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SEISMIC BEHAVIOR OF CONCRETE-FACED ROCKFILL DAMS, CONSIDERING A SPATIAL VARIATION OF MOTIONS ALONG THE RIGID BASE

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SUMMARY

Three-dimensional dynamic analyses of a hypothetical concrete-face rockfill dam having a 153 m high and a crest length of 780 m are presented. The dam is similar to La Parota dam that is projected to be built in a zone in Mexico where the seismic hazard is highest. The spatial variation of motions at dam-abutment interface is produced by considering that the train waves impinge a horizontal boundary located 150 m beneath the dam foundation. Different wave patterns are produced assuming several arrangements of rock materials underneath the dam foundation and their effects on dam response analyzed. The results point out that equal far field motions can produce important variations in the motions that act upon the dam. In fact, it is shown that these motions have a spatial variation whose patters depend on the layering of the rock materials underlying the dam.

INTRODUCTION

Most severe earthquakes in Mexico are caused mainly by the subduction of the Cocos and Rivera oceanic plates under the North America plate. The subduction of the Cocos plate embraces the coast of the Pacific, from Puerto Vallarta in the State of Jalisco to Tapachula in the State of Chiapas (see Figure 1). In this zone have been registered the strongest earthquakes in Mexican territory during the last century. The Rivera plate dips under the North American plate basically along the coast of the State of Nayarit, north to the State of Jalisco (not shown in Figure 1).

Some of the most important earth and rockfill dams have been built near to the Pacific coast. At present time a concrete face-rockfill dam is under construction in the State on Nayarit. Another, La Parota dam, is in the stage of design. The site of this dam is in the State of Guerrero, some 25 km from Acapulco Port (Figure 1). The studies carried out by Esteva et al. [1] point out that there are three sources capable to generate severe seismic events: Guerrero and Acapulco-San Marcos gaps, as well as the tectonic province of Tierra Colorada, all within a radio of 40 to 50 km. The first two sources can produce superficial (15 to

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25 km) earthquakes of 8.1 moment magnitude. And earthquakes of 7.2 degrees are likely to be generated in the zone of Tierra Colorada to intermediate depths (40 to 60 km).

