Assessment of the seismic risk associated with small earth dams: a simplified approach

Assessment of the seismic risk associated with small earth dams: a simplified approach

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Abstract. *Small earth dams are characterized by a reduced height of the retaining structure and by a limited reservoir volume of water. They are often located along slopes close to populated areas, therefore the risk associated with their potential rupture could be considerable. Also for this reason, the evaluation of their seismic vulnerability is of paramount importance for Civil Protection purposes. In addition, the usual lack of technical information represents a significant further challenge. In this regards, a simplified methodology based on a reduced number of parameters was required for vulnerability assessment studies. A simplified procedure was developed to systematically classify a large number of small earth dams. The proposed methodology is based on the compilation of data-sheets that lead to a preliminary classification of structures in terms of their associated seismic risk. The application of this procedure to about a hundred earth dams in the Piedmont region allowed identifying the most critical structures, which require a priority in the planning of further investigations and analyses.*

1 INTRODUCTION

The Italian Technical Code for Dams [1] classifies dams with respect to the maximum height of the retaining structures and the cubage of the reservoir volume of water. Dams over 15 m high or with a reservoir volume larger than 10^6 m^3 are defined “large dams”, whereas dams up to 15 m high and a reservoir volume lower than 10^6 m^3 are defined “small dams”. In addition, these structures can be classified according to the risk associated with their potential rupture as “strategic”, “significant”, and “normally relevant”. These classification methods are adopted to select the parameters for their rigorous seismic analysis. In this respect, the current Italian Technical Code [2] introduces the concept of “gradualness” for seismic risk studies performed for existing structures. The choice of the analysis model to evaluate the seismic risk depends on the available information about the structure. The seismic risk assessment study can be conducted adopting models with increasing complexity, according to the level and quality of the available information. In this regards, “large dams” are characterized by a large quantity of information and data deriving from original design documents and long-time monitoring [3]. In these cases, the adoption of complex models is possible. On the contrary, the information about “small dams” are often limited and the use of simple models is usually suggested in standard practice. The main

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goal of the “ReSba” (Resilienza degli Sbarramenti) project is to improve the knowledge regarding the risks of dams and the related resilience of the community. It is a project sponsored by the European fund for regional development (Interreg-ALCOTRA) for the French-Italian Alps. More than 900 dams [4] are located in the Piedmont region; approximately 100 of them are small earth dams located close to populated areas of the Alps region (Figure 1). Therefore, a criterion to identify the most critical structures that need a priority in planning further investigations and analyses is required. A simplified procedure was developed to systematically classify a high number of small earth dams. The proposed methodology is based on the compilation of data-sheets that lead to a preliminary classification of the earth dams in terms of their associated seismic risk. The present paper describes the procedure developed within the ReSba project and its application to a case study.

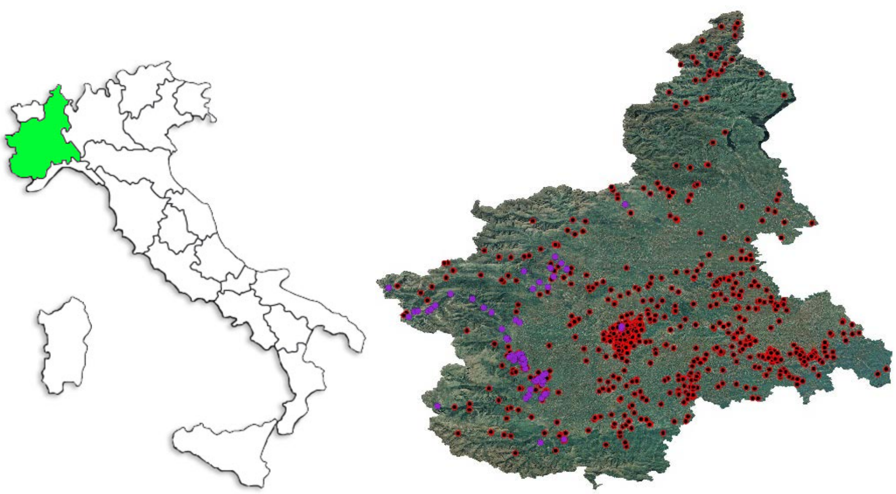

Figure 1: Localization of dams: purple dots are dams included in ReSba project.

