SEISMIC HAZARD AND VULNERABILITY OF THREE SICILIAN EARTH DAMS

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ABSTRACT

In the past years, earth and concrete dams were studied through static approach also in seismic conditions, in which the dynamic aspects were investigated and connected to pseudo-static problems. Based on the recent Italian Building Code, this approach is exceeded or at least very limited, in support of the fact that, in the new classification about Italian territory, dams fall into the category of strategic projects, or at least of projects whose potential collapse would cause huge damage. Nowadays, the legislation approach provides that the safety and functionality analysis of an existing dam is conducted with physical approach that analyzes, using analytical and numerical tools, the response to moderate or high intensity earthquakes, through a careful study of the actual conditions of the structure and the next determination of the potential seismic activity to which the structure may be subjected. Therefore, the purpose of this paper is to provide a methodological note for the safety evaluation of the earth dams in seismic conditions, such as the Poma Dam in Partinico (PA), the Trinità Dam in Castelvetrano (TR) and the Lentini Dam (SR), located in medium or high seismic hazard areas of the Sicily island (South of Italy).

Keywords: Earth dams; Seismic vulnerability; Italian Building Code.

1. INTRODUCTION

The heritage of Italian dams counts 530 works different for types, materials (earth, concrete, masonry) and year of construction. Among these, 165 are earth dams and more than 50% are located in medium-high seismicity areas. In particular, Sicily island (South of Italy) has 47 large dams, including 10 currently in use and made of loose materials. In this context emerges the importance of seismic risk assessment (Castelli et al. 2016a, 2016b) of existing dams. The need to know as soon as possible any damage that barriers can undergo after an earthquake leads into the possibility of mitigating the effects related to loss of human life, economic and environmental impact. According to the recent decree (Ministerial Decree 26/06/2014) issued by the Ministry of Infrastructures and Transport and containing the "Technical rules for the design and construction of restraints (dams and barriers)" the dams fall into the category of strategic works or, in any case, of works whose potential collapse would cause significant damage. The safety and functionality analysis of an existing dam for the Italian Building Code can be conducted with analytical and numerical tools, which analyze the real response of structures to high or medium intensity earthquakes. The seismic safety assessment of a dam made of loose material can be carried out using different approaches: the pseudo-static methods, which define the stability of the work respect to boundary equilibrium conditions by a global safety factor; the dynamic methods according to which the stability is defined by the comparison between the displacements accumulated during the seismic event and the corresponding values considered admissible (Castelli and Lentini 2010, Castelli et al. 2015, 2016c, 2017). The interpretation of the available instrumental data is important (Castelli and Lentini 2013, 2016): the examination of the

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historical series of measured parameters (displacements, rotations, pore water pressures) as a function of external stresses (construction phases, reservoir levels, past seismic events, etc.) is preliminary and indispensable and allows the preparation of more reliable calculation models. The article focuses on the criteria for the assessment of seismic vulnerability with reference to three earth dams located in Sicily (Italy): Poma Dam in the site of Partinico (PA), Trinità Dam in Castelvetrano (TR) and Lentini Dam in Lentini (SR).

2. CASE STUDIES: THE POMA, TRINITÀ AND LENTINI DAMS

Among the active earth dams in Sicily (Italy) were selected the Poma Dam, the Trinità Dam and the Lentini Dam. The main characteristics of these are summarized below (Figure 1).

![Figure 1. Lentini Dam (a); Poma Dam (b); Trinità Dam](c)

2.1 The Lentini Dam

The Lentini Dam, was built in the ’80s on the perimeter of an ancient natural internal lake and it is powered by outflows from the Simeto river and the Cave, Trigona, Barbajanni, Zena torrents. Water is used for irrigation, industrial and civil purposes through the provinces of Catania and Siracusa. The dam has the shape of a trapezoid and covers an area of about 10 km²; it has a useful capacity of 127 million m³ of water and modulates about 70 million m³/year of average outflows. It is contained by a long dam formed by two branches. The dam body, having an extensive system of filters and drainages, consists of calcarenite and basaltic rockfill, covered with bituminous concrete. The unloading and derivation systems are located near a relief of terraced floods that separates the two branches of the dam. The crowning, 6.50 m wide, is located at 36.50 m above sea level. The embankment has a section with symmetrical scarp having a slope of 1:1.8 respect to the horizontal.

