analyzed the fragility when this dam exhibited minor, moderate and severe failure.

The paper presents a numerical study of the seismic behaviour of Souk Tlata earth dam using a 2-D finite element modeling. It will mainly focus on the seismic response of the dam under the main shock of May 21, 2003 in Algeria with dominant frequency close to the fundamental frequency of the dam and with a peak acceleration exceeding the peak accelerations estimated for the dam project.

To conduct the analyses within the framework of plasticity, the behaviour of both the fill and core of the dam is described using the simple non associated Mohr-Coulomb criterion. The static analysis is conducted, prior to cyclic loading in the dam body, for various stages including end of construction, impounding and rapid drawdown.
The induced displacement under seismic loading is computed for the evaluation of the stability of the dam since it is dependent on the geometric and mechanical properties of the dam as well as the frequency and amplitude of the input loading.

This paper considers the dam with water impoundment but does not consider the fluid-skeleton interaction which could have a significant influence on the seismic response of the dam.

2. Experimental site description and geotechnical characterisation

The Souk Tlata dam on the BouGdoura stream is located at the western end of the great Kabylia 8.5 km from Tizi-Ouzou, about 80 km from Algiers in the eastern direction. The reservoir will consist essentially of two branches formed by the valleys of Acif Tlata and Tala Imedrane respectively, which meet all upstream of the dam. Souk Tlata dam of approximately 95 m high above the foundation is under construction and is the second largest hydraulic dam in the province of Tizi-Ouzou. The crest of the dams is 151 m long, 10 m wide and about 376 m width at the base. The dam will serve primarily to satisfy water supply of Tizi-Ouzou, Boumerdes and Algiers provinces, and will also cover certain local irrigation needs.

A total of 1,132,000 m^3 of earth and fill materials will be used for the construction of the Souk Tlata dam. The dam is composed of several different types of materials. In the central part of the dam, a core made up of clayey colluviums is implemented. The dam body is commonly composed of disaggregated sandstone, sandy and gravelly alluvium. Also, filter and transition materials exist in the dam. A rockfill cover protects upstream slope from erosion possibly produced by changes in the water level. It is made of a layer of limestone boulders from the Hassi Youcef quarry resting on a gravel bed from the same quarry. On the other hand, the Burdigalian sandstone sediments are widely present in the dam area and in fact constitute the foundation rock for the supports of the structure. The principal dike is founded on twenty meters of gravelly alluviums that are excavated under the core of the dam. Figure 1 shows the maximum cross section of the Souk Tlata dam.

It is mentioned in the dam monography that an extensive field exploration program was undertaken by GEOSONDA from Yugoslavia for the purpose of identifying the embankment materials, foundation soils and bedrock, and establishing the phreatic surface in the embankment. A total of 63 holes have been performed. Samples, which were carried out by the public center laboratory (LTCP), were recovered for laboratory tests which included classification tests (water content, humid and saturated density, Atterberg limits), compaction tests and triaxial tests. Some properties of the used materials in construction of Souk Tlata dam, and that were deducted from this extensive investigation, are summarized in Table 1 and Table 2 (dam monography).

No seismic fault has been recorded at the dam site for the past 200 years within a radius of 40 km but the dam is not very far from the transverse tectonic accidents with direction N140° and N75° which played an important role in the uplift of the Atlas Mountains. Therefore, it is possible that the dam area could feel the earthquakes from the surrounding active seismotectonic regions. Indeed, it is far from the large sedimentary basins, still subsidizing today from the Lower Miocene (Cheliff, Mitidja, Soummam, Hodna) which are the center of the most dangerous seismic faults in Algeria. According to Algeria's historical seismicity catalog, many earthquakes were felt in the dam area with intensities of VI at least. The peak accelerations estimated for the dam project are between 0.06 g and 0.10 g with a return period of 100 years and 0.15 g with a return period of 500 years (dam monography).

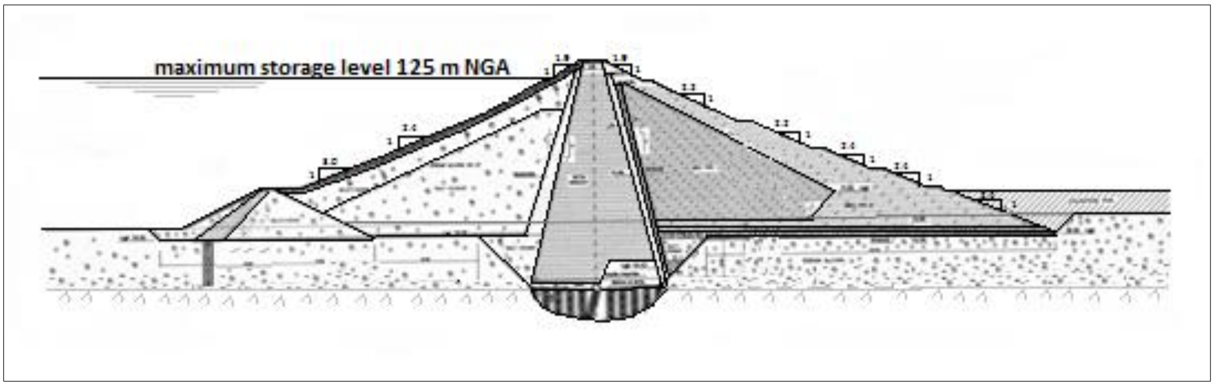

Fig 1. Cross section of Souk Tlata dam and foundation layers (adapted from dam monography).

