SEISMIC ANALYSIS OF A ROLLER COMPACTED CONCRETE GRAVITY DAM IN PORTUGAL

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ABSTRACT :

Some results of the seismic analysis of a gravity dam built in Portugal using the roller compacted concrete (RCC) methodology, with 52 m of height, are presented. The analysis was done using specific software (program EAGD-84) which, after some modifications to allow its use in the International System of Units (SI) and to obtain sequences of dependent variables along time, facilitates evaluating the seismic response of such dams. The analysis of the gravity dam as an elastic structure includes the dam-reservoir-foundation interactions, as well as the effect of absorption of the seismic waves by the sedimentary materials deposited in the reservoir bottom. The horizontal and vertical seismic actions are either synthetic artificial accelerograms satisfying design spectra or are registered real accelerograms scaled to the local peak accelerations; in this manner horizontal and vertical accelerations of the seismic action are considered, allowing the consideration of the base design earthquake (BDE) and maximum expectable earthquake (MEE). The results of the analysis include the nodal displacements and the stresses at selected elements, to assess the safety of this RCC dam structure.

KEYWORDS: RCC dam, seismic analysis, dam-reservoir-foundation interaction.

1. INTRODUCTION

The idea that the seismic action on dams could be almost neglected for structures located in areas of low seismic activity is no longer valid, and according to USACE [1] this action is the most important to be considered in safety studies involving failure rupture scenarios. The methods of analysis for evaluating the seismic behavior of a structure in certain earthquake area – under a given peak acceleration, accelerograms, response spectrum or power spectrum, characterizing the seismic action – permit to know in a more rigorous way the behavior of this type of structures.

Difficulties exist in determining the seismic response of dams [2] the most important of which are: (i) dams complex geometry and forms, motivated by the topography and geotechnical character of the implantation zone and by the structural solution adopted; (ii) dams structural response is very much influenced by the water mass in the reservoir behind the upstream face of the dam, so that fluid-structure interaction has to be considered; (iii) specific space variation characteristics of the seismic action along the different boundaries between the dam and its foundation, affecting the dam seismic response especially for the earthquakes with high return period; (iv) knowledge of the mechanical characteristics and heterogeneity of the foundation massifs, as well as of the regional tectonic activity of the dam implantation area (as measured by the anticlinals, synclinals, diaclases, fractures and faults); (v) lack of information in the characterization of the dynamic properties of the materials of the dam and of its foundation; (vi) difficulties associated with the available methodologies for the justification of the strength and stability and for the evaluation of the behavior of gravity dams.

To overcome some of the previous difficulties a specific software was developed (program EAGD-84), which evaluates the seismic time response of concrete gravity dams in the domain of the linear material behavior [3].

2. CONSIDERATIONS ON THE USE OF ROLLER COMPACTED CONCRETE FOR DAMS

The design of gravity dams constructed by roller compacted cylinders (RCC) is similar to the design of concrete gravity dams constructed by conventional methods. The largest differences are in the used construction methods and in the composition of the concrete used to allow roller compaction.

This new method proved to be technologically economic in relation to conventional one, in view of the construction high efficiencies that approach those of earth dams and rock-fill dams. The concrete (for RCC dams) is relatively dry, poor in cement and has a reduced value of the slump test. It contains fine aggregates and inert elements of small dimensions, and its compaction is accomplished by cylinders equipped with vibrators. This material leads to a RCC similar to conventional concrete, but generally with inferior mechanical resistances and high permeability. For effective consolidation, the RCC needs to be sufficiently dry to support the construction equipments and to have necessary workability to form an uniform mass without segregation.

3. THE SEISMIC ANALYSIS OF GRAVITY DAMS

The seismic analysis of dams of vibration compacted concrete (VCC) or roller compacted to cylinder concrete (RCC) is a complex structural problem, in which in its more complete formulation requests the consideration of three-dimensional (3D) finite element models with immense degrees of freedom. Other main features of the structural problem that may or may not be considered correspond to: the dynamic interaction between the water mass of the reservoir and the dam, the consideration of water compressibility, the interaction between the reservoir and the foundation boundaries including the bottom sediments, and the consideration in the models of the adequate dynamic properties of the materials used.

