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# Probabilistic assessment of structural damage from coupled multi-hazards

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## ABSTRACT

Evaluating and predicting structural damage from multi-hazards is a complex task mainly due to the varying ways in which hazards affect structures. Also, different damage scales that employ different parameters and criteria are used for evaluating the hazards, making a connection between the damage assessment of two or more hazards difficult. Attempting to compute the cumulated structural damage from various hazards becomes very difficult with these limitations.

This paper describes the implementation of a probabilistic framework that includes effects such as structural weakening due to a first-acting hazard in the analysis of structural damage when contemplating subsequent hazards. It also proposes the formulation of damage scales tailored to assess cumulative structural damage from all the hazards involved in the analysis.

This allows for the computation of probabilities for final damage states, which can be used in multi-hazard risk analysis or in design with performance objectives.

The article explores the application of the proposed framework on the case of structural damage to masonry housing due to earthquakes and earthquake-triggered floods. The particular case concerns an unreinforced masonry house located behind a levee.

## 1. Introduction

A multi-hazard analysis comprises the examination of multiple (natural) hazards such as earthquakes, hurricanes, fires, etc. Many analyses aim to combine the risk of independently-acting hazards to account for “multi-hazard risk”, but some also contemplate the possibility of hazards acting together in space and time; this is the case for the analysis of coupled multi-hazards [18]. Coupled multi-hazards, also known as sequential, chain, or cascade events, are related to increased structural damage and reduced confidence in the prediction of risk.

These coupled multi-hazards may be the result of the combination of various hazards of natural or anthropogenic origin [15]. Wind storms may cause intense wave attack on coastal structures thus combining damage from wind and wave attack (e.g. Friedland [14]); volcanic eruptions might deposit ash on the roof of buildings making them more vulnerable to earthquakes also induced by volcanic action [25]; or, earthquakes may trigger the rupture of water retaining structures, causing flooding of structures already damaged by the same earthquake.

Two approaches exist for assessing multi-hazard risk, indistinct of whether hazards are coupled or independent: the categorisation of damage in a qualitative manner, and the evaluation of loss (or damage) on a quantitative scale [14]. Both approaches face the same challenge:

hazards are likely to act via different processes, and are therefore, difficult to assess on the same scale [18].

The first qualitative approach may classify damage based on a description of failure (e.g. low to high), and the latter evaluate damage based on an absolute maximum value (e.g. 50% loss). In both cases, damage is assigned onto a simple scale which does not include a physical description of the damage, capable of becoming the input for a structural model. Without a clear insight into the physics of the damage, it is difficult to combine it when the effect of multiple hazards is considered. In fact, fully disconnecting the hazards is not possible as first-acting hazards need to be viewed as weakening or preloading of the structure for the damage analysis of second-acting hazards. Already-damaged structures are likely more vulnerable to additional damage [20]. This becomes an additional complexity when observing multi-hazard damage.

Accordingly, the probabilistic assessment becomes complex if the many uncertain (damage) states of the structure need to be considered for the analysis of the subsequent actions. Moreover, since hazards may act upon structures in various ways, each action will be related to one or many specific failure mechanisms.

Hierarchical modelling is an approach to tackle these interactions [9]. With this method, the failure of elements can influence the

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behaviour of the remaining, non-failed ones. However, the method becomes too complex for producing a physical picture of damage. Instead, it is oriented to express damage in terms of (monetary) loss which does not necessarily correlate to a representation of the structural damage and loss of strength or stiffness and their contribution to the overall capacity of the structure (see, for instance, [3]).

Similarly, the Hazus multi-hazard guideline [13] allows for an estimation of multi-hazard structural damage but does not detail the damage extensively, thus making it difficult to assess damage from hazards in a physical way that is able to differentiate the cumulated damage.

Kameshwar [17], for instance, analyses failure of bridges from both earthquakes and hurricanes, but does not discern various damage states (only failure is stated). The case of increased vulnerability to one hazard due to existing damage from another (damage coupling) is also not addressed. Asprone [1] uses a similar approach. This is representative of the literature in the field.

In sum, the majority of the current approaches are based on: uncoupling the damage produced by each hazard, and measuring the damage in qualitative or otherwise incompatible scales. This is a useful simplification (and sometimes the only possible approach) for analysing the risk produced by many (multi-)hazards, but needs to be improved if one particular (coupled) multi-hazard carries a great risk or if the design of a new structure needs to meet reliability criteria against a particular multi-hazard. Additionally, understanding the particular type of damage and its causes is important when reinforcing existing structures, formulating other prevention or mitigation solutions (that uncouple the damage produced from multi-hazards, for instance), or designing new structures.

Tsunami evacuation towers in Japan deal with a coupled earthquake and tsunami multi-hazard and are a first example of an event with an important probability of occurrence and considerable societal impact. Similarly, houses behind levees in earthquake-prone areas, can benefit from a more rigorous and insightful damage assessment. Further, in mountainous areas, floods significantly increase the risk of landslides, coupling these to a dangerous multi-hazards. These are just a few examples where the methodology just described can be of use.

Consequently, this paper aims to elaborate a method to assess structural damage for coupled multi-hazards in a quantitative and cumulative manner, including effects such as weakening.

This article presents a methodology based on the definition of a compatible damage scale for all partaking hazards; the evaluation of discrete damage states as the starting point for the assessment of second-acting hazards; and, the use of discrete hazard intensity intervals for the computation of the damage probability. This is tailored for coupled multi-hazards, but can also be employed for the analysis of independent multi-hazards. In the later case, the structure may have seen some degree of repair before the impact of the second hazard. This is not treated in this text, but the reader is referred to, for instance, Yeo [27].

This approach allows for the estimation of: damage state probabilities, the contribution of each action, and the elaboration of fragility curves based on a physical understanding of damage and the interaction of first- and second-damage.

The paper starts with a description of the framework. A general explanation for the application of the framework to the analysis of any multi-hazard combination is detailed in six steps. The process covers the study of the hazards, their interrelation, the formulation for a damage scale for the partaking hazards, the definition of weakening, the analysis of damage from the first-acting hazards, and the analysis of the subsequent hazards on the weakened structure. These steps comprise the elements necessary to compute the mathematical expression used to calculate the damage state probabilities.

It must be said that the interrelation of hazards, which can be an extensive study on its own, is only mentioned briefly insofar it concerns this methodology.

In a way, this can be compared to a Markov (chain) risk assessment (see, for instance, [2]), where a transition matrix is generated for each step and for each hazard; and, where the set of matrices for the subsequent hazards is dependent on the outcome of the first hazard. The dependency is provided via the damage scale definition.

The methodology is then exemplified with a case study where earthquakes might cause damage to existing masonry structures located nearby levees that retain an elevated water level of a navigation canal. The levees have a defined vulnerability to being damaged by the earthquake; hence, levee failure might lead to flooding which may also impact the aforementioned masonry structures. The vulnerability of the structures in respect to the flood is expected to increase due to the weakening by the earthquake.

## 2. Framework

There are six main categories of analysis required to perform a probabilistic analysis and physical appraisal of structural damage as a result of the actions of two or more hazards. While the list presented below follows a certain logical sequence, the analysis is iterative, hence, the evaluation of each step requires insight into the other categories. These steps, as summarised in Fig. 1, are described below and exemplified with a case study in the next section.

### 2.1. The study of hazards (Intensities)

Each partaking hazard needs to be represented via one or several parameters that relate to their intensity. For example, earthquakes can be represented via their peak ground acceleration (PGA) or peak ground velocity (PGV) (e.g. Cua et al. [8]), floods via their flood depth and/or flow velocity (e.g. [6,23,24]), windstorms via the velocity of the wind (e.g. [14]), and mudflows via the density and depth of the flow [29]. Some examples are summarised in Table 1 adapted from [21,31].

Depending on the scenario and the type of structure contemplated, different parameters might be relevant for the same hazard. For example, when observing the effect of a wind storm on a pier, it might be more relevant to compute and define the intensity based on the resulting wave height; but, for observing the effect on a crane on the same pier, wind speed could be a better suited parameter.

The following notation is introduced:

First-acting hazard  $\rightarrow H_1$  with intensity parameter  $h_1$

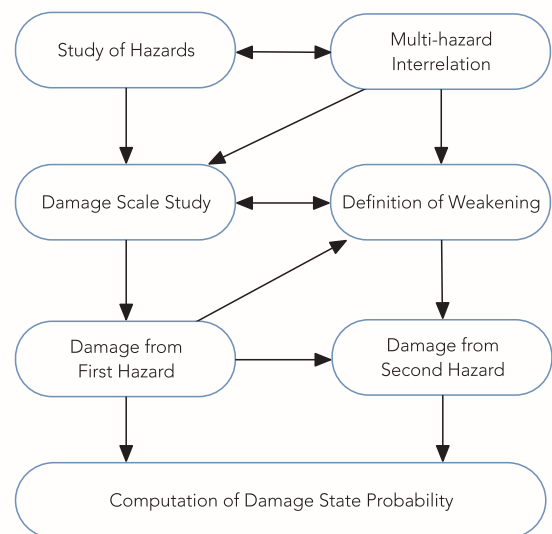


Fig. 1. Overview of all the steps involved in obtaining the final damage state probability. For clarity, only two hazards are displayed. An expanded version of this figure is found at the end of this section (Fig. 7).

