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RESPONSE OF A ROCKFILL DAM TO SPATIALLY VARYING EARTHQUAKE GROUND MOTION

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ABSTRACT

The purpose of the present study is to analyse the seismic response of the Keddara rock fill dam to varying earthquake ground motion. A space-time earthquake ground motion model that account for both coherency decay and seismic wave propagation, is used to specify the support motions. The well instrumented Keddara dam was shaken by the May 21, 2003 Boumerdes earthquake (Mw=6.8). The free field and the structural experimental responses recorded during the main shock are used to perform the numerical simulations. Seismic response analysis, using the finite difference computer program FLAC^{2D}, indicates that the spatially varying ground motion reduces significantly the acceleration response at the crest.

Keywords: rock fill dam, seismic analysis, spatial variability, coherency loss, wave propagation, Boumerdes (Algeria) earthquake.

INTRODUCTION

The response of an embankment dam should be estimated carefully and rigorously because it would bring critical disaster if it failed. Many methods for performing the seismic analysis of a dam have been suggested. Among them, the simplified methods are widely used due to an easy and convenient application, but just show whether a dam is safe or not against an earthquake [Faiz et al. (1978), Gazetas (1987), Uddin, (1999)].

However, in several studies, the seismic analysis of embankment dams is performed under the assumption that the excitations at all points along the base are identical [Abdel-Ghaffar (1979), Dakoulas and Gazetas (1986), Finn (1992)]. Observations from closely spaced seismograph arrays since the late 1970’s have shown that earthquake ground accelerograms measured at different locations within the dimensions of typical large engineered structures are significantly different. This has led to considerable research in the last decade on modelling spatially varying earthquake ground motion and on determining its effect on the seismic response of large structures such as dams [Chen and Harichandran (1998), Chen and Harichandran (1995), Haroun and Abdel Hafiz (1987), Laouami and Labbe (2001)].

This paper investigates the effect of spatially varying earthquake ground motion on the Keddara rockfill dam. This dam, located on the Boudouaou river in Boumerdes region, was shaken by the May 21, 2003 Boumerdes earthquake (Mw=6.8). It was selected since it has been well instrumented with accelerographs during this earthquake. In this study, a space time earthquake ground motion model

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that account for both coherency decay and seismic wave propagation, is used to specify the support motions. The coherency model proposed by Luco & Wong, 1986 is adopted. Two dimensional dynamic deformation analyses are performed using the computer program $FLAC^{2D}$, Itasca (2005).

In this study, the seismic response of the Keddara dam is performed assuming the soils as Mohr-Coulomb materials. Damping is accounted for by the hysteretic damping and a small amount of viscous damping (2%) is used to limit response at very low strain levels.

NUMERICAL MODEL OF KEDDARA ROCKFILL DAM

The Keddara dam, located on the Boudouaou River in Boumerdes region about 35 Km east of Algiers, was completed in 1985. This dam is 106m high above its rock foundation, consisting of schist, and 426.26m widths at the base. The crest has width of 12m and a maximum length of 486m. Figure 1 shows the vertical cross section of the dam at mid length, which has an impervious inclined clay core covered by the filters and transition zones. The dam shoulders are of limestone rockfill compacted by heavy tractor track rolling. The transition zones between core and shoulders are consisting of sand and gravel down to bed rock. The upstream and downstream slopes are of 3h/1v. The material properties used in the analysis are given in table n°1. In this study, a 2D finite difference model with 14280 quadrilateral elements was used for the analysis.

Table 1. Material properties used in Keddara dam analysis

	Core	Filter	Transition zone	Rock zone	Foundation
Dry density (KN/m^3)	19.5	20.42	20.75	27.0	24.64
Friction angle (°)	14.0	47.0	38.0	38.0	45.0
Cohesion (MPa)	0.55	0.0	0.0	0.0	2.0
Bulk modulus (MPa)	1083	1964	2502	19200	30800
Shear modulus (MPa)	519	932	1251	9590	15400