Under small amplitude vibrations the concrete gravity dam generally presents a monolithic behavior of a solid, even if small sliding occurs along the borders that separate the dam blocks [4]. However, during the occurrence of movements of great amplitude, the dam behavior depends on the value of the inertia forces that are transmitted through the boundaries.
For dams with radial plane boundaries, with or without injections, the inertia forces that occur during the movements of great amplitude are far higher than the tangential forces that the boundaries mobilize. Consequently, the boundary contours will suffer sliding and the blocks of the dams can vibrate in an independent way, as it happened in Koyna dam during the earthquake of 11th December 1967 [1]. For dams with boundaries capable to mobilize significant tangential forces, by means of fittings with saliencies among the blocks, it cannot be appropriate to assume that the blocks will vibrate independently. For these cases a bi-dimensional (2D) model simulating a plane state of deformation can be adopted.
On the other hand, for dams subjected to intense earthquakes, a 2D analysis using a model that considers a plane state of stress simulating each block is considered satisfactory for the analysis of the seismic response.

Along the last decades software programs of automatic calculation have been developed for dam analysis, namely the specific program EAGD-84 [3, 5]. This program allows evaluating the seismic response of gravity dams considering linear behavior of the dam concrete and of the foundation rock, whose possibility of fissuration is not considered in the formulation of this software. The dam-reservoir-foundation interaction and the effect of the absorption of the seismic waves, by the sedimentary materials at the bottom of the reservoir, are both included. The mechanical system constituted by the dam-reservoir-foundation is characterized by a plane state of stress or of deformation, situation that is verified in the analysis of gravity concrete dams. The hydrodynamic effect of the water contained in the reservoir is assumed as being appropriately modeled by a 2D wave equation. The compressibility of the water is also included in the analysis, since it can affect significantly the seismic response of concrete gravity dams [6, 7].
The seismic actions are translated by accelerograms of the foundation accelerations in horizontal (a_h) and vertical (a_v) directions (either independently or cumulatively).
With this software the gravity dam structure can be idealized through a plane model, using 4-node finite elements. The dissipation of energy of the dam is represented by a constant of hysteretic damping. The reservoir is idealized as a fluid domain with constant depth and semi-infinite development upstream from the dam, and the absorption of the energy by the materials deposited in the reservoir bottom is characterized by a coefficient of reflection of the seismic waves.
If the dam-foundation interaction is included in the analysis, the stiffness matrix to be included in the equations of motion of the gravity dam is evaluated with the dynamic characteristics of the foundation.

4. STRUCTURAL SEISMIC ANALYSIS OF A RCC GRAVITY DAM

Using the software referred previously (program EAGD-84), after some alterations to facilitate its operation in the SI units and new subroutines for obtaining specific results along time, an evaluation study was developed of the structural seismic behavior of a RCC dam for a specific location in Portugal. In this analysis the dam-reservoir-foundation interaction effect is included, as well as the effect of deposited alluviums and sediments at the bottom of the reservoir upstream from the dam.

4.1. Definition of the Characteristics of the Structural Model

The dam was idealized through a plane state of deformation model, constituted by 4-nodes finite elements. The structure of the considered RCC gravity dam supported on a flat horizontal foundation is referred to an (x-y) coordinate system of axes, where the *x* axis is positive along the upstream-downstream direction and *y* is the vertical direction. For the reservoir, idealized as a fluid domain with constant height and semi-infinite development upstream, the compressibility of water is admitted. The dissipation of energy transmitted by the seismic waves in the dam is represented by a constant value of the damping coefficient; the absorption of the seismic waves is characterized by a coefficient of reflection of 0.5, value located in the interval [0;1] in which the null value represents total absorption without reflection.
The material of the foundation rock and of the sediment materials deposited in the bottom of the reservoir, are idealized as being a homogeneous and isotropic flexible medium. In Table 1 a summary of the properties of the finite element model is presented, in agreement with the obtained results of several studies and tests with reasonable variations in the properties of materials for static and dynamic analyses [5].