2 SIMPLIFIED APPROACH TO EVALUATE THE SEISMIC VULNERABILITY

The most relevant earthquake-induced effects on earth dams were documented by [5] who reported the damages of these structures subjected to past seismic events. On the bases of this study, a seismic vulnerability analysis should require a deep knowledge of the structure (e.g., geometry, mechanical properties of the embankment and foundation, etc.). Therefore, a detailed analysis can be performed only for a few specific and well-characterized dams. On the contrary, when a large number of structures are under consideration, a simplified approach should be adopted.

The proposed approach is based on basic information that can be obtained through a direct survey and a collection of technical data from documents. Following this approach, the vulnerability of small earth dams is computed through an index $V_{structure}$ defined as the sum of four parameters:

$$V_{structure} = V_{condition} + V_{liquefaction} + V_{settlements} + V_{displacements} \qquad (1)$$

where: $V_{condition}$ is the vulnerability of the dam due to its general state; $V_{liquefaction}$ is the vulnerability due to liquefaction phenomena; $V_{settlements}$ and $V_{displacements}$ are the vulnerability due to the potential crest settlements, and the possible slope displacements, respectively. Five classes were defined on the base of the vulnerability index of the structure (Table 1). The global seismic vulnerability (V) is then computed as the average of $V_{structure}$. This value is incremented of 0.1 if the dam is susceptible to potential hydro-geological instabilities.

Table 1: Seismic vulnerability classes of structure and levels of risk.

Vulnerability ($V_{structure}$)	Classes of vulnerability	Levels of vulnerability
≤ 1	A	Negligible
$1 \div 2$	B	Low (hydraulic leakage into the embankment)
$2 \div 3$	C	Moderate (internal erosion of the embankment)
$3 \div 4$	D	High (internal erosion of the foundation)
≥ 5	E	Maximum (freeboard reduction and overflow)

Each vulnerability parameter is evaluated as described in the following sections.

Global dam conditions. This vulnerability parameter is defined through a direct in situ inspection. Four classes have been defined on the base of deterioration phenomena affecting the body of the dam. The fifth class refers to the absence of in situ observations. Each class is linked to a value of vulnerability as indicated in Table 2.

Table 2: Value of the vulnerability due to global dam conditions.

Condition level			$V_{condition}$
1	Optimum	No crack evidence / good condition	0.2
2	Good	Small cracks but no superficial deformation	0.4
3	Discrete	Evident superficial degradation	0.6
4	Poor	Cracks, superficial deformation especially on layer lining	0.8
5	Unacceptable	No in situ observations	1.0

Liquefaction vulnerability. Generally, earth dams consist of cohesive soils that are usually not subjected to liquefaction phenomena. However, these types of soil can be subjected to shear strength and stiffness degradation under dynamic cyclic loads due to the accumulation of excess pore-pressure, with severe plastic deformation. An index related to the exclusion criteria proposed by [2] was used aiming at guaranteeing the simplicity in the evaluation of the liquefaction vulnerability. The maximum value for this vulnerability factor is adopted in case none of the previous were satisfied or in the absence of observations (Table 3).

Table 3: Value of the vulnerability due to liquefaction phenomena.

	Exclusion condition	$V_{liquefaction}$
1	Peak acceleration at the surface under free filed conditions < 0.1 g	0.0
2	Seasonal average depth of the water table in excess of 15 m below grade	0.0
3	Clean sand deposit with $(N_1)_{60} > 30$ or $q_{c1n} > 180$ (*)	0.0
4	Grain size distribution external to the zones shown in Figure 2	0.0
5	None of the previous or no in situ observations	1.0

(*) $(N_1)_{60}$ is the normalized value of N_{SPT}; q_{c1n} is the normalized cone penetration resistance (q_c).