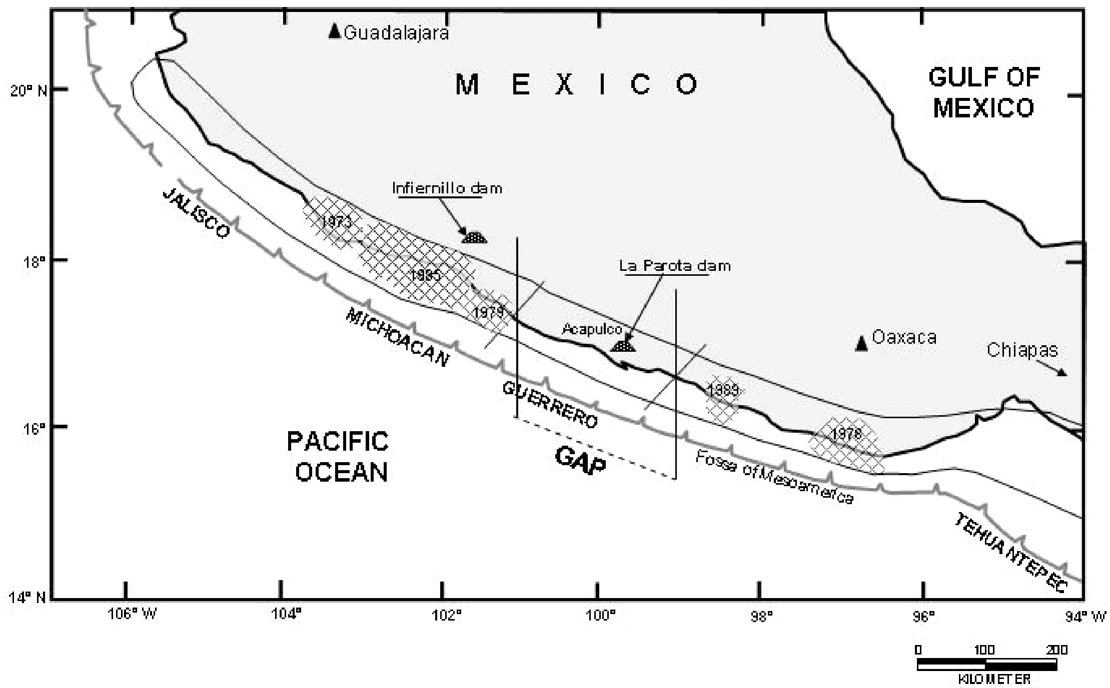

Figure 1 Seismic conditions of the site of study

One of the basic elements in the analyses of the seismic stability of earth dams includes the application of a constant seismic movement along the dam abutment, which is usually considered the boundary of the model. However, this assumption is not supported by many earthquake motions recorded at both right and left abutments of several Mexican dams. Thus, it would seem that to improve our understanding on dam behavior, it is important to consider the spatial variation of motions when investigating the response of dams. This aspect is particularly important for near site events. This work deals with this problem. It considers the effects of a spatial variation of the incident motions in a hypothetical concrete-face rockfill dam located in a seismic hazard environment equivalent to that of La Parota dam.

DAM MODELING

In this section we describe the study of a concrete-face rockfill dam that is assumed to be sited in the zone of highest seismic hazard in Mexico. The analysis considers the spatial variation of the incident motions at the base of the dam and different geologic conditions are considered in the valley. All three components of the “design” earthquake are applied simultaneously.

Model Description

The maximum section of the dam considered is presented in Figure 2, where the embankment is formed by a homogeneous compacted rockfill. The maximum height of dam is 153 m and its crest length 780 m. The concrete face slab was supposed to have a constant thickness of 0.5 m. Both upstream and downstream slopes are 1.5H to 1.0V. The dam canyon is a steep valley, where the right abutment is steeper than the left one.

Considering the topographic conditions of the valley and the proximity of the seismic sources, the dynamic analyses were carried out using the three-dimensional model of Figure 3. The dam material is assumed to behave according to the Mohr-Coulomb model, and its rock foundation is modeled as a linear-elastic material. Elastic shell elements are used to modeling the face slab. For simplicity, in these analyses vertical and horizontal joints were not included. The model has 7330 solid elements and 220 shell elements. The four vertical boundaries are removed from the most exterior parts of the dam a distance equal to half-length of the crest.

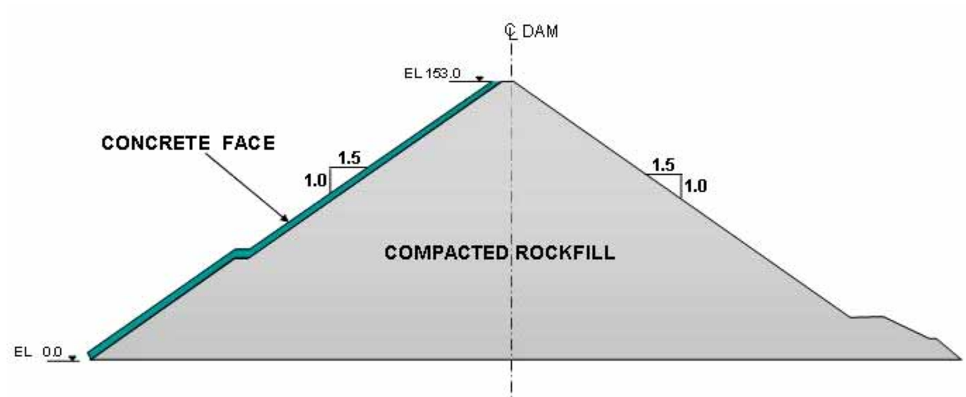

Figure 2 Maximum section of concrete face rockfill dam

A three-dimensional code was used in this example. The calculation is based on the explicit finite difference scheme to solve the full equations of motion, using lumped grid-point masses derived from the actual density of surrounding zones. This formulation can be coupled to the structural element model, for example shells elements, thus allowing to consider the interaction between the concrete slab and the rockfill embankment.

