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SEISMIC SECURITY ASSESMENT OF EARTH AND ROCKFILL DAMS LOCATED IN EPICENTRAL REGIONS

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SUMMARY

The geomorphologic and climatic features of the central-west part of Argentina determine the need of building dams to take advantage of water resources and to enable power generation. Most dams are placed upstream of the oases in which population and productive activities are concentrated. Moreover, this region is the most seismically active in the country. Historical and instrumental records show that earthquakes with magnitudes larger than 7 can be expected from a number of earthquakes sources. These facts turn seismic safety of dams into a fundamental issue for the region. In the last decade, knowledge about seismic motion in epicentral areas has been improved significantly, mainly on the basis of instrumental records. Also the analysis tools for the seismic behavior of dams were improved, mainly in the field of numerical methods, such as the development of new constitutive models, the modeling of large displacements problems and the treatment of strain localization. This paper is concerned with the factors controlling the design of dams subjected to earthquake action, the criteria for safety verification, and the analysis tools available to perform such verification.

INTRODUCTION

The geomorphologic and climatic features of the central-west part of Argentina cause most of the population and productive activities to concentrate in oases served by artificial irrigation. Water supply to these oases, both for irrigation and for human consumption and the need of power generation have encouraged the construction of large dams in all rivers with permanent flow regimes. Figure 1 depicts geographic location of 14 dams on seven rivers: Huaco, Jáchal, San Juan, Mendoza, Tunuyán, Diamante and Atuel. Six of these dams are concrete structures and the remaining are earth dams. Two of them, Caracoles and Punta Negra on San Juan River, are currently under construction while the rest is in operation.

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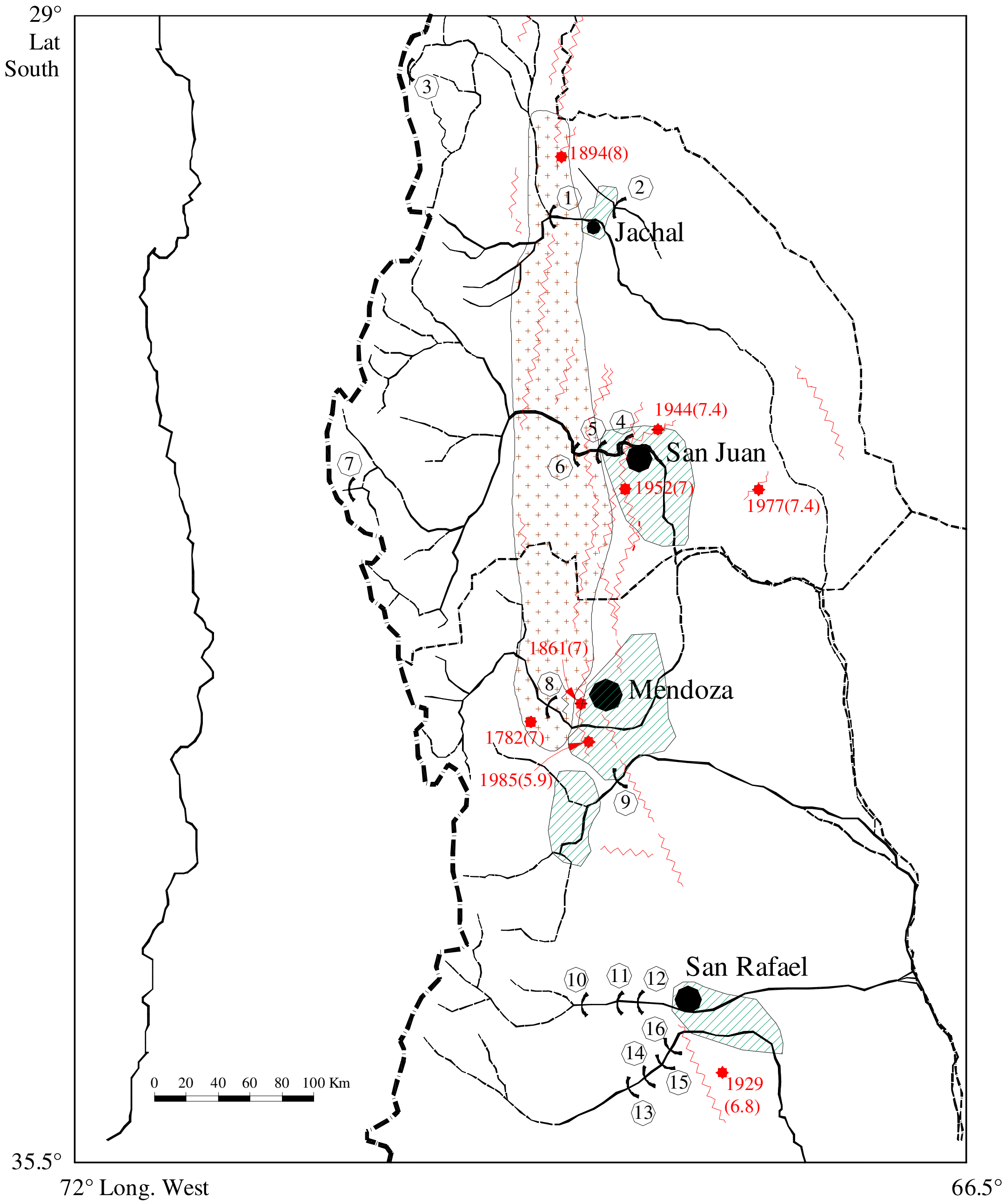

	Dam (Height[m])	Type	Stage
1	Cuesta del Viento(100)	ZER	O
2	Los Cauquenes(45)	C	O
3	Pascua-Lama(100)	TD	P
4	Ullúm(60)	ZER	O
5	Punta Negra(120)	CFD	C
6	Los Caracoles(150)	CFD	C
7	El Pachón	TD	P
8	Potrerillos(140)	CFD	O

	Dam (Height[m])	Type	Stage
9	El Carrizal(55)	ZER	O
10	Agua del Toro(120)	C	O
11	Los Reyunos(132)	ZER	O
12	El Tigre(49)	ZER	O
13	Los Nihuiles(28)	C	O
14	Aisol(38)	C	O
15	Tierras Blancas(37)	C	O
16	Valle Grande(115)	C	O

ZER: Zoned earth or rockfill C: concrete dam
CFD: Concrete faced dam TD: Tailing dam

O: Operational P: Projected
C: Construction

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Oasis under irrigation

Precordillera

1977(7.4) Historic earthquake: Year(Magnitude)

Active fault

7 Dam

Figure 1: Midwest region of Argentina. Dams, active faults and epicenters of historic earthquakes.

