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Drawdown scenarios imposed to an earth dam after a strong earthquake

Vidange des barrages en terre immédiatement après un fort séisme

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ABSTRACT: Establishing the maximum drawdown rate that may safely be imposed to an earth dam is crucial because a typical practice soon after the occurrence of a strong earthquake is that of emptying the reservoir to check the possible damages occurred to the embankment or, simply, in the unjustified believe to proceed at the safest. The unfavourable effects of earthquake and drawdown may thus critically sum up as both the dam and the reservoir slopes are subjected to two potentially critical events. Dam stability soon after the drawdown may be ascertained in terms of global safety factor (FOS), considering different drawdown levels and rates. To better characterize how the seismic-induced changes in pore water pressure and stress affect the computed FOS, a drawdown scenario was also analysed in absence of a former earthquake stage. For some drawdown rates, the seismic effects are able to induce a significant drop in FOS during the drawdown stage up to values dictating global instability of the embankment slopes.

RÉSUMÉ: Établir le taux de abaissement maximum qui peut être imposé en toute sécurité à un barrage en terre est crucial car une pratique typique, peu après un fort tremblement de terre, consiste à vider le réservoir pour vérifier les dommages éventuels que le remblai aurait pu subir ou simplement dans les injustifiés croient procéder au plus sûr. Dans ces cas, les effets défavorables du séisme et du rabattement peuvent être résumés de manière critique, car les pentes du barrage et du réservoir sont soumises à deux événements potentiellement critiques, le séisme en premier et le repli rapide plus tard. La stabilité du barrage peu de temps après le retrait peut être établie en termes de facteur de sécurité global (FOS), en tenant compte de différents taux de rabattement. Afin de mieux caractériser la manière dont les changements induits par la sismique dans la pression de l'eau dans les pores et les contraintes affectent les FOS calculés lors de la vidange du réservoir, chaque scénario de réduction a également été analysé en l'absence d'un stade antérieur de tremblement de terre. Pour certains taux de réduction, les effets sismiques induits avant la phase de réduction entraînent une chute significative du FOS vers des valeurs dictant l'instabilité globale.
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Keywords: earth dam, soil, earthquake, drawdown, slope stability.

1 INTRODUCTION

As well known, a rapid lowering of the water level may temporarily decrease the safety conditions of wetted slopes as the external stabilizing water pressure loads reduce in the meanwhile that the internal-to-slope pore water pressures, which are unfavourable to stability, delay their decrease to the updated steady-state values.

By tradition, two simplified approaches have been adopted to predict the pore water pressure distribution after the drawdown: analysis of undrained conditions of a deformable medium or analysis of transient flow stages through a rigid-unsaturated domain, referred to as "pure flow method" or also as "uncoupled approach". Simplified evaluation of the pore water pressure changes, Δu, induced by the drawdown in undrained conditions were linked by Skempton (1954) and Morgenstern (1963) to the change in major principal stress, $\Delta\sigma_1$, by the following equation:

$$\Delta u = \overline{B}\Delta\sigma_1 \qquad (1)$$

where the parameter $\overline{B}$ was assumed to be equal to 1 in most of their applications. As further simplification, Bishop (1954) proposed to assume in any point of the submerged slope the major principal stress corresponding to the vertical one.

The common case of a drawdown that is intermediate between rapid and slow, thus generating partly drained conditions in the slope, implies that during the drawdown stages the pore water pressure changes are lower than those predicted in the undrained assumption. The analysis of this more general case requires the adoption of coupled hydromechanical approaches of a three-phase unsaturated medium.

With reference to the case of the Glen Shira Dam, Alonso and Pinyol (2016) provided useful examples corroborating the necessity of performing coupled analyses to properly handle drawdown problems. They showed that the classical analysis methods could not catch the available measurements of pore water pressures induced by a rapid drawdown. A total water level drawdown of 9.1 meters in four days was applied to the Glen Shira dam. This maximum drawdown was imposed in four stages of rapid (7.2 m/day) water lowering followed by short periods of constant water level. Five porous stone piezometer disks, previously calibrated against mercury columns, were located within the upstream shell of the dam made of a morenic fill. The method of instantaneous drawdown or undrained approach resulted conservative, but very unrealistic. On the other hand, the pure flow analysis may determine unsafe underestimation of pore water pressures during the drawdown stages because this approach neglects that part of time lag in pore water pressure dissipation generated by soil volume reductions. Coupled analyses proved to capture well the measurements, independently from the sophistication of the adopted constitutive soil law. In the analysed case, plastic strains developed during the drawdown stage were found negligible compared to those induced by the construction stage of the dam embankment and first filling, so that the simpler elastic model provided a good approximation of the recorded pore water pressures during the drawdown stage.