Table 1 – Properties of the materials used in the analyses.

Properties	Values for static analysis	Values for dynamic analysis
Water in the reservoir :		
Mass density (ρ)	1000 kg.m^{-3}	1000 kg.m^{-3}
Velocity of pressure waves (v_p)	---	1439 m.s^{-1}
Concrete RCC for dam :		
Elasticity modulus (E)	18 MPa	22 MPa
Poisson coefficient (υ)	0,20	0,18
Mass density (ρ)	2400 kg.m^{-3}	2400 kg.m^{-3}
Damping coefficient (ξ)	---	0,05
Average compressive resistance (σ_c) a)	15 MPa	18 MPa
Average tensile resistance (σ_t) b)	0,8 MPa	1,0 MPa
Foundation medium :		
Elasticity modulus (E)	15 MPa	15 MPa
Poisson coefficient (υ)	0,30	0,30
Mass density (ρ)	2600 kg.m^{-3}	2600 kg.m^{-3}
Damping coefficient (ξ)	---	0,05
Absorption coefficient α	---	0,5
Velocity of shear seismic waves (v_s)	---	1470 m.s^{-1}
a) for all mass of concrete		
b) between concrete layers under treatment		

Figure 1 presents the 3D dam model and the 2D model corresponding to the higher section of the dam, the latter of which is used in the structural seismic analyses for the level of full storage (LFS) capacity (at 49 meters) [7].

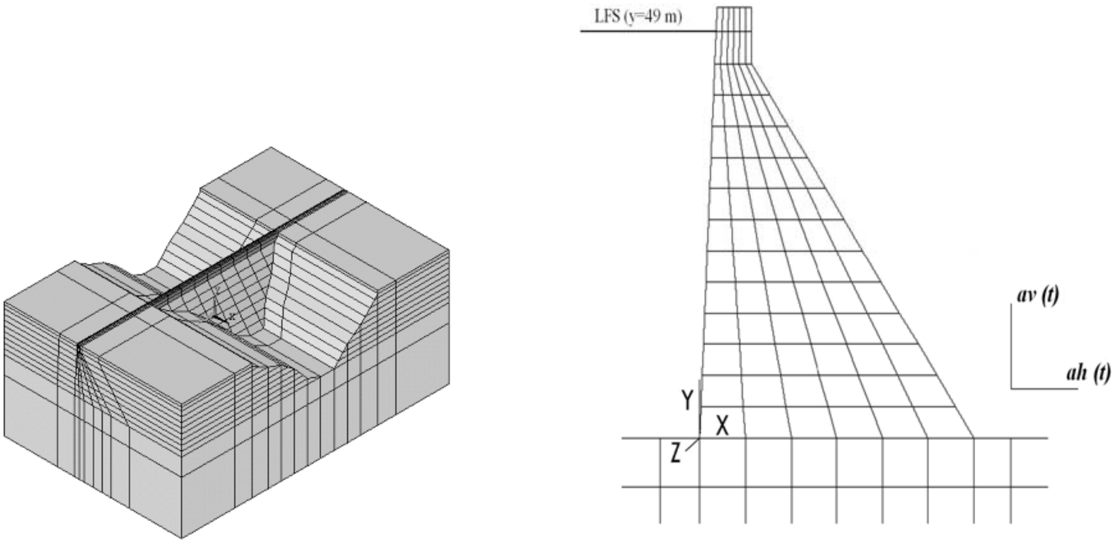


Figure 1 – Dam finite element models: 3D dam-reservoir-foundation model and 2D model for the highest section.