3. Numerical model and static analysis

The analysis is performed with the finite element program Plaxis-2D. A simplified embankment cross section, shown in Figure 2, is considered. The numerical model, shown in Figure 3, consists of a dam overlying a foundation. The model consists of 2387 plane strain finite elements. To consider the stage construction of the dam in the analysis, the dam body is built in diverse phases. The dam materials are added in horizontal layers after the calculation for the initial equilibrium state of the foundation with a depth of 100 m. The boundary conditions are specified, such as the bottom of the model is fixed from movement in both the –horizontal- and –vertical directions.

In order to assess the stresses, prior to cyclic loading in the dam body, static analyses were carried out for various stages including end of construction, impounding and rapid drawdown. The behaviour of dam materials is described using the simple non associated Mohr Coulomb criterion. The use of this constitutive model is justified by the difficulty to obtain constitutive parameters for more advanced constitutive relations including both isotropic and kinematic hardening. The used material properties for numerical analyses are presented in Table 1 and Table 2.

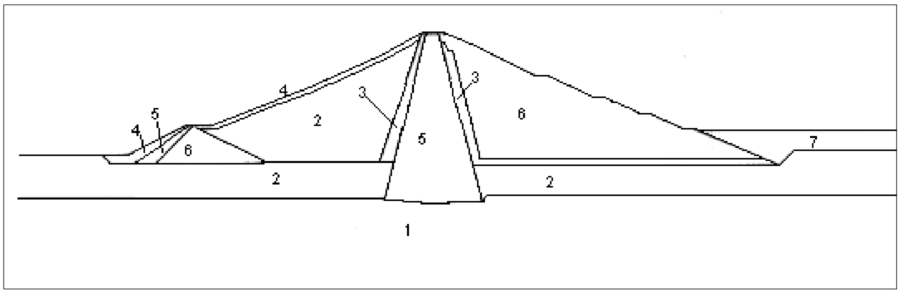

Fig 2. Simplified cross section showing different material zones.

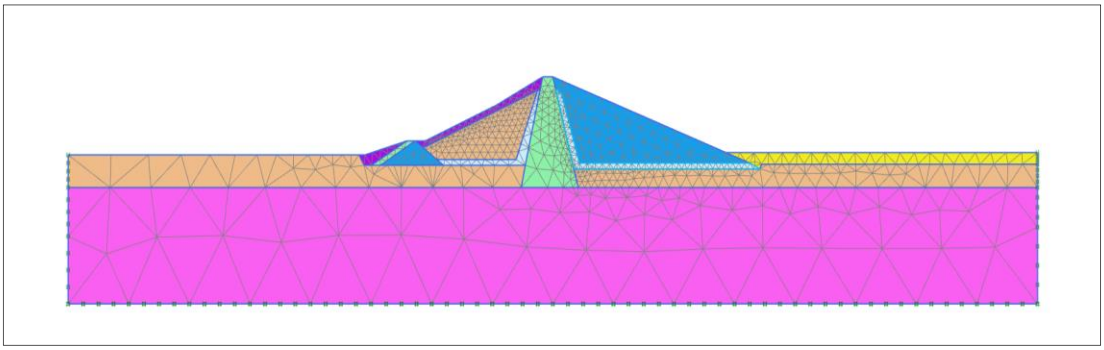

Fig 3. Finite element mesh employed in the analysis.

Table 1. Index and physical properties.

Material	γ_h (kN/m^3)	γ_{sat} (kN/m^3)	K (cm/s)	W_o (%)	W_L (%)	I_p (%)
Schist	24.5	24.5	-	-	-	-
Gravelly materials	21	22	10^{-3}-10^{-4}	7.3	-	-
Sand-gravel	20	20.5	-	-	-	-
Clayey colluviums	18	19	10^{-5}-10^{-6}	14.7	35.3	16.6
Sandstone	19.5	20	4×10^{-7}	3.6	27.4	12.2
Backfill	18	20	2.4×10^{-6}	17.5	44	22.5

Table 2. Shear strength characteristics.

Material	c' (kPa)	φ' (°)
Schist	70	30
Gravelly materials	0	35
Sand-gravel	0	32
Clayey colluviums	35-55	18-19
Sandstone	0	34
Backfill	0.5	10

3. 1. End of construction stage

To consider the stage construction of the dam in the analysis, the dam body is built in diverse phases. After the calculation for the initial equilibrium state of the foundation with a depth of 100 m, the dam materials are added in horizontal layers in order to take into account the stress history resulting from gravitational loading. As shown in Figure 4(a), a total of 30.63 cm of vertical displacement is predicted from this analysis. From Figure 4(b), a maximum horizontal displacement about 14.5 cm is induced in the upper part of the downstream side of the dam.

