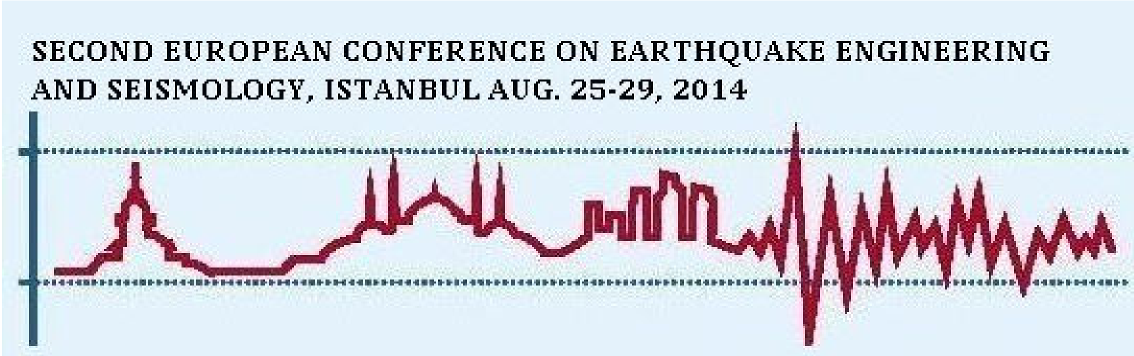

MULTIPATH SEISMIC HAZARD ANALYSIS IN DAMS

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ABSTRACT

The aim of this work is to estimate the probability of failure or reaching any limit state of damage due to natural hazards in hydroelectric systems. There are several indicators of failure, damage, or limit state. The calculation of damage or failure due to future disastrous events is a complex problem. Because of the uncertainties that affect the process, the limit states must be considered as random variables, which can only be described on the probabilistic sense through its probability distribution. Below, the adopted method to estimate the probability of failure due to natural hazards associated with return periods is described

INTENSITIES OF NATURAL HAZARDS

Intensity is defined as a local measure of the disturbance caused by a natural event in some physical characteristics of the environment that are relevant to the phenomenon under study. For almost all hazards, it is impossible to describe the intensity with a single parameter. For example, in the case of earthquakes, the maximum acceleration of ground provides general information about the size of earth movement, but gives no indication of its frequency content, crucial for an accurate estimate of the structural response. Also, in the case of flooding, the height of water is not a complete description of the intensity of the flood, because damage can also depend on the flow rate of water. In this context, it is implied that only one intensity parameter descriptor is always incomplete. However, a multivariate description of intensity is too complex for present purposes (in fact, very few risk studies performed in the past, if any, have considered multivariate intensity descriptors). It is proposed to use for all relevant hazards, a normalized intensity scale, varying from zero for zero intensities, to one, for catastrophic intensities. Obviously, this scale is qualitative, but it is adjusted to be well correlated with the damage. Still, the description of hazard intensities is incomplete. This topic must be refined in the future to have more precision about the intensity, described with a single variable. For now, the qualitative relation for hazards and damage intensities is shown in Table 1.

Once an appropriate intensity for each type of feature is chosen, a probabilistic description of the hazard must be established. Generally, hazard is expressed in terms of exceedance rates of intensity values. This concept defines how often a particular intensity value is exceeded. For its description, a form inspired by Gutenberg-Richter earthquake magnitudes is used. It is

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$$\lambda(\mathrm{I}) = \lambda_0 e^{-\beta \mathrm{I}} \tag{1}$$

In this model, β is the slope of the assumed linear occurrence rate on a logarithmic scale, while λ_0 is the number of events with intensity I_0.

For convenience, in this model the concept of rate of occurrence is used, which is the frequency of occurrence of specific size intensities, defined in an interval.

This paper only considers quake as the initial hazard, although the methodology can be extended to other hazards, such as rainfall. The initial hazard is the starting point of a sequence of events related to damage to geological, geotechnical and civil structures, culminating in the collapse of the curtain. This moment marks the beginning of a disastrous event. Indeed, this study begins with an initial hazard and ends in the collapse of a dam curtain. Subsequent risk studies will take as starting point the collapse of the curtain to assess the amount of the losses.

Table 1. Hazards and damage intensity intervals.

Intensities interval	Qualitative description of hazard	Qualitative description of damage
0	Null	Null
0.0 – 0.2	Very light	Very light
0.2 – 0.4	Light	Light
0.4 – 0.6	Moderate	Moderate
0.6 – 0.8	Heavy	Severe
0.8 – 1.0	Very heavy	Very severe

CAUSE-EFFECT RELATIONSHIPS

The interaction between hazards and consequences is complex, however it can be simplified through cause-effect relationships prescribed as vulnerability functions. This one relates the intensity of the cause-event with the expected value of the intensity of the effect-event. Vulnerability functions can have many forms. However, in order to implement a quantitative procedure, all events should be described quantitatively, even they are participating as a cause or effect. Thus, a scale of unit values is proposed, similar to that proposed to describe the intensity of the initial hazards where zero is no intensity event, while one is a catastrophic event intensity. Vulnerability functions are highly specific in terms of hazard. In other words, in the same hydroelectric system, civil and geological structures and infrastructure in general could be very vulnerable to a certain hazard and much less vulnerable to another. Vulnerability functions may change depending on the accumulated deterioration or maintenance or repairs of the structural system. It will also depend on local conditions, which may even vary with time. These variables are identified as environment variables.