4.2. Design actions

The RCC dam structural analysis was accomplished considering the static action of the self-weight of the dam, and the hydrostatic pressure on the upstream face under the LFS corresponding to a height of water of 49 m. Acting together with the previous static actions, the dynamic seismic action was defined by the two components (traverse horizontal component a_h and vertical component a_v) of the soil free acceleration on the plane section simulating the dam model.
The free acceleration field was uniformly assumed as constant in all the points of the foundation base contact of the dam. Due to this seismic action hydrodynamic pressures are generated on the upstream face of the dam, whose pressure diagram is calculated using the formulation of Chopra as mentioned in [2].
Figure 2 shows the design horizontal and vertical seismic accelerograms already considered by the authors for this dam [8, 9]. These accelerograms were obtained from the recorded Taft earthquake [3]. The accelerations of that earthquake were scaled for a peek value of 0,5g in to horizontal component, corresponding to the value of the maximum acceleration of design earthquake with 10% of probability of being exceeded during the useful lifetime of the structure (assumed as being 100 years) with a return period of about 1000 years. Equivalent proportion was considered for the vertical component of the acceleration, corresponding to a peak value 0,29g. The considered design earthquake the duration of about 20 seconds for both components, and it corresponds to two series of accelerations with a total of 2*1024 time records.

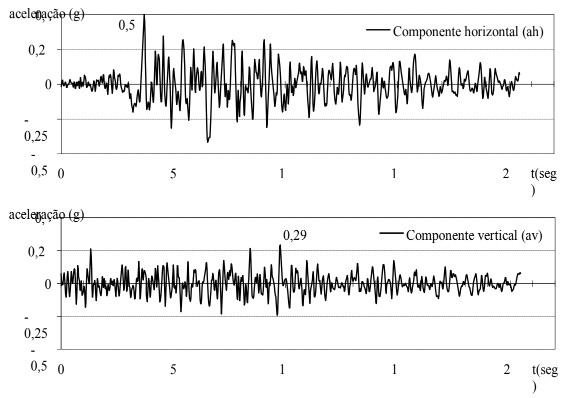


Figure 2 – Horizontal and vertical components of the free seismic acceleration at dam foundation.

4.3. Analysis of the seismic response of the RCC dam

The seismic results of the structural analysis include the nodal displacements and stresses in selected elements, due to the design actions previously considered. The results also include the dynamic characteristics of the dam, like the natural frequencies and the modes of vibration. For the considered actions and for each finite element, the values of the maximum and minimum principal stresses are presented as well as the instants of time at which such extreme happen for the given accelerograms; the temporal evolution of certain variables of interest, such as nodal displacements and element stresses, are also presented in tabular or graphical forms. Selected nodes are located in the upstream face of the dam, along its height; selected finite elements are located close to the crown and also at the connection zone of the dam with the foundation (Figure 3). Also, and in spite of having done the separate seismic analyses corresponding to accelerograms (a_h) and (a_h+a_v), only the results of the latter will be presented.