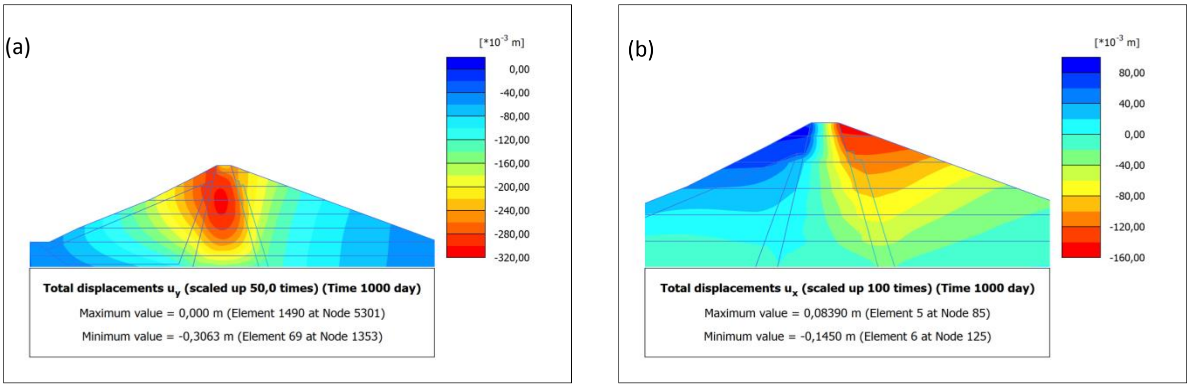

Fig 4. Vertical and horizontal displacements under gravity loads at the end of construction stage.

3.2. Impounding and drawdown conditions

Water level increases to a height of 86 m above the foundation which is considered impermeable. During impounding, the hydrostatic force acts on the upstream surface. Initial stresses and initial pore water pressures of the dam under normal working conditions are calculated using gravity loading. The water pressure distribution contours, shown in Figure 5(a), are obtained after filling to full supply level using steady state ground water flow analysis. The induced horizontal displacement is not significant like shown in Figure 6(a).

The stability of the dam under conditions of drawdown is also analyzed. The situation is considered where the water level drops 46 m rapidly. The water inside the dam does not have time to dissipate and it is important to know the behaviour of the dam in this case. To analyze this situation, a fully coupled flow-deformation is used. As shown in Figure 6(b), fast reduction of the reservoir level leads to instability of the upstream side of the dam with a peak horizontal displacement of about 1.076 m due to high pore water pressures that remain inside the dam as indicated in Figure 5(b).

The development of the safety factors as a function of the displacement of the dam crest is shown in Figure 7 for the three situations considered for the static analysis. By comparing with the minimum admissible regulatory values for each case of stability, one can note that the stability of the dam is ensured at the end of construction (F_s = 2.08), and even after the impoundment (F_s = 1.57), but in the case of a rapid drawdown, the stability of the structure is not ensured (F_s = 1.08).

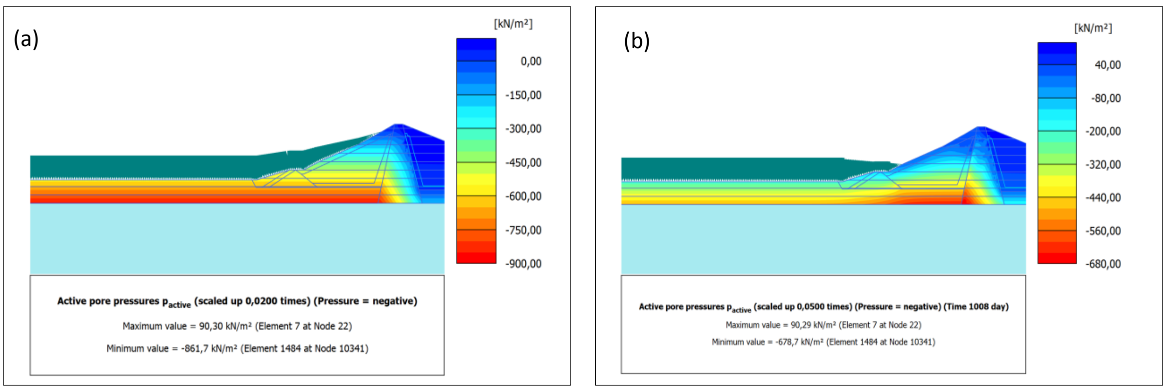

Fig 5. Pore pressure contours- (a) after impounding, (b) after rapid drawdown.