**Table 1**  
Examples of hazards and some describing parameters with a qualitative intensity categorisation. Adapted from [21,31].

Hazard (H)	Intensity Parameter (h)		Intensity		
	Description	Unit	Low	Medium	High
Earthquake	PGA	% of g	< 10	10–30	> 30
Flood	Depth	m	< 0.5	0.5–2	> 2
	Depth-Velocity	m <sup>2</sup> /s	< 0.5	0.5–2	> 2
Forest Fire	Flame height	m	< 1.2	1.2–2.5	> 2.5
	Front line power	kW/m	< 350	350–1750	> 1750
Volcanoes	Mass eruption rate	kg/s	< 10 <sup>2</sup>	10 <sup>2</sup> –10 <sup>6</sup>	> 10 <sup>6</sup>
Landslide	Rate (cm/y or cm/d)	cm	< 2/y	> 10/y	> 10/d
	Ratio of unstable over stable surface	–	< 5	5–15	> 15
Debris Flow	Depth & Velocity	m & m/s	n.d.	< 1 & < 1	> 1 & > 1
Avalanche	Pressure	kPa	< 3	3–10	> 10
Rock Fall	Energy	kJ	< 30	30–300	> 300

Second-acting hazard → H<sub>2</sub> with intensity parameter h<sub>2</sub>

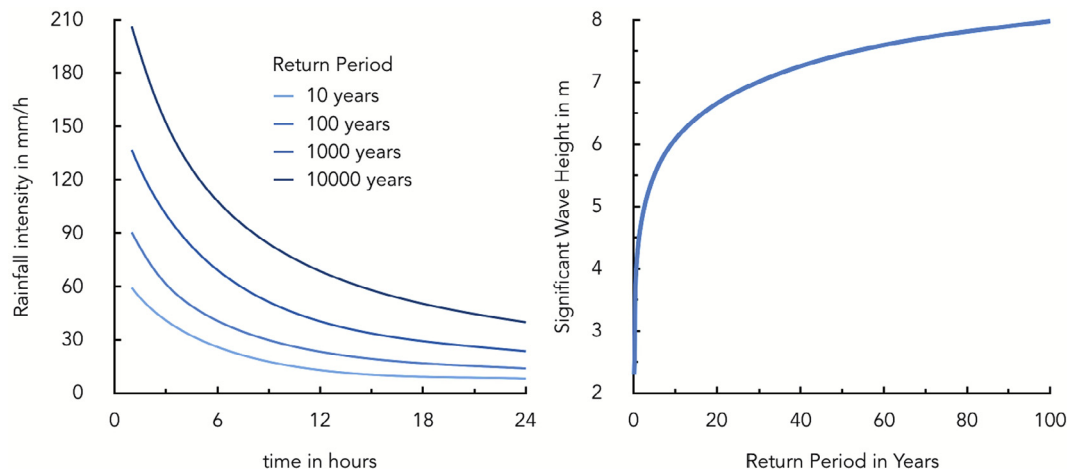
These parameters can be related to return periods to link the intensity to a probability of exceedance. Low intensities are commonly associated with lower return periods, while events of high intensity occur much less often. Two such examples are shown in Fig. 2.

Additionally, intensity parameters can also be dependent on the intensity of other hazards, so that sometimes, the parameters of the second hazard can be related to the intensity of the first hazard.

For example, the PGA of an earthquake usually follows an extreme value distribution that assigns a higher PGA to higher return periods [8]; while the flood depth of an earthquake-triggered tsunami could be a function that comprised both the intensity of the earthquake (as the intensity may reveal both magnitude and distance to the epicentre) and the tide level at a random point in time. The interaction of hazards is further discussed next.

### 2.2. The interrelation of multi-hazards

The interaction of hazards can often be modelled in scenarios such that the precise dependency of second-acting hazards can be described as a function of the parameters that detail the first hazard [15]. Additionally, the parameters of the second hazards can sometimes be related to the intensity of the first.



**Fig. 2.** Left: Rain intensity example described by two parameters (rainfall and duration) against a probability or return. Adapted from Iida [16]. Right: Wave height due to open-ocean swell against a return period. Adapted from Vitousek [26].

As a first example: floods can be related to earthquakes via the failure of a levee. The probability of failure of this levee can be expressed as a function of the intensity of the first hazard (the earthquake). The analysis of failure can then be as in-depth as the model requires it: ranging from deterministic analyses for specific intensity steps, to MonteCarlo-type analyses that include all the variability intrinsic to the parameters of the levee such as soil strength, dimensions, etc.

Similarly, wind storms can cause fires by affecting electrical installations. The stronger the wind, the more likely the occurrence of a fire. Also, the intensity and propagation of the fire can be aggravated by the wind. Structural damage will result from actions by the wind and weakening by the fire.

Though obscure (and thus unlikely) scenarios can be envisioned through which every hazard can be related to every other, some of the more common interrelations between hazards are presented in Table 2.

For the analysis of damage, the risk can be analysed for given scenarios. This is the case, for instance, of a landslide, of which a return period related to an intensity is difficult to predict. If the landslide is the primary action of a coupled multi-hazard, for example by triggering a wave on a lake, by blocking a river stream, or by damaging energy infrastructure that may cause a fire; it might be necessary to analyse the risk for given intensities, without relating them to a return period.

In the analysis of coupled multi-hazards, then:

$$P(H_2|H_{1,j})$$

Probability of occurrence of

H<sub>2</sub>: Second hazard, given

H<sub>1,j</sub>: First hazard. Event j defined with a range of the parameter of intensity.

It is also possible for hazards to be independent, such as an earthquake occurring in an area that was already under flooding. In this case, the probability of both events occurring simultaneously (which might be very small) could be incorporated but would need to be deduced from other studies or scenarios.

$$P(H_{2,g}|H_{1,j})$$

where g implies various intensity scenarios of the second hazard which are dependent on the first hazard.

### 2.3. Damage scale study

A key aspect for the appraisal of structural damage from multi-hazards is having a scale that is able to account for damage produced by

**Table 2**  
Interaction of Hazards. Adapted from Gill [15].

Primary Hazards		Secondary Hazards (as a result of PH)											
		EA	TS	VE	LS	AV	FL	GC	WS	SS	WF	AD	FR
Earthquakes	EA	•	•	•	•	•	•	•					•
Tsunamis	TS			•	•		•	•					•
Volcanic Eruptions	VE	•	•		•	•			•	•	•	•	•
Landslides	LS		•		•		•						•
Avalanches	AV			•	•	•							•
Floods	FL			•	•			•					•
Ground Collapse	GC				•								•
(Wind) Storm	WS				•	•		•					•
Hail/Snow Storm	SS			•	•	•		•					•
Wildfires	WF				•		•	•	•				•
Ash Deposition	AD												•
Fires	FR												•

the first-acting hazard, and then add the damage produced by the later hazards. Damage scales usually ranging from DS0 (no damage) to DS5 (total structural collapse) are common but the definition used is often descriptive and qualitative [14]. It is important to base the scale on a quantitative and objective measure of damage such as residual lateral deformation of the structure [13], cracking profiles, remaining capacity, or loss of stability. Moreover, the scale must be able to measure progressive damage. Fig. 3 shows a summary of the requirements for such a damage scale.

Elaborating upon Fig. 3, parameters that can be used (separately or combined) to quantitatively assess damage in a cumulative manner can be (and are certainly not limited to):

- residual (lateral) deformation
- remaining ductility
- remaining capacity
- cracking profile, percentage, width or length
- loss of stability
- remaining fatigue cycles

- remaining section
- ratio of hinges over the ones required for a collapse mechanism

Depending on the intensity measured by the chosen parameter(s), damage grades should be discretised. For instance, for a scale corresponding to four damage grades (none, low, medium, and high) measured by the mid-span deflection to span ratio of a bridge, values between 0 and 1/200 could correspond to no damage, while values higher than 1/20 would be assigned into the high grade.

If more than one parameter is used, the damage states can be assigned multiple conditions for the various parameters. For example, cracking can be used mainly to describe the lower damage states, while, for higher damage grades, where cracking is assumed to have fully developed, the loss of capacity can be used. The parameters must be chosen so that they are able to account for (relevant) damage potentially caused by all the partaking hazards. Accordingly, for the example of the overloaded bridge, the midspan deflection would not likely work as a parameter to evaluate damage caused by scour. Perhaps, for some types of designs, the angle of tilting of the piers could serve as indication of damage caused by both overloading and scour.

Finally, damage grades should also establish a picture of damage upon which to evaluate second-acting hazards. For instance, a flood wall hit by a wave is damaged to a low state (in the fictitious damage scale): Regardless of the parameter used to measure the damage (e.g., maximum out of plane displacement), the damage state should contain representative values (of strength, stiffness, etc.) so that it is possible to analyse any subsequent actions on the wall, for example, the impact of debris. This topic is expanded later.

Table 3 presents what could be a damage scale to measure the deterioration of concrete infrastructure typically found outside cities (e.g. retaining walls for roads, housing of electrical equipment, etc.). The scale could be developed to target the fact that such a structure may be exposed to a (wild)fire and later on subjected to frost-defrost cycles. Note that this is not a coupled multi-hazard, but the methodology can still be applied. For this example, the damage scale looks at the loss of section of a wall due to concrete spalling during fire and frost.