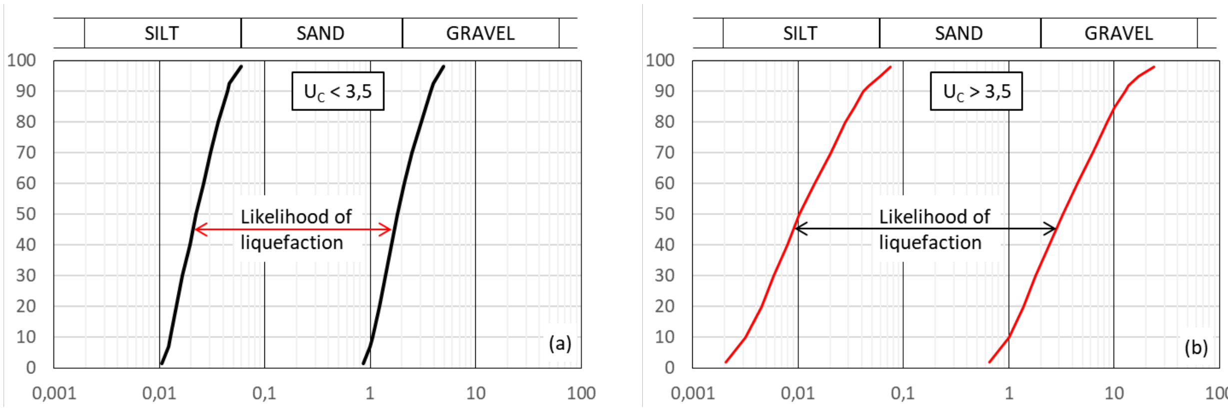

Figure 2: Grain sizes for preliminary assessment of the liquefaction susceptibility of a soil (soils of uniform grain size (a) and extended grain size (b)) [2].

Crest settlements. Two different approaches can be used to evaluate the settlements of dams under seismic loads: simplified and rigorous methods. The latter requires a very complex model and the knowledge of the mechanical properties of the soils. Due to the lack of technical information, a more simple empirical approach was here adopted for small earth dams.

The relationship (Eq. 2) proposed by [6] relates the crest settlements with the peak ground acceleration (*PGA*) and earthquake magnitude (*M*) that characterize the site:

$$w(\%) = e^{(6.07 \cdot PGA + 0.57 \cdot M - 8)} \tag{2}$$

The vulnerability due to the potential crest settlements was defined as the ratio between the predicted settlements and their admissible value. Admissible values of crest settlements have to be related to the degree of damage of dams. Following the study of [6], two values were here considered: 0.02% and 1% of the high of the dam plus the thickness of soil foundation, corresponding to moderate and serious levels of damage, respectively.

Slope displacements. Different approaches can be adopted to compute slope displacements. The simplest requires a dynamic analysis based on the well-known Newmark model [7]. This approach is commonly adopted in many empirical formulations, like the one proposed by [8]:

$$u_d = k_{max} \cdot D_{5-95} \cdot 10^{1.87 - 3.477 \frac{k_y}{k_{max}}} \tag{3}$$

where $D_{5\text{-}95}$ is the significant duration of shaking (i.e. 5-95% normalized Arias intensity), $k_{max}=PGA/g$ is the maximum acceleration and k_y is the yield acceleration of slope. This last parameter can be preliminarily estimated on the basis of the static factor of safety F_S as $k_y = (F_S - 1)\, sen(\alpha)$, where α is the average angle of the failure surface with the horizontal. In the proposed method, $k_y = 0$ if no specific slope stability analyses are available, whereas $D_{5\text{-}95}$ is related to the magnitude (*M*) and the epicentral distance (*r*) of the earthquake through the Eq. (4) proposed by [9]

$$
ln(D_{5-95}) = ln\left[\frac{\left(\frac{e^{5.04+0.851\cdot(M-6)}}{10^{1.5\cdot M-16.05}}\right)^{\frac{-1}{3}}}{15.7\cdot 10^{6}} + 0.063\cdot(r-10)\right]0.8664(r \geq 10km)
$$

$$
ln(D_{5-95}) = ln\left[\frac{\left(\frac{e^{5.04+0.851\cdot(M-6)}}{10^{1.5\cdot M-16.05}}\right)^{\frac{-1}{3}}}{15.7\cdot 10^{6}}\right]0.8664(r < 10km) \tag{4}
$$

The vulnerability associated with the slope displacements was defined as the ratio between the predicted slope displacements and their admissible value. [8] proposed two admissible values of the slope displacements: 5 cm and 15 cm.

