INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

SIMSG ISSMGE

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy,
ISBN 978-0-367-14328-2

Earth dams: Damage mechanisms and limit states in seismic conditions

L. Pagano
Department of Civil, Architectural and Environmental Engineering, University of Naples Federico II, Naples, Italy

C. Russo
Ministry of Infrastructures and Transport – General Management for Dams, Structural and Geotechnical Division, Naples, Italy

S. Sica
Department of Engineering, University of Sannio, Benevento, Italy

R.M. Costigliola
Department of Civil, Architectural and Environmental Engineering, University of Naples Federico II, Naples, Italy

ABSTRACT: The paper summarizes the main damage mechanisms suffered by earth dams under both strong earthquakes and normal operation to identify the limit states that should be taken into account for dam seismic safety assessment. In addressing limit states, a distinction is made between seismic and post-seismic stages. The limit state of global instability under the effects of inertial loads is considered both in the seismic stage, taking into account the favourable contributions of ground motion asynchronism and during the post-seismic stages, when excess pore water pressures induced by seismic shaking and by a possible rapid drawdown could affect dam behaviour. The limit state of dam freeboard loss is then dealt with, showing the importance of estimating settlement rates during the seismic and post-seismic stages. Third, the limit state of water-tightness loss is discussed with reference to seismic-induced strain concentration or stress changes. Finally, the risk of liquefaction within the embankment or in the foundation is considered, discussing how the phenomenon could be affected by changes in particle grading possibly experienced by coarse-grained materials during normal operation of the dam.

1 INTRODUCTION

In several high seismicity countries worldwide, technical regulations and guidelines prescribe how to assess the seismic safety of earth dams. Reference documents specify that seismic verifications should typically consider the four limit states (LSs) of global instability, freeboard loss, water-tightness and liquefaction. However, technical regulations are rather vague on whether such limit states have to be verified in seismic or post-seismic stages and on how to evaluate the acceptability of the predicted performance. The LS of global instability, for example, might traditionally refer to dam global collapse under the inertial forces induced by an earthquake, or could go deeper into the investigation on how sliding surfaces affect dam water-tightness. Could such investigations be limited to the seismic stage or should they be extended also to the post-seismic stage when, although inertial forces are no longer acting, redistribution of seismic-induced effects, like excess pore water pressures, may induce critical conditions?

Without specific indications in the norms, dam safety assessment requires a considerable effort: several preliminary issues have to be settled before embarking on the proper verification process. Starting from technical regulations and guidelines published worldwide and specifically referring to existing earth dams (homogeneous, upstream-faced and zoned embankment dams), this paper provides some hints on how to handle the different LSs in dam seismic safety assessment. The different significance of each LS and the appropriate verification process will be discussed below.

When dealing with an existing dam, seismic verification should be mainly posed in terms of seismic-induced safety reduction in comparison to available safety during pre-seismic operational stages. Seismic verification should thus include first of all a detailed static dam safety assessment based on the interpretation of all experimental data (monitoring, laboratory tests, *in-situ* tests) collected during the design phase, the construction works and the subsequent initial impounding and operation. The other two steps are the seismic analysis, including the effects of the earthquake, and the post-seismic analysis of the seismic-induced effects redistributing over time.

In the paper some emblematic case-studies of earth dams where strong earthquakes resulted in significant damage or collapse will be firstly outlined, together with the typically observed response of dams to earthquake loads. The main technical regulations and guidelines issued in seismic-prone countries are then illustrated and compared. For each dam type, seismic-related LSs are discussed. The importance of dam safety assessment during the post-seismic stage is particularly stressed, given the possible occurrence of a rapid drawdown, as emptying the reservoir is often considered a beneficial countermeasure to an earthquake. Case histories of zoned and upstream-faced earth dams are then illustrated, to provide some examples of LS verification.

2 LITERATURE REVIEW

The possible mechanisms causing dam collapse during or immediately after a seismic event may be retrieved from past experience and a review of the technical literature. These are both encouraging since there are only two documented cases of collapse or near-collapse of earth dams induced by earthquakes: the Lower San Fernando Dam (California, 9/2/1971) and the Fujinuma Dam (Japan, 11/03/2011). The former exhibited a global instability collapse of the upstream shell due to extensive liquefaction at the base of the embankment (Figure 1) (Seed et al., 1975). The second dam was overtopped because of freeboard loss caused by huge settlements induced by long and severe shaking (Charatpangoon et al., 2014). In both cases, the interpretation of the observed responses seems to exclude that the critical conditions were induced by the high inertial forces, since collapses appeared to be mostly the consequence of seismic-induced effects, redistributed or developed during the post-seismic stages.

The Mexican dams, El Infiernillo (Figure 2) and La Villita (Figure 3), are two interesting examples of zoned earth dams, affected by several strong-motion events during their lifetimes, which showed a significantly different behaviour. In both cases well-documented measurements of accelerations at the dam site and of permanent settlements at the dam crest are available. While the El Infiernillo dam was experimentally and theoretically recognized as showing a progressive improvement of its performance over time after successive earthquakes,

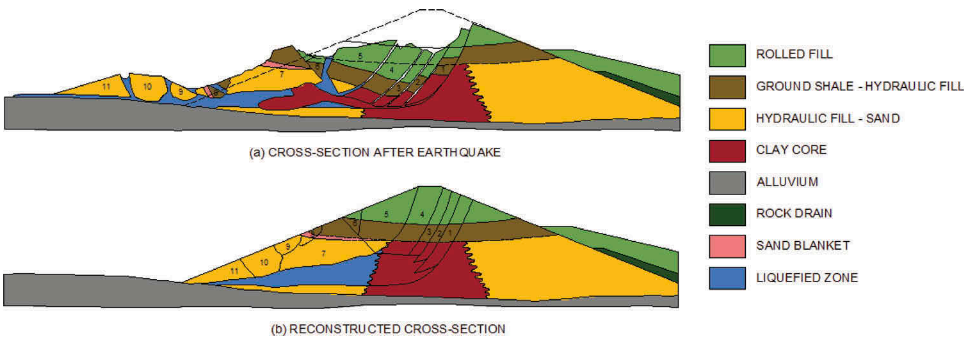

Figure 1. Lower San Fernando Dam: geometry of the cross section after the 1971 earthquake and its reconstruction (modified from Seed et al. 1989).

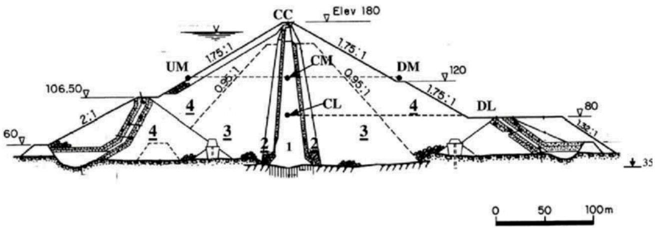

Figure 2. El Infiernillo Dam: main cross section.