#### 2.4. Modelling of damage from the first hazard

It is necessary to elaborate a model to assess the effects of the first action. The model must be able to assign this damage onto the selected damage scale. It is more transparent to perform this in discrete intensity steps and to include the uncertainty of the model and the structure in the result.

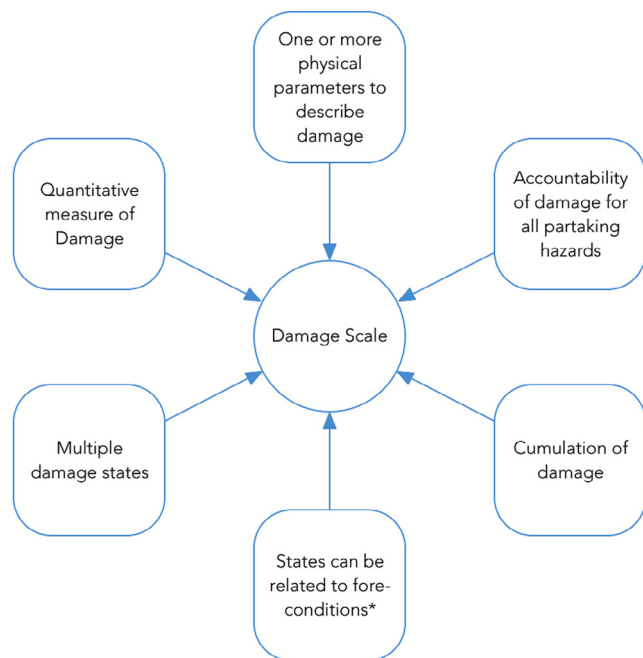


Fig. 3. Characteristics of the damage scale. \*See next subsection.

**Table 3**  
Example of a damage scale with four grades (0–3) for measuring both fire and frost damage of a concrete element.

Loss of section	DS0	DS1	DS2	DS3
Percentage of lost cross section	< 5%	5% to 15%	15% to 50%	> 50%
Qualitative description	No damage	Concrete cover is affected	Reinforcement has de-bonded	More than half the section has been affected

The complexity of the model will depend on the configuration of the structure, the type of expected damage, and the precision in which this wants to be measured. Non-linear finite element models are commonly used to assess structural damage from most processes, but simpler structures may be characterised by frame-hinge models, for instance.

For a given intensity, taking into account the uncertainty of the model and the inputs (which may include the variability of the materials, the modelled connections, gravity loads, the direction of the action, etc.) an expected damage state can be assigned, with other damage states also obtaining a probability.

The number of steps when discretising the intensity parameter is chosen based on engineering judgment. This should consider the computational requirements to evaluate each model and the probability for no damage below a certain intensity or total damage above an upper limit.

The result of this exercise should be a matrix for each given intensity step for the probability of a certain damage state contemplating only the occurrence of the first hazard.

$$p(D_i | H_{1,j}; \bar{H}_2)$$

This process is illustrated with an example in Fig. 4. Here, the damage state of a simple steel roof is observed for three intensity levels of rainfall. The model concerns the analysis of the structural behaviour of the roof under the weight of the water. This model can be relatively simple but still include the uncertainty of the parameters and models involved. Drainage of the water can also be added to the model as a

function of the water height, making the model more complex. Ultimately, for each intensity of rain, a probability distribution for all damage states can be calculated (all values are exemplifying).

It is important to note that whether the deficiencies of the structure lie in the structural design or the drainage design, and whether the best cost-benefit approach to reduce the risk is by modifying the drainage system or the structure itself, the analysis of the (damage) risk as performed with this methodology remains valid for any existing configuration.

2.5. Definition of weakening/Preloading after first damage

Based on the results of the first analysis, the damage scale can be complemented with specific damage pictures for each state (see Fig. 5). These become the fore-states upon which later actions can be analysed. Damage pictures can include modified values of strength, residual deformations, removal of elements, preloading values, cracking patterns, etc. It is worth mentioning that such modifications are not always detrimental for the structure. For example, residual earthquake deformations may modify stresses in a wall such that it is better oriented to withstand lateral actions coming predominantly from one direction. These damage pictures do not need to be deterministic, either. For each damage state, values for strength for instance, can be assigned an expected mean with deviations.

Some actions are better evaluated by setting a degree of weakening on the structure (as shown in Fig. 5), such as earthquakes, wind, or fire; but others, like added snow, ash or settlements, are more easily

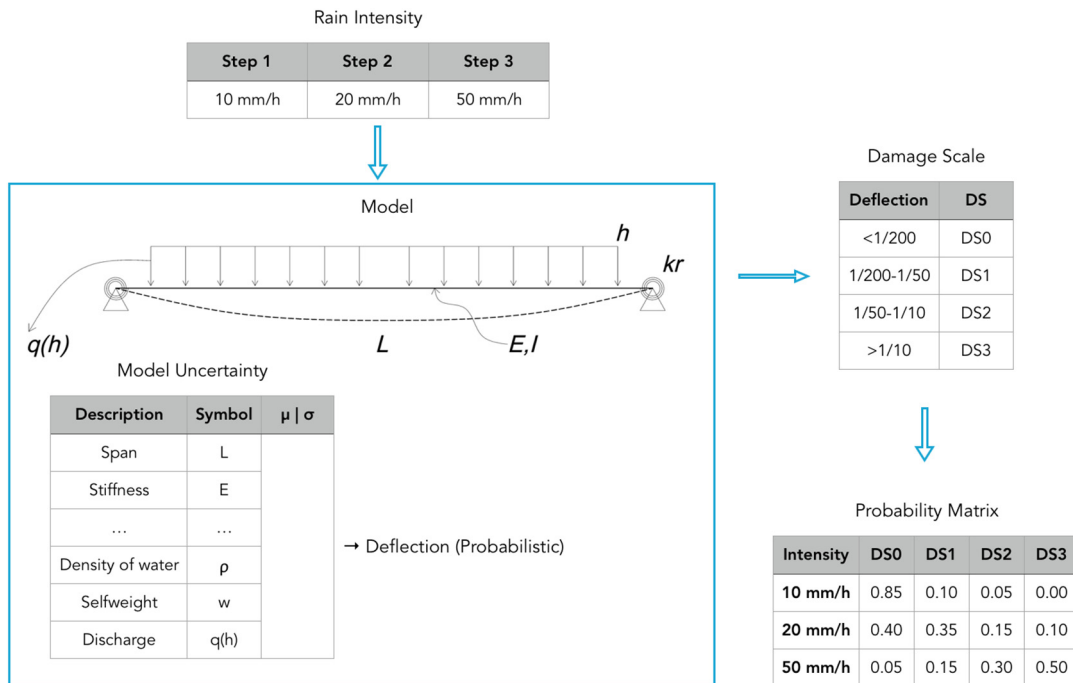


Fig. 4. Example of modelling of a roof to evaluate the probability of damage (quantitatively).

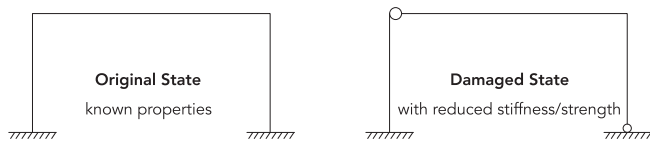


Fig. 5. Damage picture. Each damage state needs to compile a defined set of modifications of the structure.

Table 4  
Some actions and the degree of their representation as weakening or preloading of the structure.

Weakening	Floods	Rain	Snow	Preloading
Earthquakes				Ash Deposition
Frost	Landslides	Avalanches		
Fire	Settlements	Floods (static)		
Wind				
Tsunamis				

modelled as preloading of the structure. Weakening actions are those which modify the strength of the structure to withstand further actions, while preloading actions typically act simultaneously with the following or second-acting processes. Some processes, such as rain, can be considered as preloading if the weight of the rain is still on the structure when analysing the effect of further actions (and little damage has been exerted), or as weakening if the water has drained but the structure has seen changes from its original condition. A more extensive list is presented in Table 4.

This weakened or pre-loaded fore-state then serves as a basis upon which to analyse the effect of subsequent actions.

2.6. Modelling of damage from the second hazard

Just as for the first-acting hazard, the damage evaluation due to the succeeding hazards requires a model of the structure upon which to assess the actions that may contribute to damage. In this case, the initial condition of the model should be set according to the defined fore-state (see Fig. 6).

Then, the model has to be run for each possible initial damage state. For the case of a scale with three damaged grades (DS1–DS3), the model has to be evaluated for DSO to DS2 as initial conditions. The uncertainty of the model and the structure should also be included.

In the example of a roof potentially having been deflected (Fig. 6), the distinct levels of permanent sagging associated with different damage states will produce a varying response of the structure when exposed to wind loading. Both the curvature of the roof and the loss of strength that is associated with it, will cause a certain intensity of wind to damage the structure differently.

If the fore-states are probabilistic, then more models are required to obtain insight or regress a relationship between the values of the fore-states and the final damage state. If this is the case, performing a MonteCarlo simulation might be more convenient.

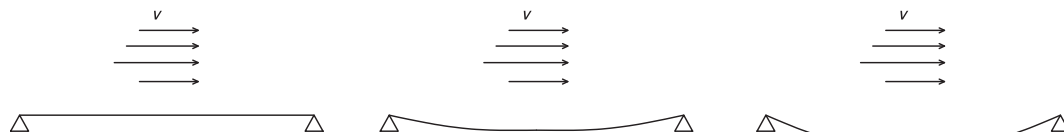


Fig. 6. Example of wind acting on different fore-states of damage of a structure. Suction effects from parallel-blowing wind will cause a different response on the different fore-states. In this case, the damaged fore-state may be advantageous to withstand the depicted wind.