Aspects such as material or structural strength, design features, age of structures, type of material are environment variables. In general, construction of vulnerability functions starts with standard criteria, and continues considering empirical aspects that allow adapting these features to classify each cause-effect relationship. Table 2 shows the cause-effect relationships identified in this study. These relationships control the passage through different states of damage in a dam.

CONSTRUCTION OF EVENT TREES

An event tree is a sequence of cause-effect events, where a cause-event is the effect of the previous event. The wealth of an event tree lies in the diversity and number of possible paths or branches. This wealth depends on the number of identified cause-effect relationships, representing processes that may be achievable. Is common to found that in Natural Risk Analysis a tree event scheme is used (Slunga, 2001). Each tree starts from an initial hazard, in this case "earthquake". Others, however, are the effects of previous hazards such as wave reservoir, damage to bankslopes at the reservoir or to both banks at the dam site, damage to the spillway, damage to dam, etc. The terminal end of each branch or path is the end of a process of cause-effect hazards. These terminal events were identified:

a) Damage to the dam
b) Damage to mechanical equipment
c) Downstream flooding
d) Storage loss
e) Reservoir level control loss
f) Powerhouse inflow decrease

Table 2. Cause-Effect relationships.

Blockage of control structure	→ Increase of pool level
Blockage of entrance channel	→ Blockage of control structure
Blockage of outlet channel	→ Blockage of control structure
Blockage of water supply intake	→ Powerhouse inflow decrease
Damage to both banks slopes at the reservoir	→ Sedimentation → Water waves through the reservoir
Damage to concrete face slabs	→ Damage to the dam → Storage loss
Damage to control structure	→ Blockage of control structure → Reservoir level control loss
Damage to dam foundation	→ Damage to the dam
Damage to entrance channel	→ Blockage of entrance channel
Damage to left and right banks at the dam site	→ Damage to concrete face slabs → Damage to control structure → Damage to entrance channel → Damage to outlet channel → Damage to the dam → Damage to water supply intake
Damage to outlet channel	→ Blockage of outlet channel
Damage to water supply intake	→ Blockage of water supply intake
Earthquake	→ Damage to both banks slopes at the reservoir → Damage to concrete face slabs → Damage to control structure → Damage to dam foundation → Damage to entrance channel → Damage to outlet channel
Earthquake	→ Damage to left and right banks at the dam site → Damage to the dam → Damage to water supply intake → Geological fault activation at the dam site → Geological fault activation at the reservoir area → Water waves through the reservoir
Free board diminish	→ Overtopping
Geological fault activation at the dam site	→ Damage to concrete face slabs → Damage to dam foundation → Damage to the dam → Damage to water supply intake
Geological fault activation at the reservoir area	→ Damage to left and right banks at the dam site → Rapid descend of pool level
Increase of pool level	→ Damage to both banks slopes at the reservoir → Damage to the dam → Free board diminish
Overtopping	→ Damage to dam foundation → Damage to the dam → Downstream flooding
Rapid descend of pool level	→ Damage to both banks slopes at the reservoir → Damage to left and right banks at the dam site → Damage to the dam
Sedimentation	→ Damage to mechanical equipment → Damage to the dam → Storage loss
Water waves through the reservoir	→ Damage to the dam → Overtopping

Of these, the most interesting is "Damage to the dam." The construction of event trees is controlled by the connectivity indicated in Table 3. According to this table there are: 1 initial hazard (earthquake), 20 intermediate events and 6 terminal events.

The connectivity shown in this table is the genetic code that leads to dozens of dam damage scenarios. Each branch or path of the tree, from the initial hazard to the terminal event is a damage scenario.

According to the connectivity table, the "earthquake" with ID = 16 has twelve connectors (N = 12) with the ID = 5, 6, 7, 8, 9, 10, 12, 13, 14, 18, 19, and 27. The smallest tree is starting with "earthquake" with ID = 16 and ends with "damage to the dam" with ID = 13, since ID = 13 has 0 connections, indicating that it is a terminal event. Another possible branch of "earthquake" is derived from "damage to left and right banks at the dam site" with ID = 10. This one has six connections (N = 6), with ID = 6, 7, 9, 12, 13 and 14, giving rise to six sub-branches. One ends with ID = 13 "damage to the dam." In total, 170 scenarios can be generated from "earthquake". Of these, 100 end in "damage to the dam."

