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# Assessment of the seismic performance of a bituminous faced rockfill dam

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ABSTRACT

In the attempt to codify a procedure exportable to other similar cases, a thorough investigation of the seismic performance of a bituminous concrete faced rockfill dam built in Italy in the early eighties is herein presented. The dam presents a 90 m tall embankment built in a narrow canyon and is situated in a highly seismic region. The implemented methodology encompasses the indications provided by the most recent literature to point out the problems potentially caused by earthquakes and to account for the paramount factors affecting the response of the dam. Particular attention has been paid to the concept of performance, defining its goals in accordance with the most recent standards and deriving the correspondent limit conditions from observations reported in the literature. In order to optimize the computational effort, dynamic analyses with two and three dimensional finite difference codes have been combined to study the coupled response of the embankment, rocky foundation and bituminous facing. After validating the numerical models with centrifuge tests performed on small scale models of the embankment, the performance of the dam has been investigated with reference to a number of possible scenarios focusing on the amplification spectra, the deformation of the embankment and the integrity of the bituminous lining.



## 1. Introduction

Since it is not possible to prevent earthquakes from occurring, quantification and mitigation of the seismic hazard is the only possible countermeasure to reduce the casualties, deaths, injuries and property damages, periodically caused by these events. Taking advantage of the considerable expertise matured in the past decades, a robust engineering practice has already been implemented for the design, assessment and rehabilitation of buildings and more and more specific requirements are being steadily introduced in the current structural codes [1–3].

Unfortunately the same level of standardization has not been attained yet for earth and rockfill dams, mostly due to the fact that each dam is a unique prototype characterized by its specific geometry, materials and local geological conditions [4,5]. Qualitative descriptions can be found of the possible failure mechanisms taking place during earthquakes [6,7] but methodologies driving to a quantitative risk assessment have not been defined. Nevertheless, the assessment of the seismic performance and the planning of rehabilitation works represent compulsory duties for the engineers faced with the design and management of dams located in highly seismic regions.

This duty becomes by far more complex for dams built in old ages and still operating. In fact, while the geometry, the structural arrangement and the materials of new structures can be designed rather freely and controlled throughout construction, the properties of existing dams are often not known and can be hardly modified. It must be additionally considered that a large part of old dams has been designed and built with out of date criteria, not including the most recent findings on the seismic characterization of the sites and on the accuracy of the mechanical models.

A methodology encompassing these studies is thus needed to assess the seismic performance of dams and to arrange a plan of economic investments for their current management. With this aim, not only the actual safety conditions of the dam against strong earthquakes should be quantified, but also the effects induced by more frequent and less destructive events should be predicted.

The analysis herein presented focuses on rockfill dams coated on their upstream face with bituminous concrete (Bituminous Faced Rockfill Dams or BFRD). Thanks to a number of technical and economical advantages [8,9], about 8% of the large dams built all over the world are made with rockfill [10] and some embankments reach very considerable heights [11].

In comparison with the clay core, the bituminous facings presents the advantage of being applied on the completed embankment, i.e.

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after the settlements induced by construction are developed. The barrier is made of an impervious sheet of bituminous concrete, but a solution consisting of multiple impervious layers separated by pervious strata is often used to monitor possible leakage [12]. In all cases, the lining should be sufficiently flexible to accommodate possible deformation induced on the embankment by the cyclic impounding of the reservoir or by seismic events.

The durability of the lining is particularly important for the integrity of the dams, as penetration of water in the rockfill embankment may produce undesired effects such as internal piping, segregation of the coarse grained materials and structural collapse, a phenomenon occurring during the first saturation and capable of determining significant compressive strains [13]. Furthermore, saturation of poorly compacted granular materials could trigger liquefaction in case of earthquakes [14]. In the most unfavorable cases, the above phenomena may in turn accumulate stresses and deformation in the facing and generate a vicious circle like the one that caused the failure of the 71 meters high Gouhou rockfill dam in China [15].

In comparison with the pioneering analytical methods [16–19], the remarkable evolution of theories and calculation tools offers nowadays the possibility to assess the seismic performance of dams with a wide class of numerical tools [20]. These methods allow not only to predict the possible collapse mechanisms induced by destructive earthquakes, but also to quantify the effects induced by less critical events. Such a possibility, together with the development of statistical analyses of the regional seismicity, has led to replace the original force-strength approach with a new design philosophy, named Performance Based Seismic Design (or PBSD). With this approach, probabilistic multi-level structural performance criteria are introduced [21] in order to plan a cost effective management of dams.