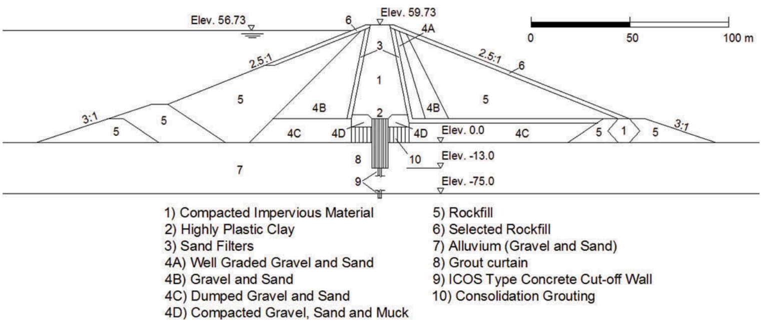

Figure 3. La Villita Dam: main cross section.

essentially due to hardening effects of embankment soils (Sica et al., 2008), La Villita exhibited increasing permanent settlements of the crest after successive earthquakes with similar intensity and epicentral distance (Figure 4 - seismic events from 1975 to 1981 - Table 1). This response may have been caused by the degradation of the construction materials (ICOLD, 2001), the different predominant frequencies of the earthquakes or even by geometrical details, since in La Villita Dam a cut-off wall extending down to the rigid bedrock, which inhibits dam foundation settlements along a portion of the core base, is responsible for deviatoric stress increments over time throughout the dam body.

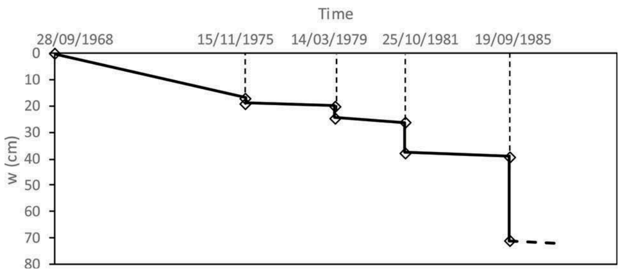

Figure 4. La Villita Dam: crest permanent settlements.

Table 1. Main features of the seismic events occurred at La Villita Dam.

Event date	Ms [-]	D [km]	a_{max} base [g]	a_{max} crest [g]
15/11/1975	5.9	10	0.04	0.21
14/03/1979	7.6	121	0.02	0.40
25/10/1981	7.3	31	0.09	0.43
19/11/1985	8.1	58	0.12	0.76

Ms = Surface magnitude; D = Epicentral distance

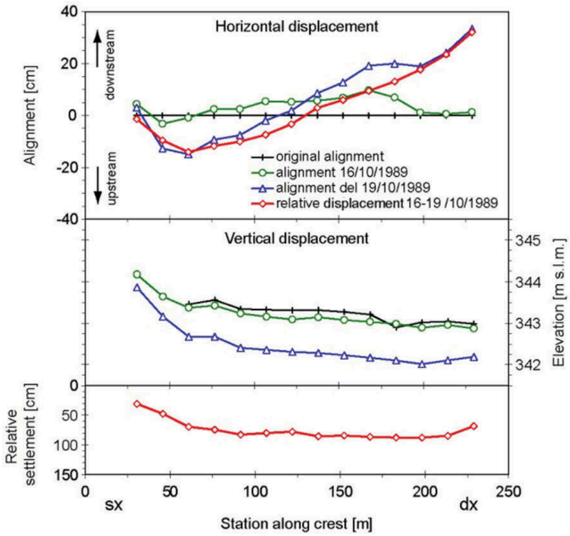

Figure 5. Austrian Dam: horizontal displacements and crest settlements measured before and after the 1989 earthquake (modified from Seed et al., 1990).

Table 2. Italian earth dams subjected to earthquakes of magnitudes higher than 4.5 (from Catalano et al., 2013).

Dam	Dam type	Height [m]	End of construction	Seismic event	D [km]	M_w [-]	PGA [g]	Effect
Selva	Zoned	32.8	1958	07/05/1984	9.5	5.7	0.15	None
Poggio Cancelli	Zoned	27.3	1969	06/04/2009	24.7	6.3	0.11	None
Masseria Nicodemo	Zoned	32.1	1975	09/09/1998	4.7	5.4	0.18	None
Collemezzo	Zoned	21.7	1928	14/10/1966	7.2	4.5	0.07	None
Castel San Vincenzo	Zoned	32.0	1958	07/05/1984	1.5	5.67	0.31	None
Acciano	Zoned	26.5	1970	26/09/1997	8.9	5.95	0.20	SLS
Vasca Ogliastro	Rockfill	22.0	1986	13/12/1990	2.2	5.41	0.24	SLS

D = Distance; M = Magnitude; PGA = Peak Ground Acceleration; SLS = Serviceability Limit State

Figure 5 shows the horizontal displacements and settlements measured on the Austrian Dam crest (California, 17/10/1989) induced by excess pore water pressure redistribution, which did not produce an uncontrolled release of water thanks to the low reservoir water level present (Seed et al., 1990).

In most other cases reported in the literature, earth dams exhibited settlements that did not produce significant damage, uncontrolled release of water or dam overtopping. The Italian scenario is described by data on the seismic response of dams to earthquakes occurring since 1920, collected by an ITCOLD workgroup (Catalano et al., 2013). As reported in Table 2, only seven earth dams were hit by earthquakes of magnitude higher than 4.5. Among them, only two cases experienced major damage: the Vasca Ogliastro Dam, which showed severe cracks of the bituminous conglomerate mantle, and the Acciano Dam, which experienced both downstream and upstream slope instabilities.

3 NTD AND INTERNATIONAL GUIDELINES

Technical regulations and guidelines of countries with high seismicity and a large number of dams were compared in terms of prescribed LSs, analytical procedures and criteria for dam

Table 3. Comparison between several guidelines and regulations on earth dams.

Country	Liquefaction	Overtopping and global instability	Cracking and internal erosion
JAPAN Guidelines, 2005	Equivalent linear analysis	Equivalent linear analysis *Then* Plastic deformation analysis *Then* Advanced dynamic analysis	Plastic deformation analysis
USA Guidelines, 2005	Empirical correlations (SPT, CPT, Vs) If in some zones the verification is not satisfied then use residual strength values for stability analysis	Pseudo-static analysis (only if there are not soils susceptible to liquefaction) *Then* Equivalent linear analysis *Then* Plastic deformation analysis *Then* Advanced dynamic analysis	Method not indicated
INDIA Guidelines, 2007	Empirical correlations (SPT, CPT)	Pseudo-static analysis *Then* Equivalent linear analysis *Then* Plastic deformation analysis *Then* Advanced dynamic analysis	Method not indicated
NEW ZEALAND Guidelines, 2000	Engineer has free choice on method to be adopted	Engineer has free choice on method to be adopted	Engineer has free choice on method to be adopted
SWITZERLAND Guidelines, 2004	Method not indicated The type of analysis depends on dam classification in terms of potential losses	Pseudo-static analysis *Then* Plastic deformation analysis The type of analysis depends on dam classification in terms of potential losses	Method not indicated
PORTUGAL Guidelines (Draft)	Method not indicated	Method not indicated	Method not indicated
ITALY Ministerial Decree, 2014	Necessary if there are saturated soils poorly compacted	Method not indicated The type of analysis depends on dam classification in terms of importance	Method not indicated

response acceptability. In most of the documents, LSs are classified as in Table 3: liquefaction, global instability, overtopping, cracking and internal erosion. In all cases, damage or collapse associated with these LSs are only briefly described and such documents prove to be a mere list of situations to be checked, with too much residual freedom for dam safety assessment. In several countries, including Italy, the types of analyses to use for dam verifications are not detailed, while in others (Japan, the USA and Switzerland) models, methods and sequential procedures are suggested, albeit with reference made always implicitly or explicitly just to the seismic stage.