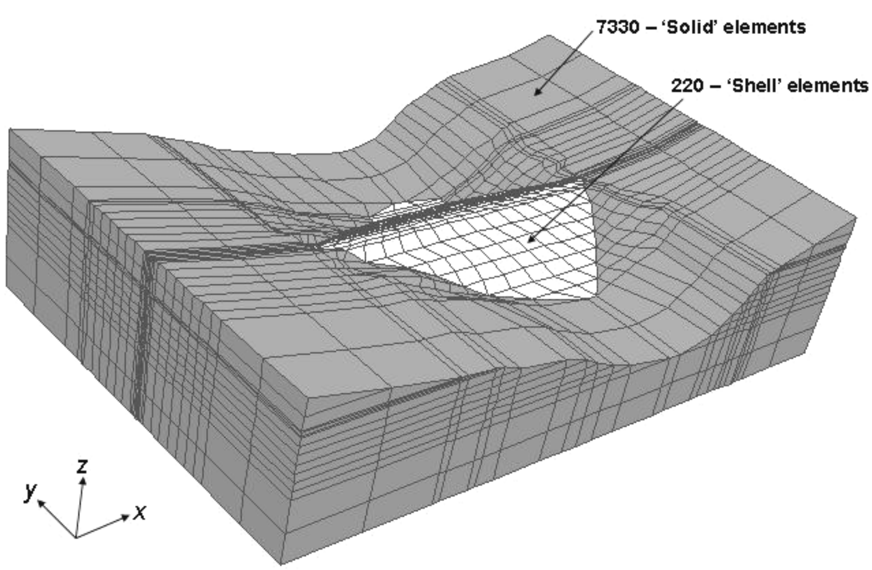

Figure 3 Finite differences model 3-D of concrete face dam

The analyses take into account the dam construction process. The embankment construction is simulated in six stages, and the concrete face slab is built afterwards. Then reservoir filling is simulated by imposing the corresponding hydrostatic pressures on the face of the slab. Finally, the excitation (three coupled components) is applied at the base of the model.

The advent of recent methods of construction, through the use of properly zoned compacted rockfills, results in a dam of reliable performance in terms of safety and leakage [2, 3]. Also, the development of concrete plinths and face slab improvements, notably abandoning the highly articulated pattern of slab and compressible joints, are the principal factors in current design trends and a resulting higher frequency of acceptance.

Seismic Environment

In practice, the excitation defined by means of a seismic risk assessment is assumed to be acting at the canyon-dam interface and in the direction of the river. This simplification is acceptable for far site conditions. However, in the case near site conditions, a three-dimensional seismic environment should be considered, as it is shown in this paper. In other words, the excitation should include the motions of the three seismic components (two horizontal, orthogonal to each other, and one vertical). Furthermore, the seismic input motion should be considered varying spatially.

The components of the input motion used in this study are show in Figure 4. These motions were recorded at El Infiernillo dam. The component in the river bed direction (y-direction) was scaled up to a maximum acceleration of 0.4 g (40% of the gravity acceleration) and the other two components were scaled up considering the proportion of maximum accelerations, with regard to the perpendicular component to the crest of the dam. The three resultant components are shown in Figure 4, along with their respective response spectra (5% of damping). These spectral curves show clearly the differences on the frequency content, which strengthen the recommendation regarding that the excitation should include the three components acting at the same time.