3 SEISMIC VULNERABILITY OF PIEDMONT EARTH SMALL DAMS: A PARAMETRIC STUDY

The proposed simplified approach was used to classify the small earth dams located in the Alps area of the Italian Piedmont Region (Figure 1). This area is included in the “ReSba” project. Initially, a parametric analysis was performed to check how the choice of admissible values of crest settlements and slope displacements influences the index of structural vulnerability. In this respect, three admissible value of crest settlements (0.02%, 0.1% and 1%) with the same amount of admissible slope displacements (5, 10 and 15 cm) were chosen.

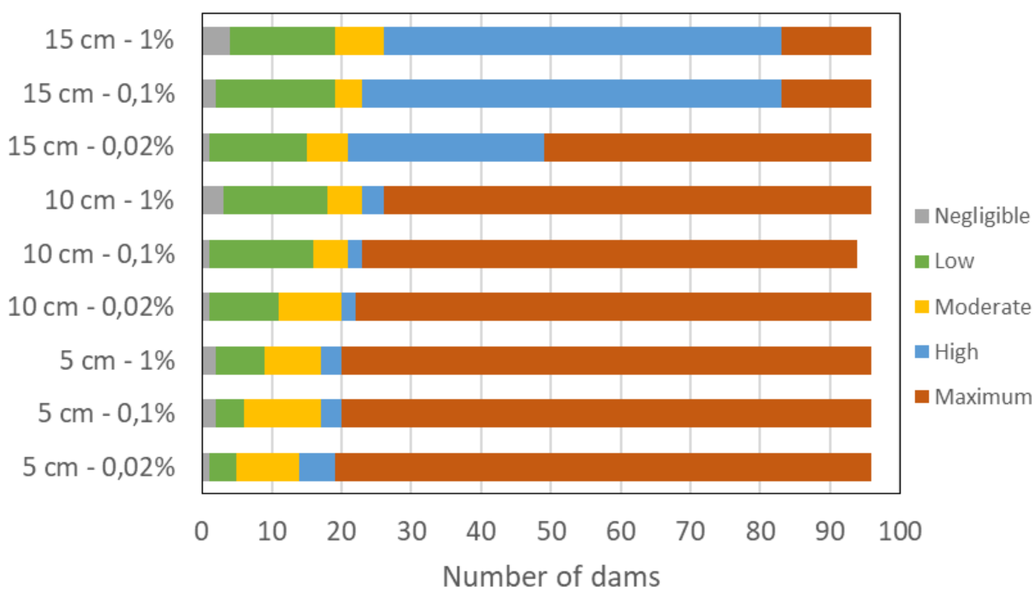

Figure 3: Comparison of risk vulnerability classification of dams assuming different admissible values of crest settlement and slope displacement.

Figure 3 shows how the classification of the seismic vulnerability of small earth dams changes with the different combination of the above admissible values. It shows that dams within high-maximum range of vulnerability slightly decrease if the highest admissible values of crest settlement and slope displacement are assumed.

In particular, 85% of earth dams have a high/maximum level of associated risk if values of 0,02% and 5 cm are adopted as admissible values of crest settlements and slope displacements, respectively (Figure 4a). The percentage decreases to 76% (Figure 4b) if the previous admissible values are 1% and 15 cm. The percentage changes very slightly because of the lack of technical information on these dams. To guarantee cautionary analyses, lower admissible values of crest settlements and slope displacements should be adopted.

