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Integrating fragility functions into earthquake early warning systems for embankment dams

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ABSTRACT: Earthquake fragility functions generally link a ground motion intensity measure with an expected level of damage (or collapse probability). Such relationships have emerged as a prominent tool to evaluate performance and risk of engineering systems under seismic actions. Their use to assess the vulnerability of geotechnical structures is gradually gaining popularity, and further applications in early warning systems and post-event emergency management have been recently developed, with the aim of mitigating seismic risk. This paper explores the inclusion of case-specific fragility functions developed for two embankment dams in Southern Italy within an Earthquake Early Warning System (EEWS). The paper presents the general framework of an EEWS for embankment dams, briefly describing the procedure to obtain the fragility functions and illustrating the potential use of various ground motion intensity measures. Fragility functions can be developed for prediction purposes, or used to assess damage following an earthquake event in real time using either (1) recordings at the dam site, if available, or (2) ground motion estimates from Shakemaps and/or similar methods. These pieces of information can be adopted to inform post-event emergency management. A description of the framework, the expected capabilities of its components, and its application to two Italian dams using earthquake scenarios will illustrate the advantages of using fragility functions as a fundamental decision-support instrument of an EEWS. The use of passive measures such as EEWS incorporating fragility functions is envisaged as an attractive, sustainable, and affordable approach to mitigate the seismic risk of embankment dams.

KEYWORDS: Seismic vulnerability, earth dams, emergency management.

1 INTRODUCTION

Safety assessments of embankment dams immediately after earthquakes remain critical tasks to estimate the risks faced by downstream populations and assets after a seismic event. These evaluations are usually carried out by dam managers, supported by visual inspections and information from monitoring records, followed by a further expert opinion to address the post-event safeguard activities (ICOLD, 2016). However, this procedure does not include quantitative assessments of seismic performance, which could be highly beneficial for better management of post-event activities after strong earthquakes. The use of case-specific fragility functions within an earthquake early warning system can bring a first quantitative estimate of the performance of the dam immediately after the event, complementing the post-event activities and improving emergency management and decision making.

In this paper, a proposal for an Earthquake Early Warning System (EEWS) using fragility functions as a tool relating the performance of the dam to the intensity of the ground shaking is presented. An application of the framework for two embankment dams in Southern Italy was also performed using ground motion fields estimated for a group of historical earthquakes, as reconstructed using historical macroseismic data and Shakemaps. Two main approaches can be adopted when using the proposed framework: (1) when ground motion recording stations are available at the dam site, the as-recorded ground motion intensity measure can be used directly; (2) the use of Shakemaps, available minutes after the event, is an alternative approach for dams without a seismic monitoring system. The use of the latter introduces an extra level of uncertainty in the estimation of the ground motion that has to be pondered when evaluating the output of the EEWS. As a result, introducing fragility functions within an EEWS is an advantageous tool for evaluating the dam's performance in near-real-time for several damage levels and potential failure modes. The presented approach could be an attractive complement to traditional post-event evaluations and bring real-time information about the performance of the asset into emergency decision-making processes.

2 FRAMEWORK OF EEWS FOR EMBANKMENT DAMS

2.1 *General framework*

The objective of the EEWS is to reduce potential earthquake-related risk by providing useful information before the consequences of the earthquake-induced damage can affect exposed communities. In traditional EEWS, risk mitigation strategies can be implemented by sending alarms alerting people and managers of critical assets before they are reached by strong ground motion.

In the case of embankment dams, the dangerous condition is not the earthquake shaking itself, but the damage that strong ground motions may induce on the dam, potentially leading to its collapse. This could result from several failure mechanisms (some of which are not instantaneous, e.g.: excess pore water pressure dissipation leading to settlements) that the dam might develop under strong shaking, with the likelihood of each mechanism depending on the combination of dam, site, and load conditions.