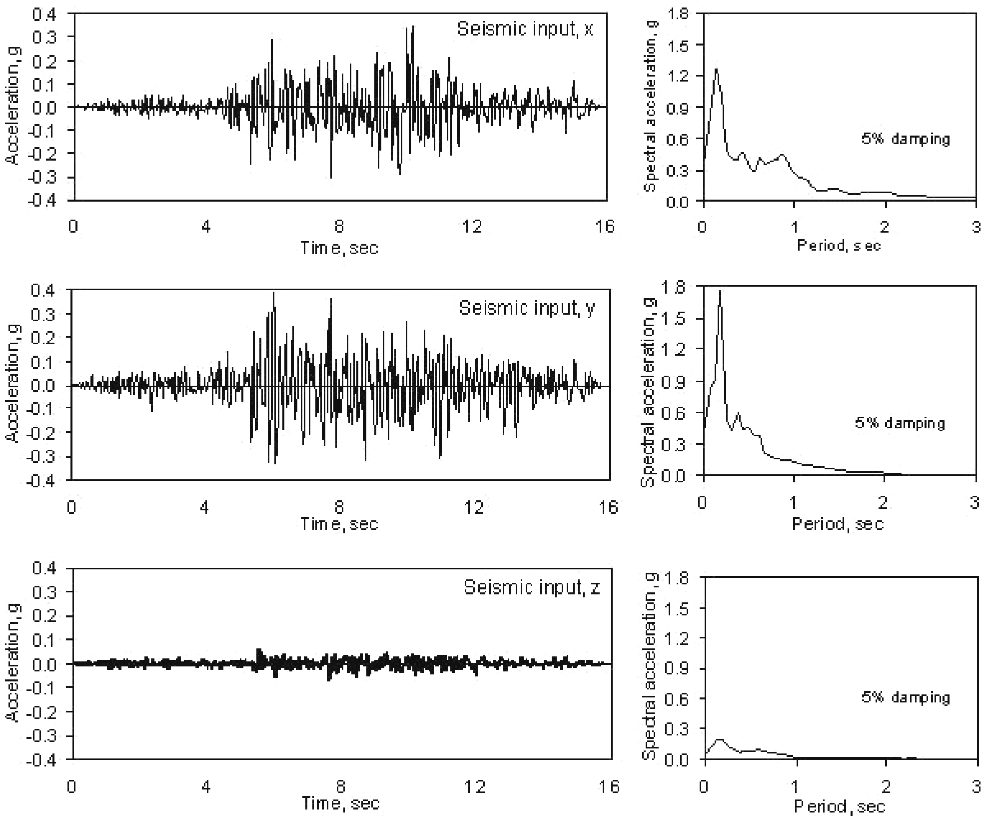

Figure 4 Input recorded acceleration time histories and their response spectra

Layering Conditions Assumed for the Rock underneath the Dam

In order to assess the effect of the input motions coupling, four cases, depicted in Figure 5, were considered. Model "A" assumes a homogeneous material, where the rock-dam foundation has a stiffness 40-times-higher than that of the embankment itself. The rockfill in the dam has a constant Young's modulus, E=500 MPa, and a Poisson's ratio, υ=0.30. Model "B" considers that the valley is formed by three layers of rock, stratified horizontally and with different stiffnesses, which increase with the depth to 40, 30 and 20 times that of embankment. Model "C" considers two rock masses outcropping at the right and left abutments. The contact between these geologic features is underneath the dam. The right abutment is 40 times stiffer than that of the embankment and the left abutment 20 times. Lastly, the model "D" is similar to model "A" but considering now that in all four vertical boundaries the same excitation is applied, the intensity of which varies vertically (see Figure 5d).