All these dams are located upstream of important population centers and crop fields. Agriculture is the region's main resource. Collapse of one of these works would threat human lives, properties and lifelines, like water provision systems for human consumption and for irrigation. Moreover, there are important mining projects currently being developed in the Andes mountains, such as Pascua-Lama and El Pachón. Building of large tailing dams is foreseen in these facilities. Hazards associated to these works, even though of a different nature, are also significant. An accident occurring in tailing dam would put in danger the quality of the water resources of a whole oasis.

In addition, the referred region is the one with the greatest seismic activity in the country. Figure 1 also shows the epicenters of destructive earthquakes from which historical records are kept. It also indicates the traces of the currently known main active faults. Considering the magnitude of past earthquakes and the length of these faults, it is clear that the region of Precordillera in San Juan and Mendoza has a seismic hazard level comparable to that of the most seismically active areas in the world. On the other hand in the neighborhood of the oasis of San Rafael, historical seismicity and neotectonic evidence suggest that seismic activity is less intense than in the region of Precordillera.

These considerations show the importance that seismic safety of dams has for people living in this region. The present work analyzes the factors that influence the safety assessment and the design of dams subjected to earthquakes. Criteria for the seismic safety verification of dams and the analysis tools currently available to carry out that verification are also discussed here.

SEISMIC INPUT FOR THE VERIFICATION OF DAMS

During the 90's decade, the knowledge about the seismic motion in epicentral areas was substantially improved. This was due to the increase in extension and density of strong motion seismographs networks, which were installed in many countries across the world upon the 80's. To illustrate this, let us compare the information obtained of 1977 San Juan earthquake with that of 1999 Taiwan earthquake. In the first case, only two strong motion records were obtained, being both instruments located at nearly 80 km from the epicenter (in the city of San Juan). On the other hand, by the time 1999 Chi-Chi earthquake occurred, there were more than 1000 recording instruments installed in Taiwan, spread in a surface of 36000 km^2 (equivalent to 40% the extension of the province of San Juan). Within a radius of 50 km from the epicenter, about 80 acceleration records were obtained, some of them located a few meters away from the trace of the source fault. The major increase in the amount of field data and the possibility of obtaining measurements of the motion within the epicentral area (less than 20 km from the seismic source), have led to the identification of new features of seismic motions that were previously unknown.

Figure 2 shows the response spectra for 5% damping, calculated from instrumental records obtained during some of the recent major earthquakes occurred worldwide. All the records belong to crustal earthquakes and have been obtained in rock or hard soil sites at short distance from the seismic source. These response spectra are compared in the same figure to those resulting from the application of the normalized design spectrum and the attenuation law proposed by Seed [1]. Such design recommendations were based on the available instrumental information before the 80's decade. Seed [1] normalized spectrum was obtained as a conservative envelope of the spectra computed from 59 rock and hard soil records. The mean envelope computed for the corresponding magnitude and distance to the earthquake source is compared with the response spectrum for each one of the field records referred in Figure 2. This comparison shows that the seismic previsions, which were assumed as conservative two decades ago, have been largely overcame by real records obtained during recent earthquakes.