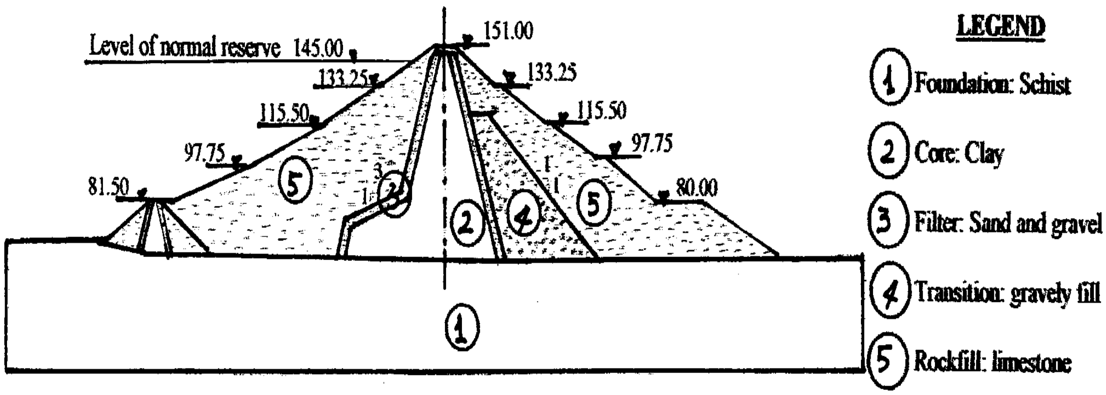

Figure 1. Typical cross section of the Keddara dam.

ESTABLISHMENT OF INITIAL STRESS FIELD

An analysis of the seismic performance of the dam should consider static equilibrium with calculations for the state of stress, the mechanical behaviour of the foundation and embankment prior to seismic loading. A bilinear, elastic-perfectly plastic stress-strain relationship with a Mohr-Coulomb failure criterion has been used in the $FLAC^{2D}$ static stress analyses. For the purpose of a static stress analysis, the low strain shear modulus, G_{max}, is determined from the in situ measured shear wave velocity, V_s, and the soil density.

The analysis is started from the state before the embankment is constructed. The dam materials will be added after the calculation for the initial equilibrium state of the foundation. The boundary conditions are specified, such as the bottom of the model is fixed from movement in both the –x- and –y-directions. The embankment materials are added by assuming that the entire construction took place in a single operation. The displacements resulting from adding the dam materials in one step are shown in Figure 2. This figure indicates that the largest vertical displacement of 7cm occurs near the crest.

The earthquake motion is considered to occur when the reservoir level is at full pool (at its full height at elevation 100m). For the second stage of the analysis, a mechanical pressure distribution is applied along the upstream slope to represent the weight of the reservoir water. The pressure, ranges from zero at elevation 100m to 1.0 MPa at the toe of the slope, is applied. The model is solved for this applied conditions and the resulting total vertical stress contour plot for the model at this stage is shown in Figure 3. Although displacements are critical near the crest, stresses are critical at the base of the model.

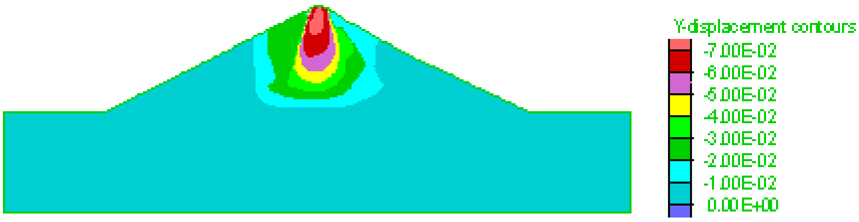

Figure 2. Contour of y-directional displacement induced by material dam construction.

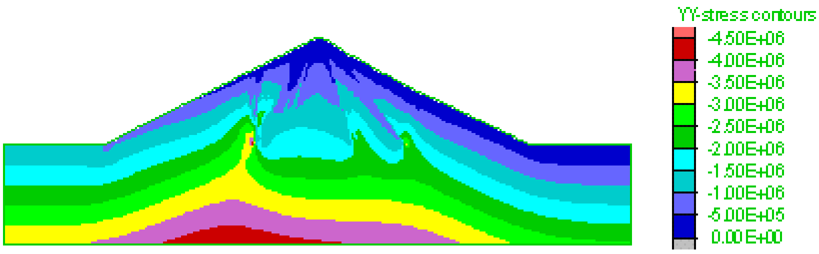

Figure 3. Vertical stress distribution with the reservoir level at full pool.