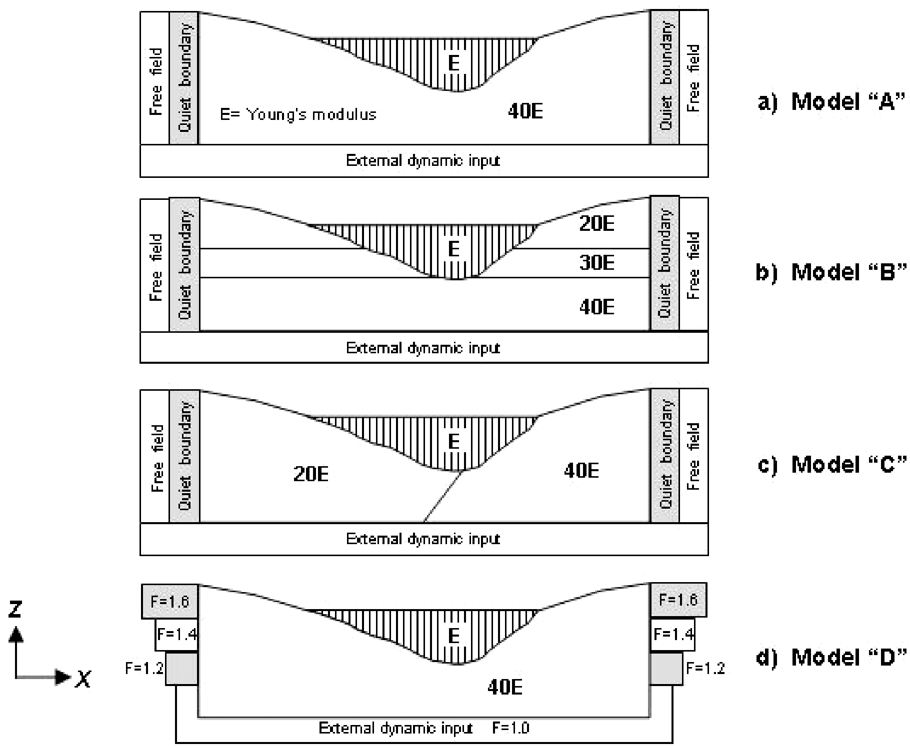

Figure 5 Comparative models of analysis

Although it is recognized that the modulus of rockfills increase with normal stresses and their characteristics [4, 5, 6], in this study a constant modulus was used to leave out this variable and highlight the influence of motion variation on dam response. To simulate energy dissipation by geometric damping, independent dashpots in the normal and shear directions at the vertical boundaries were used. The viscous boundary developed by Lysmer and Kuhlemeyer [7] was included in the model.

RESULTS

Figure 6 shows how the motions that actually act upon the dam vary spatially along it. The points indicated, refer to the maximum ground accelerations given in Table 1. These results show the degree of severity and the variability of the seismic motions along the embankment-abutment contact. The spatial variations patterns are different for each one of the three seismic components and in each of the models considered.