Some norms define a hierarchy of verifications, where soil liquefaction assessment is usually considered to be the most critical. US guidelines do not provide any specific indication on models and methods, but suggest starting with simple procedures (e.g. pseudo-static analysis or Newmark analysis) and performing advanced analysis (e.g. non-linear dynamic analysis) only if the dam response obtained with simpler methods is not appropriate.

Given that simplified models and methods have not proved to yield more conservative results than more complex approaches, the proposal of limiting the analysis to a single approach appears inconsistent and detracts from the useful synergy produced by the use of simplified and complex models.

Two LSs are included in almost all documents: ultimate limit state (ULS), corresponding to the absence of uncontrolled water release, and serviceability limit state (SLS), when dam full operation is possible without significant rehabilitation works.

Unlike other regulations, the Italian Technical Regulations on Dams (NTD, 2014) provides a specific chapter dedicated to existing dams, which prescribes an analysis of all data collected during design, construction and operation to identify possible dam weaknesses which may evolve during an earthquake and induce a possibly critical performance of the dam. Compared to new dams, for existing ones a reduction in the seismic loads for dam safety assessment is allowed.

4 ULTIMATE LIMIT STATES

The satisfactory performance of earth dams during earthquakes reported in the literature implies that some collapse mechanisms that have to be investigated are only theoretical. Actually, some of them were derived from critical phenomena that under static loads have been responsible for dam failures, assuming that they may be triggered by an earthquake and may evolve in the subsequent post-seismic stage.

4.1 *Global stability*

Global instability may develop along failure surfaces crossing the dam body, possibly involving also the foundation. Global instability may occur during the seismic event as a direct result of the inertial forces associated to the acceleration distribution within the embankment, but might also be triggered during the post-seismic stages as an effect of a redistribution process (temporarily against stability) of excess pore water pressures developing during the seismic stages. Global instability may also be induced by a rapid drawdown, whose effects could act in synergy with the seismic-induced excess pore water pressures, or by an aftershock, whose effects set in after a previous seismic event and possible drawdown.

Within traditional methods of analysis, global instability under inertial seismic forces may be assessed with a static approach, comparing the induced stresses with the failure conditions along potential slip surfaces. In a performance-based philosophy, this static approach is preliminary to a kinematic assessment of slope stability. This evaluates and verifies residual sliding at the end of the shaking resulting from progressive accumulation of sliding, increasing each time seismic-induced forces exceed equilibrium (Newmark, 1965 and Newmark-based methods).

4.1.1 *Homogeneous and zoned dams*

In most common and unfavourable conditions, the seismic load is applied when the reservoir is at its maximum level and seepage flow is at steady state. Dam deformability may produce two important changes to the incoming seismic signal: its amplification from the dam base to the crest, usually contained by damping contribution, and the asynchronism between the seismic motions of points placed at different elevations in the dam body (Bilotta et al., 2010).

Seismic effects generally consist in an increase of shear stresses (and strains) and in pore water pressure changes (Δu_w), which may be positive or negative, according to the tendency of the material to contract or expand upon shearing. The former condition ($\Delta u_w > 0$) is likely to occur in the lower part of the embankment, where high mean effective stress levels enhance a contracting behaviour, while a dilatant behaviour may occur at higher elevations. An example of seismic-induced pore water pressures computed by a coupled dynamic analysis of a zoned embankment dam is plotted in Figure 6 (Sica & Pagano, 2009). Schematically, pore water pressures at the end of the seismic stage could develop similarly to what is depicted in Figures 7-8.

The main consequence of ground motion asynchronism is a significant reduction in the so-called equivalent horizontal acceleration a_{eq}, instantaneously acting within a potentially instable mass, which affects the total inertial forces and related safety factor (Figure 9).

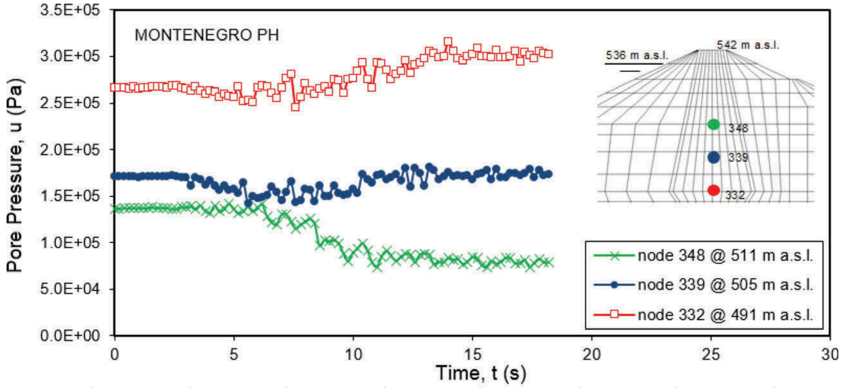

Figure 6. Camastra Dam: computed pore water pressures in three nodes along the core axis during the Montenegro PH earthquake (modified from Sica & Pagano, 2009).

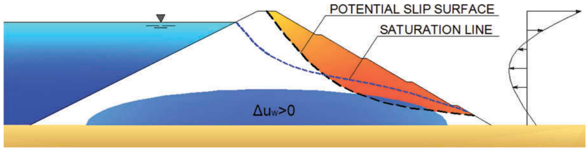

Figure 7. Homogeneous dams: schematic distribution of the excess pore water pressures induced by an earthquake.

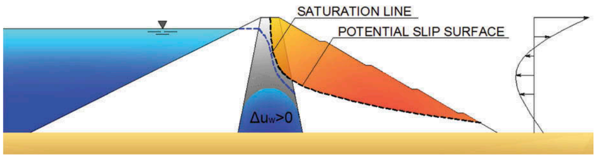

Figure 8. Zoned dams: schematic distribution of the excess pore water pressures induced by an earthquake.

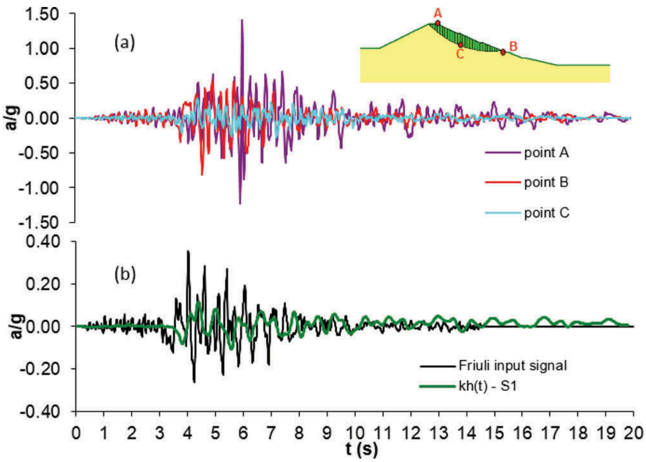

Figure 9. Camastra Dam with Friuli input signal: (a) accelerations computed in three points of the dam; (b) equivalent seismic coefficient $k_h = a_{eq}/g$ computed for surface S1 (modified from Bilotta et al., 2010).

