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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 → H_1 with intensity parameter h_1

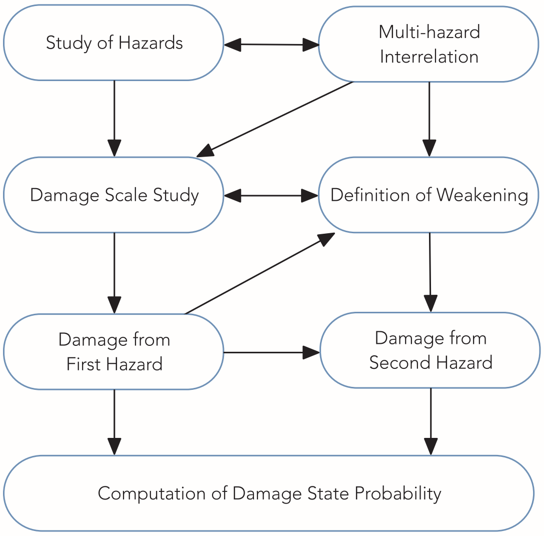

Fig. 1. Overview of all the steps involved in obtaining the final damage state probability. For clarity, only two hazards are displayed. An expanded version of this figure is found at the end of this section (Fig. 7).