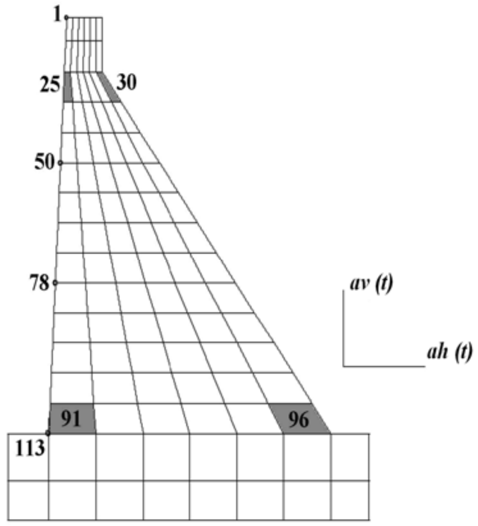


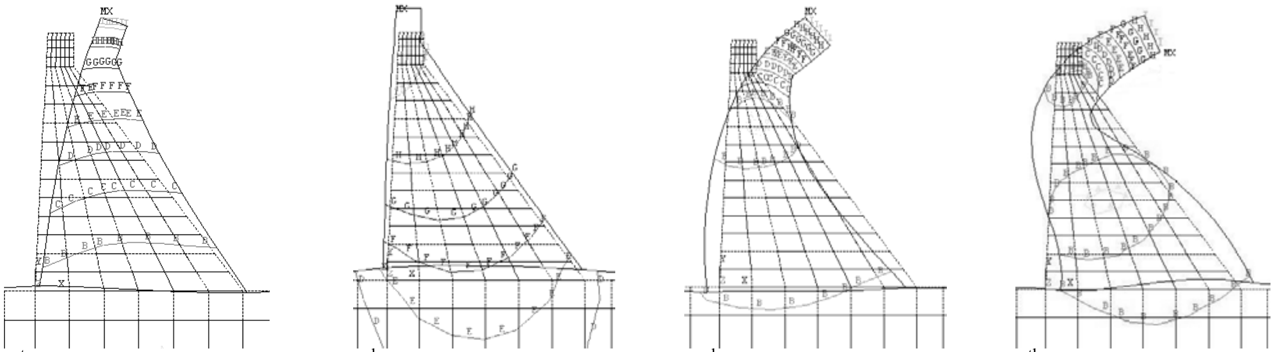
Figure 3 – Localization of nodes and elements of the 2D dam model, for evaluation of structural performance.

4.3.1 Natural frequencies and vibration modes

In Figure 4 the configuration of the first 4 vibration modes of the RCC dam with empty reservoir and the associated frequencies [8, 9] are presented (with the non-deformed configuration in the background); in the structural analyses, the first 10 vibration modes were considered. It is verified that the fundamental mode corresponds to typical deformation by flexure-bending of a cantilever, with a fundamental frequency of f_1=6,30 Hz. The second mode (f_2=10,27 Hz) corresponds to a deformation in which the vertical displacement component of the dam is preponderant. The third mode (f_3=13,40 Hz) is geometrically similar to the first mode but occurs at higher frequency with more energy of deformation involved. The fourth mode (f_4=23,41 Hz) also corresponds to a deformation by flexure-bending but with rotation in two structural sections (at base and at the zone of geometry change). Moreover it can also be verified that these four frequencies are very well separated.

4.3.2 Nodal displacements along height at the upstream face of the RCC dam

The horizontal displacement along direction upstream-downstream is the most significant and presents maximum amplitude at the crown very close to 4 cm. Figure 5 illustrates the time evolution of the horizontal and vertical displacements (U_x and U_y) in the selected upstream nodes (nodes 1 and 50). The horizontal displacements are preponderant, decreasing in amplitude along the height of the dam. For the same instants the vertical displacements are approximately constant along the height of the dam (up to a depth 2/3 of its height from the top crown) and they seem to happen simultaneously in the structure. Table 2 presents the maximum displacements of the upstream face, always occurring at the crown node number 1. The corresponding instants of occurrence are very close to the instants at which the scaled earthquake presents maximum accelerations.



1st Mode (f_1 = 6,30 Hz) 2nd Mode (f_2 = 10,27 Hz) 3rd Mode (f_3 = 13,40 Hz) 4th Mode (f_4 = 23,41 Hz)

Figure 4 – Configuration of first four vibration modes, for empty reservoir.