In the example of Fig. 6, the hazards seem to be independent; the wind can achieve an intensity that is not related to the first-hazard. In the case of most coupled multi-hazards, however, the intensity of the second acting hazard is either dependent on the intensity of the first hazard, or is fixed given an occurrence of the second-hazard.

$$P(D_i|D_k; H_2; H_{1,j})$$

where:  $D_i$  is the final damage state,  $D_k$  is the fore-state for analysis of the second hazard, after the first hazard.

Alternatively, the intensity of the second hazard can be independent in the analysis such that the final damage state will depend on both the intensity of the second hazard and the fore-state of the structure:

$$P(D_i|D_k; H_{2,g}; H_{1,j})$$

For this case, many more computations will need to be performed.

2.7. Computation of the final damage state probability

Once the function for the dependence of the second hazard on the first hazard’s intensity  $P(H_2|H_{1,j})$ , the discrete probability distribution of damage by the first hazard for multiple intervals  $P(D_i|H_{1,j}; \bar{H}_2)$ , and the discrete probability distribution of damage by the second hazard given various pre-damage conditions  $p(D_i|D_k)$  are known, the final probability of a damage state can be computed.

$$P(D_i) = \sum_{j=1}^N \left[ P(H) \left\{ P(\bar{H}_2|H_{1,j}) P(D_i|H_2; H_{1,j}) + P(H_2|H_{1,j}) \sum_{k=0}^i [P(D_i|D_k; H_2; H_{1,j}) P(D_k|\bar{H}_2; H_{1,j})] \right\} \right]$$

Eq. (1). Final damage state probability.

N: Number of intervals selected for the discretisation of the first hazard’s intensity.

$\bar{H}_2$ : Non-occurrence of  $H_2$ .

$P(H_{1,j})$ : Probability for when  $h_1$  is in the interval  $j$ .

$P(H_2|H_{1,j})$ : Probability of occurrence of the second hazard when the event  $j$  of the first hazard occurs. Note that the probability for  $H_2$  is cumulative in respect to the parameter of the first hazard  $P(H_2|h_{1,j})$ .

$P(D_i|\bar{H}_2; H_{1,j})$ : Probability of being in a certain damage state for when the first hazard’s intensity is in the interval  $j$  and only the occurrence of the first hazard is being observed, that is  $H_2$  does not or hasn’t yet occurred.

K: Fore-state for second hazard analysis.

$P(D_i|D_k; H_2; H_{1,j})$ : Probability of being in a certain damage state given a previous damage state by the first hazard and the occurrence of the second hazard.

There are two aspects worth noting in this function: Firstly, the probability of occurrence of the second hazard is cumulative; this is explained by the fact that for a coupled multi-hazard, when the intensity of the first hazard is high, the probability of occurrence of the second hazard approaches one. Secondly, the influence of the second hazard on the probability of a final damage state is a summation with a number of components one greater than the damage state being

evaluated.

This is easily explained in the following example. For computing of the probability of DS2, three second- hazard cases have to be contemplated:

- the probability of the structure having been left at DS0 by the first hazard and the second hazard having damaged the structure to DS2;
- the probability of the fore-state being DS1 and the actions of the second hazard further damaging it to DS2; and,
- the case of the first hazard leaving the structure already at DS2 and the second hazard not modifying it.

Since all these cases are mutually exclusive, the probabilities can be added.

Eq. (1) can be rewritten without the overall summation so as to

obtain the probability of each damage state for each interval of intensity of the first hazard; this becomes Eq. (2):

$$P(D_i|H_{1,j}) = P(\bar{H}_2|H_{1,j}) P(D_i|\bar{H}_2; H_{1,j}) + P(H_2|H_{1,j}) \sum_{k=0}^i [P(D_i|D_k; H_2; H_{1,j}) P(D_k|\bar{H}_2; H_{1,j})]$$

Eq. (2). Discrete values for elaboration of fragility curves.

If the results from Eq. (2) are expressed in cumulative terms, fragility curves can be elaborated. Fragility curves are cumulative probability functions that describe the probability of exceedance of a damage state in relation to a parameter of hazard or its return period.

A summary of the methodology is presented in Fig. 7 incorporating the symbols described in this section.

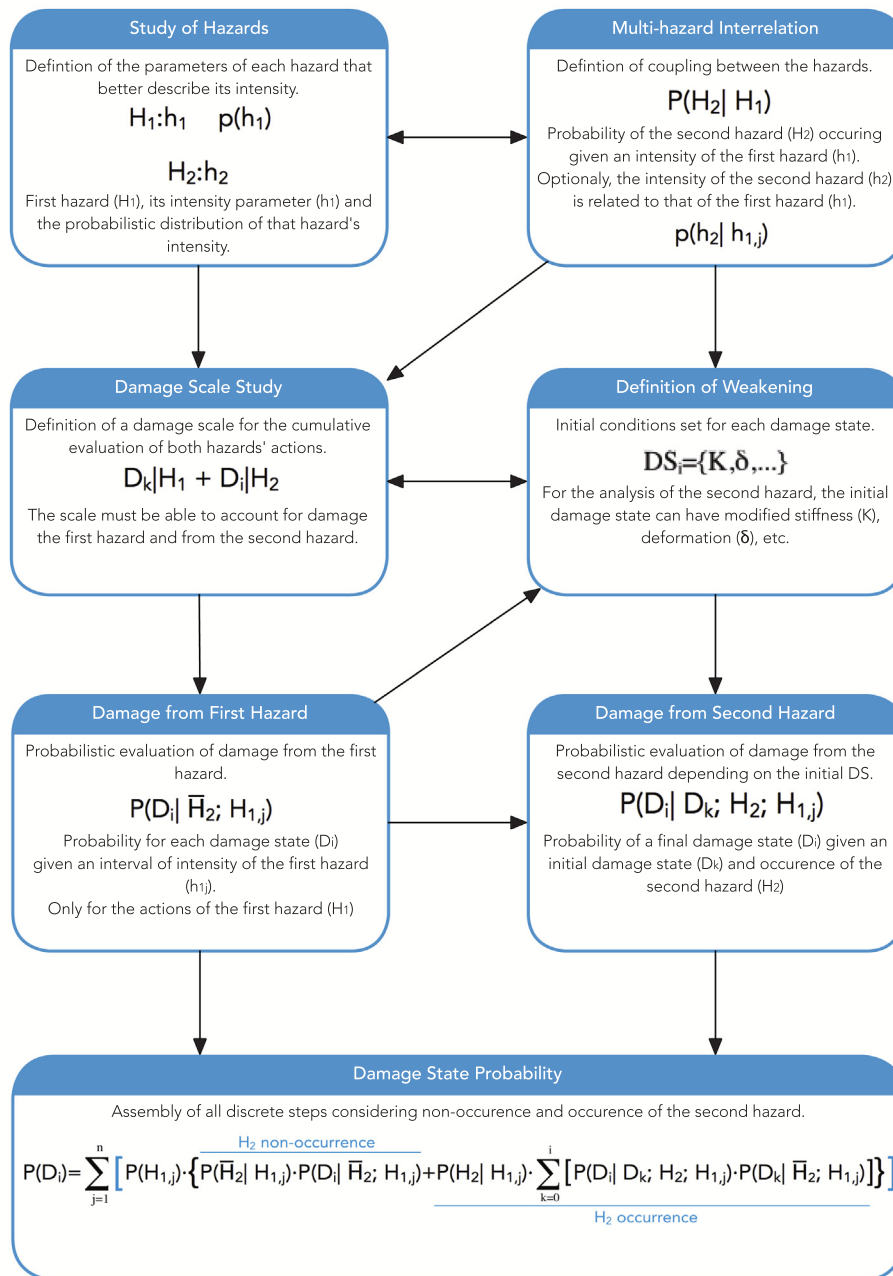


Fig. 7. Overview of all the steps involved in obtaining the final damage state probability, including detailed descriptions and formulas. For clarity, only two hazards are displayed.

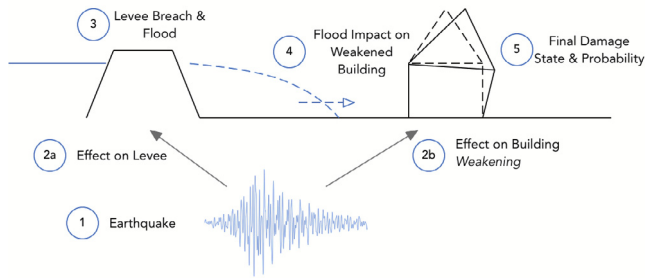


Fig. 8. Overview of the hypothetical case study based on Dutch conditions.

### 3. Application of the framework to a case study

The framework described was used to assess the (increased) risk of houses nearby levees due to earthquakes. For this purpose, a hypothetical cross-section of an earthen canal levee retaining two meters of water above street level, and an unreinforced masonry house were selected (see Fig. 8). An earthquake can lead to damage of the house and additional failure of the levee. The flood wave could then impact and damage the (weakened) house.