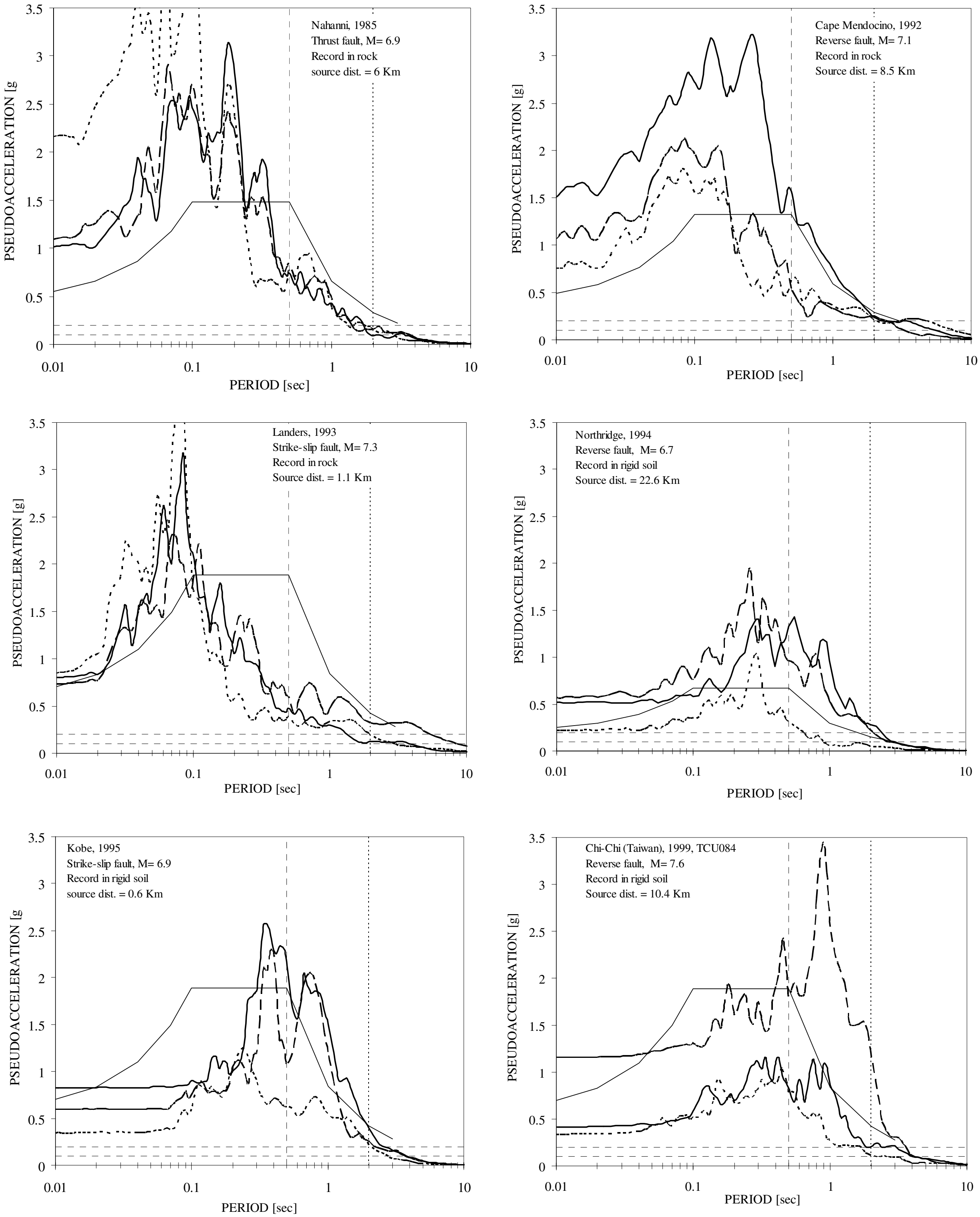

Figure 2: Linear response spectra for 5% damping, computed from records of recent earthquakes. Continuous line: N-S component; dashed line: E-W component; dotted line: vertical component; thin line: design spectrum proposed by Seed [1] (Strong motion data from PEER Database).

Several conclusions can be drawn from figure 2. First, new instrumental information shows that peak ground accelerations occurring in epicentral areas are substantially larger than the limits assumed as physically possible before the 80's decade. In rock sites, the largest ground acceleration for any earthquake magnitude was supposed to be less than 0.8g. This limit has been largely exceeded in many epicentral records obtained during recent earthquakes. This feature of motion may not be considered to be relevant for the safety of large earth dams, since their fundamental periods usually fall in the post-peak zone of the pseudoacceleration response spectrum. However, large accelerations in rock sites are determinant when verifying rigid structures as concrete gravity dams and appurtenant structures such as spillways, intake towers and other discharge structures. A critical aspect of the safety verification arises when such appurtenant structures are crucial for the dam safety and therefore they must remain operative even under the action of an extreme event.

Another important known phenomenon is the influence of topography over local features of motion. During 1994 Northridge earthquake, records were obtained simultaneously on the left abutment of Pacoima dam (113 meters high) and at the bottom of the valley. Both instruments were placed on rock. Figure 3 compares the response spectra computed for each of the three components of motion recorded in both locations. It is clear that the rock promontory that forms the left abutment of the dam caused the amplification of the acceleration values by a factor between 3 and 3.5 in horizontal components, and by 6.5 in the vertical component. North-South direction coincides with the most slender (base/height ratio ≅ 2) section of the promontory. These observations point out the shortcomings of the traditional hypothesis of considering the foundation rock and the abutments as a unique and non-deformable boundary, trough that the seismic action is input to the dam. Furthermore, they suggest that the seismic motion applied to the base of the dam as safety earthquake may be unsafe to verify an appurtenant structure, such as a spillway, in case it is founded on a slender abutment.

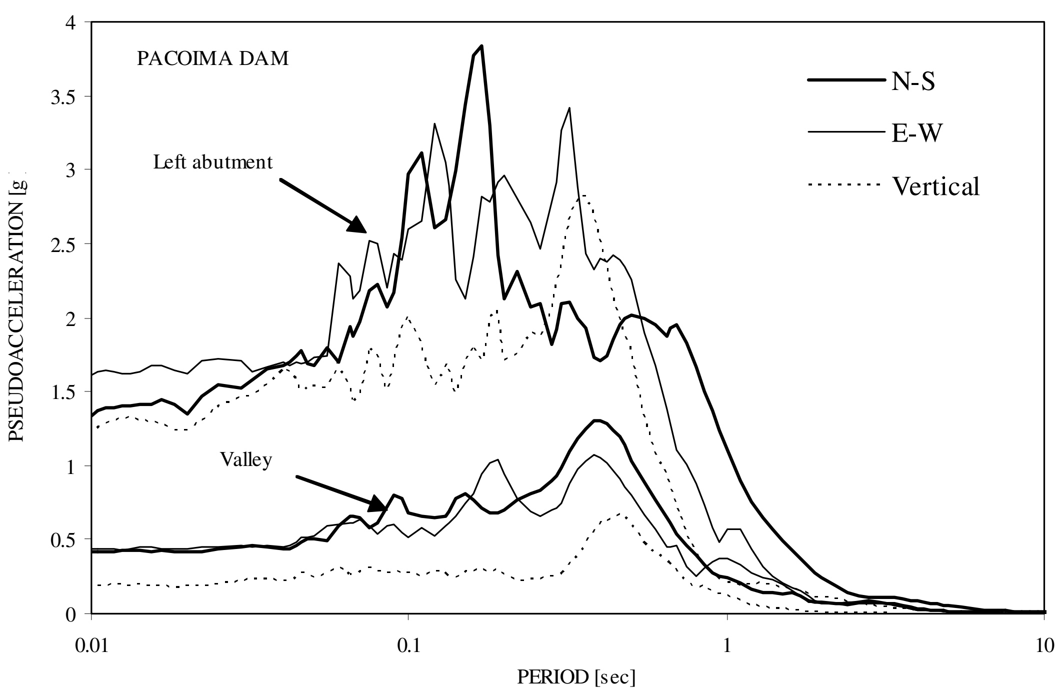

Figure 3: Linear response spectra for 5% damping, computed from rock site records obtained in left abutment of Pacoima dam and in the bottom of the valley, downstream the dam. (Strong motion data from PEER Database).