CAUSE-EFFECT VULNERABILITY RELATIONSHIPS

On a preliminary basis, and for simplicity, a linear relationship to describe the vulnerability of each cause-effect relationship has been adopted, with the care of restricting that the intensity of the effect does not exceed the maximum value defined as one. Fig. 1 shows this idealization of vulnerability between a cause-event and an effect-event.

Table 3. Connectivity relationships between events.
ID is the event identifier, N is the number of connections that has a cause-event.

ID	Event-Cause	N	Conectivity with N events-effect											
1	Blockage of control structure	**1**	20											
2	Blockage of entrance channel	**1**	1											
3	Blockage of outlet channel	**1**	1											
4	Blockage of water supply intake	**1**	22											
5	Damage to both banks slopes at the reservoir	**2**	25	27										
6	Damage to concrete face slabs	**2**	13	26										
7	Damage to control structure	**2**	1	24										
8	Damage to dam foundation	**1**	13											
9	Damage to entrance channel	**1**	2											
10	Damage to left and right banks at the dam site	**6**	6	7	9	12	13	14						
11	Damage to mechanical equipment	**0**												
12	Damage to outlet channel	**1**	3											
13	Damage to the dam	**0**												
14	Damage to water supply intake	**1**	4											
15	Downstream flooding	**0**												
16	**Earthquake**	**12**	5	6	7	8	9	10	12	13	14	18	19	27
17	Free board diminish	**1**	21											
18	Geological fault activation at the dam site	**4**	6	8	13	14								
19	Geological fault activation at the reservoir area	**2**	10	23										
20	Increase of pool level	**3**	5	13	17									
21	Overtopping	**3**	8	13	15									
22	Powerhouse inflow decrease	**0**												
23	Rapid descend of pool level	**3**	5	10	13									
24	Reservoir level control loss	**0**												
25	Sedimentation	**3**	11	13	26									
26	Storage loss	**0**												
27	Water waves through the reservoir	**2**	13	21										

The vulnerability curve, in fact, is the expected value of the intensity of the effect given the intensity of the cause. However, the intensity is a random variable to be modeled with a Beta (β) distribution. If $p(x)$ is the probability density function of the β distribution and $P(x)$ is its cumulative probability function, the probability of x to acquire a value in the interval $x_a \pm \Delta/2$, given that the median value is x_m is:

$$P(x-\Delta/2 < x < x+\Delta/2 \mid x_m) = P(x > x-\Delta/2 \mid x_m) - P(x > x+\Delta/2 \mid x_m) \qquad (2)$$

The function of probability density distribution β and the interval $x_a \pm \Delta/2$ are illustrated in Fig. 2.

Each cause-effect vulnerability function leads to a probability matrix, called Cause-Effect Vulnerability Matrix. The rows of this matrix correspond to different sizes (between zero and one) of the cause-event, while each column corresponds to various sizes of the event-effect. If the event-cause is A and event-effect is B, then i-j cell corresponds to the probability of having an event-effect of size Bj as there was an event-cause of size Ai. A similar matrix was presented and discussed by Chang, *et al* (1992).

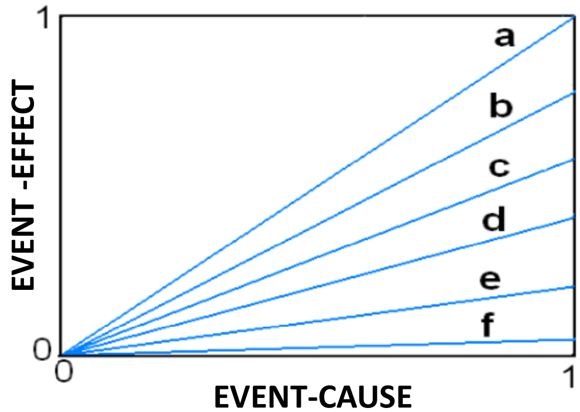


Figure 1. Examples of linear vulnerability curves to describe the cause-effect relationship.

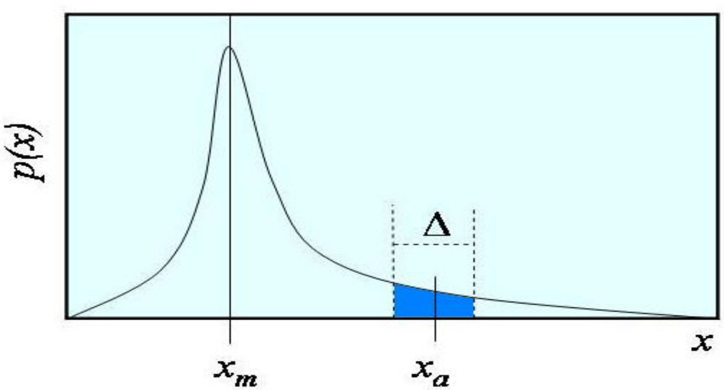


Figure 2. Probability density function with β distribution. The target area is the probability that x is in the interval $x_a \pm \Delta/2$.