Asynchronism tends to increase when higher vibration modes of the embankment dam are excited. This may occur when the seismic signal is rich in high frequencies or the natural frequencies of the dam are relatively low, as in the case of high embankments made of quite deformable materials.

Taking this into account, two main observations may be done when performing a global instability analysis under seismic loading:

1) in most cases, the analysis may be carried out assuming a drained condition, referring to a single (solid) continuum for the soil skeleton; actually, positive excess pore pressures develop far from the most critical slip surfaces (Figures 7-8) since the latter do not tend to deepen very much within the embankment and mostly affect zones where $\Delta u_w = 0$ or $\Delta u_w < 0$; in this case, a stability analysis can be performed, neglecting seismic-induced pore water pressure changes ($\Delta u_w = 0$);

2) the computation of the inertial forces within the unstable mass should take into account the effects of ground motion amplification and asynchronism caused by the deformability of the dam body and damping.

Slip surfaces along which permanent displacements accumulate during the seismic stage (performance-based stability analysis) may be fully acceptable if they do not (or barely) cross the watertight elements (Figure 10a). By contrast, they can prefigure poor dam performance if crossing the watertight element extensively (Figure 10b). In this case, even if global instability is not feared, the risk should be considered carefully that, along the discontinuity formed in the watertight element, a preferential flow path may develop and a dangerous erosion process may be triggered. The occurrence of this condition during the post-seismic stages should be tackled with appropriate monitoring of pore water pressures and seepage flows throughout the dam in order to promptly catch possible concentrated leakages that may expand critically (implementation of a monitoring plan should in this case complement dam seismic verification).

During the post-seismic stages, seismic-induced pore water pressures redistribute towards steady state conditions. The upper part of the dam, crossed by the most critical slip surfaces, may experience pore water pressure increases unfavourable to global stability due to the upward transient flow dissipating the seismic excess pore pressures increased at lower elevations of the embankment. Dam safety must also be assessed in these transient flow conditions not directly affected by seismic loads (Figures 11-12).

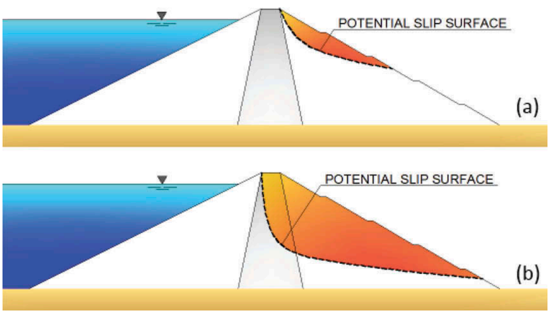

Figure 10. Potential failure surfaces in zoned dams: a) not crossing the core; b) extensively crossing the core.

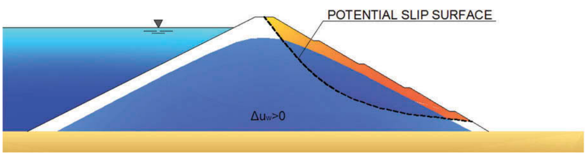

Figure 11. Homogeneous dams: schematic distribution of the excess pore water pressures in a post-seismic stage.

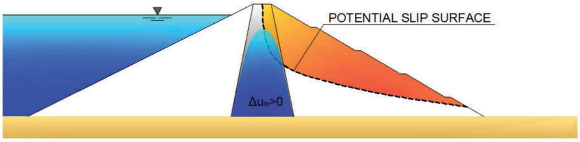

Figure 12. Zoned dams: schematic distribution of the excess pore water pressures in a post-seismic stage.

Reservoirs are often lowered after strong earthquakes to allow the evaluation of possible damage to the embankment or even just as a precaution. Although global instability LS assessment during the post-seismic stage concerns the maximum reservoir level, it is important to define additionally the maximum drawdown rate that may be safely applied to empty the reservoir after an earthquake. This is tantamount to assessing how much the safety factor against global instability may further drop due to a post-seismic drawdown. The unfavourable effects of the earthquake and of the drawdown may indeed critically sum on both the embankment and the reservoir slopes.

Figure 13 shows the case study of the Campolattaro Dam (Sica et al., 2019), analysed with a coupled dynamic finite difference analysis. Dam stability soon after the drawdown was ascertained in terms of global safety factor (FOS), considering different drawdown ratios L/H (L=water level during the drawdown, H=dam height) with the two extreme cases of L/H = 0 (full reservoir) and L/H =1 (empty reservoir). To better characterize how the seismic-induced stresses and excess pore pressure affect the computed FOS while emptying the reservoir, each drawdown scenario was also analysed in the absence of a former earthquake load (dashed lines in Figure 13). For drawdown rates higher than 1 m/day, the induced seismic effects produce a significant drop in FOS towards values of global instability.

In this framework, the possibility should be seriously considered that a major event be followed by a strong aftershock or even a long seismic sequence during drawdown. The probability of occurrence, hence the return period of the event to be introduced in the analysis, should be derived from detailed seismological studies.

4.1.2 *Upstream-faced dams*

Global instability of upstream-faced dams can also be investigated through a static or a kinematic approach. Shallow sliding surfaces usually neglected in the safety assessment of homogeneous or zoned earth dams should be taken into account if including part of the impervious liner.

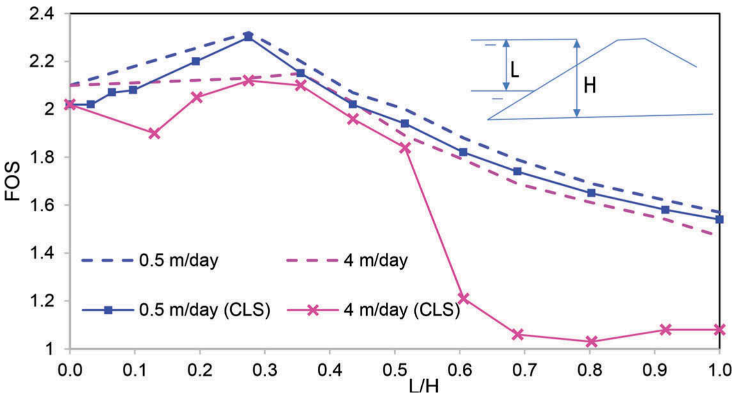

Figure 13. Campolattaro Dam: stability factor vs the drawdown ratio L/H (L= water level during the drawdown, H=dam height) for different drawdown rates, with (continuous lines) or without (dashed lines) a seismic stage before the drawdown (modified from Sica et al., 2019).