Finally, it has also been noted that many recently obtained epicentral records contain large velocity pulses, reaching values significantly larger than the ones thought as reasonable before the 80's decade. Seed [1] recommend estimating peak ground velocity within a radius of 50 km from the epicenter with the following expressions:

$$v_{\max}/a_{\max} = 55\,cm/s/g \quad \text{in rock}$$
$$v_{\max}/a_{\max} = 110\,cm/s/g \quad \text{in rigid soil}$$

where $v_{\max}$ and $a_{\max}$ are respectively peak ground velocity and peak ground acceleration. Combining these expressions with an expected maximum 0.8g peak ground acceleration, values of 44 and 88cm/s result for rock and rigid soil respectively. However, the record named TCU084 in figure 2, contains a peak ground velocity of 263cm/s. These velocity pulses are known to be caused by directivity (Somerville [2]) and fling effects (Steward [3]). Such features were detected in various recent earthquakes as Loma Prieta (USA, 1989), Landers (USA, 1993), Kocaeli (Turkey, 1999), Chi-Chi (Taiwan, 1999) and Ducze (Turkey, 1999). These velocity pulses imply the content of long period components in the acceleration record, as seen in the response spectra plotted in Figure 2 for Kobe (1995) and Chi-Chi (1999) earthquakes. These long period components particularly affect large earth dams, which have typical natural periods (in the inelastic range) between 0.5 and 2 seconds (indicated with vertical dashed lines in Figure 2).

In many seismic regions around the world, a process of revision of seismic safety of dams has started a few years ago; in several cases this has led to reinforcement works in the dams. Marcuson [4] describes seismic reinforcement works carried out in 36 dams in United States. It should be noted that several dams built before the 70s' decade were designed with pseudostatic methods applying seismic coefficients between 0.1g and 0.2g (range plotted with dashed horizontal lines in figure 2) (Seed [5]). On the other hand, advances in seismic source characterization techniques, fundamentally neotectonic and paleoseismology, have led to a re-evaluation of seismic threat in dams locations, allowing detection of cases in which this threat had been underestimated at the time of dam verification.

It is important to emphasize the main role that paleoseismicity research plays in seismic characterization of a region. This research is of main concern for seismic verification of dams, since seismic motions usually specified for the verification of these structures have return periods between 5000 and 10000 years, whereas historical seismic activity in the midwest region of Argentina has been observed and recorded just for little more than 200 years. Paleoseismicity research allows the extension of the observation window to the whole Quaternary (1.6 million years), bringing great enhancement to our ability to understand and characterize a region's seismic activity. Some evidence of paleoseismic activity has been recently identified in the region under study (Paredes [6], Fauqué [7]).

CRITERIA FOR SEISMIC VERIFICATION OF DAMS

According to ICOLD recommendations, dams should be verified under two scenarios: normal operation earthquake and safety earthquake. The latter often coincides with the maximum believable earthquake for the location of the dam (Wieland [8]). Under the normal operation earthquake, the dam is expected to sustain seismic action with minor damage that not implies interruption in operation. On the other hand, verification with safety earthquake aims to prove that the dam does not jeopardize human lives or properties downstream the dam. For the safety earthquake, the structure is expected not to collapse nor reach a situation of uncontrolled water release, although it is acceptable the occurrence of important damage leading to the need of stopping the operation or even to empty the reservoir in order to carry out reparations.

From a methodological point of view and considering available tools, analysis of the behavior of a dam sustaining normal operation earthquake does not pose great difficulty in most cases. Verification normally involves stability check, permanent deformation and displacements estimation and stress check in concrete structures. In contrast, when considering the safety earthquake, dams located in areas of high seismic activity are expected to sustain major damage, taking the structure to a near-collapse stage. In fact, evaluation of safety should include analysis of all possible collapse mechanisms for the structure, in order to study the structure's safety margin with respect to each of these mechanisms. Different natures of damage that an earthquake can induce over earth dams (Seed [5]) and over concrete dams (USACE [9]) are summarized broadly in Table 1.

Table 1: Damage induced by earthquakes over earth and concrete dams.

EARTH DAMS	Settlement (loss of freeboard)
	Embankments sliding
	Sliding of dam over foundation
	Cracking of watertight members and uncontrolled water leaks
CONCRETE DAMS	Cracking of concrete
	Openings of construction joints
	Sliding along construction joints
	Sliding and/or rotation over foundation

Safety evaluation at high damage stages such as those expected to be produced by the safety earthquake may require sophisticated analysis tools. From a mechanical and hydraulic point of view, the analysis should take into account a series of complex phenomena. In earth dams, such phenomena may include the occurrence of plastic strains, liquefaction or cyclic mobility of saturated granular materials, strain localization in sliding surfaces, cracking, large displacements problems and water seepage with particle erosion. The analysis of collapse of concrete dams may include structure, water and foundation dynamic interaction, cracking and scale effects, the action of water pressure inside cracks and below foundations, and sliding or rocking of the dam over its foundation with temporary loss of contact.

In general, the kind of analysis tools that would be required to perform a complete analysis of the dam behavior under the action of the safety earthquake are still under development, some of them being used for research purposes, but they are not of common use in engineering practice. The main obstacle to achieve the spreading of sophisticated analysis tools to practice is that they are not yet conveniently tested against measurements and observations of real cases, being an additional difficulty the low number of dams that had sustained intense, epicentral area seismic motion. Moreover, it is worth noting that even lower is the number of instrumental records of dynamic response of dams subjected to seismic motions.

ANALYSIS TOOLS FOR EVALUATION OF EARTHDAMS SEISMIC BEHAVIOR.

New knowledge about epicentral seismic motions has led, in some cases, to the specification of more intense safety earthquakes than in the past and this has brought new challenges to the field of analysis of dams' seismic behavior. Under higher levels of seismic excitation, the limitations of some tools commonly used in engineering practice are revealed. The level of seismic excitation currently considered for safety verification of dams takes the analyses into behavior stages that were not considered previously, changing in many cases the scope and methodology of verification.

As an example, in the case of earth dams with central clay core, a few years ago the goal of verification was to ensure that, within the body and the foundation of the dam, the water pressure built-up due to earthquake action is limited to moderate values. This was the logical design criterion following the

Terzaghi's effective stress principle, since if the pore pressure increase becomes equal to the existing effective stress, the material's strength would drop to zero and such a dangerous situation should be avoided. Classic methodology of analysis consisted of estimating the increase in pore pressure caused by the earthquake and then to evaluate post-earthquake stability condition of the embankment considering effective stresses (Banerjee [10]). If such analysis is performed for a dam being subjected to currently known seismic input corresponding to the epicentral area of a destructive earthquake, the pore pressure ratio (ru = pore pressure increase due to earthquake/pre-earthquake mean effective stress) would result near 100% in extensive areas of the structure and foundation. Even if the shell materials are well-compacted gravels, as it is the case of the dam referred in Figure 4, showing r_u contours obtained with the Seed-Lee-Idriss method (Zabala [11]), under the action of the safety earthquake specified for the site (M = 7.5, PGA = 0.5g). In this particular case the analysis would conclude that the upstream slope becomes unstable due to earthquake action. Moreover, no practical corrective measures are known in order to avoid large pressure built-up. This means that for many dams located in epicentral areas the adopted design criterion is impossible to meet.