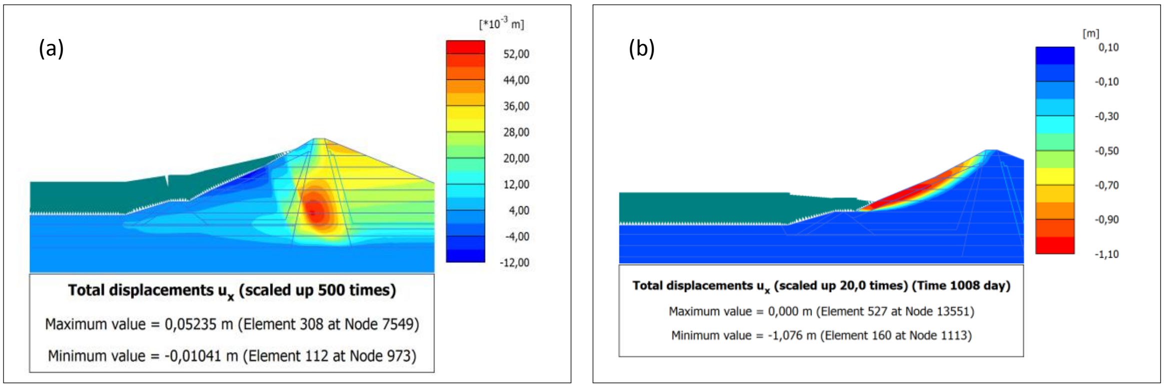

Fig 6. Horizontal displacement- (a) after impounding, (b) after rapid drawdown.

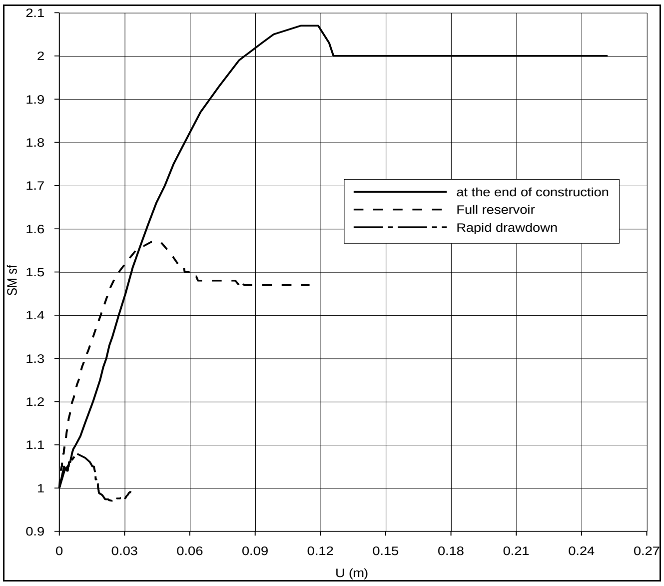

Fig 7. Safety factors as a function of the displacement of the dam crest.

4. Dynamic analysis

4.1. Input loading

The earth dam is subjected to earthquake loading representative of the 2003 Boumerdes main shock in Algeria (*Mw*=6.8), recorded at bedrock by the stations of the national accelerograph network in the N-S direction. The estimated peak acceleration is approximately -0.228 g, and the duration is approximately 28 s. The record for base acceleration and velocity waves are shown in Figure 8(a) and Figure 9(a) (records at Keddara site). The computed acceleration Fourier spectra indicates that the seismic power mainly concentrated in a range of frequencies lower than 15 Hz. It should be noted that two wavelets are present in the spectral representation of the motions like shown in Figure 8(b). The first one corresponds to content lower than 5 Hz and the second one greater than 5 Hz. Fourier analysis of the recorded velocity results in a power spectrum depicted in Figure 9(b). The velocity spectrum reveals a dominant frequency of about 0.52 Hz. From the other hand, the natural frequencies of the dam-foundation system were determined by a Fourier analysis of the free vibration response of the dam (Figure 10). It shows a fundamental frequency f_1=0.38 Hz which is close to dominant frequency of seismic loading (f=0.51 Hz).

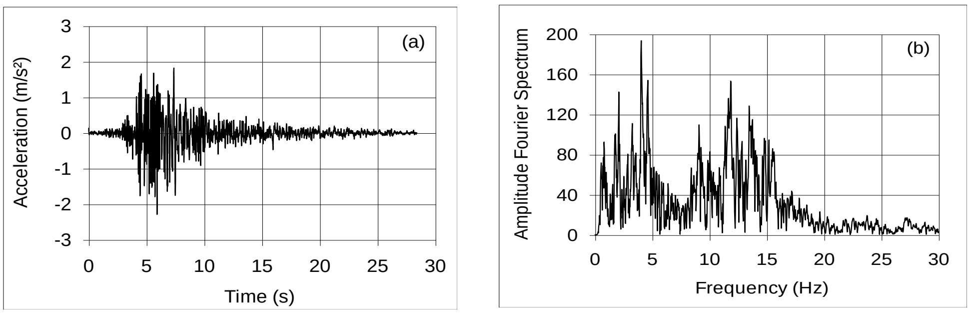

Fig 8. Acceleration time history of rock station in the N-S direction recorded during 2003 main shock in Algeria and respective Fourier spectrum.