Properties of the Cause-Effect Vulnerability Matrix

a) The vulnerability matrix PAB corresponds to the vulnerability of the effect B given the cause A. If the domain of study covers all intervals of intensity of the event-effect B, then the sum of all elements in a row of this matrix is always one (elemental property).

b) If two cause-effect vulnerability matrices, PAB and PBC are consistent under the requirements of the product operation, then the product of these matrices is PAC, i.e. the vulnerability matrix of the cause A and the effect C (transfer property).

c) If two cause-effect vulnerability matrices, PAB and PBC are consistent under the requirements of the product operation, then the product of these matrices, PAC, retains the elemental property indicated in a.

Figures 3 and 4 illustrate these properties.

CALCULATION OF FAILURE PROBABILITIES: ANNUAL RATE OF OCCURRENCE OF DAMAGE STATES

The annual probability of failure or of achieving different states of damage is known as annual rate of occurrence of damage. To calculate this rate of damage, the annual rate of occurrence of the initial hazard must be specified. This is obtained from local seismic hazard studies (Esteva, 1967; Cornell, 1968). Overall exceedance rate curves (represented by eq 1) are obtained. Their relationship with the rate of occurrence is the following expression.

$$\nu(I) = -\frac{d\lambda(I)}{dI} \tag{3}$$

$$\begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{21} & P_{22} & P_{23} & P_{24} & P_{25} \\ P_{31} & P_{32} & P_{33} & P_{34} & P_{35} \\ P_{41} & P_{42} & P_{43} & P_{44} & P_{45} \\ P_{51} & P_{52} & P_{53} & P_{54} & P_{55} \end{bmatrix} \Rightarrow \begin{matrix} \sum_{j=1}^{5} P_{1j} = 1 \\ \sum_{j=1}^{5} P_{2j} = 1 \\ \sum_{j=1}^{5} P_{3j} = 1 \\ \sum_{j=1}^{5} P_{4j} = 1 \\ \sum_{j=1}^{5} P_{5j} = 1 \end{matrix}$$

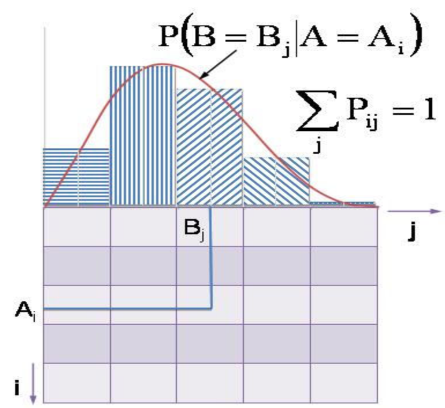
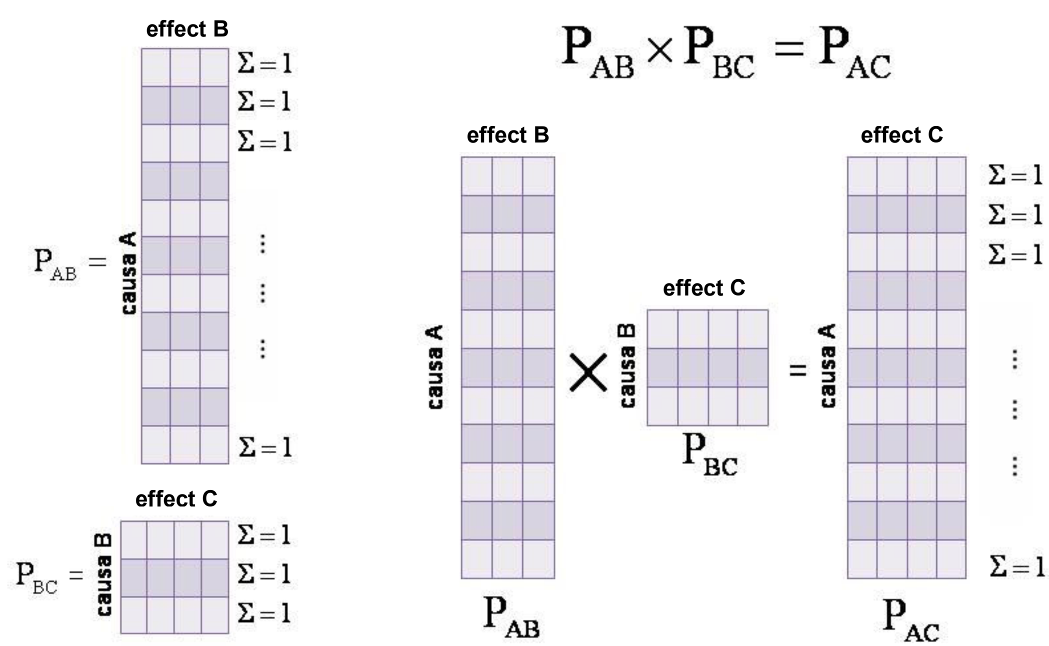


Figure 3. Elemental Property of the Cause-Effect Vulnerability Matrix.