An EEWS for embankment dams, according to Pagano and Sica (2013), should comprise four components:

a) a seismic monitoring system able to bring a measure of the ground shaking at the site, which could be alternatively estimated using a regional seismic network combined with Shakemaps or similar tools;

b) one or more interpretative models that use the monitored variables to provide a prediction of the seismic effects on the dam, in terms of representative performance parameters;
c) threshold values of performance parameters related to increasing damage levels, which in turn correspond to different alarm levels;
d) the definition of the actions linked to the different stages of alert.

Every component should be adapted to the specific case, and different approaches and levels of complexity could be considered through the development of the EEWS, seeking a suitable cost-benefit balance while managing uncertainty.

2.2 *EEWS for embankment dams using fragility functions*

Based on the previous general framework, an EEWS for embankment dams is summarized in Figure 1 (Barbagelata et al., 2024). This framework introduces fragility functions as interpretative models (component b), as listed before), bringing as an outcome the probabilities of developing different damage states depending on the sustained seismic actions. These evaluations of performance could define, together with visual inspections and monitoring records, different alert levels with a risk-based definition.

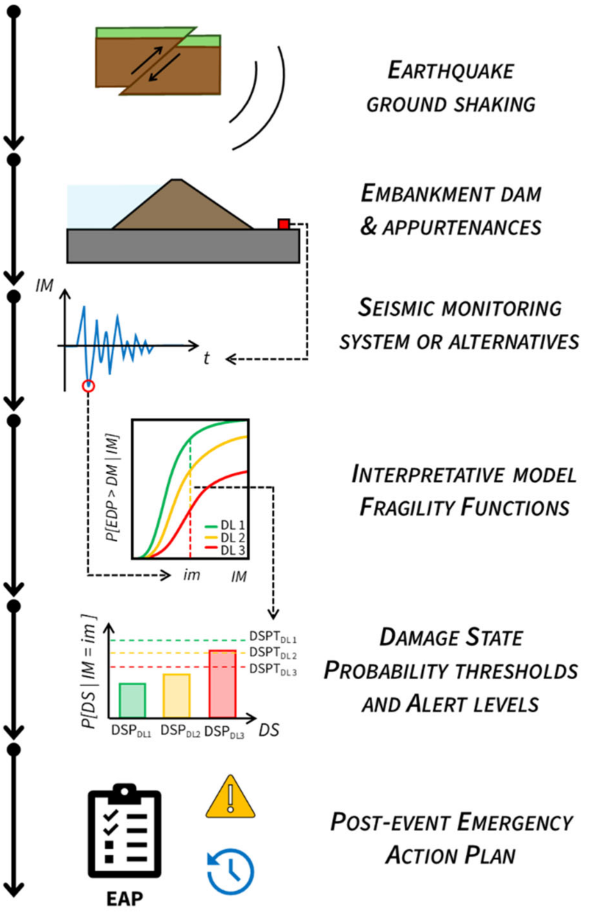

Figure 1. EEWS using fragility functions (Barbagelata et al., 2024).

Under this framework, two definitions closely related to the fragility functions which should be carefully considered are: (1) the Intensity Measure (*IM*) used to characterize the ground motion and (2) the Engineering Demand Parameter (*EDP*), which was selected to represent a given Potential Failure Mode (PFM) in the construction of the fragility functions.

The *EDPs* are, in general, kinematic or static variables representative of the overall seismic response of the system during the development of a given PFM. The *EDPs* should be selected based on the availability of Damage Measures (*DM*), which define the damage levels developed by the dam. The *DMs* can be set as *EDP* thresholds or through probabilistic relationships among *DM* and *EDP*, and they are essential to mark the boundaries between the damage states experienced by the dam during earthquakes.