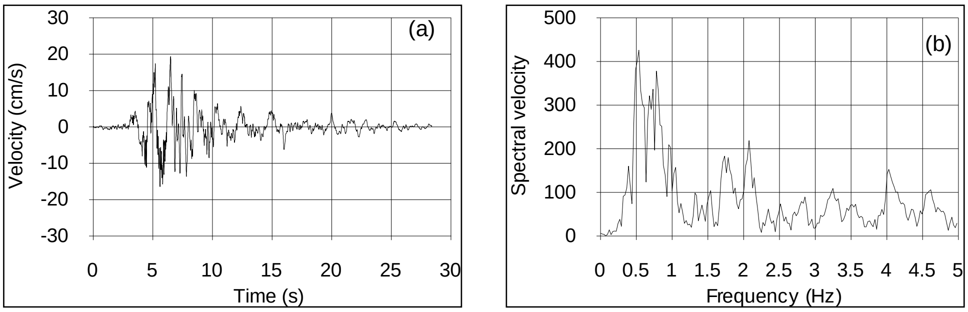

Fig 9. Velocity time history of rock station in the N-S direction recorded during 2003 main shock in Algeria and respective Fourier spectrum.

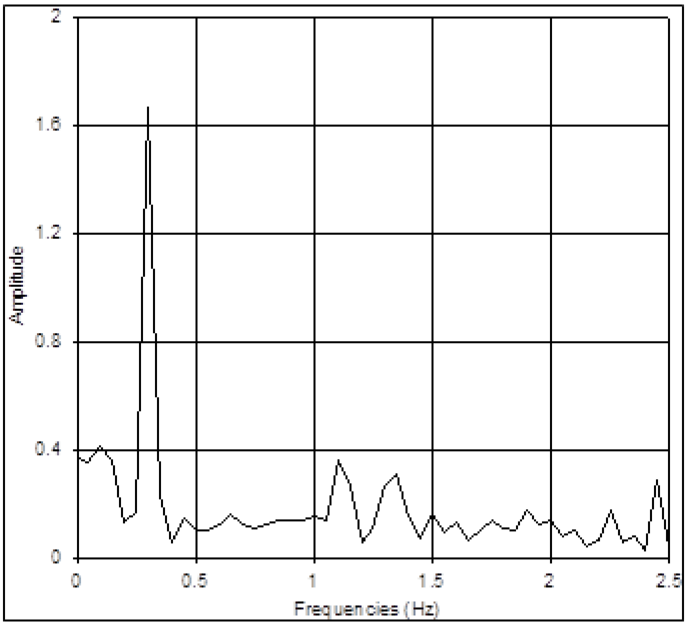

Fig 10. Response spectra of the free horizontal motion at the dam crest.

4.2. Analysis of the seismically induced response in the Souk Tlata dam

Dynamic loading is applied at the base of the foundation layer as an acceleration excitation. The procedure of free-field boundaries used in Plaxis-2D aims absorbing outward waves originating from the structure. The lateral boundaries of the main grid are coupled to the free field grid by viscous dashpots to simulate a quiet boundary. Amount of 2% of Rayleigh damping is considered to compensate the energy dissipation through the medium (Paolucci, 2002; Lokmer et al. 2002).

Figure 11 shows the acceleration time history computed at crest in the upstream-downstream direction, and respective Fourier transform. At the base of the foundation, the aforementioned peak acceleration was -0.228g. The dam responded to the applied motion with amplification, and a peak acceleration of approximately -0.31 g is reached. The computed Fourier spectra indicates that the response of the dam at crest is observed during the first wavelet corresponding to a frequency content less than 5 Hz while the response of the dam to the second wavelet with the frequency content below 15 Hz is not significant.

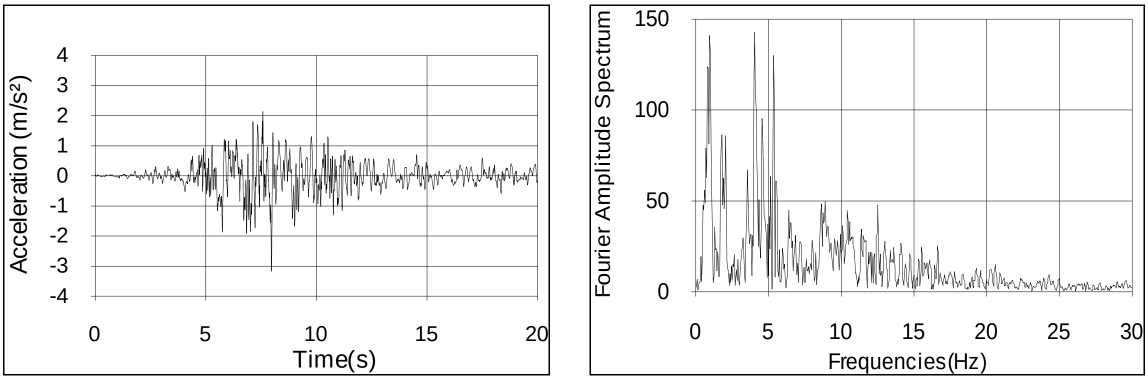

Fig 11. Acceleration time history of dam crest response in the upstream-downstream direction and respective Fourier spectrum.