The practical application of the methodology consists in fixing values of specific performance target variables (e.g. levels of displacement, stress, maximum acceleration or mobilized strength) tolerable with prescribed recurrence times [22] and in verifying that these values are not exceeded for seismic inputs probabilistically occurring with the same return periods. The main difficulties to apply this methodology to BFRD consist in:

i. the identification of performance variables representative of critical scenarios;
ii. the analysis of the coupled seismic response of the foundation-dam-facing system.

With regard to the first issue, only few examples exists in the literature where a sound similar methodology has been proposed for other dam's types [23,24]. With regard to the second issue, former studies highlight the fundamental role of the seismic input [25], the nonlinear, irreversible, stress dependent behavior of the materials [26,27], the geometry of the embankment [28] and the interaction among the different components [29,20].

In the attempt to codify a methodology exportable to other BFRD dams, a procedure has been defined in the present study to assess the seismic performance of an Italian dam. This dam was built in the end of the last century in a highly seismic area of southern Italy (earthquakes with magnitudes as high as 7.2 have been recorded in the past), and represents with its 90 m tall embankment the highest BFRD dam in Europe. As a preliminary step, the general objectives of the performance analysis are determined in accordance with the rules currently adopted for the design of buildings. Considering different levels of damage (limit state), a set of target variables indicative of the dam's performance is defined together with their benchmark values. Assessment then consists of verifying with a numerical calculation that the limit values of the performance variables are not exceeded for earthquakes compatible with the seismicity of the area.

## 2. The case study

The studied dam was built in the period between 1984 and 2000 along the Menta river, a watercourse flowing through the Aspromonte Mountain in southern Italy (Fig. 1a), to create a reservoir of about $18\times10^6$ m$^3$ capacity with a maximum water level positioned at 1431.75 m above sea level (a.s.l.) (Fig. 1b). The barrage closes a complex section formed by two distinct gorges, a left one whose bottom (1343 m a.s.l.) hosts the former bed of the river and a right one having the bottom located at an upper level (1418 m a.s.l). These two gorges are divided by a massive rocky spur steeply emerging in the middle of the section up to an altitude of 1433 m a.s.l (Fig. 1b). Such a peculiar section was completely filled with an irregularly shaped embankment made of rockfill quarried from a nearby hill of metamorphic rocks.

The embankment, which incorporates in its central part the rocky spur, has a curvilinear plan trend of the crest developing for about 450 m, a total volume of about $2.1\times10^6$ m$^3$ and a maximum height of about 90 m (Fig. 1c). It includes a central core of coarse grained material (zone 3 in Fig. 1c), a layer of finer soil placed below the upstream face as a foundation of the waterproofing lining (zone 1), a transition zone with particles having intermediate size (zone 2) and a composite cliff made of boulders which covers the downstream face (zone 4).

The grading of the materials forming the different portions of the embankment is shown in Fig. 2 together with the grain size composition of the samples subjected to laboratory tests. The reported envelopes represent the particle size distribution of the materials after placement, which differs from the one prescribed by designer due to a significant breakage suffered by the metamorphic rock during compaction. The latter was achieved by vibratory rollers in order to obtain dry unit weights variable between 20 and 25 kN/m$^3$.

On the upstream face of the dam a multi-layered (sandwich type) bituminous concrete lining was placed, anchored all along its foot to a peripheral tunnel having drainage functions (Fig. 3). In order to prevent seepage of the stored water from the dam's foundation and abutments, this impervious barrier was prolonged into the upper weathered part of the rocky basement by creating a sealing curtain of cement grout injections (Fig. 3a).

The properties of rockfill, basement rock and bituminous concrete were continuously investigated throughout design and construction stages by means of different experimental campaigns. Results of these investigations will be presented in the next sections devoted to the calibration of the constitutive models.

## 3. Numerical modeling

The seismic assessment of the Menta dam has been carried out combining a large number of bi-dimensional calculations, performed on representative sections of the dam (A–A' in Fig. 1c), with few selected analyses performed on a full three dimensional model (Fig. 4). In both cases the calculations have been conducted with finite difference codes (respectively FLAC2D [30] and FLAC3D [31]) implementing models (Fig. 4a and b) which extend to about 80 m below the dam's base and 100 m sideways to include a meaningful part of the rocky foundation, the embankment's body and the bituminous lining.

As a particularly delicate step of these analyses, the dimension of the mesh has been decided mediating two opposite needs, one that leads to a subdivision into very fine elements to better represent the maximum traveling wavelength, the other leading to a