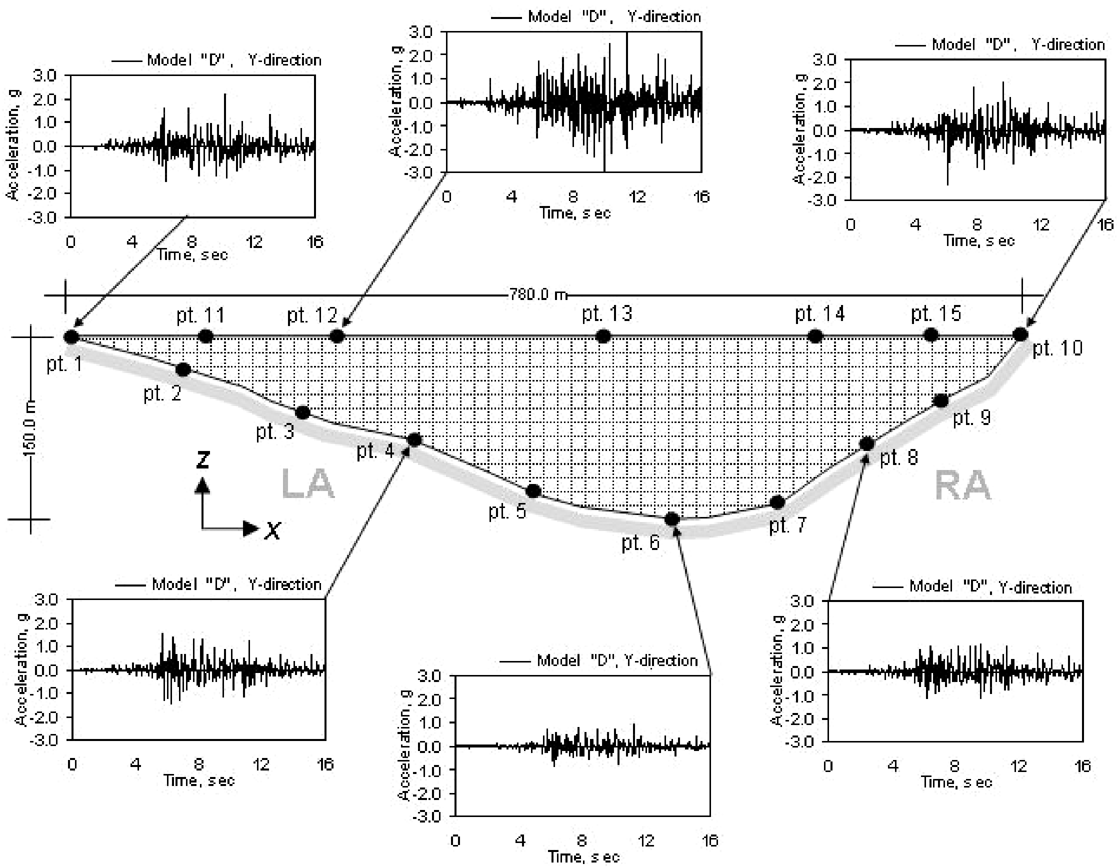

Figure 6 Vertical section along the crest of dam

Table 1 Maximum accelerations, in m/s², along the abutment and crest of the dam

DIRECTION	MODEL	ABUTMENT										CREST				
		p1	p2	P3	p4	p5	p6	p7	P8	p9	p10	p11	p12	p13	p14	p15
- X -	A	8.2	6.7	4.8	6.1	4.1	4.1	6.1	5.0	6.5	8.4	12.4	13.0	13.6	18.4	8.7
	B	11.1	9.2	10.4	6.1	4.7	4.3	4.5	7.8	7.5	10.4	10.8	21.1	15.9	10.6	9.5
	C	9.5	6.4	4.8	5.1	3.7	4.6	5.5	4.0	5.9	6.5	9.5	14.8	11.1	14.9	9.3
	D	12.7	10.1	9.8	7.0	8.1	7.7	5.7	9.1	11.0	12.3	18.3	20.7	16.6	15.0	8.2
- Y -	A	6.4	6.5	5.5	4.8	3.9	3.3	3.4	4.8	6.2	6.2	9.4	14.9	11.0	6.5	7.1
	B	7.7	7.0	5.8	5.7	3.7	3.4	4.1	5.5	6.0	8.1	14.0	21.4	8.3	9.2	7.9
	C	4.9	4.0	3.9	3.7	3.0	2.7	2.8	4.0	5.4	6.3	9.0	14.2	8.8	7.7	7.8
	D	19.6	10.8	14.5	13.9	9.3	7.8	10.7	10.3	15.6	20.3	22.5	28.9	11.4	15.6	18.1
- Z -	A	5.0	3.3	2.2	2.6	1.8	2.3	3.2	3.5	3.2	5.2	11.0	9.3	5.2	7.1	5.9
	B	6.4	4.8	2.9	2.2	2.0	2.1	2.5	3.7	5.0	4.9	6.8	13.2	10.1	8.0	9.2
	C	3.2	2.1	1.9	1.8	1.7	2.0	2.6	3.8	3.4	4.3	5.3	13.3	5.7	7.4	9.0
	D	9.5	5.8	3.9	3.6	4.5	3.7	5.4	5.1	5.7	10.1	15.2	18.3	10.9	11.0	9.3