The situation is loosely based on the analysis of earthquake and induced flood risks in the North of the Netherlands. It concerns a hypothetical case, with input data that are not representative of the actual situation. As such, the absolute outcomes of the calculations cannot be used for actual applications. Nevertheless, the case is characteristic of a real situation that requires study as:

Firstly, the Netherlands lies below sea level and flooding is a constant danger which requires attention. Secondly, until recently, houses and levees in the Netherlands were not designed against earthquakes because only limited seismic activity was present; however, man-induced earthquakes because of gas-extraction have now been recorded, hence, it appears that a multi-hazard with earthquake and subsequent flooding need to be considered.

The house of the case study resembles two storey, two-dwelling structures with thin, single-wythe structural URM walls and concrete slab floors, typical of the post 1970s period in the Netherlands (see Fig. 9). In many of these houses, only the transverse walls are load bearing, with the rest of the walls being in-filled and connected to the bearing walls using only steel ties to provide some additional lateral rigidity.

#### 3.1. Definition of Intensities

The main hazard in this study is the earthquake. It was decided to characterise it via the peak ground acceleration (PGA) of its acceleration signal at the underground stiff layer.

This PGA was modelled to follow an extreme value distribution type II (Fréchet) derived from available PGA prediction values for specific return periods from the Dutch meteorological institute [19], then amplified for local soil conditions with a value of 1.8 (for weak soils) as suggested by the EuroCode (EC8). For specific locations more precise soil amplifications are available [4], but these were deemed too complex for this example. Similarly, PGA values have recently been revised [19], but were not updated for this study in view that its exemplifying purpose still holds.

The flood is the triggered hazard, acting second on the structure. It was described with two intensity parameters: the flood depth and the flow velocity at the walls of the house. These were estimated with a 2D-flow hydraulic model (see Fig. 10) and related to the water level in the canal, and the dimensions, location and development time of the levee breach, all of which were given probabilistic distributions. For the example, only the occurrence of the flood was dependent on the intensity of the earthquake; the intensity of the flood was not dependent on the intensity of the earthquake.

Hazards definition:

$$H_1(\text{earthquake}) \rightarrow h_1(\text{PGA})$$

$$H_2(\text{flood}) \rightarrow h_2(\text{depth, velocity})$$

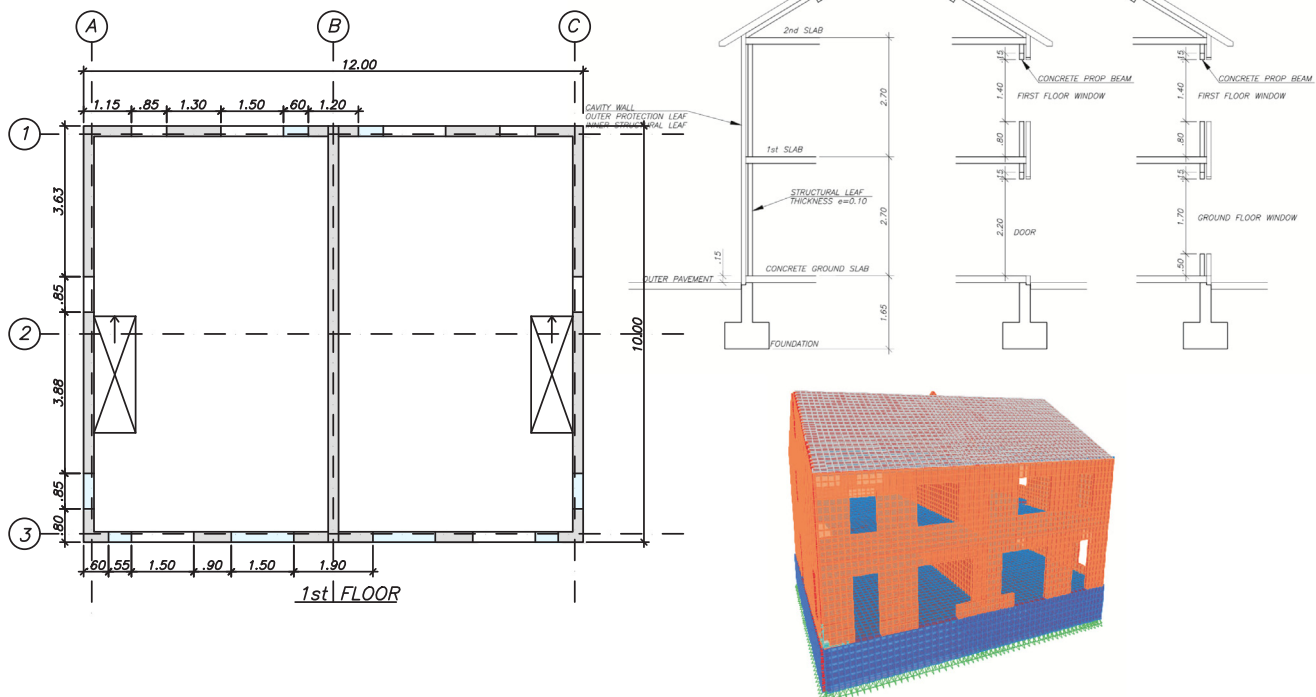


Fig. 9. Floor plan, elevation, and 3D sketch of the house used for the case study.

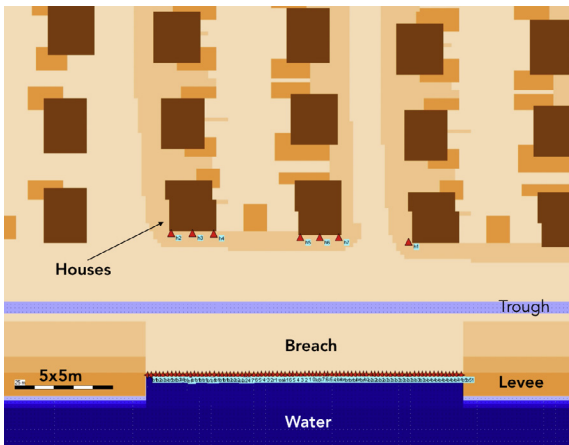


Fig. 10. Top view of a section of the 2D hydraulic SOBEK model with history points in front of the breach, as used to estimate the parameters of the flood. Brown colours represent dry areas and become darker with increasing elevation; blue colours represent wet areas and become darker with increasing water depth. 15 houses in front of a levee. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 3.2. Interrelation of earthquake and flood

For this case, the multi-hazard is due to the failure of the levee because of earthquake actions. The connection between the earthquake and the flood is thus related to the strength of the levee. The critical PGA for levee failure was characterised with a single PGA value which was assigned a lognormal probability distribution loosely based on the study of Zuada et al. [28] on levee capacity of similar canal levees (see Fig. 11); from this study, only a few values were ported to produce the probabilistic distribution shown in Fig. 11. If the critical acceleration of the levee was exceeded, failure was assumed to have occurred, hence resulting in a flood.

This is a simplification of the interaction between earthquake and flood, as the focus of this study is on the proposed methodology to combine and assess the resulting (structural) damage. The usage of a single-parameter distribution to relate the occurrence on the flood to the earthquake was deemed sufficient to illustrate the methodology. The study performed by Zuada et al. [28], for example, evaluates levee strength due to multiple failure mechanisms which depend on various properties of the levee. Such variations, and other variations of the first hazard (frequency content or principal direction for the case of an earthquake) and their consequence on the properties of the second

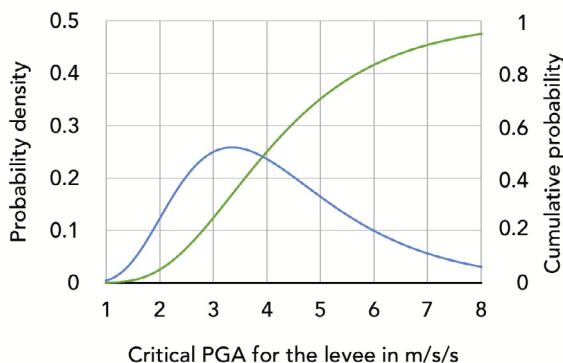


Fig. 11. Vulnerability of the levee expressed in critical PGA. Probability density: blue, left; cumulative distribution: green, right. Logarithmic mean: 1.386; scale parameter for the logarithmic distribution: 0.422. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hazard (type of levee breach, for example), can be (but have not been) included.

$$p(H_2 | h_1)$$

Probability of occurrence of

$H_2$ : Second hazard: flood from failure of a levee due to

$h_1$ : Parameter of intensity of first hazard: earthquake peak ground acceleration

### 3.3. Damage scale

Barring soil and foundation failure mechanisms, both earthquakes and floods can be analysed as lateral actions causing lateral displacement of the structure and out of plane effects on its walls (see Fig. 12). Hence, a scale measuring the number of walls and the amount of cracking that each wall has incurred, both related to the maximum lateral displacement of the structure (or of a particular storey) and the out-of-plane displacement of the walls, will be able to account for damage produced by both actions.

Moreover, the position of the structure on the scale then represents a loss of strength. If a great number of walls have incurred into heavy cracking, then it is clear that the structure has reduced capacity and is less prepared to withstand the effect of additional actions.

The longitudinal direction shown in Fig. 12 (and Fig. 14) is the weak direction of the house's structural configuration. For this direction, it can be observed that part of the damage corresponds to the transverse load-bearing walls incurring into out-of-plane bending, which causes horizontal cracking along the brick-mortar interfaces, especially when there is no brick interlocking between the wall. Such behaviour has been observed on full-scale pushover tests recently performed at the Delft University of Technology (e.g. [11]). These cracks reduce the capacity of the wall to withstand out-of-plane forces [5] such as the hydrostatic pressure of the flood [20]. As mentioned, the additional cracking caused by such loads can also be modelled and reflected on the damage scale.