In former literature studies, the combined effect of earthquake and drawdown has never been considered.

The effects of an earthquake stage preceding the drawdown may be that of changing the pore water pressure distribution in some embankment zones, effects which could dangerously sum to those induced by the drawdown itself.

The paper illustrates the mathematical-numerical model developed for the case-history of Campolattaro Dam to simulate the effects of different drawdown scenarios carried out soon after a strong earthquake.

2 PROBLEM STATEMENT

2.1 Geometry and geotechnical features of the sample dam

The Campolattaro dam (Figure 1) is a zoned earth dam placed close to Benevento (Italy). The embankment is about 60 m high. The maximum water storage of the reservoir is around 125 Mm^3 for a plan dimension of 256 km^2.

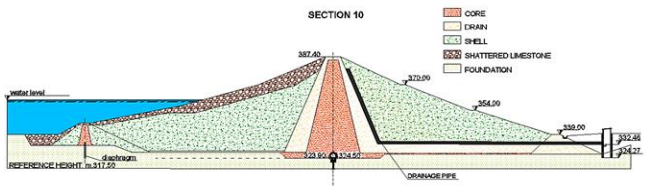

Figure 1. Main cross section of the Campolattaro Dam

The geotechnical characterization of the foundation and embankment soils was based on the documents of the original design-construction stages (1986-1992) and on the results of two more recent in-situ investigations (2009 and 2016). The core is a medium-plasticity silt with clay (permeability of the order of 10^{-9} m/s); the shells (k = 1.7 x10^{-5} m/s) are mostly gravel while the drains (k=5.3 x10^{-7} m/s) are made of sand with gravel; the foundation soil consists of silty clayey sandstone dating back to the Miocenic Age. Table 1 lists the main geotechnical parameters of the soils adopted as construction materials for the different zones of the dam. The shear wave velocity V_s of the dam soils was measured by Down-hole tests carried out in the middle section of the core and in the foundation. The V_s along the core axis varies between 280 m/s and

500 m/s. In the foundation, V_s varies between 315 m/s and 540 m/s in the upper 24 meters below the ground level; below this depth the bedrock was intercepted (Vs = 1200 m/s). For the fine soils of the dam core and foundation, the non linear response at different strain levels (G/G_0-γ and D-γ) was experimentally determined from Resonant Column Torsional Shear (RCTS) laboratory tests carried out by d'Onofrio (2016).

Table 1. Main parameters of the Campolattaro Dam soils

Parameter	γ_d[kN/m^3]	*PI%*	*n*	*c' [kPa]*	*φ' [°]*	*k [m/s]*
Core	17.38	30	0.35	50	23	$1.49 \cdot 10^{-9}$
Shells	21.09	0	0.25	0	43	$1.68 \cdot 10^{-5}$
Drains	19.75	0	0.25	0	30	$5.27 \cdot 10^{-6}$
Foundation	17.21	33	0.30	130	22	10^{-9}

2.2 Analysis stages and constitutive laws

To simulate the different stages of the dam lifetime (embankment construction, first impounding, operation, earthquake) to subsequently characterize the different drawdown scenarios, the main cross-section of the Campolattaro Dam was analysed in terms of effective stresses with the finite difference method (f.d.m.) implemented in the commercial code FLAC2D (Itasca, 2005). The discretized 2D model (Figure 2) consists of 3678 elements. The model includes the dam body (base width 338 m, crest width 9 m and maximum height of about 60 m) and a portion of the foundation soils, characterized by a rectangular domain of about 1 km and 170 m in the horizontal and vertical direction, respectively.

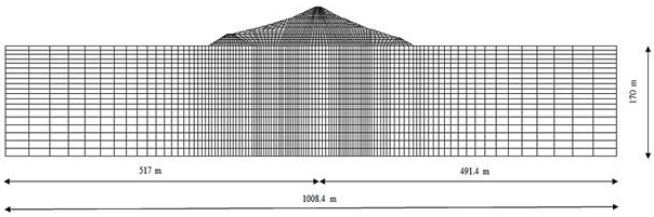

Figure 2. Campolattaro Dam 2D grid model

For the sake of simplicity, all dam stages up to the dynamic analysis (construction, ooperational stages, earthquake) were solved in the hypothesis of full saturation in the wet portion of the dam, while a three-phase formulation was adopted only after the seismic stage to simulate the drawdown.