Matrices P_{AB} and P_{BC} Matrices product

Figure 4. Transfer Property of the Cause-Effect Vulnerability Matrix

For an arbitrary location, the rate of occurrence of the earthquake in firm ground may be represented as shown in Table 4.

Table 4. Annual rate of earthquake occurrence at an arbitrary site.

INITIAL HAZARDS	Anual rates of occurrence (1/ año)				
	Very light	Light	Moderate	Heavy	Very heavy
EARTHQUAKE	1.00E-01	3.16E-02	1.00E-02	3.16E-03	1.00E-03

Suppose the initial hazard is A, and that the sequence of events that comprise a stage is: B → C → D → ... → Z, then the product of the rate of occurrence vector of A with the vulnerability matrix A-B is the rate of occurrence vector of the event B. That is, this product means that the rate of occurrence of all damage states B, are obtained by considering the effects of all possible sizes of hazard A. The product of the rate of occurrence of event B with the vulnerability matrix of B-C is the rate of occurrence vector of event C, and so on. If H is the rate of occurrence and P is the vulnerability matrix

$$\begin{aligned} H_B &= H_A \times P_{AB} \\ H_C &= H_B \times P_{BC} \\ &\vdots \\ H_Z &= H_Y \times P_{YZ} \end{aligned} \tag{4}$$

That is, the rate of occurrence of a terminal event is:

$$H_Z = H_A \times P_{AB} \times P_{BC} \times P_{CD} \times \cdots \times P_{YZ} \tag{5}$$

Note that this model allows knowing the rates of occurrence of each intermediate event of a path or arbitrary scenario (for intensities such as those exemplified: very light, light, moderate, heavy and severe).

The total annual rate of occurrence of the terminal event Z, given the hazard A, is the sum of all rates of occurrence of the terminal event Z due to each one of the scenarios that start with A and end at the event Z.

$$H_Z^A = \sum_{i=1}^{N} H_{Z\,i}^A \tag{6}$$

Where H_Z^A is the annual event rate of the event Z given the hazard A, N is the number of scenarios that start with A and end with Z, I denotes each one of the scenarios. Considering the influence of other initial hazards such as rainfall, the annual rate is

$$H_Z = \sum_{j=1}^{M} \sum_{i=1}^{N} H_{Zij} \tag{7}$$

Where M is the number of initial hazards and j is the index denoting each of the hazards.

Note that with this procedure it is possible adding and decomposing different components, whether hazards or scenarios. This allows detailed analysis of the nature of the damage resulting from natural hazards in a dam. Here's an example.

APPLICATION EXAMPLE

To illustrate the described methodology to calculate probabilities of failure or of reaching states or damage, the seismic hazard and the cause-effect relationships showed previously (table 1) were considered. To quantify the vulnerability, the scale in Table 5 was proposed by adopting linear relationships of vulnerability. The variable E (Ic = 1) is the expected value of the intensity of the effect (damage) when the intensity of the cause (Ic) is 1. E (Ic = 0) = 0 was considered in all cases.

Table 5. Vulnerability values.

Vulnerability	Qualitative level	$E(I_c=1)$
a	Very high	0.8
b	High	0.6
c	Moderate	0.4
d	Small	0.2
e	Very small	0.1
f	Null	0.025

To characterize the vulnerability, two types of dams were proposed: Arc-concrete and Earth-rock. Maximum operational water level was considered. Reasonable values of vulnerability (a-f), were assigned for each cause-effect relationship in table 6. They are equivalent and linked by table 3.

Table 6. Vulnerability of the considered events conected with the cause event (table 3)

ID	**Event cause**	**N**	**Connectivity of N events (Vulnerability)**	
			Concret-arc	Earth embankment dam
1	Blockage of control structure	**1**	d	d
2	Blockage of entrance channel	**1**	c	c
3	Blockage of outlet channel	**1**	c	c
4	Blockage of water supply intake	**1**	b	b
5	Damage to both banks slopes at the reservoir	**2**	c b	c b
6	Damage to concrete face slabs	**2**	f f	f f
7	Damage to control structure	**2**	c d	c d
8	Damage to dam foundation	**1**	b	c
9	Damage to entrance channel	**1**	c	c
10	Damage to left and right banks at the dam site	**6**	c f c b c c	c f c c c c
11	Damage to mechanical equipment	**0**		
12	Damage to outlet channel	**1**	c	c
13	Damage to the dam	**0**		
14	Damage to water supply intake	**1**	c	c
15	Downstream flooding	**0**		
16	**Earthquake**	**12**	c c c f d c b c c b c c	c c c f d c c c c b c c
17	Free board diminish	**1**	c	c
18	Geological fault activation at the dam site	**4**	f c b a	f c b a
19	Geological fault activation at the reservoir area	**2**	a d	a d
20	Increase of pool level	**3**	d c b	e c b
21	Overtopping	**3**	b d c	d b c
22	Powerhouse inflow decrease	**0**		
23	Rapid descend of pool level	**3**	f c b	c c b
24	Reservoir level control loss	**0**		
25	Sedimentation	**3**	d c e	f c e
26	Storage loss	**0**		
27	Water waves through the reservoir	**2**	e d	d c

Rates of occurrences were determined for all events of the table 3 with an ID number. In calculating rates, the maximum operating water level was considered for the two dam types, concret-arc dam and earth-rock embankment. In all cases, it was assumed that the starting event was the quake. These results are showed in table 7.