Table 5 defines the damage scale based on the parameters that comprise it.

### 3.4. Earthquake damage

For the example of an earthquake acting on a masonry house, the analysis was conducted by observing damage on a pushover curve where the drops in capacity corresponded to the brittle cracking of walls (Fig. 13). Then, the effect of the earthquake was observed in a time-history analysis where the maximum displacement was matched to the pushover curve.

Inferring damage from pushover curves is a methodology usually coupled with spectral demand (e.g. [7]; [30]). In this case, however, it was paired with a non-linear analysis to obtain a greater insight into the damage mechanisms (see Fig. 14).

To establish the probability of a damage state, one single model uncertainty was introduced with a variation coefficient of 30% which was applied to the displacement results obtained from the non-linear models; i.e. they were multiplied with a random normally distributed parameter to reflect this uncertainty (a mean of 1 and a deviation of 30%). The models were run for values of 0.05 g to 0.45 g in steps of 0.05 g. Results for values above 0.45 g (up to 0.7 g) were inferred based on the displacement demand observed for lower PGAs. This is presented in Table 6.

### 3.5. Weakening due to the earthquake

The house affected by the earthquake will be weaker the more it is damaged. To model this, fore-states were defined based on the results observed from the non-linear earthquake analyses and the limits defined in Fig. 13; these included lateral residual deformations, reduced lateral capacity and stiffness, and horizontal brick-interface pre-

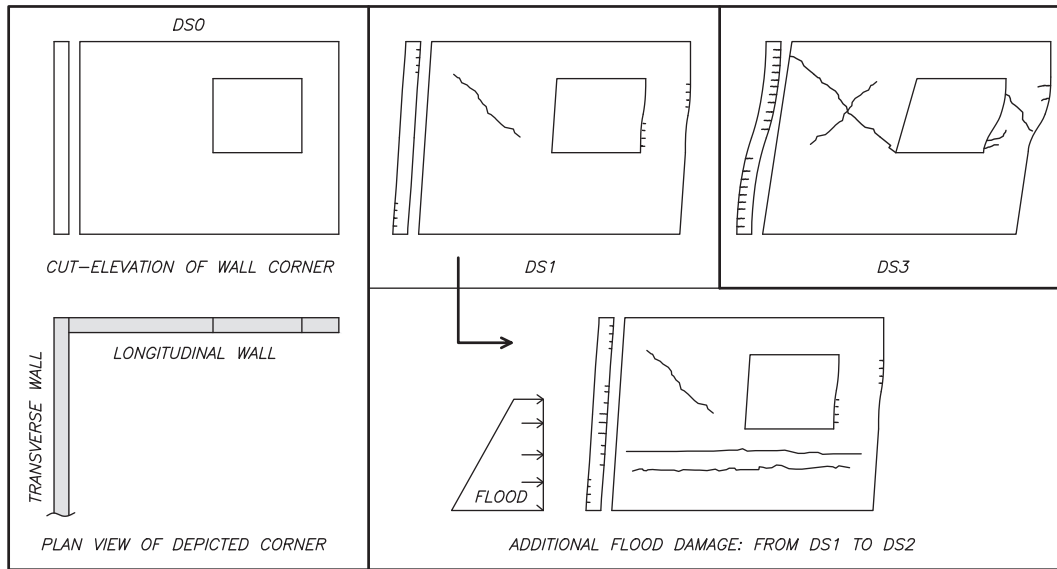


Fig. 12. Damage progression for a corner of the example case in the longitudinal direction. Thickness and separation are exaggerated.

cracking on walls. Table 7 presents some values for the study case.

### 3.6. Flood damage

For this case study, the intensity of the flood was set to be independent of the intensity of the earthquake. Only the occurrence of the flood was dependent on the intensity of the earthquake as shown in Fig. 11. Nonetheless, the intensity of the flood could still vary depending on probabilistic parameters such as the water level and the location of the breach.

From the flood depth and velocity computed for in front of the structure (with the 2D flow model, see Fig. 10), a hydrostatic and hydrodynamic pressure was applied to the wall; this was then evaluated with a non-linear model of the load-bearing walls which allowed for the inclusion and cumulation of cracks originating from out-of-plane-effect stresses (see Fig. 15). With this model it was possible to observe whether the actions of the flood increased the damage level of the walls and whether the walls lost stability (causing major damage to the structure).

A MonteCarlo simulation was used to compute the probability of the flood further damaging the house for all possible initial damage states.

The simulation was run so that at least 300 values were obtained for each possibility. The simulation included uncertainties for the water level in the canal, the dimensions and location of the breach, the time to develop the breach, the residual deformation of the earthquake taking into account the initial damage state, whether there was debris which could impact the wall, and the parameters pertaining to the collision of such debris; additional details are found in Korswagen [20].

The result is a matrix as shown in Table 8, where it can be observed that structures that start more damaged, are more likely to be brought to DS5.

### 3.7. Damage state probability

Combining the results from Table 6  $p(D_i|h_{1j})$ , from Table 8  $p(D_i|D_k)$ , the probability for levee failure, and the return period of earthquake intensities using equation 1, leads to the yearly probability for each damage state as shown in Fig. 16.

It can be observed that the second hazard (slightly) reduces the probability for the structure to end up in lower damage states and (noticeably) increases the probability of higher damage states. These

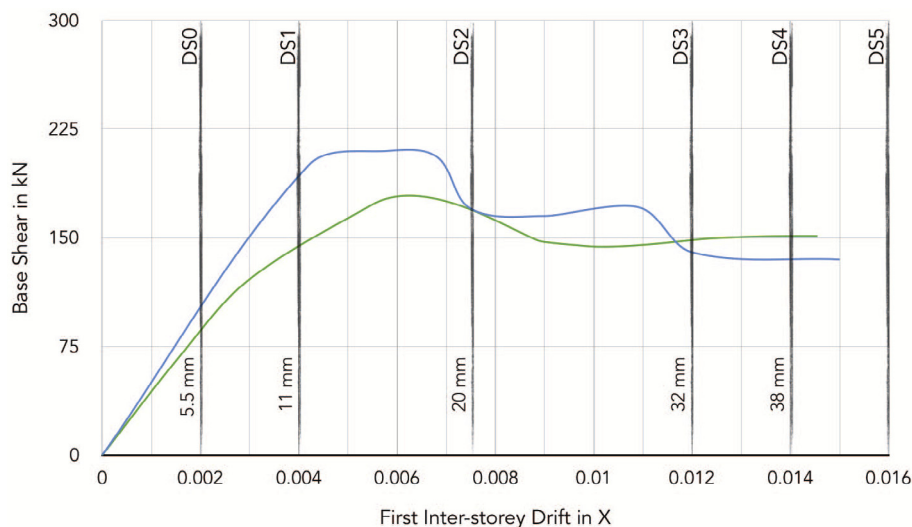


Fig. 13. Example of push-over behaviour related to damage states. Curves show both back and front walls. The displacement indicated is the absolute value of the first inter-storey drift which is the maximum inter-storey drift for the two-storey example.