An elastic-perfectly plastic stress-strain relationship was assigned to the different embankment zones. In particular, a non-linear elastic behaviour was assumed within a stress domain bounded by the Mohr-Coulomb yield criterion. The elastic modulus G_0 was assumed to increase with the mean effective stress p' through a polinomial law calibrated on the experimental results provided by the aforementioned Down-hole tests.

During the dynamic stage of analysis, the cyclic soil behavior was described through a hysteretic model, which is an extension of the one-dimensional non-linear models based on the Masing (1926) rules to produce hysteresis loops. The model requires the small-strain shear modulus G_0 and a decay curve (*sigmoidal*) that describes the reduction of the shear modulus with the shear strain amplitude. This curve was calibrated to reproduce the experimental modulus decay obtained from the resonant column tests carried out on the fine-grained soils (core and foundation), while for coarse-grained material of the shells and filters reference was made to literature curves specific for coarser soils (Seed et al., 1986; Rollins et al., 1998). In the analyses, the hysteretic model was used to update at each step the shear modulus of the elastic-plastic soil model. In a hierarchical way, an excess pore water pressure (p.w.p.) model was added to the stress-strain law assigned to the core and shell soils. The Finn-Byrne formulation links the excess pore water pressure Δu induced in undrained conditions under seismic loading to the volumetric change in drained conditions $\Delta\varepsilon_{vd}$ (Byrne, 1991).

The simulation of the drawdown stage after the seismic analysis was carried out by assuming a coupled unsaturated approach (3-phase formulation) for the embankment soils (with exception of the dam foundation) and with the adoption of a water continuity equation, in which S_r has been considered as a further variable of the problem. The soil-water retention curve was defined through the Van Genuchten (1980) model. Parameters were quantified on the basis of literature indications (Van Genuchten, 1980; Alonso and Pinyol, 2016). Five drawdown rates between 0.5 m/day and 4 m/day were considered. These drawdown rates were combined to different values of the ratio L/H, where L reprents the reservoir lowering and H the maximum dam height (Figure 3).

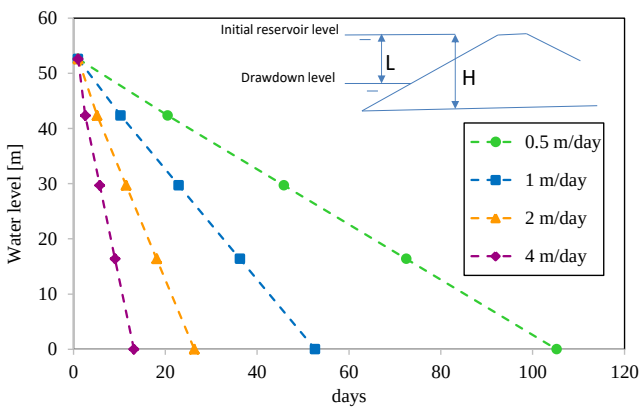

Figure 3. Simulated drawdown scenarios at different rates R (m/day)

Slope stability analyses were performed for any analysis set with computation of the dam safety factor (FOS). The shear strength reduction technique proposed by Duncan (1996) was adopted following the specific procedure implemented in FLAC2D by Dawson et al. (1999).

2.3 Accelerogram selection for the seismic analysis of the dam

The seismic stage was simulated by retrieving the stress distribution at the end of the static analyses and later applying a time-history of shear stress (Itasca, 2005) at the base of the analysis domain (compliant base). Since the purpose of the study concerns the rapid drawdown after a strong earthquake, the dynamic analyses were performed with input signals required for the assessment of the Collapse Limit State (CLS) of an existing dam of relevant importance by the current Italian regulations (NTC 2018; NTD 2014). After the definition of the return period (T_R) for the selected limit state and the associated maximum rock accelerations (PGA) at the reference site, a disaggregation of the seismic hazard was carried out to get the magnitude-distance (M-R) combinations, which address the selection of natural accelerograms. The selection was constrained to assure a suitable matching with the elastic response spectrum required by the Italian code (NTD, 2014).