In fact, the situation depicted in Figure 4 does not really imply the structure to be at risk of collapse. Since dense granular materials tend to dilate when subjected to shear strains, the pore pressure would drop immediately if any minor sliding takes place. The undrained residual strength of dense granular materials is high, and therefore the stability of the structure is ensured even if the earthquake does cause the high pore pressures showed in Figure 4. In fact, the dilatant material can reach cyclic mobility during the seismic motion, which implies a momentary loss of stiffness without loss of strength. If this were the case, it would be necessary to estimate permanent deformations caused by the earthquake, and to check that these deformations do not represent a risk to the structure (overtopping risk, for example).

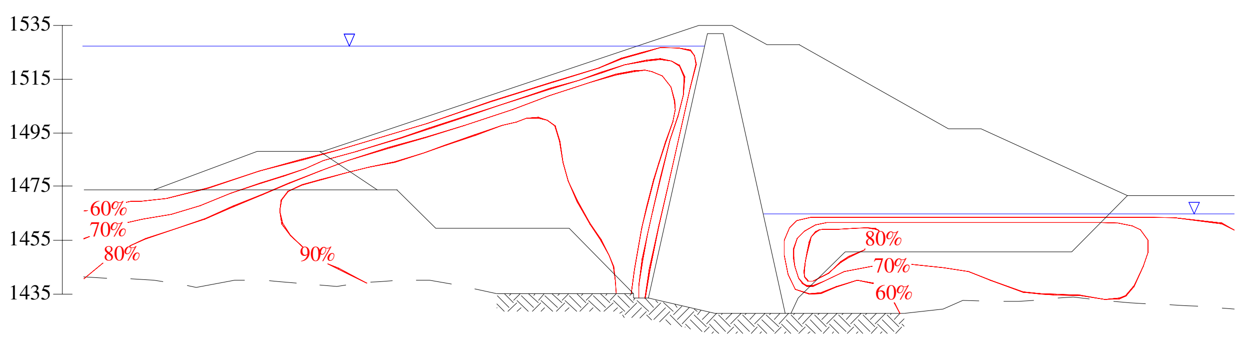

Figure 4: Pore pressure increase in Cuesta del Viento dam, obtained with Seed-Lee-Idriss method for the safety earthquake (Mw = 7.5, peak ground acceleration = 0.5g)

The previous example illustrates the change of design criteria, verification methodologies and analysis tools promoted by the fact that current design motions are significantly larger than before. The traditional tools to perform the safety analysis of dams subjected to seismic action are the stability evaluation by limit equilibrium methods, the dynamic response analysis by means of elastic or linear equivalent finite element models and the estimation of permanent displacements using Newmark [12] method. All these tools are based in relative simple algorithms. They require little initial information and provide results that are easily interpreted. In addition there is plenty of experience on their application.. However, it is important to take into account that these advantages arise from the strong simplifying hypothesis used in model formulations, which necessarily imply strong limitations to their application.

A finite element code called GEOSIS (Zabala [13]) has been developed with the main goal of performing dams deformation analysis under the action of seismic motions. Coupled nonlinear dynamic analysis in effective pressures with pore pressure generation is performed by using a generalized plasticity constitutive model (Zabala [14]). The constitutive model allows, with reasonable approximation, the reproduction of relevant aspects of granular materials behavior at different conditions: dry material (in drained condition), saturated material (in undrained condition), gravity loads and seismic (dynamic) loads. Some of mechanical behavior aspects this model accounts for are:

- Dependence of volumetric and shear stiffness with confinement level.
- Generation of permanent deformations depending simultaneously on load increment, current effective stress state and load history of the material.
- Representation of contractive or dilatant behavior in drained condition, depending on void ratio and confinement level.
- Peak and residual strengths in drained and undrained conditions.
- Material densification in drained condition due to cyclic loading.
- Liquefaction and cyclic mobility phenomena in undrained saturated materials due to cyclic loading.

Figure 5 shows typical examples of results obtained with GEOSIS. Figure 5.a shows the deformed configuration (amplified 10 times) of a model of Los Reyunos dam at the end of the verification earthquake. This dam is built with a clay core and alluvial gravel shells. Figure 5.b shows the deformed configuration of a mesh representing Caracoles, a concrete faced gravel dam. The resulting configuration is caused by combined effects of seismic action and gravity loads, self-weight and water load over the concrete face. It is worth noting that the behavior of each type of structure is different. In zoned dams, upstream displacements of the upstream shell are expected due to the phenomenon of cyclic mobility taking place in the saturated materials. On the contrary, in concrete faced dams, larger permanent displacements are expected to occur in the downstream slope. The upstream portion of the dam is under very high confinement stresses due to the action of water loads over the concrete face and hence this portion is very much stiffer than the rest. These results qualitatively show that the model is able to capture these significant features of the behavior of each type of structure.

a)

b)

