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Performance-based flood safety-checking for non-engineered masonry structures

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ABSTRACT

Demand and Capacity Factor Design (DCFD) is a probability-based safety-checking format for performance-based seismic design and assessment of structures. Inspired from the original DCFD formulation for seismic excitation, this work proposes a similar performance-based safety-checking format for flooding, adopting the flood height as the intensity measure. The proposed DCFD formulation implements the fragility/hazard parameters for flooding. The structural fragility is evaluated by adopting an efficient and simulation-based method yielding the so-called "robust" fragility curve and an associated plus/minus one-standard deviation interval. The structural performance is measured by the (critical) demand to capacity ratio for the weakest element of the weakest wall within the structure, subjected to a combination of hydro-static, hydro-dynamic and accidental debris impact loads. Analogous to the incremental dynamic analysis method proposed for seismic demand assessment, an incremental flood height analysis is used to monitor the structural performance as a function of increasing water height. For each structural modelling configuration, generated based on the characterization of uncertainties in loading and material mechanical properties, the incremental flood height analysis is employed in order to calculate the critical water height corresponding to a demand to capacity ratio of unity. The application of the proposed methodology is demonstrated for both flood fragility/risk assessment and comparative screening of various viable flood mitigation strategies for a non-engineered building made of cement bricks in Dar Es Salaam, Africa.

1. Introduction

Non-engineered structures can be characterized by unclassified construction practice, non- well-documented material mechanical properties, lack of reference technical codes and lack of a structural design basis. Aforementioned qualities would arguably result in buildings that are particularly vulnerable to extreme natural events. As far as it regards hydro-geological hazards like flooding, this very often pairs up with poor and un-informed "choice" of the construction site. Considering their un-programmed nature, the non-engineered building sites often coincide with flood plains and potentially flood-prone areas.

Flooding vulnerability and risk assessment is the subject of increasing attention in the past decades. Smith and Greenway [1], Torres et al. [2], Davis [3], Scawthorn et al. [4,5] define general methodological approaches to flood risk assessment. Various research efforts are focused on several aspects of flooding problem, such as loss of life [6,7], economic losses [8,9], and damage to buildings [10–12]. These works are mainly based on damage observed after the flooding event classified using different discrete scales. Kelman [13] classifies the damage with a scale of six damage states (from DS0 to DS5) from no water contact to structural collapse or undermining of the foundation. Analogous to the definition of the damage grades in the European Macroseismic Scale EMS-98 [14], Schwarz and Maiwald [11,15] proposed a modified damage scale distinguishing between structural and non-structural damage. Charvet et al. [16] have applied a statistical model to assess the fragility of different buildings to Tsunami based on the damage state classification of the Ministry of Land, Infrastructure and Transport (MLIT) index damage state (DS) after the tsunami occurred in Japan (2011). Formulations to assess the vulnerability of a building in terms of damage state probability are proposed by Haugen and Kaynia [17] (for the impact of debris flow) and Nadal et al. [18] (for riverine and coastal floods). Dawson et al. [19] have evaluated the flooding risk of a dike system through

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a sampling technique in a MC simulation approach. Yue and Elligwood [20] have highlighted the importance of considering the modelling uncertainties in the assessment of hurricane risk for different configurations of structures (e.g. different number of floors, connection systems, materials). Very few analytical models for vulnerability assessment have so far been proposed for flash-flood and debris flow phenomena. Nigro and Faella [21] have classified the various resisting mechanisms for reinforced concrete frames and masonry structures. They have used limit analysis in order to calculate the critical flow velocity that can activate a mechanism in the structure. Haugen and Kaynia [17] have proposed a methodology for calculating the dynamic response of an equivalent single degree of freedom system to debris flow impact.

This work documents the research being conducted in the context of the European FP7 project Climate Change and Urban Vulnerability in Africa (CLUVA) with regard to flooding vulnerability of informal settlements. In previous works, De Risi et al. [22], Jalayer et al. [23] and [24], De Risi et al. [25] and [26], the authors have proposed two distinct approaches for flood risk assessment for urban areas in Africa suitable for micro- and meso-scale, respectively. The work by De Risi et al. [22], which focuses on flood risk assessment in micro-scale, illustrates how a modular performance-based methodology for risk assessment (a.k.a, the Pacific Earthquake Engineering Research (PEER) approach for seismic risk assessment; see for example, Cornell et al. [27]) can be used in order to calculate the flooding risk for a portfolio of informal settlements. Along the same lines and focusing on the assessment of structural vulnerability, the present work applies the Demand and Capacity Factor Design (DCFD) for safety-checking and upgrade decision-making for informal settlements. The original DCFD is a probability-based safety-checking format for seismic assessment (Cornell et al. [28] and Jalayer and Cornell [29]). According to this format, the factored capacity is compared with the factored demand corresponding to a prescribed allowable risk [29]. Using the flooding height as the intensity measure between hazard and fragility, the structural capacity for a prescribed limit state is described in terms of the critical water height corresponding to the limit state in question. In the context of safety-checking based on DCFD format, this translates into comparing the factored critical flood height for a given building to the flooding height corresponding to a prescribed return period, providing an efficient and graphical procedure for structural assessment and upgrade decision-making [30].