Even for failure surfaces crossing the impervious liner, the likelihood of fractures in the watertight element should be ascertained (Costanzo et al., 2011). In general, what was discussed in the previous section for homogeneous and zoned dams may also be extended to the upstream-faced dam type, although analysis of global stability during a rapid drawdown after the earthquake is meaningless, as the embankment is typically made of coarse-grained materials with a low degree of saturation, generally not affected by seismic loads. This does not apply if the embankment has medium or low permeability or is already affected by leakage problems through the liner, since a significant rise in the saturation line in the dam body could occur that may influence stability.

4.2 *Freeboard reduction*

The assessment of freeboard loss is aimed at ensuring that, after the seismic stage and the post-seismic consolidation, the embankment is not overtopped. Although reference should be made to the top of the watertight element, which has to remain above the maximum reservoir level, verification is generally performed through the computation of the permanent settlement of the dam crest. Freeboard reduction is the result of plastic vertical deformations of the dam body.

The settlement of the dam foundation has to be considered only if it differs from the settlement of the reservoir bottom, since only the differential settlement is pertinent to freeboard loss.

In general, settlements take place not only during the seismic stage, but also during the post-seismic consolidation stage, as an effect of dissipation of excess pore water pressures accumulating in the fine-grained layers of the foundation and/or of the dam body (homogeneous dam or core of a zoned dam). The rate of the delayed post-seismic contribution is the key point for safety evaluation: if the settlement rate is compatible with a safe drawdown rate, the post-seismic contribution may be less important and even neglected. However, if settlements develop more rapidly, not allowing a safe drawdown, the post-seismic contribution increment to total settlement has to be carefully considered.

Settlement induced by the seismic load may be viewed as composed by two contributions, associated to distinct deformation processes: the plastic strains distributed within the domain and the sliding of an unstable mass along a surface, as described for global instability LS. The former component is always present if the latter takes place, while the opposite might not be true. This means that the prediction of settlements with Newmark and Newmark-derived approaches may not be conservative, since the former component is neglected *a priori*. Elasto-plastic dynamic analyses, instead, can take into account both components (Sica, 2001).

In Figure 14 the crest settlements computed for the Monte Cotugno Dam performing Newmark, Newmark-derived and elastoplastic dynamic analyses, under different seismic scenarios are compared: all the Newmark approaches yielded crest settlements about 50% smaller than those obtained with the elastoplastic dynamic analysis.

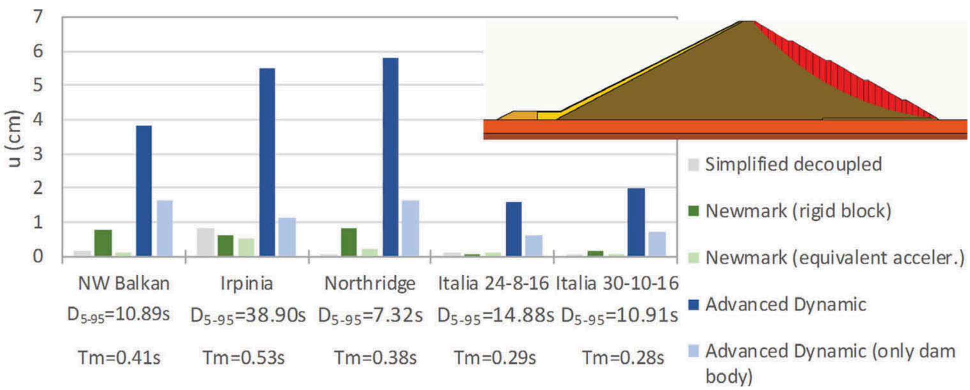

Figure 14. Crest settlements of the Monte Cotugno Dam computed with different methods of analysis.

4.3 *Seismic-induced cracks and internal erosion*

The term internal erosion includes several different phenomena, like backward erosion, concentrated leak and suffusion, all sharing the transport of fine particles by seepage forces. Internal erosion may take place throughout the embankment, the foundation layers or from the embankment towards the foundation. The presence of well-designed filters between the impervious element and the dam body is fundamental to tackle an erosion process and inhibit it over time.

An earthquake may generate different damage patterns in a dam, such as cracks, slips, stress-relaxation across the dam body and foundation soils, which in turn may represent or determine discontinuities where preferential flow paths and erosion phenomena may develop. It is worth noting that these damage patterns, even if predicted, are unlikely to be contemplated in a ULS safety assessment of the dam, as the possible attainment of the ultimate limit state is related to the evolution of erosion phenomena up to collapse. In other words, although the dam may be significantly damaged by the earthquake, the erosion phenomenon that may be triggered may either develop further until collapse during the post-seismic stage or may be inhibited by efficient filters or self-repairing processes of the discontinuities.

The uncertainties associated with the prediction of the possible evolution of the damage pattern towards an ultimate limit state may be more easily and functionally tackled by evaluation of the dam susceptibility to erosion phenomena after a strong earthquake. This susceptibility may be assessed through prediction of the earthquake-induced damage pattern and verification of the correct design and construction of filters. In addition, a specific monitoring system, suitably calibrated on this assessment, should be implemented to detect the possible critical evolution of erosion processes, through measurements of seepage flows, turbidity of drained water and pore water pressures during the post-seismic stages.

4.3.1 *Homogeneous and zoned dams*

In homogeneous dams, shear distortions induced by a strong earthquake might result in cracks. If such cracks are widespread, a hydraulic connection between upstream and downstream could be established, creating a preferential flow path that may further develop into internal erosion (Figure 15).

Evaluation of the effects that consolidation or rapid drawdown could exert during the post-seismic stage, in terms of improvement or worsening of the cracking pattern, is in any case arduous. Assessment of susceptibility to cracking and its evolution requires the computation of seismic-induced plastic shear strains and the simulation of consolidation processes. Therefore, coupled dynamic elastoplastic analyses are the only predictive tools available (Prevost et al., 1985; Elgamal & Gunturi, 1993; Sica et al., 2008; Sica & Pagano, 2009; Elia et al., 2011, Masini et al., 2015).

For zoned dams, the above considerations should refer to the core: seismic-induced cracks may connect the upstream and downstream core boundaries hydraulically, thus leading to concentrated leaks and internal erosion (Figure 16). Compared to homogeneous dams, in zoned dams the occurrence of the latter phenomena is enhanced by the smaller thickness of the watertightness element.

The seismic event could also cause finite sliding along a surface crossing the core (Figure 10b), where concentrated flow and erosion phenomena may take place. In this case, it is mandatory to verify that the amount of sliding does not exceed approximately 30% of the filter thickness, in order to avoid loss of filter continuity and hence the ability to inhibit erosion processes.

Cracks might also be indirectly generated as an effect of seismic-induced permanent settlements differing between the core and the shells. The stiffer shells tend in fact to sustain the

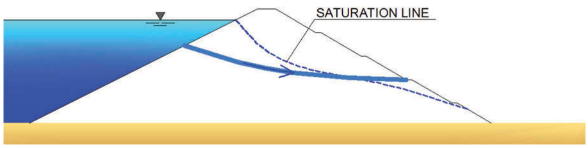

Figure 15. Homogeneous dams: preferential seepage flow path in the embankment after an earthquake.