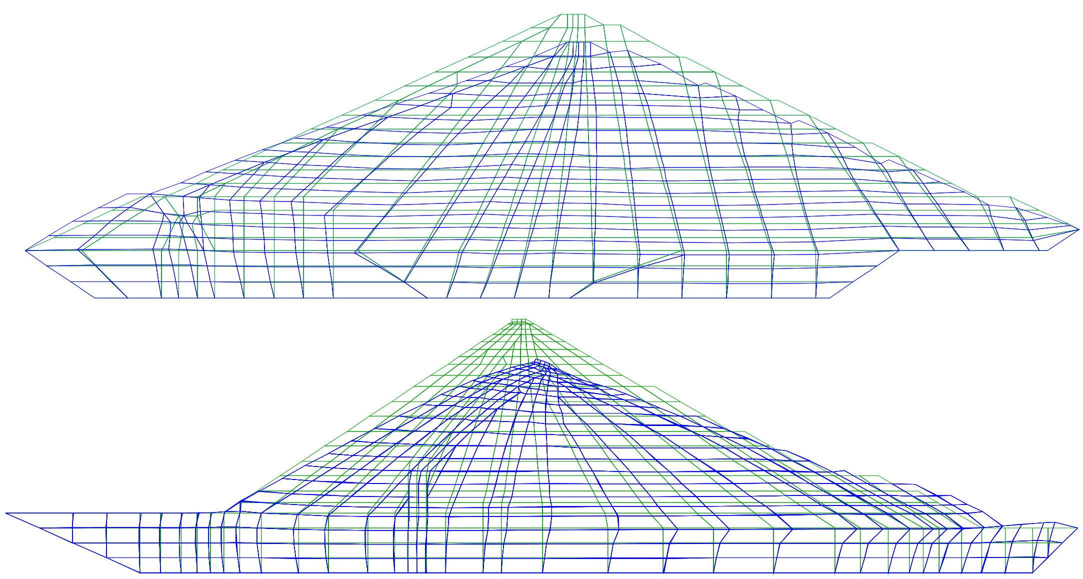

Figure 5: Results obtained with GEOSIS. Permanent displacements (amplified) due to seismic input (a) a zoned dam with clay core (Los Reyunos), and (b) a concrete faced dam (Caracoles).

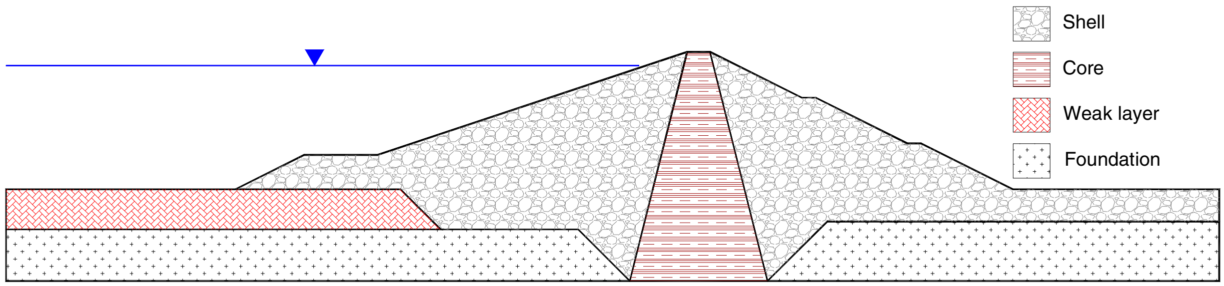

Figure 6: MPM Analysis of an earth dam. Materials used in the model.

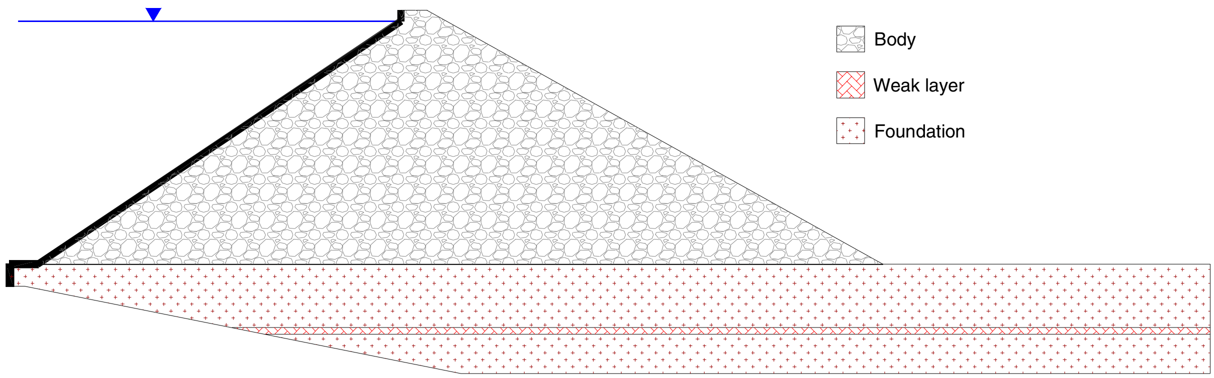

Figure 7: MPM Analysis of a concrete faced dam. Materials used in the model.

In addition, it must be considered that within a dam under earthquake action, failure mechanisms involving strain localization, sliding surfaces or cracks , may develop. High accelerations are to be expected at the crest of dams, due to dynamic amplification effects. These accelerations may induce sliding failures in the crest area. Other failure surfaces may occur by the presence of weak zones. In these cases, unless special techniques are applied, usual finite element codes cannot satisfactorily reproduce this kind of failure involving strain localization. Models with the ability of representing these phenomena are currently in development, using adaptive finite element meshes and particle methods with regularization techniques.

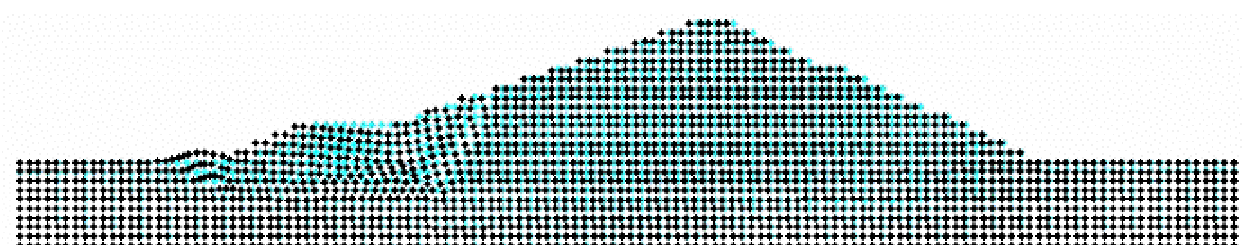

Figure 8: MPM analysis of an earth dam. Deformed configuration of an earth dam including a weak zone in the upstream (left) shell, for 0.56g lateral pseudostatic acceleration.

Figures 8 to 11 show results of analysis of two dams. These analyses have been performed using a code currently being developed at National University of San Juan; the software is based on a meshless particle method called material point method (MPM) (Sulsky [13]). The analyses were aimed to determine collapse mechanism and the corresponding values of lateral pseudostatic acceleration that trigs collapse.