The check was performed in terms of compatibility of the peak horizontal acceleration, quantified through an acceleration scale factor F_S and in terms of root-mean square deviation D_{rms} (Bommer and Acevedo, 2004) between the spectra of the selected input motions and the target one. The selected input signals correspond to rock outcrop accelerograms. The horizontal input signals at the bottom of the discretized 2D model were computed through a deconvolution analysis using the 1D wave propagation code, EERA (Bardet et al., 2000). The deconvoluted signals were applied at the base of the 2D model as time-history of shear stresses τ_{xy}, linked to the velocity time-history of the signal via the S wave velocity of the foundation soil. In this way a quiet boundary was applied at the bottom of the f.d.m. model to avoid wave reflection inside the analysis domain.

Table 2 Accelerograms selected for the seismic analysis of Campolattaro Dam at the Collapse Limit State for a return period T_R = 1460 years; PGA = 0.415g; $5.5 \leq M \leq 7.5$; $0\ km \leq R \leq 20\ km$

ID	Earthquake	Date	M	Epicentral distance [km]	PGA [g]	F_S	Scaled PGA [g]	D_{rms}
7142ya	Bingol	01/05/2003	6.3	14	0.297	1.40	0.415	0.037
6277xa	South Iceland	17/06/2000	6.5	15	0.518	0.80	0.415	0.062
4674xa	South Iceland	17/06/2000	6.5	5	0.318	1.31	0.415	0.067
182ya	Tabas	16/09/1978	7.3	12	0.385	1.08	0.415	0.085
182xa	Tabas	16/09/1978	7.3	12	0.338	1.23	0.415	0.127

3 RESULTS

Figure 4 shows the evolution of pore water pressure distribution within the embankment during the different stages of the dam lifetime.

Significant increments of pore water pressure were calculated in the core throughout the entire construction process (Figure 4a). These increments are still noticeable during the first filling stages (Figure 4b-c) with the impounding assumed to occur in about 4 months after the end of the construction; the steady state conditions were reached after almost 30 years of operation (Figure 4d). The distribution of pore water pressures (as well as of the effective stresses) induced by the earthquake in the dam body are crucial to understand the role of the seismic stage on dam response to the following drawdown operations. Since among the accelerograms listed in Table 2 the signal *4674xa* was the most severe in terms of permanent deformation accumulated within the dam embankment, Figure 4e shows the pore water pressures induced by this input motion. As stated before, the numerical model is able to predict accumulation of pore water pressure under seismic loading according to the Finn-Byrne pore pressure model (Byrne, 1991). This law was activated only during the seismic stage of the computation process. The induced excess pore water pressures in three nodes (D, E, F) of the core are shown in Figure 5. Higher changes in pore water pressure were found approaching the core base (point D) while lower values were computed towards higher elevation (points E and F) as already observed in other case-histories of zoned earth dams investigated by a coupled effective stress approach (Sica et al. 2008, Sica & Pagano 2009, Pagano et al. 2010, Bilotta et al. 2010, Dello Russo et al., 2017). These pore pressure changes are important as they affect the dam response to the drawdown scenario.

Dam stability was ascertained by computing the global safety factor (FOS) soon after the imposed drawdown ratio L/H had been reached. Dam stability was hence evaluated at the end of the empting operations for every ratio L/H when steady-state conditions were not reached yet.

Figure 6 plots the FOS vs L/H for the two drawdown rates of 0.5 m/day (slow drawdown) and 4 m/day (very fast drawdown). To better understand how and to what extent the seismic stage affected the FOS computed soon after the imposed drawdown, the FOS for different L/H ratios was also computed under the hypothesis that no earthquake had occurred before the drawdown itself (Figure 6, dashed lines).

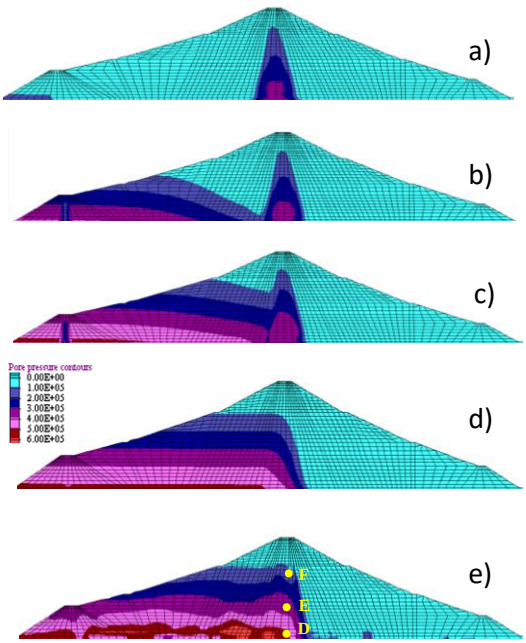

Figure 4. Pore pressure contours at different stages of the dam lifetime: a) end of the construction stage; b) water level at +42.36 m; c) water level +52.62 m, d) steady-state at the maximum water level; e) the end of the dynamic stage considering the 4674xa input signal.