The general pattern of horizontal and vertical displacement, respectively, as a result of seismic loading is shown in Figure 12. It is evident that the predicted deformation involves settlement at the crest. At 10 s of shaking, a peak of vertical displacement of 22 cm is reached and slumping of upper part of the rip rap on the upstream side of the dam is observed.

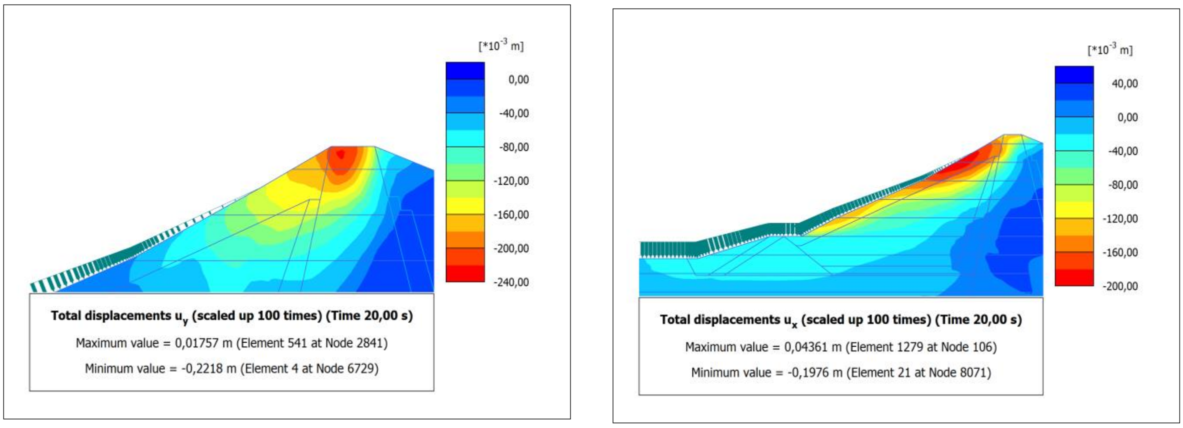

Fig 12. Vertical and horizontal displacement under seismic excitation at 10 s.

Figure 13 summarizes the change of horizontal and vertical displacement at crest of the dam for 20 s of shaking. As this figure illustrates, the maximum horizontal and vertical displacement occurs at approximately 10 s of dynamic excitation. The displacement is increasing almost linearly until 10 s and then remains relatively constant. The maximum magnitude of the horizontal movement is about 14 cm like shown in Figure 13(a) and as depicted in Figure 13(b) a maximum settlement of 22.18 cm is reached.

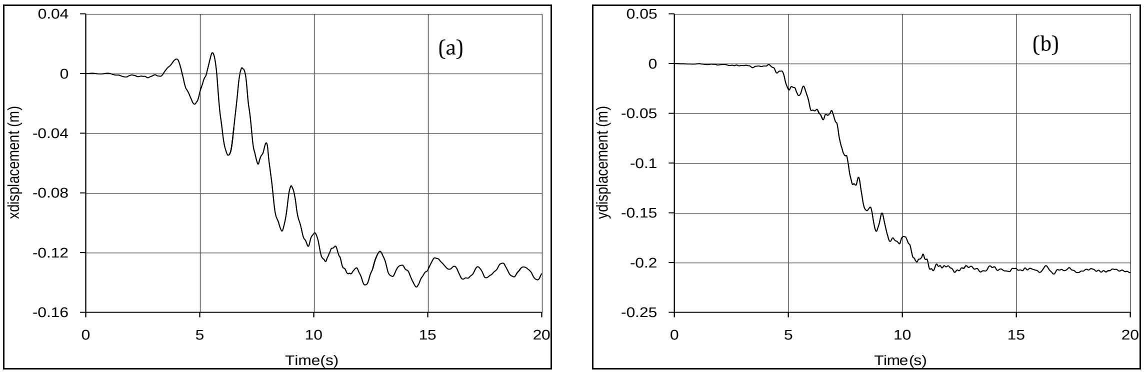

Fig 13. Horizontal and vertical displacement under seismic excitation at crest of the dam.

Figure 14 shows the displacement pattern in the axis of the dam and in the transversal direction at the middle height of the dam at the maximum of seismic excitation. It can be observed that the displacement increases with the distance from the foundation to the crest of the dam. It displays significant increase in the upper one-third of the dam, like shown in Figure 14(a). Okamoto (1973) points out that all observations indicate that the top part of the dam vibrates more severely as compared to the bottom part, and moreover the ration is fairly high, it reasonable to consider the design seismic coefficient at a high value for the top of the dam in the case of a high dam. On the other hand, the variation of the lateral displacement in the transversal direction at the middle height of the dam, shown in Figure 14(b), indicates a uniform distribution of the displacement in the downstream side but we observe a significant increase of the displacement when approaching the lateral extremity near the upstream side of the dam.