Figure 8 shows deformed configuration of an earth dam when subjected to a horizontal pseudostatic acceleration. The dam has a clay core and gravelly shells. There is a weak material layer at the toe of the upstream (left) shell (see Figure 6). Figure 9a shows the position of sliding surfaces (where strain localization occurs), and Figure 9b plots displacement vectors, giving a picture of the potential collapse mechanism. The yield pseudostatic acceleration determined by the model has a relatively large value, 0.56g, from which low permanent displacements are expected to occur in the dam.

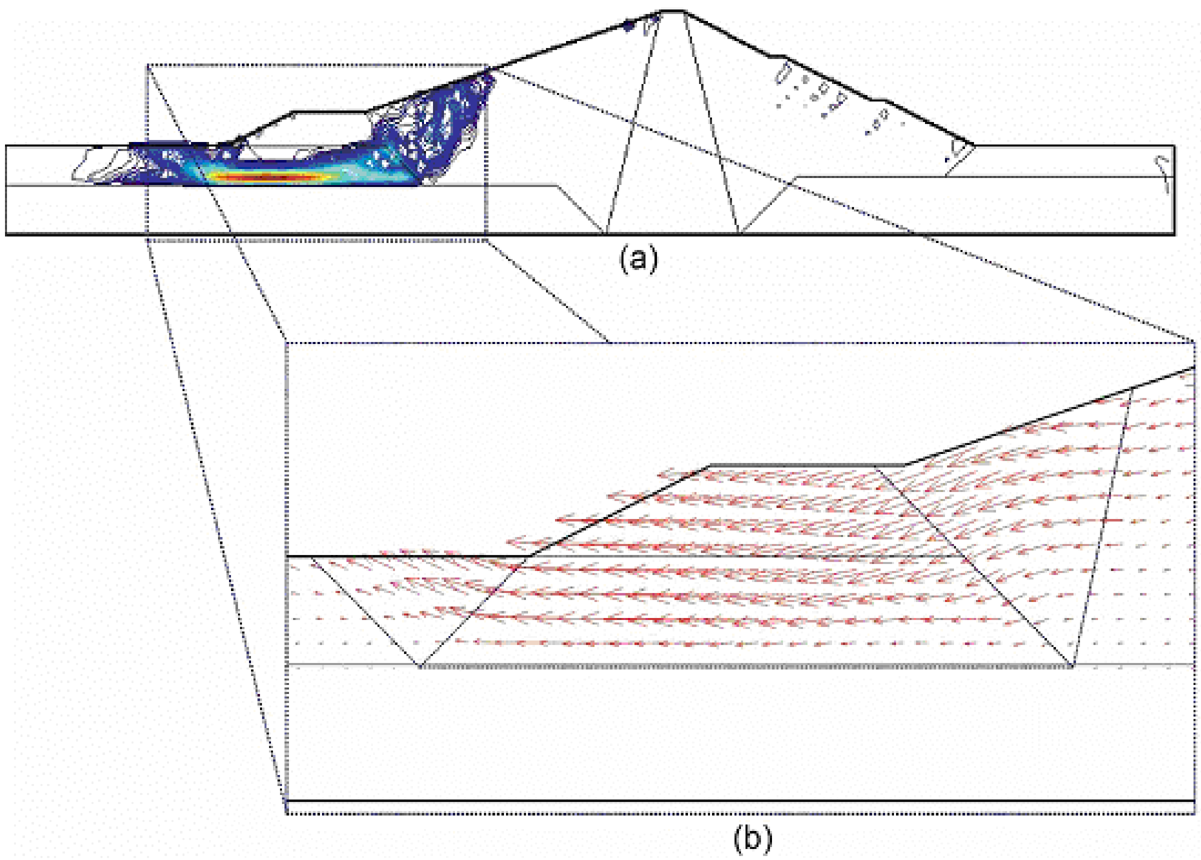

Figure 9: MPM analysis of an earth dam. Analysis performed applying Mohr-Coulomb yielding criteria. (a) Contours of plastic strain. (b) Displacement vectors and trace of deduced collapse mechanism.

Figure 10 shows the sliding mechanism of a concrete faced dam founded on an alluvial deposit containing deep-seated weak, liquefiable layer. Distribution of materials considered in the model is depicted in figure 7. Sliding is triggered by a 0.06g lateral pseudostatic acceleration, involving the entire body of the dam. Figure 11 plots contours of plastic strain, showing high strain localization along the weak layer. Note the passive wedge expelled upwards in the lower part of downstream (right) abutment, in order to accommodate lateral motion of the dam.

The results presented in Figures 8 to 11 suggest that the MPM is able to capture the strain localization phenomenon, and to detect, without a priori assumptions, the collapse mechanisms of the structure involving sliding surfaces. Although the pseudostatic analyses presented here do not provide quantitative information about permanent displacements or strains caused by earthquake action, the yield acceleration determined with the model can be used in a Newmark type analysis in order to estimate the final configuration of the structure.

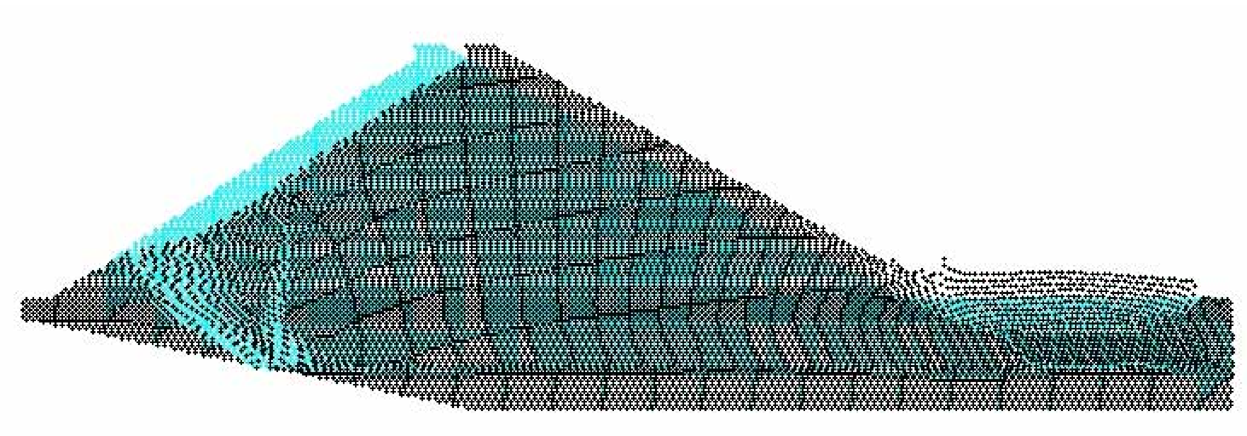

Figure 10: MPM analysis of a concrete faced dam founded on alluvium containing a deep-seated weak layer. Sliding mechanism triggered by 0.06g horizontal pseudo-static acceleration.