2. Methodology

2.1. Limit states, the performance variable and the sources of uncertainty

The structural limit states are used as a proxy in order to describe the various damage states in the structure. This paper focuses on the limit state of collapse (CO) that is identified based on the corresponding critical water height threshold. This choice is further justified recalling that the flood height can be used as the scalar intensity measure for the integration of flooding hazard and vulnerability to calculate the flood risk [22]. The structural collapse limit state consists in the failure of the bearing structure, collapse of the walls, loss of support of the roof, or loss of loading bearing capacity of the building due to elongated contact with water or deterioration. Generally speaking, structural collapse entails the loss of vertical loading capacity in the structure. The structural limit state exceedance is described herein in terms of a structural *performance variable* – denoted as Y and defined in terms of a systemic critical demand to capacity ratio – that exceeds unity for the limit state in question. Given the potential fragile nature of collapse and the possible lack of box behavior in non-engineered buildings, it has been chosen to define the critical demand to capacity ratio according to a *weakest link* formulation where the weakest element in the structure arrives to the onset of collapse limit state [31].

As it has been mentioned above, the flooding height is being used as the *intensity measure*; that is, the parameter in terms of which the evaluation of capacity and demand is performed. Consequently, it has been chosen to work with a structural performance variable defined as the critical flooding height corresponding to $Y = 1$; where Y is the critical demand to capacity ratio defined in the previous paragraph. This structural performance variable is denoted generically as $h_{Y=1}$. In fact, the use of limit state thresholds defined in terms of the intensity measure is already established and examples can be found in various works such as [32,33]. Based on the definitions presented herein, the flooding fragility, defined as the probability of exceeding the limit state conditioned on the flooding height h can be described as:

$$P(LS|h) = P(Y > 1|h) = P(h_{Y=1}(\boldsymbol{\theta}) < h) \tag{1}$$

It should be noted that the critical water height $h_{Y=1}$ is a function of the uncertain parameters $\boldsymbol{\theta}$ present in the fragility estimation problem. However, for the sake of brevity, the dependence on $\boldsymbol{\theta}$ is dropped hereafter. The structural fragility can also be interpreted as the cumulative distribution function for the performance variable or critical water height $h_{Y=1}$. In general, the uncertainties in the vulnerability assessment of non-engineered structures can be classified in three main categories, namely, (a) the uncertainties in the characterization of material mechanical properties; (b) the uncertainties in the characterization of the structural and geometrical modelling parameters; and (c) the uncertainties in loading. In the case-study presented in this work only the uncertainties in mechanical material properties and loading (only related to debris impact) are considered.

2.2. The Incremental Flood Height Analysis (IFHA)

For a given realization of the vector of uncertain parameters $\boldsymbol{\theta}$, the incremental flood height analysis procedure consists of calculating the value of the critical demand to capacity ratio in the structure for increasing values of flooding height. That is, for each given value of the water height h, the critical demand to capacity ratio Y is calculated for the structure and the resulting Y-h data points can be connected in order to form the incremental flood height analysis (IFHA) curve. Fig. 1 shows a schematic representation of an IFHA curve.

It can be noted that a given IFHA curve corresponds to a prescribed realization of the vector of parameters $\boldsymbol{\theta}$. Therefore, a sample of $\boldsymbol{\theta}$ vector realizations would lead to sample of IFHA curves. It can also be noted that the IFHA curve can be used to find (by interpolation) the critical water height value corresponding to the onset of (a prescribed) limit state identified as $Y = 1$.

2.3. An Efficient Bayesian fragility assessment procedure

Jalayer et al. [34,35] have discussed how a simulation-based Bayesian procedure can be employed in order to derive flooding fragility curves conditioned on a Log Normal fragility model. This method can efficiently implement the results of the incremental flood height analysis (i.e., the critical flooding height values corresponding to $Y = 1$) for a limited sample of $\boldsymbol{\theta}$ realizations as "*data*" in order to provide a *robust* flood fragility curve (as a mean estimate over all possible fragility curves defined by a prescribed model, e.g., Log Normal model) and the mean plus/minus one standard deviation curves. In this section, a brief overview of this method is provided.