The *IMs* are variables characteristic of a particular feature of the ground shaking, such as peak intensities (maximum acceleration or velocity) or integral parameters linked to the energy or duration of the motion (e.g. Arias intensity or cumulative absolute velocity). Some *IMs* are better than others to capture the variations in the response of the dam, and for this reason, there exist metrics that identify the optimal *IM* based on different criteria (Regina et al., 2023). Selecting the best *IM* for building fragility functions and their further use in EEWS remains decisive, as the selected *IMs* should accurately predict the performance of the dam in a broad range of intensities.

3 FRAGILITY FUNCTIONS OF TWO EARTH DAMS IN CALABRIA, ITALY

The fragility functions considered in this work represent the response of two zoned earth dams located in the Calabria Region, Southern Italy, analyzed in detail by Regina (2021). The main features of both dams are presented in Figure 2.

The Farneto del Principe is a zoned earth dam 30 m high and 1200 m long. The dam is placed over about 25 m of alluvial material overlying a thick clay bed, with a fine-grained soil core and cut-off walls as impervious barriers embedded in the clay bed. The dam is in the north of the Calabria Region, in a high seismicity zone.

The 27.8 m high and 195 m long Angitola zoned earth dam is located 100 km south of the Farneto del Principe dam, within the same tectonic context. The foundation is characterized by a complex layering, with a thin potentially liquefiable layer of sandy silts on the downstream side, placed over an old and more consolidated alluvium. In the upstream side, a Pliocenic silty clay formation with variable thickness is placed over a heterogeneous sand layer resulting from the weathering of the underlying rock foundation, made up of fractured gneiss.

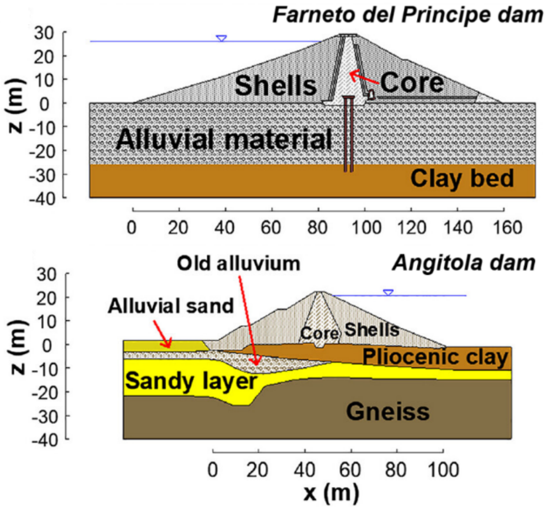

Figure 2. Main features of Farneto del Principe and Angitola dams, after Regina et al. (2023).

The analytical fragility functions for these dams were calibrated using the Multiple Stripes Analysis (Baker, 2015). The calibration was based on a large number of nonlinear dynamic analyses carried out using the finite difference software FLAC, using advanced constitutive models for capturing the cyclic behavior of the soils from the dam and foundation under seismic actions. The functional form of a lognormal cumulative distribution function (CDF) was considered for expressing the probability of damage as follows:

$$P(EDP > DM|IM = im) = \Phi\left(\frac{\ln(im/\theta)}{\beta}\right) \tag{1}$$

where *im* is a particular value of the intensity measure *IM*, while θ and β are the median and standard deviation of the CDF.

For the Farneto del Principe dam, the mechanism of overtopping was chosen as the most representative PFM, with threshold levels characterized by the 'Fell damage' classes that relate the normalized crest settlement with the severity of the damage (Fell et al., 2014), and referred to the peak ground acceleration, *PGA*, as *IM* (Figure 3). On the other hand, for the Angitola dam the selected PFM was the global instability, and the reference *IM* was the peak ground velocity, *PGV* (Figure 4).