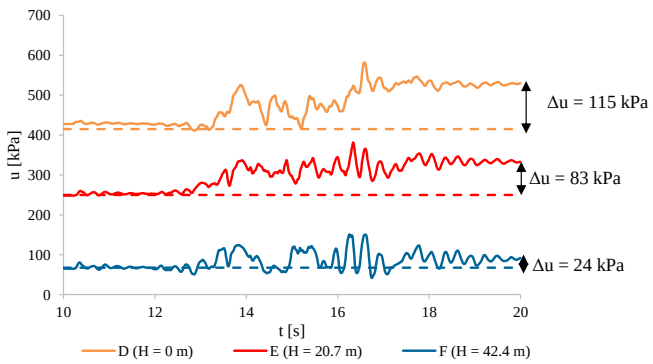

Figure 5. Time histories of pore water pressure in three points of the core considering the 4674xa seismic signal.

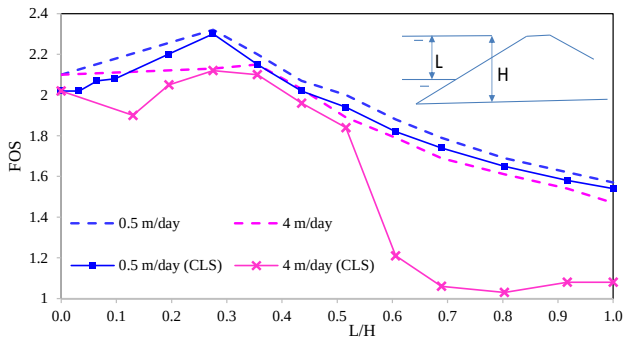

Figure 6 Global safety factor FOS vs the drawdown ratio L/H

If a strong earthquake had occurred before starting the reservoir lowering with a rate of 0.5 m/day (blue continuous line in Figure 6), the FOS coefficients are higher than the value (FOS=2) computed at L/H=0 (no drawdown) with an increasing trend up to L/H = 0.3. This means that in the first stage of the reservoir lowering, stability of the upstrteam shell is increased. Converseley, if a very fast drawdown is applied (R=4 m/day), the FOS initially drops and then starts increasing for 0.15 < L/H < 0.3. For the case at hand, the condition L/H=0.4 marks the drawdown depth over which the drawdown is no longer beneficial for the stability of the dam since the FOS coefficients are lower than the value corresponding to the initial condition (L/H=0). For L/H > 0.4 and a faster rate (0.4 m/day), dam safety decreases up to a near-collapse state (FOS=1) for L/H>0.65. Conversely, for a slower drawdown operation, no collapse takes place. It is worth noting that indipendently from the drawdown rate, no collapse occurrs even when the drawdown starts directly from a static stage, i.e. without simulation of a previous earthquake stage.

In order to properly interpret the numerical results above described, it is worth considering that up to L/H=0.3 the global instability phenomenon develops entirely within the upstream shell, where nearly drained conditions, only slightly affected by R, take place (slip surface S_1 in Figure 7). The stabilizing effect of pore pressure reductions prevails on the non-stabilizing one of static pressure removal on the upstream boundary of the dam. With increasing the drawdown ratio beyond L/H=0.3, the critical slip surface partly crosses the core (slip surface S_2 in Figure 7) with the consequence that the amount of excess pore water pressures delaying and affecting stability conditions increases.

The occurrence of an earthquake before the drawdown operation produces excess pore water pressures in the core such as shown in Figure 5. These excess pore water pressures will sum to those caused by the drawdown itself. The worst condition happens when also the core is involved in the sliding mechanism.