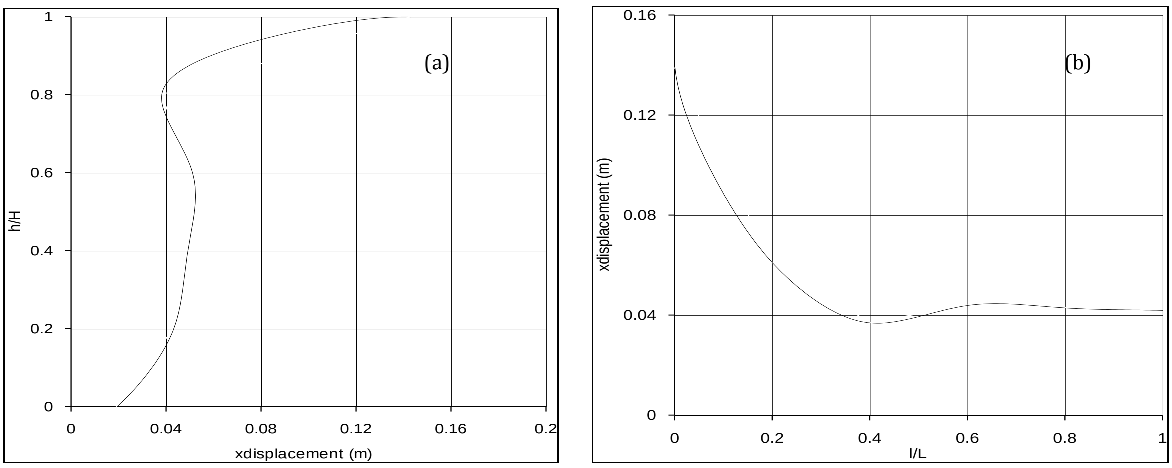

Fig 14. Displacement pattern at maximum of acceleration- (a) in the axis of the dam, (b) the transversal direction at the middle height of the dam.

Figure 15 shows the location of the zones concerned by plastic deformation at the peak of the seismic excitation. It can be observed that plasticity is induced on the rip-rap on the upstream face of the dam and in the backfill layer in the downstream side of the dam. The whole others parts of the dam remain in the elastic domain.

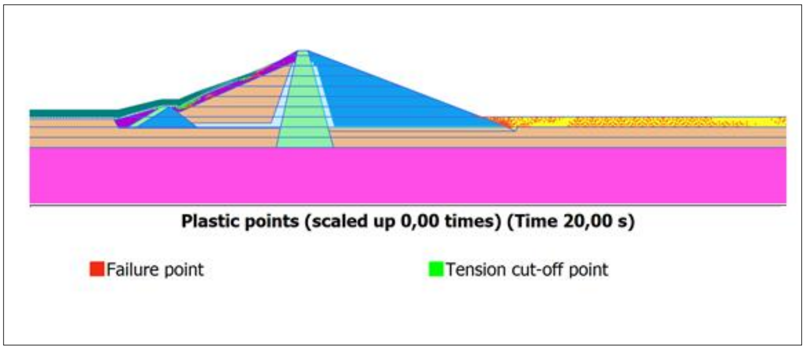

Fig. 15. Distribution of plasticity points in the dam under the dynamic excitationat 10 s.

5. Conclusions

This study presents a preliminary investigation of the behaviour of Souk Tlata earth dam under earthquake loading with a dominant frequency close to the fundamental frequency of the dam. The induced response was evaluated using the two-dimensional finite element program Plaxis and the Mohr Coulomb constitutive model. The main shock of May 21, 2003, Boumerdes earthquake in Algeria was selected for this study. The seismic behaviour corresponds to the response of the dam after water impoundment. The conducted static analysis to assess the stresses, prior to cyclic loading in the dam body, reveals significant instability of the upstream side of the dam under drawdown conditions with a safety factor lower than 1.2.

Under the given excitation, nonlinear dynamic analyses show that the predicted deformation involves settlement of 22 cm at the crest and slumping of rip rap and alluviums on the upstream side of the dam. The mechanical role of the central core is not significant compared to the shell in the induced response of the dam. The variation of the displacement in the middle height shows a sharp increase at the upstream extremity, which could indicate the imminence of instability in this area. A design should take into account dominant frequency of the seismic excitation and the dam where the amplification is significant and particular consideration should be given to the crest and the upstream side. Advanced analyses must also be undertaken to predict alluviums liquefaction above the foundation of the dam as well as the extent and timing leading to significant permanent deformation.

6. References

Ambraseys, N. N. (1960). On the Seismic Behaviour of Earth Dams. Proc. 2nd World Conf. Earthquake Eng. 2, 331–358.