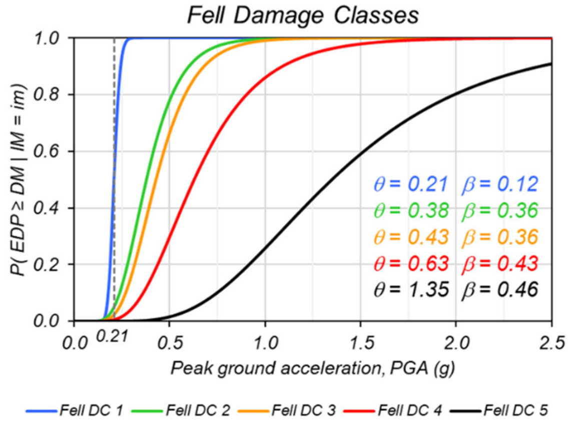

Figure 3. Selected fragility functions for Farneto del Principe dam, considering the PFM of overtopping with reference to *PGA* as *IM*. The parameters of the lognormal CDF are listed for each one of the Fell damage classes (Regina, 2021).

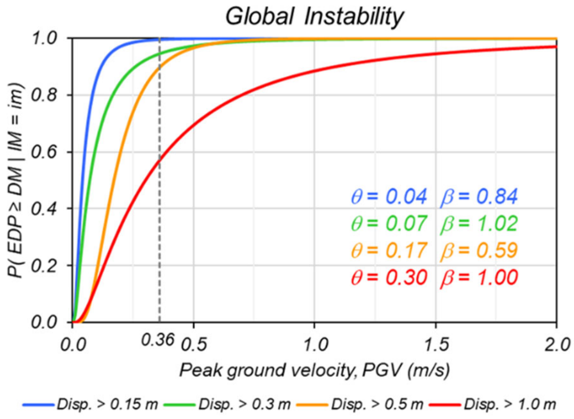

Figure 4. Selected fragility functions for Angitola dam, for the PFM of global instability with reference to *PGV* as *IM*. The parameters of the lognormal CDF are listed for each threshold displacement of a potentially sliding mass (Regina, 2021).

4 TEST OF THE EEWS UNDER SCENARIO-BASED GROUND MOTIONS FROM HISTORICAL SHAKEMAPS

To test the applicability of the EEWS, a scenario-based ground motion distribution from a historical seismic event reported in the Shakemap Atlas of Historical Earthquakes in Italy (Oliveti et al., 2024) was considered to define the hypothetical ground shaking at both dam sites. The Shakemaps from the atlas were constructed by combining the information of the Italian Macroseismic Database with different ground motion conversion equations, for transforming the macroseismic data into ground motion intensity measures, useful for engineering applications.

The historical earthquake selected was the event of March 27th of 1638, with an estimated magnitude of M = 6.8 (Galli and Bosi, 2003) and an epicenter located between both dams. The Shakemaps for this case were reconstructed considering more than 200 data points of macroseismic intensity; the contours of the mean values of *PGA* and *PGV* are plotted in Figure 5 and Figure 6, respectively. Under this scenario, the reconstructed *PGV* for Angitola dam was equal to 0.36 m/s, and the *PGA* for Farneto del Principe dam was equal to 0.21 g, both corresponding to a moderate to large intensity of the ground shaking.

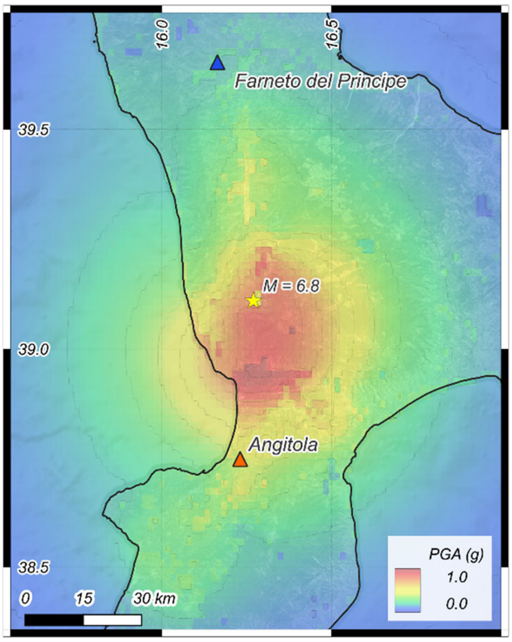

Figure 5. Contours of *PGA* estimated for the historical event of March 27th, 1638 (after Oliveti et al., 2024).