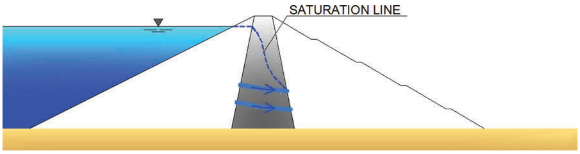

Figure 16. Zoned dams: hydraulic connection between upstream and downstream shells after an earthquake.

core, discharging it and reducing the principal components of stress. This phenomenon, termed "arching", is already present in the static stages as an effect of dead load application. Reduction of principal stresses was recognized to be responsible for core hydraulic fracturing in static conditions (Sherard, 1986), with soil cracks induced or enlarged by the reservoir water pressure exceeding existing lateral stress.

Different theories and experimental approaches have been developed to define the stress state distribution favourable to the formation and development of a crack induced by the hydraulic pressure. Crack initiation or expansion (Wang et al., 2014) may be related to critical tensile stress or to the critical shear stress acting on or along the crack plane. Both approaches propose similar mathematical formulations, which relate crack formation or enlargement to an amount of hydraulic pressure (p_w) exceeding a fraction of the minimum total principal stress σ_3 ($p_w > f(\sigma_3)$). The simplest approach (Sherard, 1986) suggests verifying the condition $p_w > \sigma_3$.

Core consolidation and consequent additional stresses transferred from core to shells may increase the susceptibility to hydraulic fracturing during the post-seismic stages.

Prediction of the phenomenon requires estimation of the stress state evolution during static loading and the seismic and post-seismic stages. Therefore the only suitable predictive tool is coupled dynamic elastoplastic analysis.

Figure 17 illustrates the local safety factor for hydraulic fracturing, defined as the ratio between the minimum principal stress and the hydraulic pressure, at different elevations within the core, predicted for the Camastra Dam (Pagano & Sica, 2013) for different earthquake scenarios, provided by *ad hoc* seismological studies and represented by the Arias intensity of the input motion. The plot shows a significant drop of the local safety factor inside the core with increasing Arias intensity of the input signal.

4.3.2 *Rockfill dams*

Seismic-induced distortions experienced by the upstream slope produce shear or tensile stresses in the impervious liner, which should be lower than the failure limit to avoid leakage (Figure 18). Assessment of the liner damage may be carried out by comparing axial and shear strains at each point of the dam boundary with those inducing liner failure. This estimation should be carried out during the seismic and post-seismic stages, since if consolidation involves the foundation soils, shape changes of the dam boundary may take place after the earthquake. An example of liner strains computed for the Monte Cotugno Dam is reported in Figure 19 and Table 4.

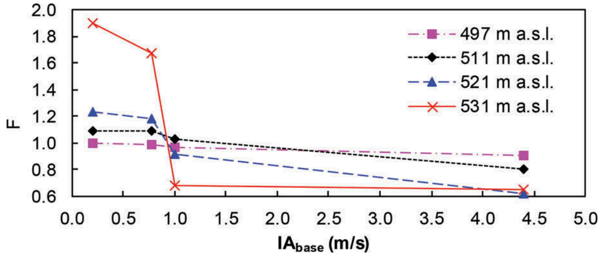

Figure 17. Camastra Dam: hydraulic fracturing safety factor F= σ_3/p_w at different elevations of the core axis vs the Arias intensity of the input signal (modified from Pagano & Sica, 2013).

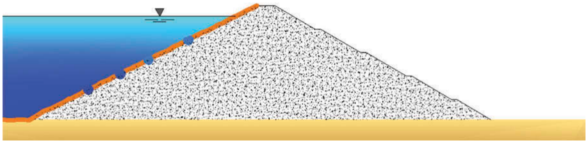

Figure 18. Rockfill dams: potential failures of a bituminous liner after an earthquake.

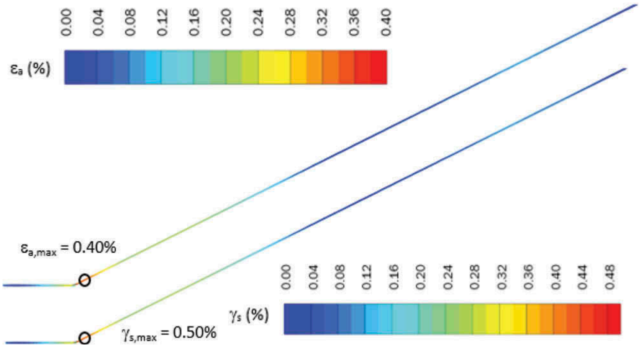

Figure 19. Monte Cotugno Dam: contours of the seismic-induced strains in the liner.

Table 4. Maximum values of axial and shear strains of the Monte Cotugno Dam liner.

Seismic event	ε_a (%)	γ_s (%)
NW Balkan	0.26	0.33
Irpinia	0.40	0.50
Northridge	0.30	0.38
Italia 24-8-16	0.15	0.19
Italia 30-10-16	0.26	0.34

Extensive liner failure undoubtedly represents a serviceability limit state for leakage increments, but not necessarily an ULS. Indeed, if the liner is completely damaged, the embankment is crossed by a seepage at steady state (Figure 20) that could be a condition not necessarily implying dam collapse. It could be then worth first checking embankment safety through a simple global instability analysis, with pore water pressures calculated at steady state, before performing much more expensive dynamic elastoplastic analyses for liner verification.

4.4 *Liquefaction*

Modern well-compacted embankments are commonly considered not susceptible to liquefaction.

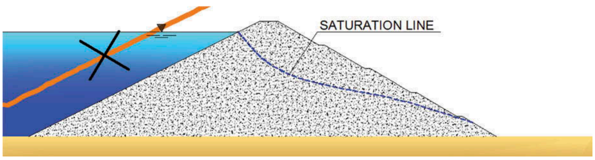

Figure 20. Rockfill dams: hypothetical configuration without the bituminous liner for static stability analysis and internal erosion checks.

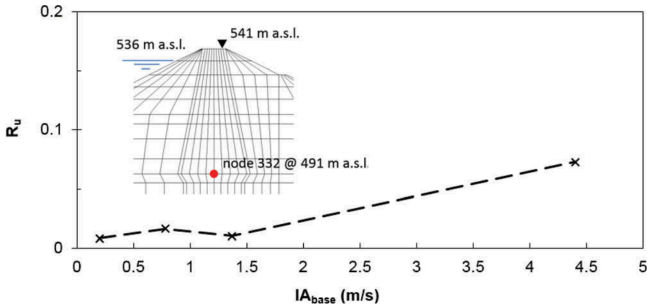

Figure 21. Camastra Dam: pore pressure ratio, Ru, versus the Arias intensity at the dam base, IA_{base} (modified from Sica & Pagano, 2009).