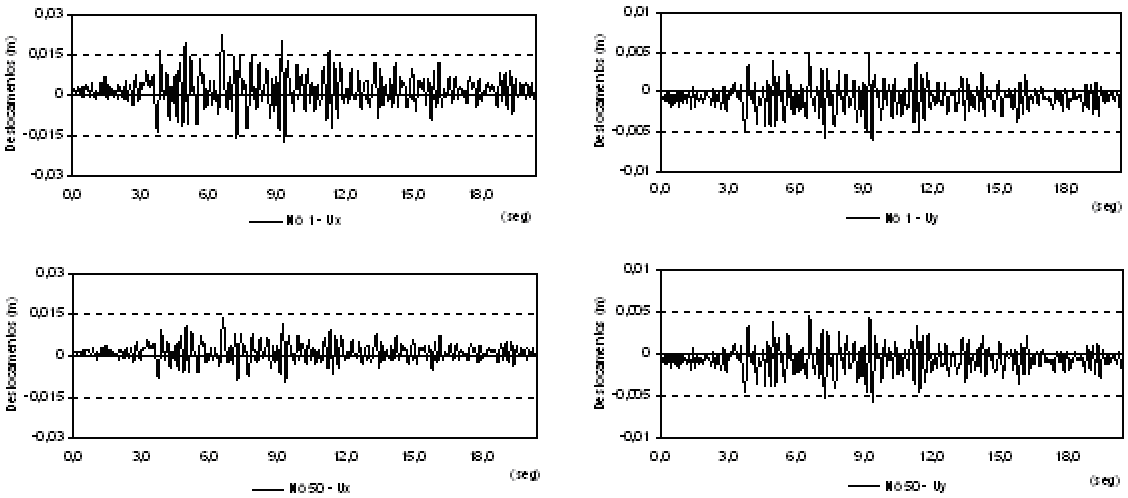


Figure 5 – Displacements (horizontal on the left; vertical on the right) of nodes 1 and 50, at the upstream face of the RCC dam, due to the design cumulative actions of self-weight, hydrostatic pressure at LFS and horizontal and vertical design accelerograms (jointly combined).

Table 2 – Displacements Envelope: Maximum values registered for the selected nodes at upstream face.

Displacements		*Value (cm)*	*Instant t (s)*	*Element*
max x	downstream	2,16	6,60	1
max x	upstream	- 1,81	9,38	1
max y	upwards	0,44	4,98	1
max y	downwards	- 0,59	9,38	1

4.3.3 Stresses in the elements of the RCC dam

As was done for nodal displacements, the four elements 25-30-91-96 (at the crown zone and at the foundation interfaces) were selected as elements for evaluation of the stress state in the body of the dam (Figure 3). The time evolution of the stresses in these elements (in terms of average stresses across the element) was already included earlier [8, 9] showing the prevalence of the vertical stresses s_y over the other two stress fields of horizontal normal stress s_x and shear stress t_{xy}; here, positive values correspond to tensile stresses. According to Table 3, the vertical stress is maximum at the upstream face close to the foundation (element 91). In that element the maximum tensile stress in the vertical y-direction (s_y) is about 1,4 MPa and the maximum vertical compressive stresses is about -2,7 MPa. Shear stresses t_{xy} are also included in Table 3.

Table 3 – Maxima and minima stresses at the selected finite elements.

Type of Stress	*Element*	*Instant t (s)*	*Stress value (MPa)*
max *sx*	30	9,38	0,269
min *sx*	96	6,60	-1,294
max *sy*	91	6,60	1,395
min *sy*	91	9,38	-2,677
max *txy*	96	6,60	1,467
min *txy*	91	3,74	-0,430

As the high magnitude design earthquake chosen corresponds to a failure rupture scenario (nevertheless accidental in terms of Eurocode design principles) with a return period of about 1000 years and with peak acceleration of 0.5g, the RCC dam structure (in the zone of tensile stresses and in the boundaries between adjacent concreting layers) will probably not present sufficient resistant capacity for the registered tensile stress values. However that high value of tensile stress only happens once at a specific instant, and in just about four times it presents values higher than 1 MPa (Figure 6).