INPUT MOTION FOR THE UNIFORM ANALYSIS

The Keddara dam was shaken by the May 21, 2003 Boumerdes earthquake (Mw=6.8). The seismic input motion for the uniform analysis is taken from that recorded at the left abutment of the dam. The transversal component of the acceleration recorded at the bedrock is considered. The peak ground acceleration (PGA) is 0.228g where g is the modulus of the gravity vector, and the duration is 28 sec. The acceleration time history and the power spectrum of the used record are shown in Figure (4-a) and Figure (4-b) respectively. The Figure (4-b) indicates that the highest frequency is less than 20 Hz.

The mesh size for the FLAC model is selected to ensure accurate wave transmission. The largest zone size in the model is set to 3m; and the maximum frequency that can be modelled accurately is 15 Hz. Before applying the seismic input record, it is filtered to remove frequencies above 15 Hz. The filtered acceleration history is shown in Figure (4-c), and the corresponding power spectrum is shown in Figure (4-d). The filtered wave is also checked for baseline drift (i.e., continuing residual displacement after the motion has finished).

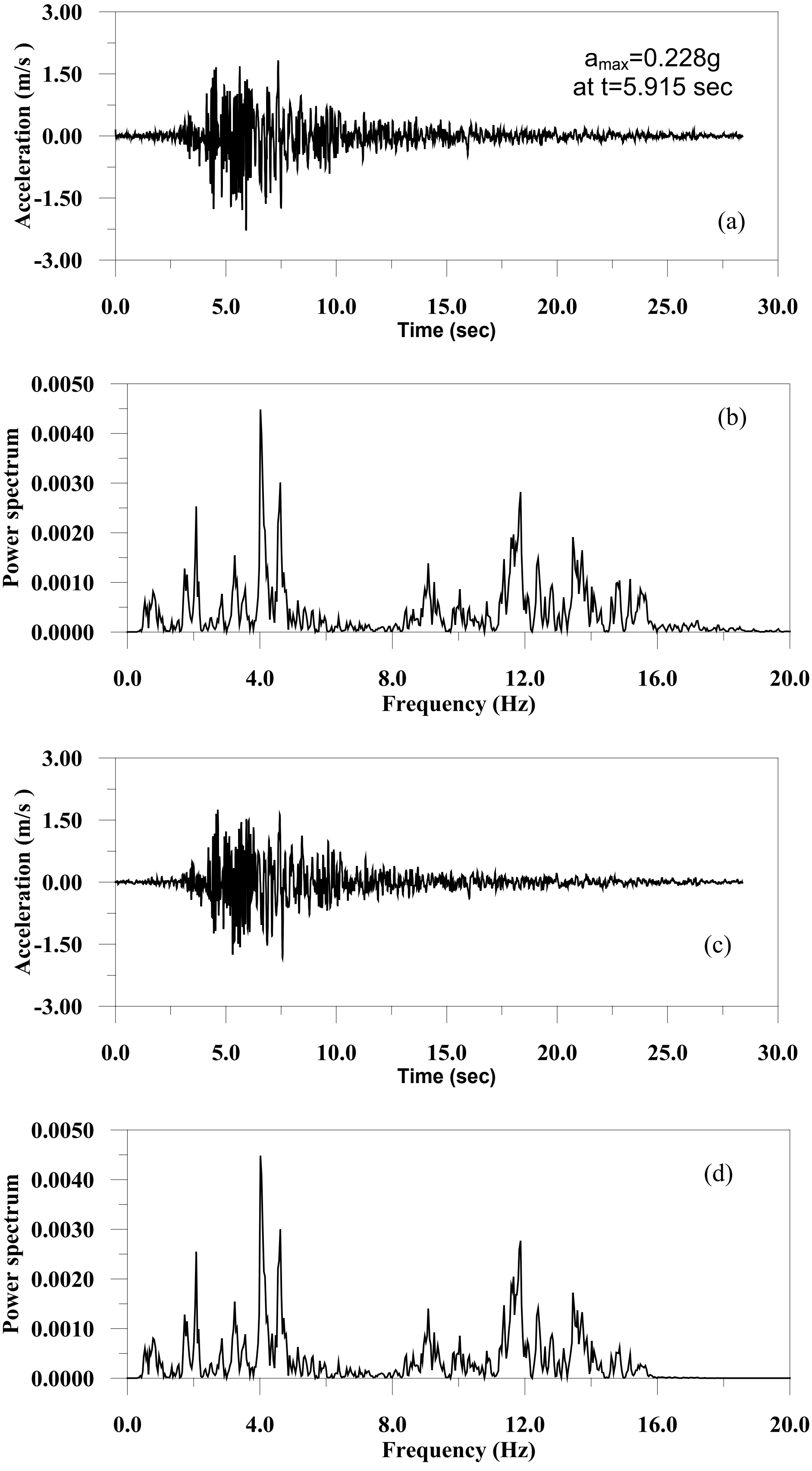

Figure 4. Input base motion representative of the 2003 Boumerdes Earthquake at the dam site, left abutment record at the bed rock.; (a)- acceleration time history, (b)- power spectrum, (c)-acceleration time history with 15 Hz filter, and (d)- power spectrum with 15 Hz filter.

ANALYTICAL MODELLING OF SPATIAL VARIABILITY

We consider that the spatial variability of seismic ground motion is attributed to the combination of:

1. The loss of correlation (incoherent effect) between the motions at separate points, resulting from random reflections and refractions as the waves travel through the soil.
2. The so called wave passage effect that is the difference in the arrival times of the seismic waves at different stations.

Spatial variability is described by means of a second order random field, discrete in space and continuous, zero mean, in time. The stationary version of this filed is thus completely described by the *nxn* symmetric matrix of the auto and cross power spectral density (PSD) functions. Where *n* is the number of stations. It is useful to introduce the following non dimensional coherency function:

$$\gamma_{ij}(\omega)=\frac{\left|S_{ij}(\omega)\right|}{\sqrt{S_{ii}(\omega)S_{jj}(\omega)}} \tag{1}$$

The value of the modulus of $\gamma_{ij}(\omega)$ at all frequencies is bounded by zero and one, and it provides a measure of the linear statistical dependence of the two processes at the stations i and j.

The adopted form of the coherency function is that one developed by Luco & Wong (1986), expressed by:

$$\gamma_{ij}(\omega)=\exp\left[-\left(\frac{\alpha\omega d_{ij}}{v_s}\right)^2\right]\times\exp\left[i\frac{\omega d_{ij}^L}{v_{app}}\right] \tag{2}$$

Where v_s is the shear waves velocity, d_{ij} and d_{ij}^L the distance and the projected distance along the direction of propagation of the waves between the stations i and j, respectively, v_{app} is the surface apparent velocity of waves. Zerva (1990) reports for the coherency parameter '*α'* values in the range 0.1 to 0.5.

Generation of samples

Samples of stationary field defined by the auto – and cross power spectral density *S(ω)* can be obtained by the procedure developed by Shinozuka (1972). Matrix S*(ω)*is decomposed into product:

$$S(\omega)=H(\omega)H^{*T}(\omega) \tag{3}$$

Between a matrix *H(ω)*and the transpose of its complex conjugate *H*(ω)*. A sample motion at the generic station 'i' is obtained from the series:

$$x_i(t)=2\sum_{j=1}^{i}\sum_{l=1}^{N}\left|H_{ji}(\omega)\right|\sqrt{\Delta\omega}\cos\left(\omega_l t+\theta_{ij}(\omega_l)+\phi_{jl}\right) \tag{4}$$

Where N is the total number of frequencies ω_l in which the significant bandwidth of $S_{ij}(\omega)$ is discretised, $\Delta\omega=\omega_x/N$, and the angles Φ_{jl} are a set of N independent random variables uniformly distributed in the interval [0,2π]. $\theta_{ij}(\omega_l)$ is the spectral phase obtained from:

$$\theta_{ij}(\omega_l)=Tan^{-1}\left(\frac{imH_{ji}(\omega_l)}{\mathrm{Re}H_{ji}(\omega_l)}\right) \tag{5}$$

Input motions with spatial variability

For this case, coherency loss and wave effect in the upstream-downstream direction at the base of the model are considered. The base foundation is divided into three strips. All base nodes located within a strip are assumed to have identical excitation. Accelerogram segments applied at the extreme downstream and upstream corners and at the middle of the base model are shown below in Figures (5-a), (5-b) and (5-c).