Table 7. Rates of occurrences for events prescribed with an ID number in table 3

ID	Rate of damage: Concret-Arc					Rate of damage: Earth embankment dam				
	1	2	3	4	5	1	2	3	4	5
1	1.01E+00	2.96E-03	1.56E-04	8.05E-06	1.28E-07	1.01E+00	2.96E-03	1.56E-04	8.05E-06	1.28E-07
2	3.49E-01	2.23E-03	1.33E-04	7.28E-06	1.20E-07	3.49E-01	2.23E-03	1.33E-04	7.28E-06	1.20E-07
3	3.49E-01	2.23E-03	1.33E-04	7.28E-06	1.20E-07	3.49E-01	2.23E-03	1.33E-04	7.28E-06	1.20E-07
4	4.78E-01	4.06E-03	3.00E-04	2.14E-05	5.28E-07	4.78E-01	4.06E-03	3.00E-04	2.14E-05	5.28E-07
5	1.10E+00	2.53E-02	6.06E-03	1.52E-03	2.27E-04	1.10E+00	2.53E-02	6.06E-03	1.52E-03	2.27E-04
6	2.70E-02	2.49E-12	0.00E+00	0.00E+00	0.00E+00	2.70E-02	2.49E-12	0.00E+00	0.00E+00	0.00E+00
7	3.58E-01	1.18E-02	1.54E-03	1.85E-04	7.47E-06	3.58E-01	1.18E-02	1.54E-03	1.85E-04	7.47E-06
8	1.92E+00	9.43E-03	2.01E-04	8.33E-06	1.29E-07	1.74E+00	3.70E-03	1.73E-04	7.48E-06	1.17E-07
9	3.58E-01	1.18E-02	1.54E-03	1.85E-04	7.47E-06	3.58E-01	1.18E-02	1.54E-03	1.85E-04	7.47E-06
10	2.33E-01	9.92E-03	1.42E-03	1.78E-04	7.35E-06	2.33E-01	9.92E-03	1.42E-03	1.78E-04	7.35E-06
11	1.01E+00	1.20E-03	5.76E-05	2.72E-06	3.86E-08	1.01E+00	1.20E-03	5.76E-05	2.72E-06	3.86E-08
12	3.58E-01	1.18E-02	1.54E-03	1.85E-04	7.47E-06	3.58E-01	1.18E-02	1.54E-03	1.85E-04	7.47E-06
13	5.68E+00	3.58E-02	6.09E-03	1.37E-03	1.94E-04	5.41E+00	2.57E-02	2.48E-03	2.94E-04	1.47E-05
14	4.87E-01	1.97E-02	3.15E-03	5.17E-04	5.26E-05	4.87E-01	1.97E-02	3.15E-03	5.17E-04	5.26E-05
15	1.61E+00	2.11E-04	1.99E-06	1.97E-08	4.56E-11	1.80E+00	1.00E-03	3.48E-05	1.35E-06	1.65E-08
16	1.00E-01	3.16E-02	1.00E-02	3.16E-03	1.00E-03	1.00E-01	3.16E-02	1.00E-02	3.16E-03	1.00E-03
17	7.70E-01	2.54E-03	7.38E-07	1.38E-08	9.06E-11	7.70E-01	2.54E-03	7.38E-07	1.38E-08	9.06E-11
18	1.28E-01	9.89E-03	1.42E-03	1.78E-04	7.35E-06	1.28E-01	9.89E-03	1.42E-03	1.78E-04	7.35E-06
19	1.28E-01	9.89E-03	1.42E-03	1.78E-04	7.35E-06	1.28E-01	9.89E-03	1.42E-03	1.78E-04	7.35E-06
20	7.91E-01	2.13E-05	8.89E-08	2.28E-10	4.05E-14	7.91E-01	2.13E-05	8.89E-08	2.28E-10	4.05E-14
21	1.71E+00	8.84E-04	1.13E-05	5.48E-08	2.72E-11	1.90E+00	5.65E-03	4.00E-04	2.91E-05	7.17E-07
22	4.68E-01	3.05E-03	1.92E-04	1.63E-05	8.15E-07	4.68E-01	3.05E-03	1.92E-04	1.63E-05	8.15E-07
23	1.11E-01	1.63E-04	1.59E-06	7.20E-09	2.13E-12	1.11E-01	1.63E-04	1.59E-06	7.20E-09	2.13E-12
24	2.92E-01	1.78E-04	1.67E-06	7.40E-09	2.17E-12	2.92E-01	1.78E-04	1.67E-06	7.40E-09	2.17E-12
25	1.07E+00	6.50E-03	6.87E-04	6.46E-05	1.99E-06	1.07E+00	6.50E-03	6.87E-04	6.46E-05	1.99E-06
26	4.51E-01	1.16E-06	2.54E-10	8.88E-15	2.20E-22	4.51E-01	1.16E-06	2.54E-10	8.88E-15	2.20E-22
27	1.22E+00	2.54E-02	4.04E-03	7.21E-04	7.03E-05	1.22E+00	2.54E-02	4.04E-03	7.21E-04	7.03E-05