2.2 The Poma Dam

The Poma Dam, built from 1963 to 1968 on the river Jato in Torre Lazzarola (PA) is currently one of the largest gravity earth dam in Sicily. It allows the irrigation of thousands of hectares of land in the Piana of Partinico and contributes to the water supply of the city of Palermo and some coastal areas. The dam collects the waters from the river Jato and Fico, Ciurro Murro, Malpasso, De Landro, De Simone, Carrubbella, Sardo, Santa Caterina, Girgentano torrents. The dam is developed over an area of 163.6 hectares and has a useful capacity of 78.3 million m³ of water; at the maximum filling height (196.85 above sea level) occupies a liquid surface of 5.37 km² and has an average depth of 14.6 m. The dam is constituted by a central core of a waterproof fine-grained material, with a sealing function, and two large-material abutments with variable shoe vestments. The central core is inclined towards mount and ends at the foot with a clamping retaliation in the foundation clays.

2.3 The Trinità Dam

The Trinità Dam is an artificial dam built between 1956 and 1959 by damming the Delia river in the territory of Castelvetrano (TP). The dam, which was originally used for irrigation purposes by the
municipalities of Campobello di Mazara, Mazara del Vallo and Castelvetrano, collects the waters of the river Arena, which in correspondence of the reservoir is called Delia. The total surface is 200 km². The reservoir has a useful capacity of 20 million m³ of water, an average depth of 9.5 m, and the maximum reservoir (69 m above sea level) occupies a liquid surface of 2.13 km². The dam consists of a massive central core of material from the reservoir and an upstream abutment of sandstone material of crushed quarry and downstream of the silt of the reservoir.

3. SEISMIC HAZARD

The study of earthquakes and the identification of faults able to deform the topographic surface (called capable faults) is extremely important in an area like the Italian territory, where the danger associated with these phenomena is sometimes very high and it allows a characterization of the territory in terms of dangerousness, assuming a key role for risk mitigation actions. The knowledge of the distribution in the territory of capable faults is of primary importance for the seismogenic study. The information related to these faults, among which lie, geometry, kinematics, associated earthquakes and average deformation rate, are collected in a catalog (ITHACA - ITaly HAzard from CApable faults) managed by ISPRA, consisting of a constantly updated database and a detailed cartography managed in the GIS environment (Fig. 2).

Figure 2. Synthesis map of the faults capable of Sicily contained in the ITHACA database

The seismic hazard of a site must be described with sufficient level of detail, in terms of space and time. The relative results are given, in correspondence of the considered area, as maximum horizontal acceleration values \( a_g \), referred to a rigid ground (characterized by shear wave propagation velocity \( V_S > 800 \) m/sec) and for different probabilities of overcoming and/or different return periods \( T_R \). The seismic action so identified is subsequently changed to take account the changes produced by the local stratigraphic conditions of the subsoil and the morphology of the topographic surface. Currently, the evaluation of the seismic hazard of reference in Italy is based on a probabilistic approach (Probabilistic Seismic Hazard Analysis - PSHA), which consists in estimating the probability of a seismic shaking level greater than a given value within a given period of time. The level of shaking can be expressed by the maximum horizontal acceleration on rigid ground \( a_g \) (Peak Ground Acceleration - PGA) which, being a synthetic parameter, is useful for the classification of the territory but it is not representative of the energy released nor of the effects on buildings. Therefore, for the seismic response, it is necessary to consider the site response spectrum (which allows to evaluate the maximum effects according to the dynamic characteristics of the structures) or a large number of accelerograms, representative of the possible shaking and that can be assumed as input to the base of the structures. The assessment of the Seismic Hazard in these considered areas, was made with a probabilistic approach based on the Cornell’s Method (1968), which counts 4 phases: Reconstruction
of the site historical seismicity and identification of seismogenic zones; Determination of the cumulative distribution function of earthquakes magnitudes \( FM(m) \), for each seismogenic zone (this is a relationship between the number of events and the intensity (or magnitude) called recurrence relation); Construction of a model that represents the variation of macroseismic intensity with the distance from the epicenter; Calculating the Seismic Hazard Curve, which consists of a function that represents the annual frequency of exceeding of the considered parameters, for example the peak ground acceleration. Note the Hazard Curve for each site is immediate to pass to a probabilistic estimate of the danger.