As can be seen, the results presented in Table 1 show that when a homogeneous material is considered, the maximum accelerations develop at the right abutment (points 1 to 5) and are almost of the same magnitude that those of the left abutment (points 7 to 10), as one would expect. The difference can be attributed to the geometric asymmetry of the canyon. These results change radically for the other models. When different rock stiffnesses are considered, a more marked spatial variation of the incident motions in de dam is observed. For the case of model "D", where input motions are considered all around the model, more severe motions develop on the dam.

Model “D” is likely to be the most representative when we deal with near seismic sources, especially if they “surround” the dam site. In this case the waves arrive at the dam site from different azimuths. Some computed acceleration time histories in the direction of the river bed (y-direction) for model “D”, are showed in Figure 6.

Also, the spatial variation of the maximum accelerations of the three components is presented in Table 1, where it can be seen that amplifications higher than usual (for a rockfill dam) develop. The maximum values occur at points 11 and 12. Again, model “D” provides the most severe seismic conditions for the dam.

It is interesting also to observe the variation of the motions on the slab face, which was considered without the presence of vertical and horizontal joints. We can appreciate the magnitude of the maximum accelerations on the slab face-abutment contact at the central zone of the slab (see Figure 7 and Table 2).

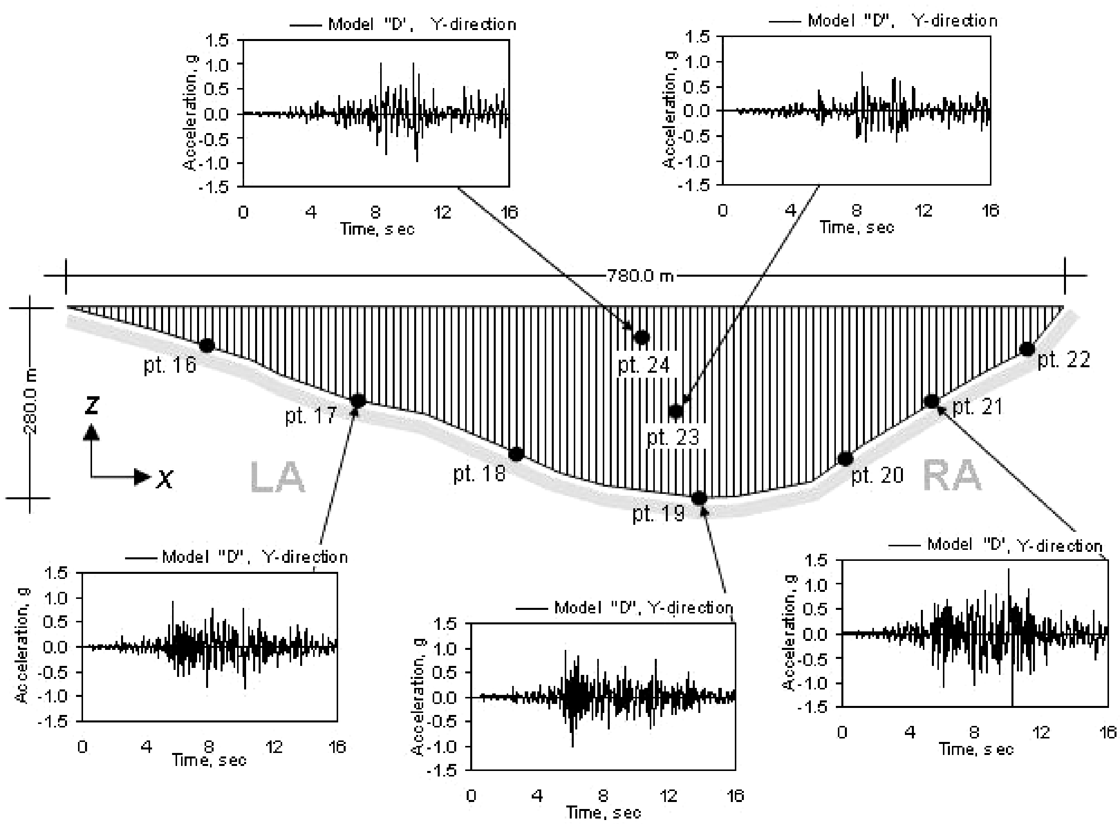

Figure 7 Front view of the concrete face

These results indicate the variation and severity of the motions on the slab face, which warn about their importance for its structural design. If we had considered constructive vertical joints, these motions would be partially dissipated by the back and forth movement that most likely would produce separations in the joints. This aspect should be given due consideration in its design.

Some of the computed acceleration time histories on the concrete face are shown in Figure 7, all correspond to the component in the direction of the river bed (y-direction) and for the model “D” conditions. It is interesting to notice, that the accelerations in the center of slab (points 23 and 24) are smaller than in the slab face-abutment contact, mainly in model "D" and y-direction (along the river bed).