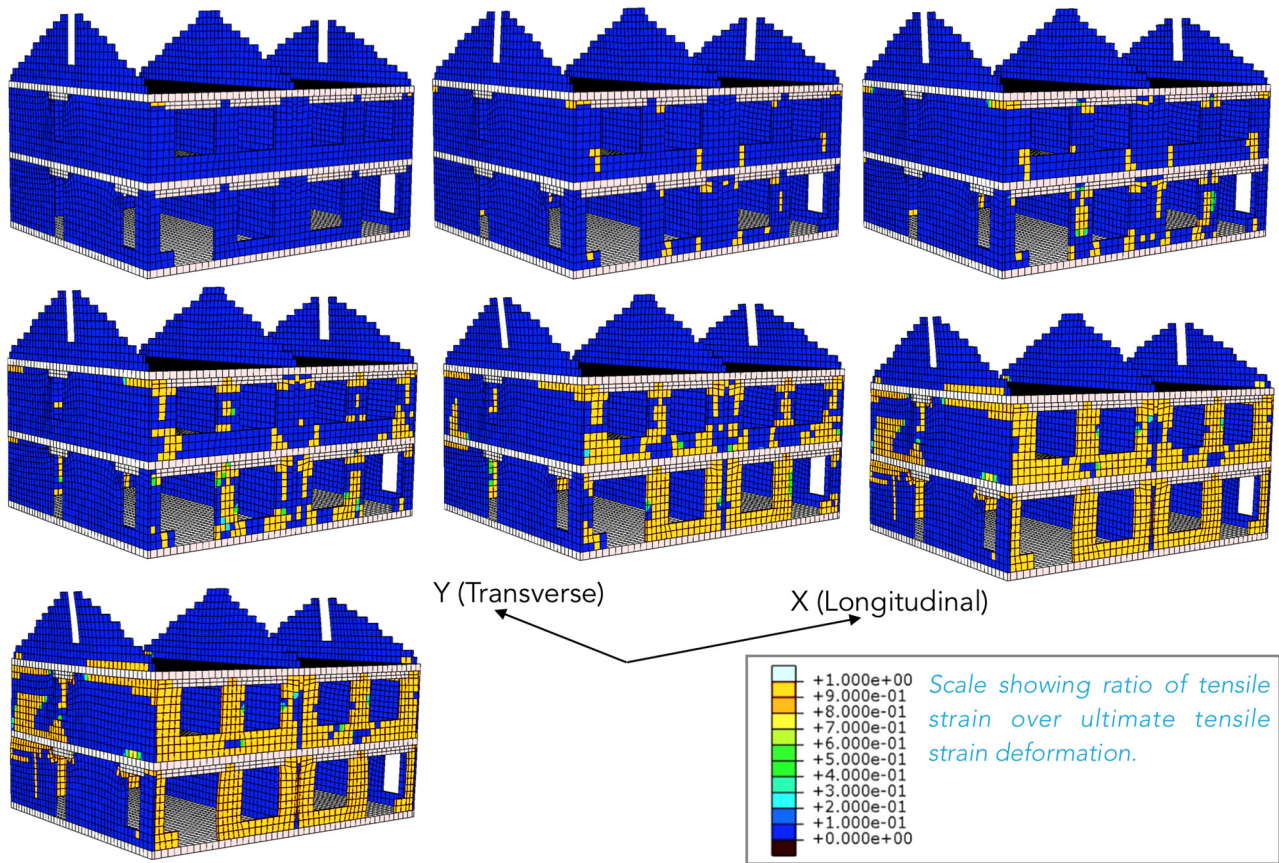


Fig. 14. Sequence of captures from an 'Abaqus' time history analysis in the longitudinal direction with a PGA of 0.35 g. Yellow squares indicate elements where tensile cracks have developed. Intensification of earthquake acceleration signal from top-left to bottom.

Table 5  
Damage scale definition (example for the longitudinal direction).

Parameter	DS0	DS1	DS2	DS3	DS4	DS5
Maximum lateral displacement	Up to 5 mm	Up to 11 mm	Up to 20 mm	Up to 32 mm	Up to 38 mm	> 38mm
Cracking in load-bearing walls	None	Up to 15% of horizontal interfaces are cracked	Up to 40% of horizontal interfaces are cracked	All horizontal interfaces are cracked	All horizontal interfaces are cracked	All horizontal interfaces are cracked
Crushing in load-bearing walls	No	No	No	No	Yes	Yes
Instability in load-bearing walls	No	No	No	No	No	Yes

Table 6  
 $P(D_i | H_{1,j})$ . Example of matrix for the probability of a specific damage state given a certain PGA interval, only due to earthquake-action.

$a_j$ (g {m/s <sup>2</sup> })	DS0	DS1	DS2	DS3	DS4	DS5
0.05 ... 0.10	0.21	0.75	0.04	0.00	0.00	0.00
0.10 ... 0.15	0.05	0.46	0.48	0.00	0.00	0.00
0.15 ... 0.20	0.02	0.17	0.68	0.13	0.00	0.00
0.20 ... 0.25	0.01	0.07	0.50	0.41	0.01	0.00
0.25 ... 0.30	0.01	0.05	0.37	0.53	0.04	0.00
0.30 ... 0.35	0.00	0.02	0.21	0.57	0.14	0.05
0.35 ... 0.40	0.00	0.02	0.17	0.54	0.18	0.09
0.40 ... 0.45	0.00	0.01	0.07	0.34	0.23	0.35
0.45 ... 0.50	0.00	0.01	0.05	0.25	0.20	0.49
0.50 ... 0.55	0.00	0.01	0.03	0.18	0.17	0.61
0.55 ... 0.60	0.00	0.00	0.03	0.13	0.13	0.71
0.60 ... 0.65	0.00	0.00	0.02	0.10	0.10	0.77
0.65 ... 0.70	0.00	0.00	0.01	0.07	0.08	0.83

Table 7  
Example of weakening parameters for fore-state definition in the damage scale.

Parameters	DS0	DS1	DS2	DS3	DS4
Lateral Rigidity in X-direction (kN/m)	40,000	35,000	17,000	9400	7900
Residual Lateral Displacement $\delta$ (mm)	0	5.5	11	20	32
Maximum Lateral Resistance (kN)	390	390	340	300	280
Initial Cracking Location					
Top	no	no	yes	yes	yes
Middle	no	no	no	yes	yes
Bottom	no	yes	yes	yes	yes
Total ratio of cracked interfaces	0	0.15	0.36	1 (minor)	1 (major)

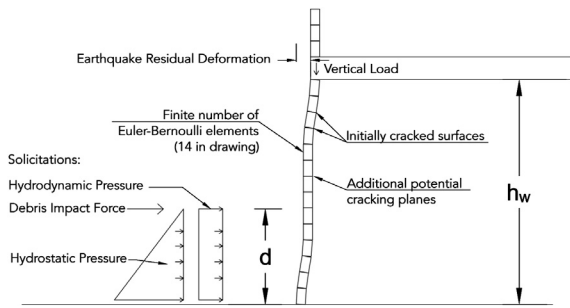


Fig. 15. Scheme of the one-dimensional, finite element model used to analyse structural behaviour in response to flood-induced solicitations. With “d” as the water depth, and “h<sub>w</sub>” as the wall height.

Table 8

Example of end-state probabilities given an initial damage state and the occurrence of the second hazard.  $P(D_i | D_k; H_2; H_{1,j})$ .

Probability for $D_i$ given $D_k$ and a flood ( $H_2$ )	End State – After Flood ( $D_i$ )						
		DS0	DS1	DS2	DS3	DS4	DS5
Fore State – After Earthquake ( $D_k$ )	DS0	0.45	0.15	0.04	0.23	0.10	0.016
	DS1	0	0.48	0.17	0.27	0.06	0.017
	DS2	0	0	0.33	0.60	0.05	0.020
	DS3	0	0	0	0.82	0.15	0.025
	DS4	0	0	0	0	0.96	0.043
	DS5	0	0	0	0	0	1.00

this regard, only the dotted lines in Fig. 17 are comparable to Fig. 16.

For lower intensities, the contribution of the second hazard is small because the probability of its occurrence is also small; while, for higher intensities, the damage caused by the first hazard is high and hence there is little additional damage possible (from the second hazard).

Accordingly, the potential influence of the flood is higher for DS3 and DS4; this is visible in Fig. 17, particularly when increasing the vulnerability of the levee. More so, Table 9 shows the cases of vulnerable and very vulnerable levees, described by a reduction in the mean critical PGA (that is, the PGA which causes failure). Here it can be further observed that including the second part of the multi-hazard, leads to a reduction of the probability to remain in a lower damage state and the consequent increase of the probability to arrive at a higher damage state. It is to note, however, that the flood is well capable of further damaging the structure, but this does not necessarily lead to collapse (DS5). The occurrence of collapse is mostly related to the availability of debris and their flood-induced collision against structures. For a more detailed explanation the reader is referred to Korswagen [20].

### 4. Discussion

#### 4.1. Methodology

Firstly, the methodology here described relies on the use of discretised steps for the intensity of the first hazard. The usage of discrete steps gives a more transparent overview of the process, as opposed to using a continuous domain approach; however, discrete steps may not produce sufficiently accurate results. To achieve greater accuracy, a large number of steps is required, thus increasing the work expense.

Employing discrete steps requires a finite number of evaluations of structural models. Linear-elastic models cannot be used because they rarely are able to consider damage; non-linear models are required and they can only cope with one specific input at a time.

Secondly, since the damage scale employed is also segmented into discrete steps, the assessment of the second hazard based on defined initial steps must also be discrete. This may lead to an increase in the number of computations.

Thirdly, since damage is assessed on this single scale, it cannot be used for evaluating “incompatible” actions, those that cannot be measured together or which have no dependency on each other (they cause different structural damages). For example: for a multi-hazard from floods and high winds, while both could be categorised as lateral actions, the first acts mainly on the base of the structure, while the wind acts on the upper parts. It may be that there is no parameter that can be used to measure damage from both processes. In this case, the methodology offers no benefits over the use of a damage scale which (qualitatively and separately) accounts for the typical failure mechanisms of each action.

When observing more than two coupled hazards, the definition of compatible parameters only becomes more complex.

Fourthly, precisely because of the difficulty in defining compatible parameters for assessing damage, the damage scale may not be sufficiently representative. As in the example case provided, the significance of each failure mechanism towards the overall damage state of the structure is often difficult to elaborate. For lower damage states, earthquake damage may be present in a higher percentage of the structure in contrast to flood damage which might be limited to the lower walls. For analyses such as these, it is recommended to further detail the damage scale on a component basis, referring the damage state of each structural component towards the damage state of the entire structure, based on the significance of the component. Foundations, or load-bearing walls on the ground floor would be examples of the most significant components. Such a damage sub-scale would require additional fore-states, which in turn would ask for additional computations. Nonetheless, it could also help when assessing

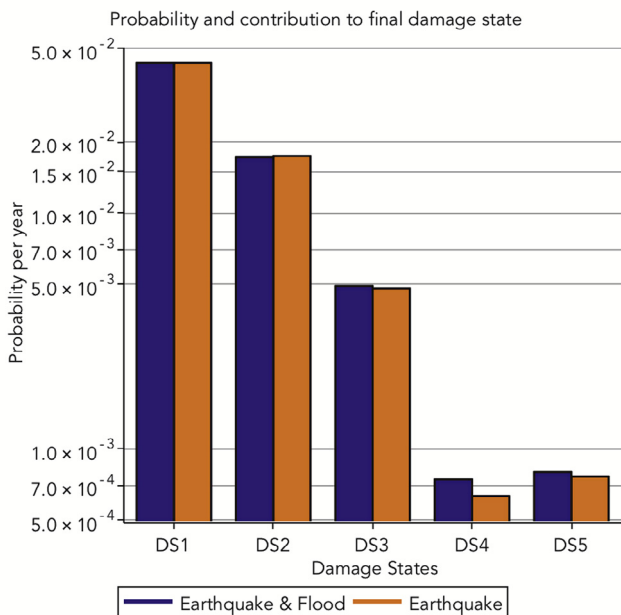


Fig. 16. Final damage state probability showing the contribution of the second hazard. Note that probabilities are displayed on a logarithmic scale.

are the DS that are expected to lead to most damage and risk to life. In the case study, the probability for the occurrence of the flood is low for moderate intensity values of the earthquake (for instance, only 25% for 0.3 g), therefore, the contribution of the flood appears equally small.