Remarkable results are those with differences in scenarios that are attributed to the type of dam. In Fig. 8 occurrence rate curves are showed for those events that dependent of the type of dam: Damage to dam foundation (ID=8), Damage to the dam (ID=13), Downstream flooding (ID=15) and Overtopping (ID=21). The most relevant result is Damage to the dam. For concret-arc dam, an annual rate of Very heavy intensity of damage is 1.94E-04, i.e. it has a return period of 5154 years, while for the embankment dam, and the annual rate of Heavy intensity of damage is 1.47E-05, i.e., a return period of 68027 years. In contrast, the annual rates of Heavy intensity of damage in foundation (ID=8), Downstream flooding (ID=15) and Overtopping (ID=21) are higher for the embankment dam. This behavior is due to the concrete structure is more vulnerable to the earthquake than embankment, dam, but the latter is more vulnerable to the overtoppings and downstream floods than concret-arc dam.

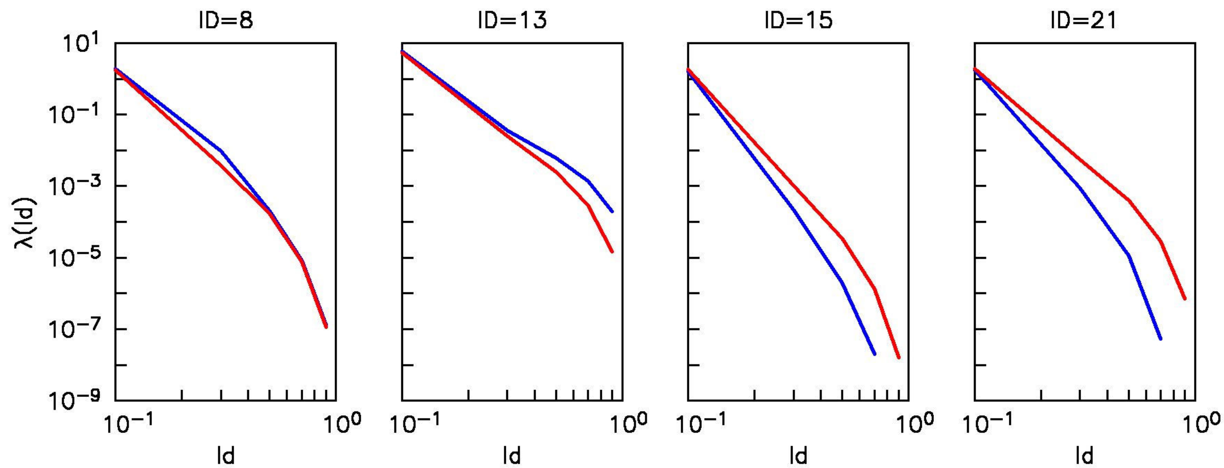


Figure 8. Occurrence rate curves for: Damage in foundation (ID=8), Damage to the dam (ID=13), Downstream flooding (ID=15) and Overtopping (ID=21). Blue line and red line are used to represent concret-dam and earth-rock embankment, respectively.

In Fig. 9 rate of occurrence curves are showed for terminal events, these are: Damage to mechanical equipment, Powerhouse inflow decrease, Reservoir level control loss and Storage loss. These events are not type-dam dependent. The largest rate for Very heavy damage is 8.15E-07, this value corresponds to Powerhouse inflow decrease. In descending order, Damage to mechanical equipment (3.86E-08), Reservoir level control loss (2.17E-12) and Storage loss (2.20E-22).