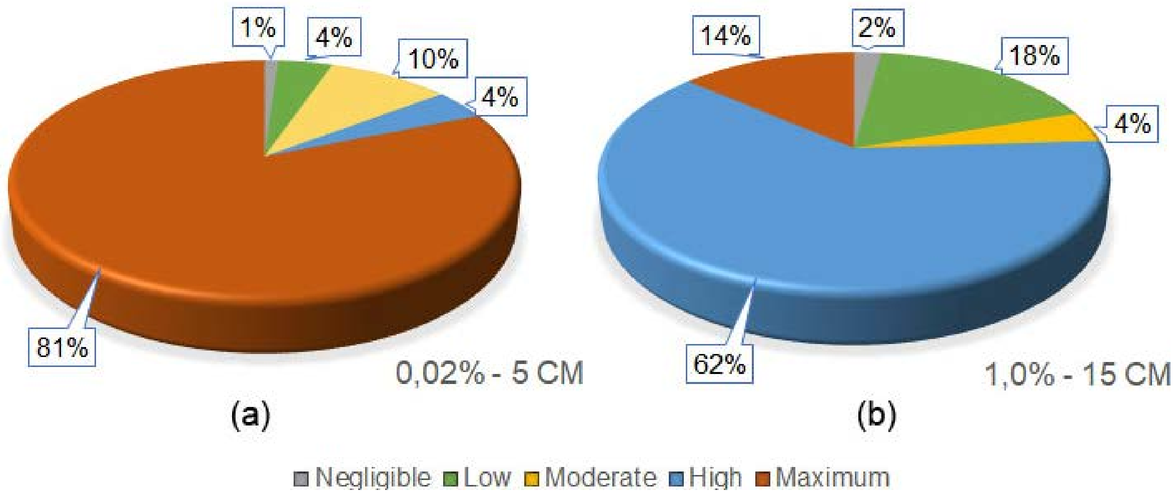

Figure 4: Comparison of risk vulnerability classification of dams assuming two different couples of an admissible value of crest settlement and slope displacement.

4 SEISMIC RISK ASSESSMENT

The seismic Risk (R) is defined as the probability of losses occurring due to earthquakes within a given period of time, and it is computed by the convolution ($\otimes$) of three quantities: $R=H\otimes V\otimes E$, where: H is the seismic Hazard; V is the seismic Vulnerability and E is the Exposure. Therefore, the seismic risk assessment of structure needs the independent evaluation of these three factors. The procedure previously described for the assessment of the seismic vulnerability assessment has been implemented in a simple data-sheet. This sheet collects all information obtained with a survey of direct observations and the analysis of the technical documents. The framework of this data-sheet is composed of four main sections:

- S1 – General information (localization and regional classification);
- S2 – Description (geometry, characteristics of the soil, exposure and seismic data);
- S3 – Calculation of the vulnerability;
- S4 – Conclusions.

Input data in sections S2 and S3 allow defining the seismic hazard, exposure and seismic vulnerability. In addition, seismic hazard and exposure are computed through simple approaches.

The hazard factor is computed as:

$$H = (4 - Z) + 1 \tag{5}$$

where Z is an integer number that represents the zone in which the earth small dam falls. Since 2003, the national territory has been classified in four seismic categories, according to the maximum outcrop acceleration with a probability of exceedance equal to 10% in 50 years (zone

1=0.35 g, zone 2=0.25 g. zone 3=0.15 g, zone 4=0.05 g). Intermediate classes were added in 2015 when an update of this classification was released.

The exposure factor takes into account the consequences on the surrounding anthropic environment produced by potential damage or the complete collapse of the dam. Therefore, it can be defined through a simplified study of breakdown scenarios. For example, the Piedmont regional administration has defined three levels of exposure (Table 4) on the base of different scenarios [10].

Table 4: Exposure values.

Classes of exposure		E
Low	Negligible economic and environmental losses in downstream areas	1
Medium	Serious environmental consequences or significant economic losses and damage of commercial and/or industrial facilities, public services and/or structure in downstream areas (unlikely loss of life)	2
High	Losses of life and significant economic damage in downstream areas (urban areas with several inhabitants)	3

At the end of the data-sheet (section S4), the three factors that define the seismic risk are combined following a Multi-Criteria Decision Making (MCDM) protocol to evaluate the seismic criticality of the dam. In this respect, the following matrix is used:

	Vulnerability	Maximum			High			Moderate			Low			Negligible		
	Exposure	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low
Hazard	Zone 1	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3
	Zone 2	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2
	Zone 3	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
	Zone 4	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

On the base of this index, five degrees of criticality were defined (Table 5).

Table 5: Scale of seismic critical index.