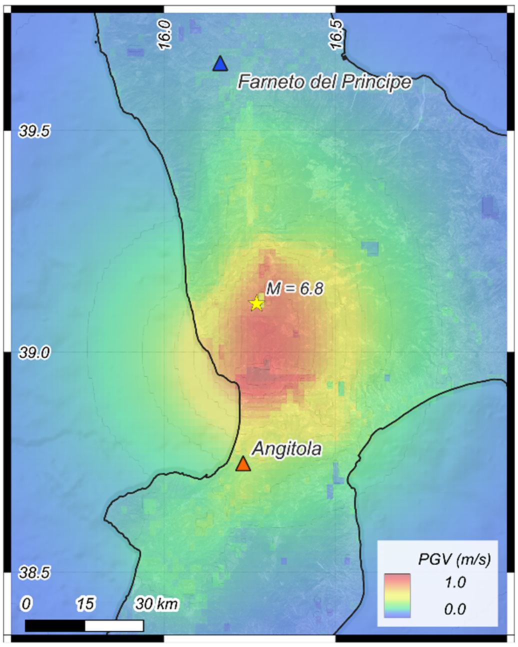

Figure 6. Contours of *PGV* estimated for the historical event of March 27th, 1638 (after Oliveti et al., 2024).

With the assumed ground motions defined, it was possible to calculate the probability of occurrence of each damage state by simply calculating the difference of probability between the fragility functions corresponding to the abovementioned *PGA* and *PGV* values (see Figures 3-4). The results are presented in Figure 7 and Figure 8 for the case of Farneto del Principe and Angitola dam, respectively.

From the first inspection of the results, it is evident that under this hypothetical scenario, the Angitola dam is more likely to develop considerable displacements if the PFM of global instability is considered, whereas the Farneto del Principe dam is not expected to suffer significant damage in terms of Fell damage classes, if the *PGA* reconstructed for this scenario earthquake take place.

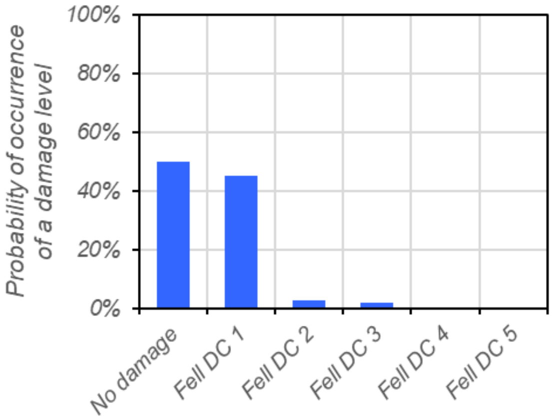

Figure 7. Probabilities of developing the different Fell damage classes for Farneto del Principe dam, with reference to the PFM of overtopping, under the scenario-based ground motion.

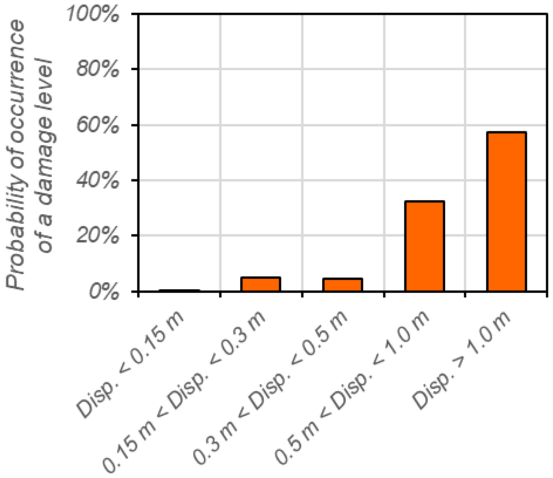

Figure 8. Probabilities of developing different maximum displacements of an unstable mass for Angitola dam, with reference to the PFM of global instability, under the scenario-based ground motion.