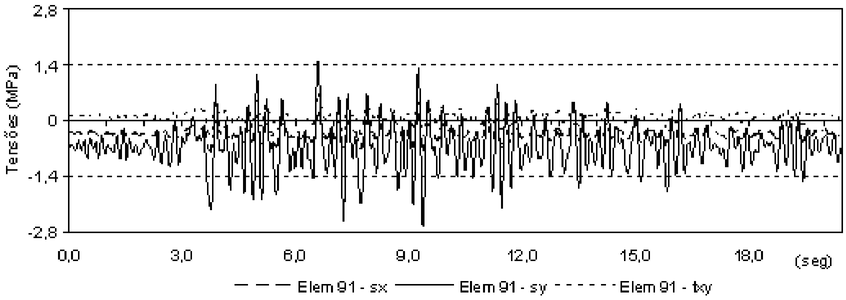


Figure 6 – Stresses in finite element 91 due simultaneously to self-weight, hydrostatic pressure at LFS and horizontal and vertical design accelerograms (jointly combined).

From the analysis it is not predicable that instability behavior and failure of the RCC dam structure might occur as a consequence of the localized and instantaneous high tensile stresses at specific sections or finite elements; nevertheless localized damages are expected in such circumstances. To understand the magnitude and spread of the latter damages, a more rigorous analysis can be done with material non-linear behavior through an adequate constitutive equation [8, 9].

In Table 4 a summary of the maximum and minimum principal stresses is presented. They occur at finite elements 91 and 96 close to dam-foundation contact. It is observed that the values obtained for the element 91 approach the values of the vertical stresses presented in Table 3; also, as anticipated, for finite element 96 the maximum compressive stress is higher than the vertical stress, having approximately an orientation parallel to the downstream face of the RCC dam. The instants of time at which the maximum principal stresses occur coincide with the instants at which the maximum vertical stresses were already determined and observed.

Table 4 – Principal stresses (maximum and minimum) near contact dam-foundation.

Element	*Instant t(s)*	*Maximum principal stress (MPa)*	*Instant t(s)*	*Minimum principal stress (MPa)*
91	6,60	1,815	9,38	- 2,747
92	6,60	0,581	9,38	- 1,099
93	6,66	0,030	5,70	- 0,861
94	6,64	0,115	6,60	- 1,229
95	9,36	0,319	6,58	- 1,887
96	9,38	0,467	6,60	- 3,105

From the finite element analyses it was observed that the element 96 registers practically compressive stresses and at element 25 occur compressive stresses and tensile stresses close to 0,8 MPa.. The horizontal normal stress s_x and shear stress t_{xy} have more reduced values, except for horizontal normal stress s_x in element 96 at the downstream zone of the dam close to the foundation that attains a magnitude of 1,2 MPa.

5. CONCLUSIONS

In this article the seismic analysis of a RCC gravity dam was accomplished – through the combination of the static self-weight and hydrostatic pressure of LFS with the dynamic seismic actions associated with scaled design accelerograms – for which were considered the mechanical characteristic properties of that RCC material. In spite of the three-dimensional geometry of the dam, it is possible to proceed to its structural analysis considering a finite element model simulating a plane state of deformation. The seismic analysis was accomplished with specific software, modified to operate in the International System of Units and also to allow obtaining the results of any variable in the time-domain. In the analysis were included: the hydrodynamic effect of the compressible water of the reservoir; the partial absorption of the seismic waves of hydrodynamic pressure in the foundation, aspect that allows attenuating the effects of the seismic action.
The considered seismic action is associated with free field design accelerograms (horizontal and vertical components) of a scaled earthquake with high values of the peak accelerations; it corresponds to a scenario of failure by rupture, with all the free field accelerations assumed constant in all the points of the dam-foundation contact interface. The analyses were performed in the domain of the linear behavior of the materials, and the results indicated the reduced possibility of occurrence of localized ruptures mainly in the upstream zone close to the dam foundation. The evaluation of those ruptures can only be conveniently accomplished using non linear behavior material models.

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