Range of CS	Class of criticality	Degree of criticality
0 ÷ 4	A	Low
5 ÷ 7	B	Low – medium
8 ÷ 10	C	Medium
11 ÷ 13	D	Medium - high
14 ÷ 17	E	High

5 CASE HISTORY: EARTH DAM OF ENVIE (CN) - ITALY

The proposed approach is herein applied to a small earth dam located in the city of Envie (CN) – Italy (Figure 5).

(a)

(b)

Figure 5: Earth dam of Envie: (a) Localization of dam in the regional map. (b) Overview of the dam.

The main characteristics of this dam are reported in Table 6:

Table 6: Characteristic of the dam.

Characteristics of the dam	
Crest length	155 m
Height of dam	15 m
Top width.	3.6 ÷ 13.6 m
Reservoir volume	22.000 m^3
Freeboard	1 m
Maximum top water level	349 m a.s.l.
Normal top water level	349 m a.s.l.
Soil of dam	Sandy silt

According to the Italian seismic hazard map (http://esse1.mi.ingv.it) reported here for the Piedmont region (Figure 6a), the maximum outcrop acceleration (return period of 475 years) is a_g = 0.132 g. Peak ground acceleration (*PGA*) was then computed through the simple approach proposed by [2]:

$$PGA = S_s \cdot S_T \cdot a_g \tag{6}$$

where S_S and S_T are the stratigraphic and topographical amplification factors, respectively. Considering the type of soil and the geometry of the dam (see Table 6), the values assumed for these amplification factors were: S_S = 1.6 and S_T = 1.0.

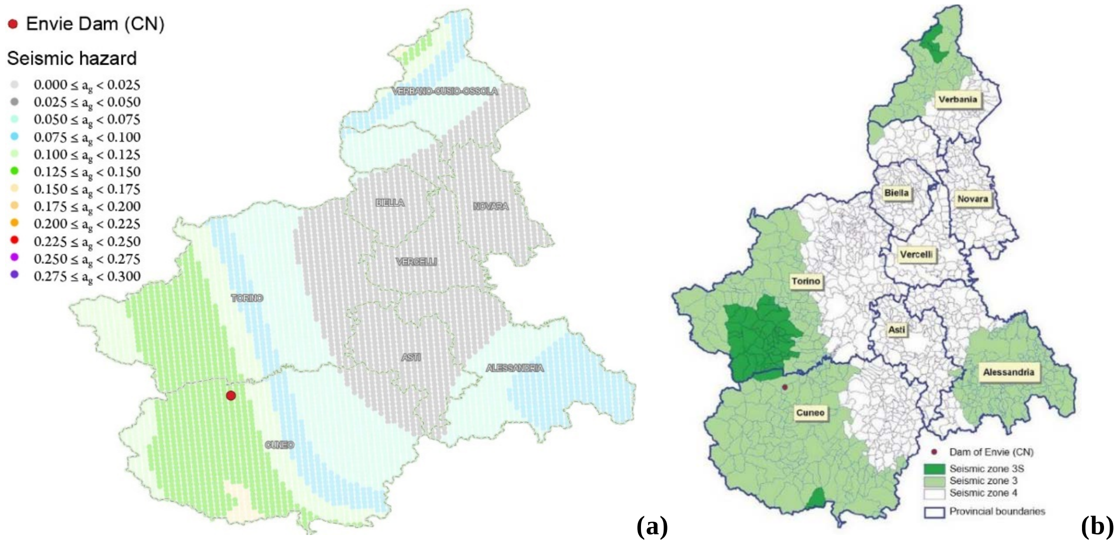

Figure 6: Localization of dam in the regional: (a) seismic hazard map and (b) seismic zonation map.

The earthquake magnitude (*M*) and the epicentral distance (*r*) were evaluated through a disaggregation analysis in accordance with the national probabilistic seismic hazard analysis (Figure 7) (http://esse1.mi.ingv.it). These average values were evaluated: M = 4.72, r = 8.23 km.