These apparently simple results constitute very useful information minutes after an earthquake, as only based on the monitored or real-time forecasted ground shaking, since can bring information about the performance of the dam in terms of the probability of developing a given damage state of a certain PFM.

This analysis should be carried out for all the PFMs; as a result, the hazardous damage state characterized by the largest probabilities of occurrence, combined with the first visual inspections and analysis monitoring records, will focus the efforts during the post-event emergency management activities.

5 CONCLUSIONS

Earthquake early warning systems (EEWS) are an efficient non-structural measure for mitigating the seismic risk of critical civil infrastructures such as embankment dams. By integrating the general framework of an EEWS for embankment dams with a set of fragility functions as an interpretative model, it is possible to develop a powerful tool that links dam performance to ground shaking intensity in real time. This approach can serve as a valuable complement to conventional methodologies used in the post-earthquake evaluation of dam safety.

An EEWS framework using fragility functions is presented in this work. This framework was further tested using the fragility functions developed for two earth dams located in the Calabria Region, Italy, subjected to the scenario-based ground motion from the reconstructed Shakemap of a historical earthquake. The results obtained exemplify the capability of the framework to evaluate the probability of developing various damage states, arising from different potential failure modes, and considering selected intensity measures to characterize ground shaking.

The use of this EEWS for future earthquakes, using the ground motions monitored by accelerometric stations suitably located along the embankment, the abutments and the foundation, or Shakemaps generated shortly after the event, constitutes a convenient tool for the better management of the post-earthquake activities on the dams, and the migration from the methodologies which rely only on visual inspections and expert opinion, to risk-informed decision making approaches.

6 REFERENCES

Baker, J.W., 2015. Efficient analytical fragility function fitting using dynamic structural analysis. Earthquake Spectra, 31(1), pp.579–599. https://doi.org/10.1193/021113EQS025M.

Barbagelata, J.M., Zimmaro, P., d'Onofrio, A., Pagano, L. and Silvestri, F., 2024. A proposal for earthquake early warning systems for embankment dams using fragility functions. Incontro Annuale dei Ricercatori di Geotecnica 2024 - IARG 2024. Gaeta, Italy.

Fell, R., Macgregor, P., Stapledon, D., Bell, G. and Foster, M., 2014. Geotechnical engineering of dams. CRC Press/Balkema.

Galli, P. and Bosi, V., 2003. Catastrophic 1638 earthquakes in Calabria (southern Italy): New insights from paleoseismological investigation. Journal of Geophysical Research: Solid Earth, 108(B1). https://doi.org/10.1029/2001JB001713.

ICOLD, 2016. Bulletin 166 - Inspection of dams following earthquakes guidelines. International Comission on Large Dams.

Oliveti, I., Faenza, L., Antonucci, A., Locati, M., Rovida, A. and Michelini, A., 2024. The ShakeMap Atlas of historical earthquakes in Italy: configuration and validation. Seismological Research Letters, 95(1), pp.21–37. https://doi.org/10.1785/0220230138.

Pagano, L. and Sica, S., 2013. Earthquake early warning for earth dams: concepts and objectives. Natural Hazards, 66(2), pp.303–318. https://doi.org/10.1007/s11069-012-0486-9.

Regina, G., 2021. Probabilistic assessment of the seismic performance of two earth dams in Southern Italy using simplified and advanced constitutive models. PhD Thesis. Università della Calabria.

Regina, G., Zimmaro, P., Ziotopoulou, K. and Cairo, R., 2023. Evaluation of the optimal ground motion intensity measure in the prediction of the seismic vulnerability of earth dams. Earthquake Spectra, 39(4), pp.2352–2378. https://doi.org/10.1177/87552930231170894.