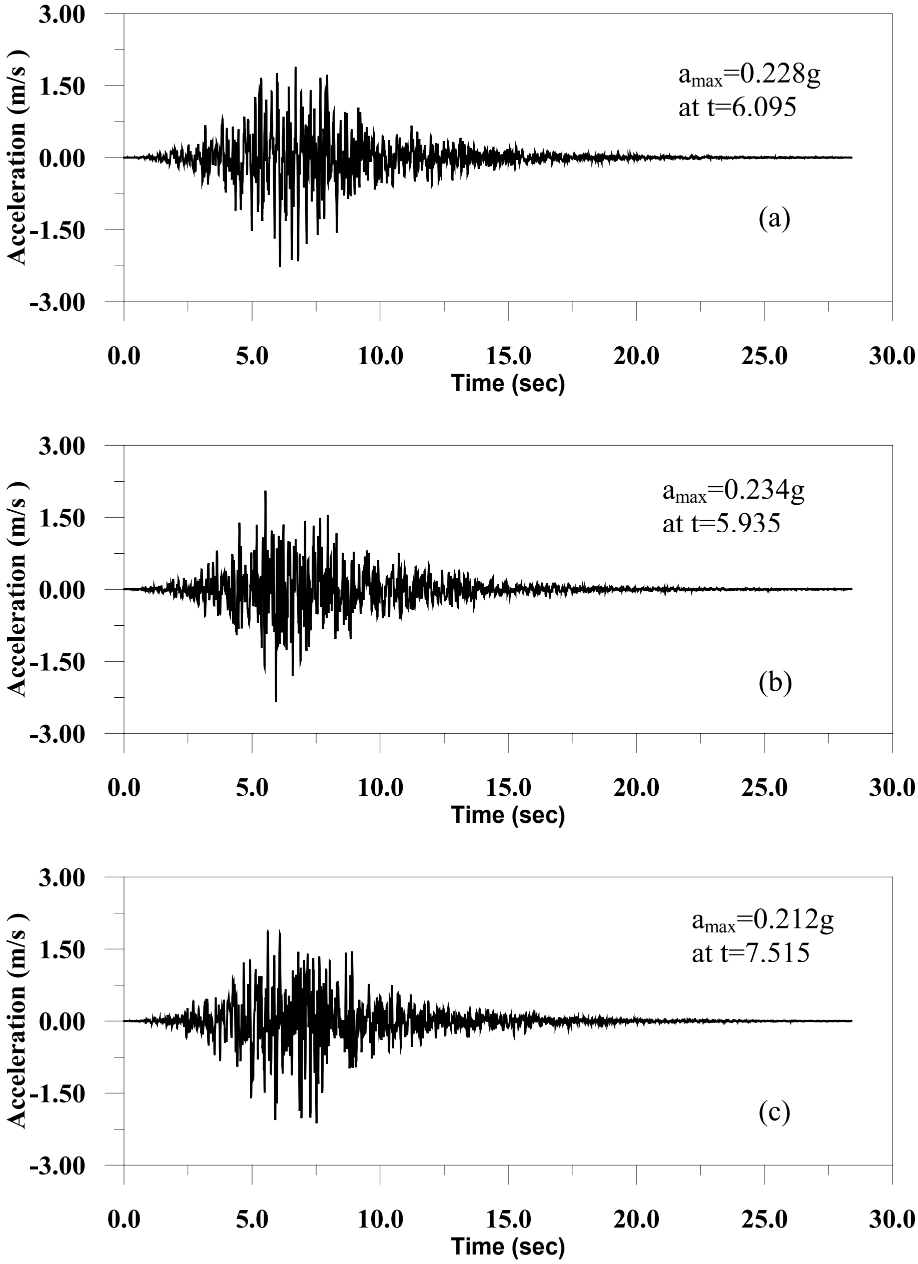

Figure 5. Accelerogram segments applied at the base; (a)- at upstream side, (b)- at the middle and (c)- at downstream side.