Cao, Z. Z., Youd, T. L., & Yuan, X. M. (2011). Gravelly Soils that Liquefied During 2008 Wenchuan, China Earthquake, Ms _ 8.0. Soil Dyn. Earthq. Eng. 31,1132–1143. doi:10.1016/j.soildyn.2011.04.001.

Chen, G., Jin, D., Mao, J., Gao, H., Wang, Z., Jing, L., et al. (2014). Seismic Damage and Behavior Analysis of Earth Dams during the 2008 Wenchuan Earthquake, China. Eng. Geology. 180, 99–129. doi:10.1016/j.enggeo.2014.06.001.

Chen, L. W., Yuan, X. M., Cao, Z. Z., Hou, L. Q., Sun, R., Dong, L., et al. (2009). Liquefaction Macrophenomena in the Great Wenchuan Earthquake. Earthq. Eng. Eng. Vib. 8, 219–229. doi:10.1007/s11803-009-9033-4.

Dakoulas, P. (2012). Nonlinear seismic response of tall concrete-faced rockfill dams in Narrow canyons. Soil Dynamics and Earthquake Engineering. 34:1,11-24.

Harder, L.H., Bray, J.D., Volpe, R.L., & Rodda, K.V. (1998). Performance of earth dams during Loma Prieta Earthquake. The Loma Prieta, California, Earthquake of October 17, 1989- Earth Structures and Engineering Characterization of Ground Motion. 3-26.

Holzer, T, L., Jayko, A. S., Hauksson, E., Fletcher, J. P. B., Noce, T. E., Bennett, M. J., et al. (2010). Liquefaction Caused by the 2009 Olancha, California (USA),M5.2 Earthquake. Eng. Geology. 116 (1–2), 184–188. doi:10.1016/ j.enggeo.2010.07.009.

Hou, L. Q., Li, A. F., & Qiu, Z. M. (2011). Characteristics of Gravelly Soil Liquefaction in Wenchuan Earthquake. Appl. Mech. Mater. 90–93, 1498–1502. doi:10.4028/www.scientific.net/amm.90-93.1498.

Huang, Y., & Jiang, X. M. (2010). Field-Observed Phenomena of Seismic Liquefaction and Subsidence During the 2008 Wenchuan Earthquake in China. Nat. Hazards. 54, 839–850. doi:10.1007/s11069- 010-9509-6.

ICOLD (2019). General Synthesis of World Register of Dams, in: https://www.icoldcigb. org/GB/world register/general_synthesis.asp.

Kong, X. J., Pang, R., Zou, D. G. Xu, B., Zhou, Y. (2018). Seismic performance evaluation of high CFRDs based on incremental dynamic analysis, *Yantu Gongcheng Xuebao/Chinese J. Geotech. Eng.*, vol. 40, n.o 6, pp. 978-984.

Liu, Z, J., Wang, P., Zhang, Z. H., Li, Z. G., Cao, Z. Z. Zhang, J. Y., et al. (2016). Liquefaction in Western Sichuan Basin during the 2008 Mw 7.9 Wenchuan Earthquake. China: Tectono-physics, 1–25.

Lokmer, I. , Herak, M., Panza, G.F., & Vaccari, F. (2002). Amplification of strong ground motion in the city of Zagreb, Croatia, estimated by computation of synthetic seismograms. Soil Dynamics and Earthquake Engineering, 22, 105-113.

Monographie du barrage Souk Tlata (2002). Avant projet détaillé du barrage de Souk Tlata : mémoire de synthèse. Agence Nationale des barrages, pp 1-66.

Okamoto, A. (1973). Introduction to Earthquake Engineering, University of Tokyo Press.

Paolucci, R. (2002). Amplification of earthquake ground motion by steep topographic irregularitie. Earthquake Engineering and structural Dynamics, 31, 1831-1853.

Seed, H.B. (1979). Considerations in the earthquake resistant design of earth and rockfill dams. 19th Rankine Lecture of the British Geotechnical Society, Geotech., 29(3), 215-263.

Seed, H.B., Makdisi, F.I., & De Alba, P. (1978). Performance of earth dams during earthquakes. J. Geotech. Eng., American Society of Civil Engineering, 104(GT7), 967-994.

Wang, C. Y. (2007). Liquefaction Beyond the Near Field. Seismological Res. Lett. 78 (5), 512–517. doi:10.1785/gssrl.78.5.512

Wood, J. (1973). Earthquake-Induced soil pressures on structures. Report EERL 73-05, California Institute of Technology, Pasadena p. 311.

Youd, T. L., & Idriss, I. M. (2001). Liquefaction Resistance of Soils: Summary Report From the 1996 NCEER and 1998 MCEER/ NSF Workshops on Evaluation of Liquefaction Resistance of Soils. J. Geotechnical Geo-environmental Eng. 2001(10), 297–313. doi:10.1061/(asce)1090-0241(2001)127:4(297)

Yu, L., Kong, X., & Xu, B. (2012). Seismic response characteristics of earth and rockfill dams. 15th World Conference on Earthquake Engineering, Lisboa, Portugal.