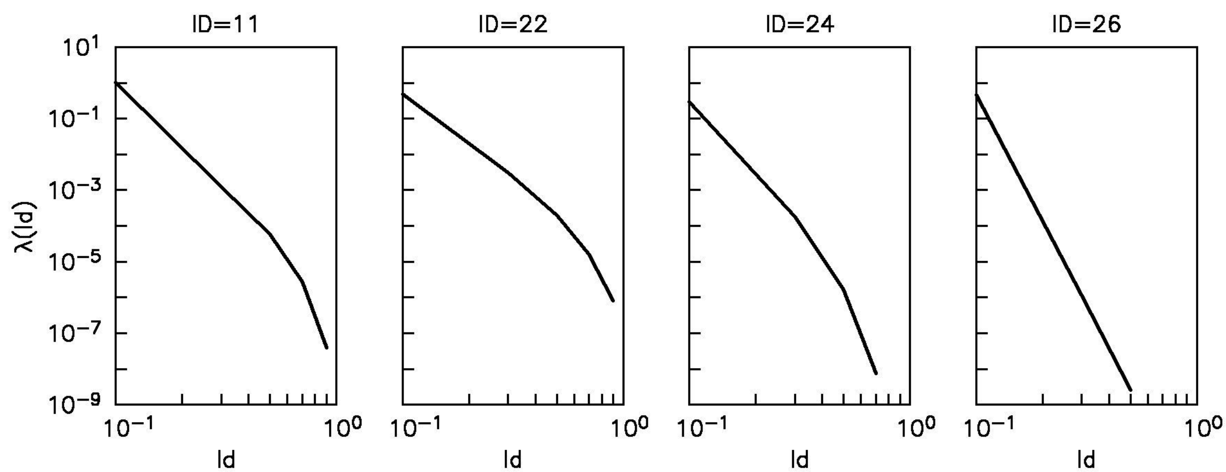


Figure 9. Exceedence rate curves for: Damage to mechanical equipment (ID=11), Powerhouse inflow decrease (ID=22), Reservoir level control loss (ID=24) and Storage loss (ID=26).

In Fig. 10 rate of occurrence curves are showed for some intermedial events (also type-dam independent) these are: Damage to both banks slopes at the reservoir, Damage to control structure, Damage to left and right banks at the dam site, Water waves through the reservoir. Rates of Very heavy damage in descending order are: Damage to both banks slopes at the reservoir (2.27E-04), Water waves through the reservoir (7.03E-05), Damage to left and right banks at the dam site (7.35E-06) and Damage to control structure (7.47E-06).

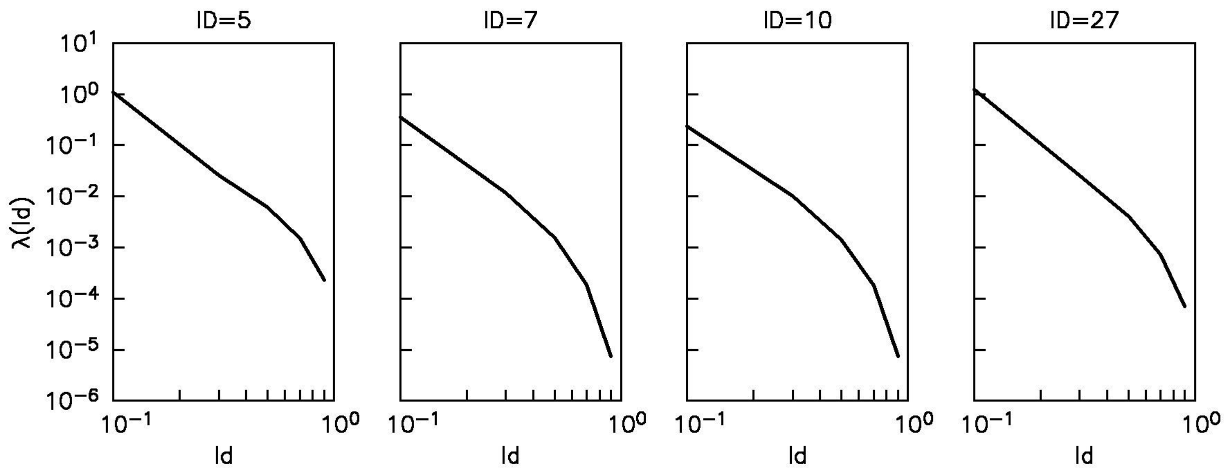


Figure 10. Occurrence rate curves for: Damage to both banks slopes at the reservoir (ID=5), Damage to control structure (ID=7), Damage to left and right banks at the dam site (ID=10), Water waves through the reservoir (ID=27).

CONCLUSIONS

Natural hazards are taken into account by occurrence rates. The rates of occurrence are complete descriptions of the process of occurrence of the hazard. That is, values of occurrence of different intensities ranges are given. Events with full scales ranging from small to major intensities are accounted for.

It is proposed that the initial hazard, described by its occurrence rate, be an event that causes another named effect-event. This establishes a cause–effect relationship, which is characterized by a curve of vulnerability. This one is represented in a matrix form that fulfills several properties of probability, since the vulnerability function is the expected value of the effect, given the cause, that accomplishes a probability distribution.

A scenario can be build as a sequence of events in which one is the initial event (initial hazard), another is the final event (which may be the damage to the dam), and the rest are intermediate events that each one is, indeed, cause of the following and effect of the previous event.

The mathematical representation of a scenario is a matrix scheme that allows to know the occurrence rate of each intermediate event and, consequently, the occurrence rate of the final event, in this case, the damage to the dam. This scheme allows overlap the final effect on the dam due to various hazards, or multipath damage caused by the same initial hazard.

The proposed methodology is a formal and systematic method to quantify the probability of failure that is displayed on the classical event trees commonly used in risk analysis. In this work, a seismic hazard tree was presented as an example with two types of dams: arc-concrete and earth-rock.

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