### 3.1 Reference seismicity

The study takes into consideration the historical and instrumental seismicity of the sites of the dams. Deaggregation data from Seismic Hazard Map allows the estimate of the most likely earthquake magnitude and distance: the mean annual rate of exceedance is expressed as a function of magnitude and distance. According to the classification of the national territory, the Lentini Dam falls in seismic zone 1. The Lentini Dam is part of the "relevant projects" type and therefore we will refer to a nominal life \( V_N \) equal to 50 years, of use \( C_U \) equal to 1.5, and a reference period \( V_R \) of 75 years. The periods of return of the seismic action are equal to 45, 75, 710 and 1460 years, respectively corresponding to the probabilities of 81, 63, 10 and 5% associated with the operating limit states (operating limit state, SLO and damage limit state, SLD) and last limit states (life-saving limit state, SLV, and collapse limit state, SLC). Finally, the Italian territory has been divided into a grid and for each node of the grid the reference legislation (NTC 2008) defines an elastic response spectrum which is function of three parameters: the horizontal acceleration of peak on rock outcropping \( a_g \); the maximum amplification factor of the spectrum in horizontal acceleration \( F_0 \); the start period of the constant velocity segment of the accelerating reference spectrum \( T_c^* \). The values of these parameters related to the site of Lentini Dam are shown in Table 1. The Poma Dam falls into seismic zone 2 and it is classified as "strategic work" and therefore we will refer to a nominal life \( V_N \) equal to 50 years, a coefficient of use \( C_U \) equal to 2, and a reference period \( V_R = 100 \) years. The return periods of the seismic action are equal to 60, 100, 950 and 1946 years, respectively corresponding to the probabilities of 81, 63, 10 and 5% associated with the operating and last limit states. The values of the parameters \( a_g \), \( F_0 \) and \( T_c^* \) relative to the site of the Poma Dam are shown in Table 2. The Trinity Dam falls into seismic zone 2 and it is classified as "relevant work" and therefore we will refer to the same parameters of the Lentini Dam. The values of the parameters \( a_g \), \( F_0 \) and \( T_c^* \) relative to the site of Trinity dam are shown in Table 3. The characteristic parameters of the response spectrum for the limit states mentioned above in terms of variation of \( a_g \), \( F_0 \) and \( T_c^* \) have been calculated for the three sites, through the use of the SPETTRI-NTC software (version 1.0.3) and they are reported in the Figures 3-5.

#### Table 1. Hazard parameters for the Lentini Dam.

<table>
<thead>
<tr>
<th>Limit State</th>
<th>( T_R ) years</th>
<th>( a_g ) g</th>
<th>( F_0 )</th>
<th>( T_c^* ) s</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLO</td>
<td>45</td>
<td>0.065</td>
<td>2.485</td>
<td>0.265</td>
</tr>
<tr>
<td>SLD</td>
<td>75</td>
<td>0.087</td>
<td>2.488</td>
<td>0.285</td>
</tr>
<tr>
<td>SLV</td>
<td>710</td>
<td>0.326</td>
<td>2.313</td>
<td>0.449</td>
</tr>
<tr>
<td>SLC</td>
<td>1460</td>
<td>0.465</td>
<td>2.343</td>
<td>0.504</td>
</tr>
</tbody>
</table>

#### Table 2. Hazard parameters for the Poma Dam

<table>
<thead>
<tr>
<th>Limit State</th>
<th>( T_R ) years</th>
<th>( a_g ) g</th>
<th>( F_0 )</th>
<th>( T_c^* ) s</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLO</td>
<td>60</td>
<td>0.062</td>
<td>2.306</td>
<td>0.250</td>
</tr>
<tr>
<td>SLD</td>
<td>100</td>
<td>0.083</td>
<td>2.299</td>
<td>0.262</td>
</tr>
<tr>
<td>SLV</td>
<td>950</td>
<td>0.226</td>
<td>2.392</td>
<td>0.305</td>
</tr>
<tr>
<td>SLC</td>
<td>1946</td>
<td>0.290</td>
<td>2.449</td>
<td>0.323</td>
</tr>
</tbody>
</table>
Table 3. Hazard parameters for the Trinità Dam.

<table>
<thead>
<tr>
<th>Limit State</th>
<th>$T_R$ (years)</th>
<th>$a_g$ (g)</th>
<th>$F_0$</th>
<th>$T_C^*$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLO</td>
<td>45</td>
<td>0.032</td>
<td>2.376</td>
<td>0.204</td>
</tr>
<tr>
<td>SLD</td>
<td>75</td>
<td>0.042</td>
<td>2.407</td>
<td>0.242</td>
</tr>
<tr>
<td>SLV</td>
<td>710</td>
<td>0.123</td>
<td>2.426</td>
<td>0.305</td>
</tr>
<tr>
<td>SLC</td>
<td>1460</td>
<td>0.164</td>
<td>2.469</td>
<td>0.320</td>
</tr>
</tbody>
</table>

3.2 Spectrocompatible accelerograms

A set of natural accelerograms have been selected with reference to the most severe limit state both in the case of an operating limit state (SLD) and in the ultimate limit state (SLC), considering a surfacing rock soil (ground A). The data contained in the Seismic Hazard Map of Italy represent the contributions of the seismic sources in the node closest to the site in question and allow to identify the magnitude and distance intervals to be used as criteria for the search of natural records in the accelerometric databases. The Seismic Hazard Map of Italy is realized by INGV (National Institute of Geophysics and Vulcanology) and it is based on the maximum expected ground acceleration in homogeneous rigid soils within a depth of 30 meters.