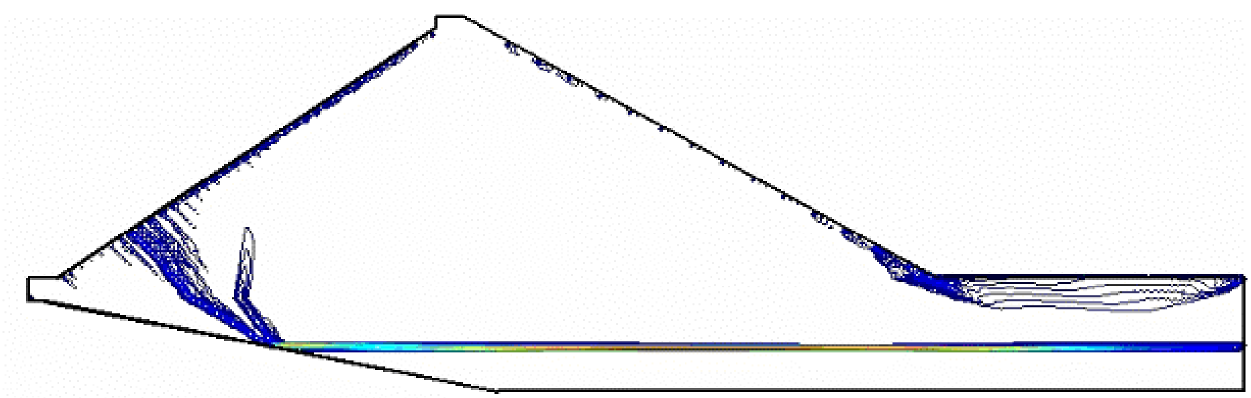

Figure 11: MPM analysis of a concrete faced dam. Contours of plastic strain. Analysis performed applying Mohr-Coulomb yielding criteria.

Table I shows some features of analysis methods evolution, from the linear equivalent model used in the 80´s to particle models. This last kind of models can provide better estimates of the position and shape of localized zones , i.e. yield surfaces and cracks. Also they can deal with large displacement without the mesh distortion that arises with finite element method. Mesh preparation and 3d models are more simple to develop.

Table I. Evolution of models for safety assessment of earthdams

Type of analysis	Dynamic analysis with linear equivalent finite element model.	Nonlinear coupled effective stress analysis. Finite elements without remeshing.	Nonlinear coupled effective stress analysis. Particle methods. (MPM)
Results	Final pore pressure distribution. Acceleration response.	Step by step pore pressure buildup and dissipation. Acceleration response. Permanent deformations.	Step by step pore pressure buildup and dissipation. Acceleration response. Permanent deformations. Localized deformation zones. Collapse mechanism arises from the model.
Safety checks	Post-earthquake stability analysis with effective stresses. Deformation potential. Newmark displacement analysis using acceleration response.	Post-earthquake stability analysis with materials residual strength. Newmark displacement analysis. Final freeboard loss.	Final displacements. Final freeboard loss.
Model features	Dynamic response errors. No estimation of plastic deformation.	Poor definition of localized zones, yield surfaces and cracks. Mesh dependence of localized deformation zones. Need of regularization techniques.	Need of regularization techniques for softening materials. Large displacement without mesh distortion. Simple 3D implementation.

CONCLUSIONS AND FINAL REMARKS

Seismic safety of dams is of great interest for midwest region of Argentina. Dams are the biggest and more complex structures built in the region today and this region is also the most seismically active of the country. These facts justify the effort to acquire enhanced comprehension of seismic behavior of these structures, and to develop more reliable technologies to assess their safety.

It is important for dam engineering to recognize the fact that in the 90's decade important advances have taken place in knowledge of seismic hazard, by means of instrumental records obtained in epicentral areas, at different locations around the world. This knowledge has direct impact when specifying the safety earthquake, which has to be used for verification of dams placed short distance (less than 20 km) from seismic sources. In many cases, consideration of this new knowledge has led to a significant increase of verification accelerogram intensity, subsequently requiring remediation actions for operational dams, and updating of projects for future structures. Though this change of criteria has already taken place in some dam engineering teams, there is still a strong ideological inertia leading to think as universally valid seismic design criteria established since mid of XX century. This may be partially because only a few dams have collapsed as result of earthquakes in the past decades; and this can lead to think that dams are "intrinsically" safe against seismic action. Nevertheless, it should be considered that destructive earthquakes are very infrequent phenomena, and that dams are rare structures. Consequently, it can be stated that there is still not enough experience on what the behavior of an earth dam would be when subjected to seismic motions such as the ones recorded in the last earthquakes.

Analysis tools currently used in engineering practice include relative simple models, which offer advantages in reliability and ease of result interpretation, but have shortcomings in their applicability. It is important to take care in validating these models and interpreting their results. This is particularly important when the behavior of a dam includes complex phenomena such as liquefaction or cyclic mobility of saturated granular materials, loss of stability due to strength degradation, strain localization, dynamic response of plastic systems, cracking, scale effects, dynamic response of block separated from foundations, etc.

On the other hand, there are sophisticated analysis tools nowadays, which allow consideration of many complex phenomena occurring in a dam subjected to seismic action. Many of these tools are still in development stage and have a promising future. Others are already available as commercial software. The main difficulty for their application is, given the complexity of algorithms used in the models, that it is often impossible to judge how approximate these results to reality are. In order to overcome this difficulty model predictions should be contrasted with real behavior data. However, data from measurement of seismic behavior of dams are still very scarce.

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