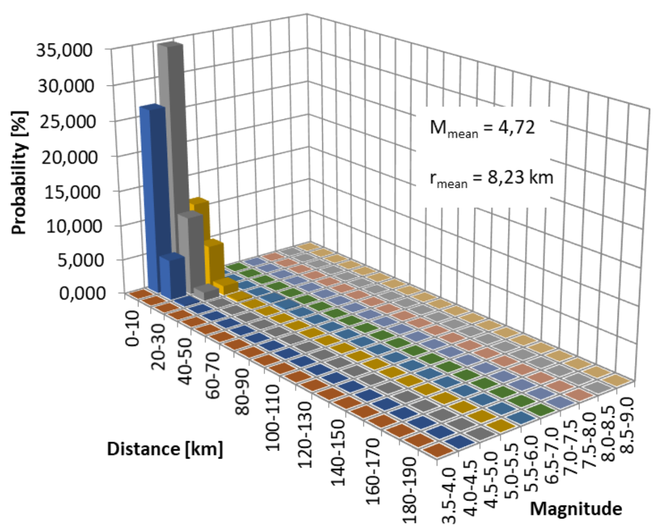

Figure 7: Disaggregation graphs referring to a return period of 475 years.

Following the above described procedure, the values of *PGA*, *M* and *r* were then used to evaluate the crest settlement (Eq. 2) and the slope displacement (Eq. 3). Assuming the most restrictive admissible values of crest settlement (0.02%) and the slope displacement (5 cm), the value of vulnerability parameters due to these aspects are $V_{settlements}$ = 0.881 and $V_{displacements}$ = 0.688. Since only small cracks without other surficial deformations were observed during a survey conducted in April 2014, the vulnerability of dam due to its general state is $V_{condition}$ = 0.4 (see Table 2). Finally, the vulnerability due to potential liquefaction phenomenon was evaluated equal to $V_{liquefaction}$ = 0.0, because the embankment was built with dense soils (q_{c1n} > 180 – see Table 3).

Therefore, the vulnerability of the dam given by Equation (1) is $V_{structure}$ = 1.97, i.e. the dam has a low level of vulnerability (Table 1). Since no potential hydrogeological instability was established, the global vulnerability is V = 0.5.

Since the whole municipality is included in seismic zone 3 (Figure 6b), the seismic hazard (E. 5) is H = 2. Instead, the level of exposure assigned to the dam is medium, due to some buildings very close to the dam (< 500m) that could be hit by the flood wave, how shown in a breakdown scenario reported in Figure 8.

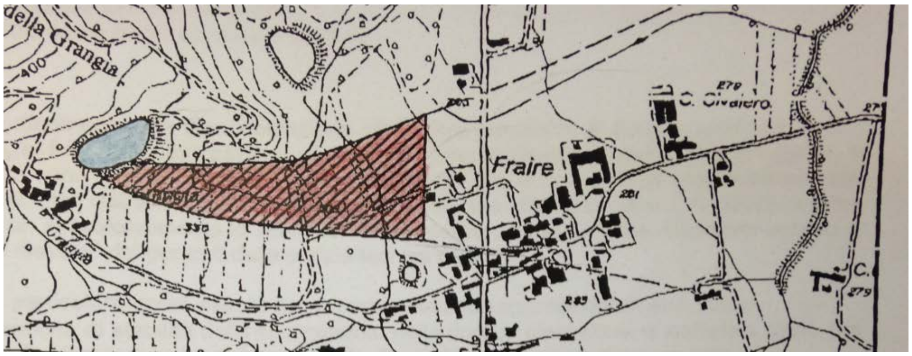

Figure 8: Breakdown scenario: the shadow zone represents the potential area hit by flood wave up to the first building.

Ultimately, following the Multi-Criteria Decision Making (MCDM) protocol, the dam of Envie is within the low-medium range of criticality.

6 CONCLUSIONS

In the present study, a simplified approach has been developed to evaluate the seismic risk of small earth dams. It is based on the quick compilation of data-sheets, where a reduced number of parameters deriving from in situ survey and documents are collected. The method allows a preliminary classification of small dams in terms of their associated seismic risk. It is very useful when a high number of structures have to be analyzed and the available technical information is lacking. The application of this procedure to about 100 earth dams in the Piedmont region allowed identifying the most critical structures that require a priority in planning further investigations.

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