Accordingly, so that the contribution of the second hazard can be more easily observed, the strength of the levee is also assumed to be 50% of the value modelled initially (see Fig. 11); this is for the purpose of illustration. This result is included in the fragility curves of Fig. 17. In

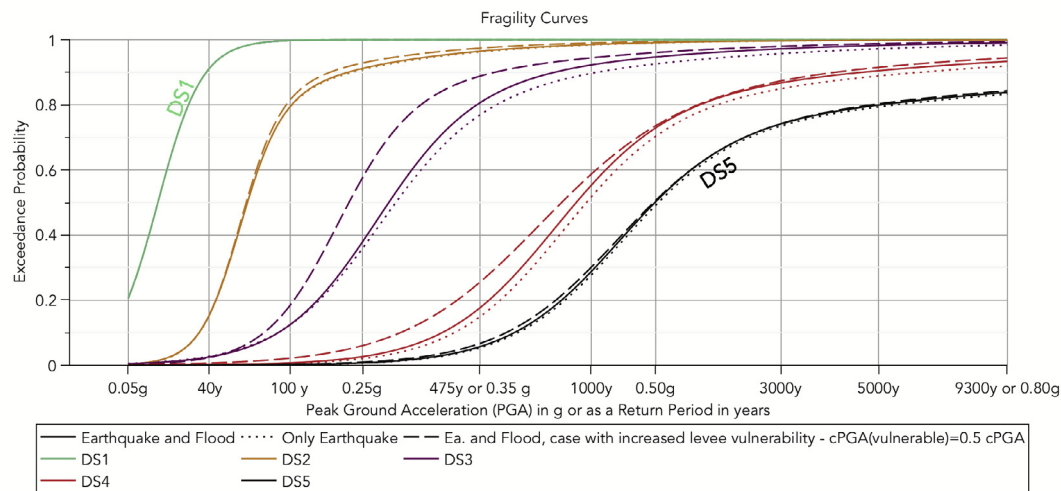


Fig. 17. Fragility curves for the case study showing the impact of the second hazard over the earthquake-only hazard. Also depicting the influence of the probability of occurrence of the second hazard by modifying the vulnerability of the levees.

Table 9

Comparison of the contribution of the flood to the multi-hazard. Relative change in damage state probability (base: only earthquake). Strength of the levees expressed in critical PGA.

Damage State	Earthquake Probability	Earthquake + Flood Base Levees	Earthquake + Flood Vulnerable Levees (50% reduction in cPGA)	Earthquake + Flood Very Vulnerable Levees (90% reduction in cPGA)
DS1	4.3E-02	-0.1%	-1.0%	-5.6%
DS2	1.8E-02	-1.4%	-13%	-42%
DS3	4.8E-03	2.3%	26%	56%
DS4	6.3E-04	15%	50%	69%
DS5	7.6E-04	4.3%	19%	35%

“incompatible” actions as discussed in the previous point. FEMA [12] addresses the type of component-based damage analysis mentioned here, but does not include many of the elements that are key in the multi-hazard analysis proposed in this paper, such as a damage scale based on relevant structural parameters which can measure damage caused by the multiple hazards.

Additionally, in certain cases, the damage evaluation might cease to be quantitative or objective. It is difficult to define which failure mechanisms are more representative of damage. Also, the definition of the damage scale is done upon arbitrary limits; moreover, employing a damage scale will always entail a degree of coarseness.

The latter depends on the qualitative description of the damage scale: if only four instead of five damage states were defined, the limits would correspond to different failure mechanisms and set at different values. This depends on the desired level of refinement, but, because damage is assigned on discrete grades, some grade-sensitivity exists.

The former relies on the type of damage that is picked up by the chosen damage parameter. In the case study, damage to the non-load-bearing walls is not accounted for directly, only inferred by the state of the load-bearing walls. Even if damage were evaluated directly for every wall, it would be difficult to quantitatively state which walls contribute more to the overall damage state. A relationship with the ease and cost of repair of the various failure mechanisms and their intensity may help with quantifying damage.

Finally, this methodology is designed to look extensively at the consequence of one coupled multi-hazard for one specific (type of) structure. For this effort to be warranted, the probability of and/or exposure to this multi-hazard need to be high; thus, a significant risk must exist, possibly with high societal impact. Such is the case, for instance, of the damage analysis of Japan’s tsunami evacuation towers for an earthquake-tsunami multi-hazard [22], or of the houses next the vulnerable levees that occur in the Netherlands and which are taken as

the case study of this article.

Moreover, even if the probability of co-occurrence is significant, the effect of the second-acting hazards may not be important. However, it is not possible to determine this a-priori, further placing the proposed methodology as a means to assess whether the observed multi-hazard is of relevance. The characteristics of the hazards-structure system will define if the multi-hazard damage risk is prominent.

Additionally, because the method includes the physical consequence of the hazards in the damage assessment, it can be particularly convenient when evaluating the influence of reinforcement measures. Firstly, the outcome failure mechanisms can help in selecting reinforcement measures, and secondly, the performance of the measures can be quantitatively evaluated.

It is also worth mentioning that the study of the interrelation of hazards is not contemplated in this paper, but is also an essential step when assessing multi-hazards. Advanced models can be used to characterise the dependability of the hazards. See, for instance, De Risi [10]. Some examples of the possible interrelation of hazards have been mentioned in this article and a few more are summarised in Table 2. For further discussion, the reader is referred to Gill [15].

In sum, the search and application of a compatible damage scale to be able to sum up damage in a physical way, can be seen as the main contribution of this paper. The incorporation of physical methods as part of a probabilistic framework also deserves some attention. When applying this framework, care needs to be exercised to produce results with adequate accuracy and reliability by: selecting a reasonable number of intensity steps and damage grades, and defining compatible and representative parameters for measuring damage.

#### 4.2. Study

The case study employed in this paper was selected to illustrate the

damage analysis for an unreinforced masonry house from a potential earthquake-flood multi-hazard. A realistic case was chosen to warrant the use of the proposed methodology: here, unreinforced masonry houses built next to levees, both originally not designed to sustain earthquakes in the north of the Netherlands, lead to an earthquake and possibly a coupled flood.

The case is well suited to demonstrate the applicability of the methodology, but cannot be representative of all possible hazard-structure-damage combinations. In particular, the cases of multi-hazards with damage parameters that are difficult to combine are not addressed.

Moreover, one further limitation of the case study has already been mentioned: the significance of each failure mechanism is not quantitatively taken into account when assessing damage. This is because, while both earthquake and flood damage are concentrated in the lower level of the structure, earthquake damage is also expected in the upper level and this is not combinable with nor influential to the flood damage. As such, it was neglected when composing the damage scale, but would need to be included if a more precise evaluation is needed.

Nevertheless, from the example, it was observed that considering the effect of a coupled multi-hazard will (predictably) increase damage and risk when compared to the individual hazards. Since increased structural damage is commonly associated with increased loss of life and injury - as severe structural failure will directly harm individuals - the analysis of structural damage is expected to also have applications in the field of individual risk analysis.

Finally, a clear recommendation for improving this methodology, is the detailed study of additional, likewise relevant, cases.

## 5. Conclusions

In this paper, a methodology to evaluate structural damage from coupled multi-hazards was presented and discussed. It was concluded that when measuring damage with a parameter that can be related to the behaviour of the structure, the effect of all partaking hazards can be assessed, and most importantly, the progression of damage can be observed quantitatively. Moreover, the probability for various damage states observing the return period of the main hazard could be computed, and fragility curves for multiple damage grades could be elaborated. Also, the additive effect of the second hazard can be included in the fragility curves.

In other words, the methodology for searching and applying a damage scale compatible with multiple hazards, as is proposed in this paper, allows the consideration of damage cumulatively and in a physical way.

With the case study, the application of the methodology was demonstrated. Here, it was observed that structural risk and specifically, the probability of higher levels of structural damage, is increased by multi-hazards. In this sense, evaluating structural damage by combined actions does not only serve to assess the structural risk, but that of life loss as well.

Nonetheless, further research is required to study the application onto damage produced by (coupled) multi-hazards comprised by seemingly unrelatable hazards. Additionally, a more extensive, component-based damage scale approach needs to be studied to determine whether its additional complexity warrants the potentially more accurate results.

## 6. Conflict of interest

None.

## Acknowledgments

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