Figure 21 shows, as an example, the pore pressure ratio ($R_u = \Delta u/\sigma'_{v0}$) computed for the Camastra Dam (Sica & Pagano, 2009). For a node of the core axis where the highest seismic-induced excess pore water pressures were computed, the liquefaction factor was correlated with the Arias intensity of the input motion, showing that the core is really quite far from experiencing liquefaction. Existing dams, which have been in operation for decades, may however have experienced changes in grain-size distribution due to deposition or erosion phenomenon. The problem may affect zoned dams, where fine particles from the reservoir may deposit in the upstream shell, while the core might have lost part of its fine particles due to internal erosion, then deposited in the downstream shell. Theoretically, all these three zones could have experienced changes in grain-size distribution and state conditions, with an increasing susceptibility to liquefaction.

Liquefaction assessments should be carefully performed for the foundation soils where saturated loose sand layers of the river bed may be present if not removed or compacted before dam construction.

5 SERVICEABILITY LIMIT STATES

Serviceability limit state (SLS) assessment, although prescribed by the technical regulations on dams, requires a preliminary definition, as previously shown for ultimate limit states. Damage mechanisms to be investigated for SLSs are of the same types as those described for ULSs, but ensure that no significant rehabilitation works are required after seismic loading. The earthquake loads are, in fact, of lower intensity and shorter return periods.

Dam safety assessment may in all cases be related to the entity of a single indicator: the permanent settlement of the dam crest. If under the SLS earthquake scenarios the crest settlement does not exceed 0.01-0.05% of dam height, the dam may be considered as reacting almost elastically to the earthquake, with an automatic verification of all SLSs.

6 THE PROBLEM OF SINGULARITIES

Earth dams may have structural singularities which, being much stiffer than the surrounding soil, tend to become stress attractors and therefore represent weaknesses in the entire dam system, especially under seismic loading. The list of singularities is extensive: the most widespread elements are diaphragm walls (as in the previously mentioned La Villita Dam), grout curtains, spillways, pipelines and tunnels crossing the embankment. The assessment of dam seismic performance should account for their presence to assess their vulnerability within the overall system, wherever they are inserted.

The deformation pattern generated by a structural singularity or a geological discontinuity in the foundation could lead to local hydraulic discontinuities and preferential flow paths, enriching the list of erosion patterns that may develop in a dam during the post-seismic stage.

The possible initiation of such flow paths has to be assessed through the interpretation of the deformation pattern predicted by calculation. If dangerous scenarios are yielded by the analyses, they could be tackled by appropriate monitoring during dam operation, with the measurements - for sake of comparison - to be performed during the post-seismic stages.

7 KNOWLEDGE OF THE DAM

Safety assessment of existing dams that have been in operation for decades is a completely different issue from the design of a new dam, as loading history and processes experienced by the dam could have significantly changed the working patterns initially designed and envisaged.

As an example, Figure 22 plots the piezometric head contours of the Polverina zoned dam derived from the interpretation of the pore water pressure measurements recorded throughout a transversal dam section, after more than three decades of operation (Fontanella et al., 2012). Unexpectedly, the pore water pressure contours in the core extend into the downstream shell, with the saturation line (which connects the points where the total head equals the geometric height) crossing the shell itself extensively. The dam clearly experiences an unexpected seepage pattern, with the downstream shell actively contributing to the embankment watertightness. This behaviour is the result of a diffuse migration of finer particles from the core to the shell (core suffusion), which reduces the difference in hydraulic conductivity between the two zones. The assessment of global instability and liquefaction LSs obviously cannot be based on the design assumption of a downstream shell entirely consisting of coarse-grained materials.

Detailed knowledge of the dam is of paramount importance. Geometry and properties of construction materials have to be first obtained from design documents and tests carried out during the dam construction and operation and then updated through specifically designed new investigations aimed at confirming the values or detecting possible changes over time. Site measurements performed on Camastra Dam core are depicted in Figure 23, showing the dry density (Figure 23d) measured during embankment construction and the shear modulus at small (Figure 23 a) and medium (Figure 23 b) strains together with the undrained cohesion (Figure 23 c), delivered by recently performed Down Hole (DH) and Dilatometer tests. Both old and new data show the presence of less stiff core layers between 20 and 25 m or 30 and 35 m below the dam crest.

Dam safety assessment must also consider the behaviour of the dam during construction, experimental filling and operation, in search of possible initial deficiencies due to design or construction faults, or subsequent complications occurring, which may influence the dam response to seismic loading (e.g., Pagano et al., 2010). This can only be achieved by examining all the available documents of the dam, starting from the design phase, with particular reference to results from monitoring. Interpretation of the observed behaviour of the dam should provide both an overall picture of the dam in normal operation, especially with respect to functionality of the watertight elements and adequacy of the existing monitoring instruments, and the parameters to calibrate mathematical-numerical models that will be applied.

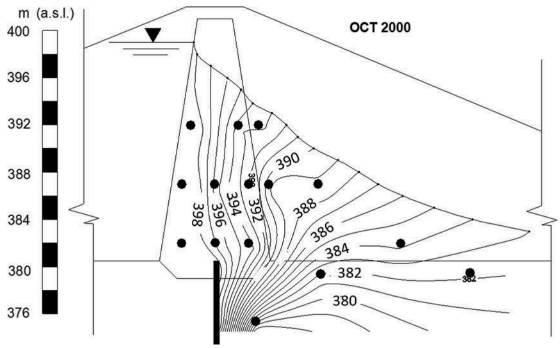

Figure 22. Polverina Dam: saturation line obtained from pore water pressure measurements after more than three decades of operation (Fontanella et al., 2012).

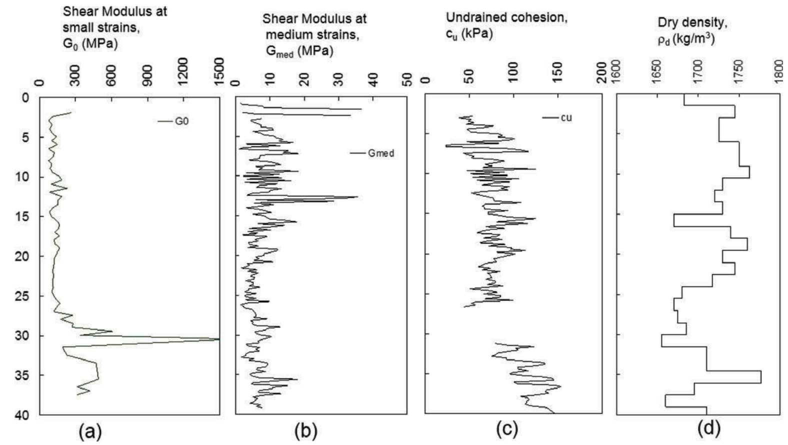

Figure 23. Camastra Dam: in situ test with the seismic dilatometer (SDMT) in the core axis. (a) small strain shear modulus (G_0); (b) medium strain shear modulus (G_{med}); (c) undrained cohesion (c_u); (d) dry density (ρ_d).

8 CONCLUSION

This paper showed that seismic safety assessment of an existing dam requires a totally different approach from what is followed in designing a new dam. The sequence of construction, impounding and any other significant event experienced during operation could appreciably affect the dam response to earthquakes. Therefore any possible analysis must start from a careful study of all available data.