Figure 3. Diagrams of the values of the parameters $a_g$, $F_0$ and $T_C^*$ calculated for the Lentini Dam
Figure 4. Diagrams of the values of the parameters $a_g$, $F_0$ and $T^*_{C}$ calculated for the Poma Dam
The accelerograms have been selected considering the values of magnitude intervals \((M)\), the site-source distance \((d)\), the peak ground acceleration \((PGA)\) and the return period \((T_R)\), for each dam and for the damage limit state \((SLD)\) and collapse limit state \((SLC)\), shown in Table 4.

<table>
<thead>
<tr>
<th>Dam</th>
<th>Limit State</th>
<th>(M)</th>
<th>(d) km</th>
<th>(PGA) g</th>
<th>(T_R) years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lentini</td>
<td>SLD</td>
<td>5.5 - 6.4</td>
<td>0 - 38</td>
<td>0.084</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>5.8 - 7.0</td>
<td>0 - 24</td>
<td>0.240</td>
<td>1460</td>
</tr>
<tr>
<td>Poma</td>
<td>SLD</td>
<td>5.5 - 6.0</td>
<td>0 - 40</td>
<td>0.082</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>6.0 - 6.7</td>
<td>0 - 20</td>
<td>0.280</td>
<td>1946</td>
</tr>
<tr>
<td>Trinità</td>
<td>SLD</td>
<td>5.3 - 5.6</td>
<td>20 - 30</td>
<td>0.039</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>SLC</td>
<td>6.0 - 8.0</td>
<td>0 - 37</td>
<td>0.139</td>
<td>1460</td>
</tr>
</tbody>
</table>

The most representative accelerograms (Fig. 6-8), for each of the limit state, were performed as a function of the frequency compatibility verification between the extracted recordings and the elastic spectra given by legislation, using the REXEL numeric code v.3.5 (Iervolino et al., 2010).

SLD – \(T_R = 75\) years

SLC – \(T_R = 1460\) years

\(a_g = 0.088\) g

\(a_g = 0.316\) g

\(a_g = 0.053\) g

\(a_g = 0.224\) g
Figure 6. Spectrocompatible Accelerograms for the Lentini Dam.

The Spectrocompatibility criterion refers to two indicators: i) the scale factor of the FS amplitude, given by the ratio between the maximum acceleration forecast by the Seismic Hazard Map and the peak value of the recorded accelerogram; ii) the spectral form factor, expressed by the Pearson coefficient $R^2$, which represents the conformity of the content in frequencies between the recorded signal and the one to be reproduced. The Spectrocompatibility criterion is inspired by literature (Bommer and Acevedo 2004, Pagliaroli and Lanzo 2008)

- SLD - $T_R = 100$ years
- SLC - $T_R = 1946$ years
Figure 7. Spectrocompatible Accelerograms for the Poma Dam

SLD - $T_R = 75$ years
SLC - $T_R = 1460$ years
The compatibility between the response spectra of the selected recordings and the normative ones is shown in Figures 9-11 for the Lentini, Poma and Trinità Dam respectively, highlighting that the spectral forms for the SLD are generally characterized by frequency contents on average higher than to the SLC. The same diagrams also show the average trends of the recorded spectral shapes.
Figures 9. Comparison between the spectral shapes of the selected accelerograms and those of the Normative (Target spectrum) for the SLD (a) and SLC (b), with indication of the field of significant periods for the Lentini Dam.

Figures 10. Comparison between the spectral shapes of the selected accelerograms and those of the Normative (Target spectrum) for the SLD (a) and SLC (b), with indication of the field of significant periods for the Poma Dam.

Figures 11. Comparison between the spectral shapes of the selected accelerograms and those of the Normative (Target spectrum) for the SLD (a) and SLC (b), with indication of the field of significant periods for the Trinità Dam.
4. CONCLUSIONS

This study provides a methodological approach aimed to evaluate the seismic vulnerability of three Sicilian earth dams: the Poma Dam in the site of Partinico (PA), the Trinità Dam in Castelvetrano (TR) and the Lentini Dam (SR), all situated in areas of medium or high seismic hazard in Sicily (South of Italy). In relation to the recent legislation (Ministerial Decree 26/06/2014) issued by the Ministry of Infrastructures and Transport and containing the "Technical standards for the design and construction of restraints (dams and barriers)", the dams fall into the category of strategic projects or, in any case, of projects whose potential collapse would cause significant damage. The aim of this study, therefore, consists in the preparation of guidelines and criteria for the estimation of seismic hazard, preliminary to the assessment of the safety degree and the design of the most suitable interventions for the adaptation to the current Italian Building Code of the three earth dams taken into consideration.

5. REFERENCES