COMPARISON BETWEEN THE NUMERICAL AND THE OBSERVED KEDDARA DAM SEISMIC RESPONSES

This section shows the comparison between the numerical and the observed seismic responses of the Keddara dam for the uniform and non uniform seismic cases:

Case I: Identical ground motion; this considers the earthquake excitation to be identical at all support points, an assumption often used in practice.

Case II: Spatial variability of ground motion is considered; in this case, both correlation and wave propagation effects are includes for the base excitations.

The results, obtained using time analysis are examined, focusing on the maximum acceleration at the crest of the dam model. Each case is compared to the acceleration recorded at the crest of Keddara dam shown in Figure (6-a). Field measurements of response of Keddara rockfill dam during the Boumerdes earthquake indicate that crest accelerations are amplified from the base.

Figures (6-b) and (6-c) display the results obtained for the identical and delayed, incoherency excitations respectively. The result obtained for the case II using delayed and incoherent excitations indicates that the spatially varying ground motion reduces significantly the acceleration response at the crest.

The comparison between the computed crest responses with spatial variability, with the recorded one show a good agreement, while the uniform input motion case overestimates the dam response. The slight difference which remains between the recorded response and the computed one in the case II is due probably to the stress-strain relation ship that used in this study. We hope that the results will be better with a sophistically model.

Other selected results of analysis

The distribution of maximum nodal responses for each component with depth (y) in the upstream-downstream direction, along the dam middle axis, are extracted for the two cases of the applied excitations shown in Figure 7 and listed in table 2.

In 2D analysis, the total displacement response consists of x,y components. The results indicate that the x-displacement dominates the total displacement response.

The results for the two cases compared in table 2, show that the maximum x-displacement occurs at the crest. The maximum x-displacement response to identical excitation is larger than that due to delayed and incoherency excitations.

The maximum shear stress response for each case is also listed table 2. The results indicate that the traditional assumption of uniform earthquake ground motion over-estimates slightly the stress response at the base.

Although stresses are critical at the base, strains are critical at the top of the model near the crest because the material at the top is not stiff as the material of the base. The effect of spatially varying earthquake ground motion slightly lowers the maximum shear strain response along the dam middle axis.

Table 2. Maximum nodal response for each component along the dam middle axis.

Nodes (i,j)	Node Location	x-Acceleration (m/s²)		x-displacement (cm)		Y-displacement (cm)		Shear strain $X10^{-4}$		Shear stress (MPa)	
		CaseI	CaseII	CaseI	CaseII	Case I	CaseII	CaseI	CaseII	CaseI	CaseII
106,34	Base (Y=0.0H)	3.347	2.20	5.10	3.90	0.03	2.50	7.07	5.08	0.321	0.296
106,42	Y=0.25H	3.985	2.86	6.50	2.20	0.36	2.30	4.49	4.09	0.254	0.224
106,50	Y=0.50H	5.216	2.93	6.80	2.10	0.72	1.40	9.20	9.72	0.208	0.192
106,58	Y=0.75H	5.287	3.12	8.60	3.60	2.82	2.80	25.0	18.8	0.151	0.193
106,69	Crest Y=H	5.361	3.25	21.10	11.40	6.73	6.0	-	-	-	-