Limit states typically addressed by international technical regulations were described and discussed both in the seismic and post-seismic stages, with a view to assisting the choice of suitable predictive tools. It was shown that some procedures, such as those aimed at assessing fracture susceptibility for dam core or liners or at investigating dam behaviour under rapid drawdown, should not be intended as a mere assessment of safety, but rather point out dam susceptibility to dangerous phenomena (erosion or instability), which may in some cases be tackled with suitable countermeasures (performing, for example, specific monitoring of the critical parameters or imposing a maximum drawdown rate, if reservoir lowering is required). The definition and implementation of these countermeasures represent the final and most important aspects of the safety assessment of the dam.

Finally, the paper emphasised the importance of a safety assessment of the dam in the post-seismic stage, often disregarded by technical regulations, but critical, since several collapse phenomena may occur after the earthquake event. This delay offers the chance to reduce the risk through a post-seismic alert, but requires the knowledge of the dam seismic response to any seismic scenario predicted at the dam site by seismological studies. The analyses should then indicate the most vulnerable elements, the possible damage that may have occurred and the physical quantities to monitor and interpret dam behaviour in the post-seismic stage.

ACKNOWLEDGEMENTS

The authors wish to thank the Management Staff of the Italian Dam authority who promoted and financed this research project and, in particular, Paolo Paoliani, for his help and suggestions throughout.

REFERENCES

Bilotta E., Pagano L. & Sica S. 2010. Effect of ground-motion asynchronism on the equivalent acceleration of earth dams. *Soil Dynamics and Earthquake Engineering* 30: 561–579.

Catalano A., Caruana R., Del Gizzi F. & De Sortis A. 2013. Observed behaviour of Italian Dams under historical earthquakes. *Proc. 9th ICOLD Symposium – Venice, 10-12 April 2013*.
Charatpangoon B., Kiyono J., Furukawa A. & Hansapinyo C. 2014. Dynamic analysis of earth dam damaged by the 2011Off the Pacific Coast of Tohoku Earthquake. *Soil Dynamics and Earthquake Engineering* 64: 50–62.
Costanzo A., Sica S. & Silvestri F. 2011. Verifica della sicurezza in condizioni sismiche della diga sul fiume Melito. *Rivista Italiana di Geotecnica* 45 (2): 35–64 (in Italian).
Darbre G.R. 2004. Swiss Guidelines for the earthquake safety of dams. *13th World Conference on earthquake Engineering, Vancouver, 1-6 August 2004*.
Decreto Ministero LL PP 24-03-1982. *Norme tecniche per la progettazione e la costruzione delle dighe di sbarramento*. Ministero dei Lavori Pubblici, Rome (in Italian).
Elgamal A.W. & Gunturi R.V. 1993. Dynamic behaviour and seismic response of El Infiernillo Dam. *Earthquake Engineering and Structural Dynamic* 22: 665–684.
Elia G., Amorosi A., Chan A.H.C. & Kavvadas M.J. 2011. Fully coupled dynamic analysis of an earth dam. *Geotechnique* 61 (7): 549–563.
FEMA 65 2005. *Federal Guidelines for Dam Safety - Earthquake analysis and design of dams*.
Fontanella E.M., Pagano L. & Desideri A. 2012. Actual and nominal pore water pressure distribution in earth dams. *Electronic Journal of Geotechnical Engineering* 17: 2485–2494.
ICOLD 2001. *Design features of dams to effectively resist seismic ground motion*, International Commission On Large Dams, Paris, Bulletin 120.
IITK-GSDMA 2005. *Guidelines for seismic design of earth dams and embankments*.
Masini L., Callisto L. & Rampello S. 2015. An interpretation of the seismic behaviour of reinforced-earth retaining structures. *Geotechnique* 65(5): 349–358.
Ministério das Obras Públicas, Transportes e Comunicações de Portugal - Regulamento de Segurança de Barragens art. 8 (draft)
Newmark N.M. 1965. Effects of earthquakes on dams and embankments. *Geotechnique* 15 (2): 139–160.
NTD 2014. Ministero delle Infrastrutture e dei Trasporti. *Norme tecniche per la progettazione e la costruzione degli sbarramenti di ritenuta (dighe e traverse)*. Decreto del Ministro 26 giugno 2014, Gazzetta Ufficiale n°156 del 08.07.2014 (in Italian).
NZSOLD 2000. New Zealand dam safety guidelines. New Zealand Society on Large Dams.
Pagano L., Fontanella E., Sica S., Desideri A. (2010). Effectiveness of pore water pressure measurements in the interpretation of the hydraulic behaviour of two earth dams. Soil and Foundations (ISSN:0038-0806) pp. 295-307 Vol. 50
Pagano L. & Sica S. 2013. Earthquake early warning for earth dams: Concepts and objectives. *Natural hazards* 66 (2): 303–318.
Prevost J.H., Abdel-Ghaffar A.M. & Lacy S.J. 1985. Nonlinear Dynamic Analyses of an Earth Dam. *Journal of Engineering Mechanics* ASCE 111 (7): 882–897.
Seed H.B., Idriss I.M., Makdisi F. & Banerjee N. 1975. Representation of irregular stress time histories by equivalent uniform stress series in liquefaction analyses, *Rpt. No. UCB/EERC-75-29*, U.C. Berkeley.
Seed H.B., Seed, R.B., Harder L.F. & Jong H.L. 1989. Re-evaluation for the lower San Fernando dam, Report 2, Examination of the post-earthquake slide of February 9, 1971. H. B. Seed, Inc., *Department of the Army, ASCE*.
Seed R.B., Dickenson S.E., Riemer M.F., Bray J.D., Sitar N., Mitchell J.K., Idriss I.M., Kayen R.E., Kropp A., Harder L.F. & Power M.S. 1990. Preliminary report on the principal geotechnical aspects of the October 17, 1989 Loma Prieta earthquake. *College of Eng. – Univ.of California at Berkeley*.
Sherard J. L. 1986. Hydraulic fracturing in embankment dams. *J. of Geot. Eng*., 112 (10): 905–927.
Sica S. 2001. *Analisi dinamica di dighe in terra*. PhD. Thesis. Naples: Consorzio delle Università di Roma la Sapienza e Napoli Federico II (in Italian).
Sica S., Pagano L. & Rotili F. 2019. Rapid drawdown on earth dam stability after a strong earthquake. *Submitted for publication to Computers and Geotechnics* paper reference COGE-S-18-01635.
Sica S., Pagano L. & Modaressi A. 2008. Influence of past loading history on the seismic response of earth dams. *Computers and Geotechnics* 35: 61–85.
Sica, S. & Pagano, L. 2009. Performance-based analysis of earth dams: procedures and application to a sample case. *Soils and Foundations* 49(6): 921–939.
Wang K., Wang F., Cui W., Hayat T. & Ahmad B. 2014. Prediction of short fatigue crack growth of Ti-6Al-4V. *Fatigue & Fracture of engineering Materials & Structures* 37: 1075–1086.
Yasuda N., Shimamoto K., Yamaguchi Y.& Sasaki T. 2005. Outline of “Guidelines for seismic performance evaluation of dams during large earthquakes (Draft)”.