Table 2 Maximum accelerations, in m/s^2, along the concrete face

Direction	MODEL	p16	p17	P18	P19	p20	p21	p22	p23	p24
- X -	A	5.8	4.9	4.6	4.4	4.4	5.3	4.7	7.3	6.9
	B	8.5	6.0	6.0	4.6	5.2	6.7	4.7	5.2	7.6
	C	4.4	4.6	5.5	5.3	3.9	3.9	5.7	7.1	6.7
	D	10.7	13.1	6.7	8.2	7.3	11.3	10.8	7.6	11.1
- Y -	A	6.3	4.6	4.2	4.8	4.3	5.7	7.2	3.7	5.0
	B	6.5	6.6	5.2	4.7	4.5	8.0	7.1	3.6	4.9
	C	4.0	4.6	4.3	5.1	4.0	6.5	7.9	3.3	4.9
	D	9.6	8.0	8.1	8.7	8.2	15.7	16.4	6.7	9.1
- Z -	A	2.2	2.3	1.9	2.5	3.3	3.7	3.4	5.5	3.2
	B	3.1	2.5	1.9	2.3	2.6	4.3	5.1	7.4	3.4
	C	2.3	2.4	1.7	3.5	2.5	4.0	3.9	6.4	3.0
	D	5.0	4.8	3.8	4.1	3.9	4.5	7.2	8.1	6.2

CONCLUSIONS

The results indicate the importance of considering a three-dimensional-spatial-variation seismic environment at the embankment-abutment contact, for near site sources.

It is worth mentioning that the studies of seismic risk (determinists or probabilistic) use attenuation relationships that in general are obtained considering the most severe of the two horizontal (orthogonal) components. In some occasions the arithmetic average of these two components is used. This means that the resulting earthquake of the study has the same direction of the component (or resultant) computed. Usually, the input motion is considered acting in the direction of the river, which implies that the seismic environment is one-dimensional. In the case of sites far from the seismic source this supposition is considered appropriate, on the basis of the generally good behavior of dams built in passed decades. However, in the case of dams which can be affected by diverse seismic sources having similar seismic hazards and are near the dam site, the seismic environment is undoubtedly three-dimensional. In other words, the excitation (besides being considered as varying spatially) should include the three components: two horizontal orthogonal to each other and one vertical. It is pertinent to point out that two of the components must not be the result from scaling the "earthquake" obtained from a seismic hazard analysis, but rather each component should be the product of studies of this nature.

In practice, the main use of the assessment of seismic hazard is to define the maximum credible earthquake (or one equivalent) in a rock outcropping nearby the dam. However, in the case where there are diverse rocks outcropping in the dam site, the application point of the excitation is not defined clearly. This evidently has an important impact in the calculation of the response of the dam.

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