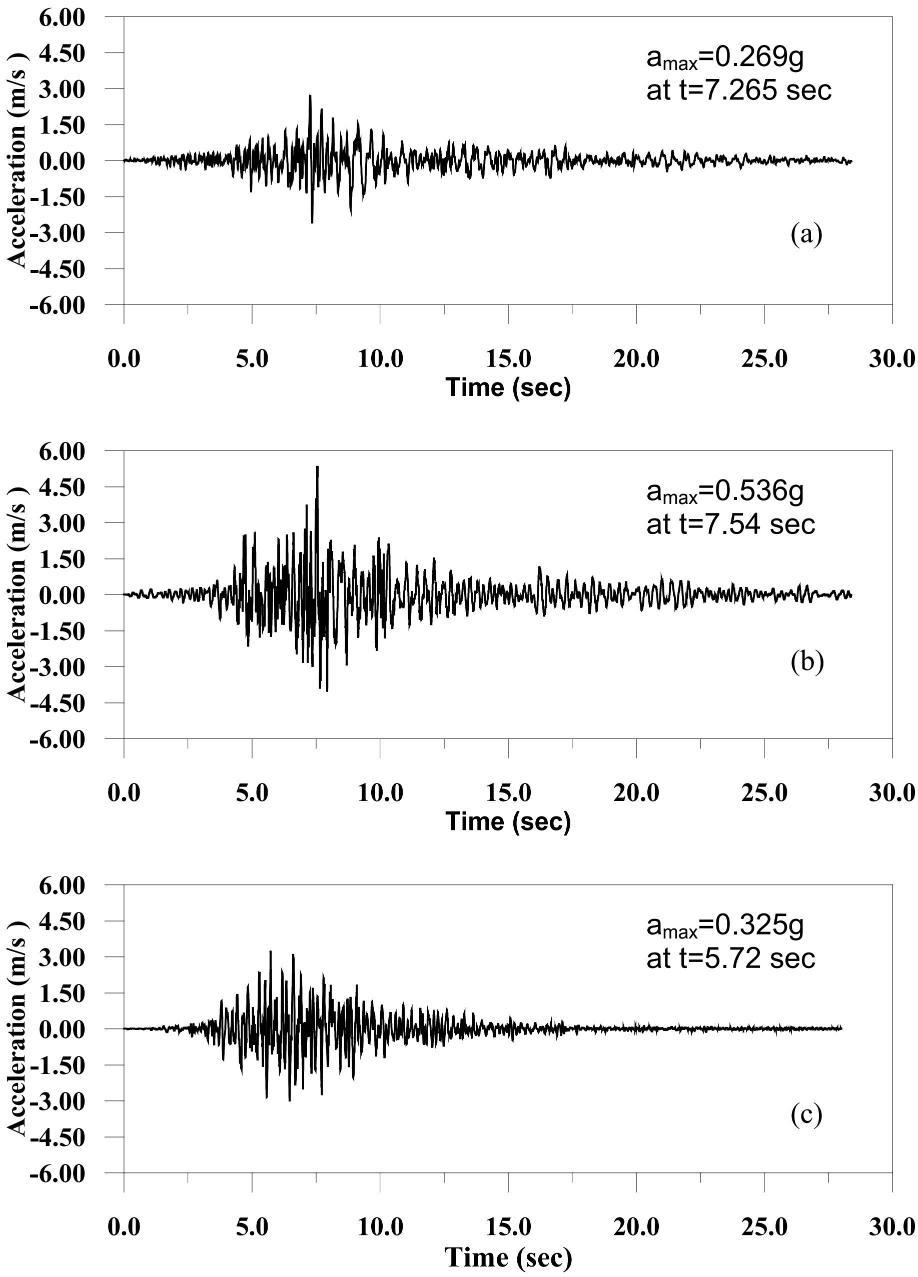

Figure 6. Acceleration at the crest of Keddara dam; (a)- Observed during the 2003 Boumerdes earthquake; (b)- Computed with identical ground motion and (c)- Computed with spatial variability of ground motions.