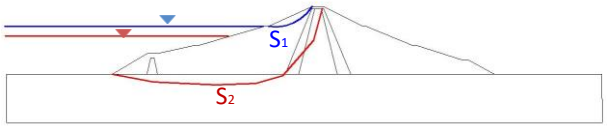

Figure 7 Slip surfaces S_1 and S_2 corresponding to L/H=0.2 and L/H=0.4, respectively

4 CONCLUSIONS

Different drawdown scenarios were simulated on a zoned earth dam considering the combined effects of two sequential stages, i.e. a strong earthquake first and a drawdown later. For the case-history considered in this study, Campolattaro Dam, the earthquake stage proved to be crucial in affecting dam stability during the reservoir lowering operations. The global safety factor (FOS) dropped to one only in case that a very fast drawdown was superimposed to a previous severe seismic stage. If the same drawdown scenario would be imposed to the dam without simulating any seismic stage, no collapse is predicted. This finding should warn the dam managers on the risk of a rapid emptying of the reservoir soon after a strong earthquake in the unjustified believe to proceed at the safest.

5 REFERENCES

Alonso E., Pinyol N. (2016). Numerical analysis of rapid drawdown: Applications in real cases. Water Science and Engineering, http://dx.doi.org/10.1016/j.wse.2016.11.003.

Bardet J. P., Ichii K., Lin C. H. (2000). EERA: A Computer program for Equivalent-linear Earthquake site Response Analysis of Layered soil deposits. Department of Civil Engineering, University of Southern California.

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.

Bishop A.W. (1954). Use of pore-pressure coefficients in practice. Geotechnique vol 4, no 4, pp 148-152.

Bommer J., Acevedo A. (2004). The use of real earthquake accelerograms as input to dynamic analysis. Journal of Earthquake Engineering, 8 (Special Issue 1), 43-91.

Byrne P. M. (1991). A Cyclic Shear-Volume Coupling and Pore Pressure Model for Sand. International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics. Paper 1.

d'Onofrio A. (2016). Prove geotecniche di laboratorio - Rivalutazione della sicurezza sismica dello sbarramento, opere accessorie e sponde del serbatoio della Diga di Campolattaro sul fiume Tammaro – Provincia di Benevento (in Italian)

Dawson E.M., Roth W.H. and Drescher A. (1999). Slope stability analysis by strength reduction. Géotechnique, 49(6), 835-840.

Dello Russo A., Sica S., Del Gaudio S., De Matteis R., Zollo A. (2017). Near-source effects on the ground motion occurred at the Conza Dam site (Italy) during the 1980 Irpinia earthquake. Bulletin of Earthquake Engineering, vol. 15, p. 4009-4037, ISSN: 1570-761X, doi: 10.1007/s10518-017-0138-2

Duncan J. M. (1996). State of the art: limit equilibrium and finite-element analysis of slopes. J. Geotech. Engn Div. Am. Soc. Civ. Engrs 122, No. 7, 577-596.

Itasca Consulting Group Inc. (2005). FLAC - Fast Lagrangian Analysis of Continua. Version 5.0, User's Manual.

Masing G. (1926). Eignespannungen und verfestigung beim messing. Second International Congress on Applied Mechanics, Zurich, Switzerland, pp. 332–335

Morgenstern N. (1963). Stability charts for earth slopes during rapid drawdown. Géotechnique 13(1),121-131.

NTC (2018) Ministero Infrastrutture e Trasporti. Aggiornamento delle Norme Tecniche per la Costruzioni. D.M. 17/01/2018. Gazzetta Ufficiale n. 8, 20/02/2018

NTD (2014) Ministero Infrastrutture e Trasporti. Norme Tecniche per la Progettazione e la Costruzione degli Sbarramenti di Ritenuta (dighe e traverse). D.M. 26/06/2014. Gazzetta Ufficiale Serie Gen. n. 156, 08/07/2014.

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. Soils and Foundations, 50 (2), 295-307

Rollins K. M., Evans M. D., Diehl N. B., Daily W. D. (1998). Shear Modulus and Damping Relationships for Gravels. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 124(5):396-405.

Seed H.B., Wong R.T., Idriss I.M. and Tokimatsu K., 1986. Moduli and damping factors for dynamic analyses of cohesionless soils. Journal of Geotechnical and Geoenvironmental Engineering ASCE; 112(11):1016-32.

Sica S., Pagano L., Modaressi A. (2008). Influence of past loading history on the seismic response of earth dams. Computers and Geotechnics, 35 (1), pp. 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.

Skempton A.W. (1954). The pore pressure coefficients A and B. Géotechnique 4(4), 143-147.

Van Genuchten M. Th. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. J. Soil. Science 44:892-898