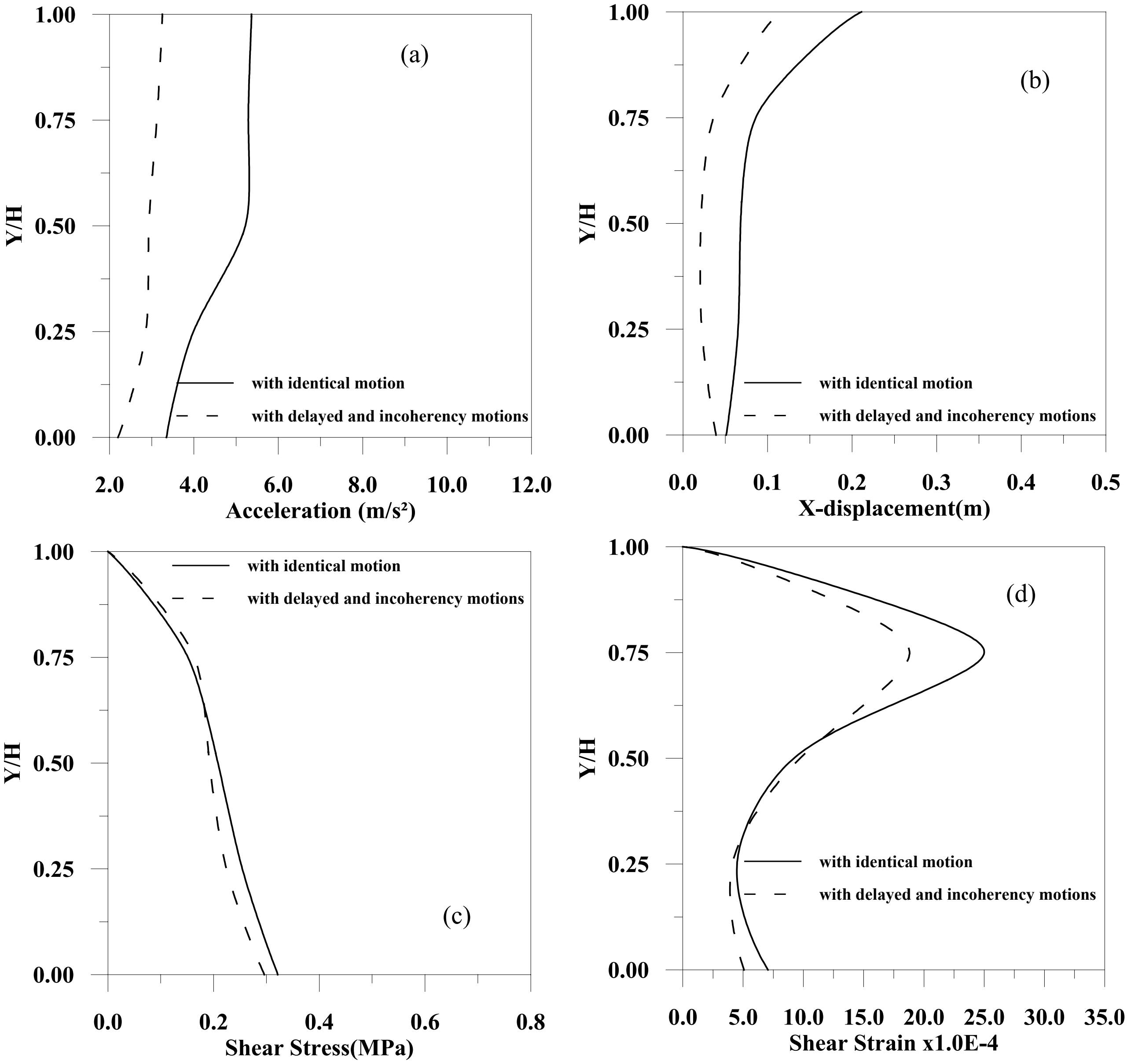

Figure 7. Comparison of distribution of peak variables with depth along the dam middle axis; (a)- Peak acceleration, (b)- Peak x-displacement, (c)- Peak shear stress and (d)- Peak shear strain.

CONCLUSION

The seismic response of keddara rockfill dam, shaken by the Boumerdes earthquake is computed using the finite difference program FLAC^{2D}. In order to study the response of Keddara rockfill dam to spatially varying earthquake ground motion, two cases were considered:

- At first, the transversal component of the acceleration recorded at the bedrock is used to represent the spatially uniform ground motion at the base of the foundation.

-The model which accounts for both spatial correlation and wave passage effects, developed by Luco and Wong, is used to specify the base motions in the upstream-downstream direction of the dam.

A parametric study of the effects of spatially non uniform ground motions on the response of Keddara rockfill dam indicates that the spatially varying ground motion reduces the acceleration and the displacement responses at the crest. The effect of the spatial variation of seismic motions on the numerical dam's response is to be considered in the light of the considered assumptions. Of course, some effects are not taken into account in the present study as the non linear behaviour of the dam under the 21 May Boumerdes earthquake strong motions and the variation in material properties. Further work is also needed to investigate the effects of other soil models.

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