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Flow-type landslide fragility of reinforced concrete framed buildings

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ABSTRACT

Flow-type landslides may be triggered by several events such as heavy rainfalls, typically producing huge losses. Landslide risk may be rationally evaluated and mitigated with probabilistic approaches. In this paper, physical vulnerability of reinforced concrete buildings to flow-type landslides is assessed. Fragility analysis was carried out by assuming flow velocity as intensity measure, several damage states, and different mechanical models for beams, columns and masonry infill walls. Uncertainties in landslide impact loading, material properties, size and reinforcement of members, and capacity models were taken into account. Both earthquake-resistant and gravity-load designed framed buildings were assessed as being representatives of two building classes. Based on Monte Carlo simulation and a specific fragility analysis methodology, a set of landslide fragility curves were derived. Analysis results show that landslide fragility significantly depends on the presence and type of infill walls, which influences both out-of-plane and in-plane failure modes of walls themselves and RC frames. In addition, the proposed landslide fragility curves demonstrate that seismic design of RC buildings also plays a key role in the mitigation of their flow-type landslide fragility.

1. Introduction

Hydrogeological risk strongly affects many regions all over the world. Windstorms, snowfalls, heat waves, landslides, floods and coastal erosion are typical examples of hydrogeological phenomena, some of which are also influenced by an improper land use. For instance, the construction of unauthorized buildings and continuous deforestation has definitely deteriorated river beds and soil slopes, inducing a major increase in hydrogeological instability and catastrophic events in urban areas. In this respect, landslides notably contribute to the overall risk level. Every year landslides occur as a result of several triggering events such as rainfalls and earthquakes, causing fatalities and heavy damage to buildings and infrastructure systems, e.g. roadways, railways and lifelines. According to the EM-DAT International Disaster Database [1], 671 landslides have occurred in the period 1900–2014 and have affected 13,700 million people, causing more than 65,000 casualties and an economic loss greater than 8.7 billion USD. Besides, a detailed investigation by Petley [2] highlighted that the amount of landslides and fatalities is an order of magnitude greater than above. Such data emphasise that landslide risk management is a key challenge for modern society, including loss assessment, mitigation and communication to people and stakeholders. Quantitative risk analysis [3] can be a rational approach to face the problem, as it provides the probability of exceeding a prescribed loss level in a given spatio-temporal scale by considering uncertainty in hazards as well as vulnerability and exposure of elements at risk (e.g. houses, lifelines and people). A probabilistic evaluation of landslide risk allows scientists and decision makers to overcome incomplete and/or qualitative information provided by landslide susceptibility and hazard maps, which are the most common tools so far. Dealing with the vulnerability component of landslide risk, one should account for physical, socio-economic and environmental vulnerabilities. As far as physical vulnerability is concerned, a significant knowledge gap affects the landslide vulnerability assessment of buildings. Physical vulnerability may be evaluated through expert opinion (judgmental methods), damage data from past events (empirical methods), or mechanical models (analytical methods). Depending on the territorial scale adopted for landslide risk analysis, vulnerability assessment may focus on either individual buildings representative of a building class or building classes as a whole.

This paper investigates the vulnerability of reinforced concrete (RC) framed building structures to flow-type slides, which are rapid landslides with high proportion of water to solid material. This study is motivated by two facts as follows: (i) RC buildings

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are a large fraction of the worldwide built heritage, providing a major contribution to landslide vulnerability in many countries; and (ii) flow-type slides, which are usually triggered by heavy rainfalls, rapid snowmelt or earthquakes, are among the most destructive landslides. After that the research methodology is outlined, this paper presents the models used for landslide impact load, structural capacity and uncertainties, ending with the derivation of probabilistic models that quantify the landslide vulnerability of building structures selected from two building classes of interest for structural engineers.

2. Methodology

Landslide vulnerability is assessed by means of fragility analysis, which is a well-established tool in earthquake engineering [4] and has been recently used for vulnerability assessment to seismically triggered landslides [5] and other natural hazards [6]. Fragility analysis is an effective procedure to assess the probability of exceeding a certain damage state/level as a function of a scalar or vector-valued intensity measure (IM). In other words, fragility is the conditional probability of exceeding a damage state given an IM level. The output of fragility analysis consists of a set of fragility curves associated with different damage states, which may be convolved with hazard and exposure to estimate landslide-related losses in a given timeframe and territorial scale (e.g. single site, urban area, region).

Fuchs et al. [7] fitted a second-order polynomial function to observed damage data from a debris flow event in the Austrian Alps to derive an empirical vulnerability function for alpine buildings located on fans of torrents. That study focused on building structures made of clay brick masonry or RC and the proposed vulnerability function applies to debris flow depths lower than 2.5 m.

Haugen and Kaynia [8] presented a method based on empirical fragility functions and dynamic response analysis of single-degree-of-freedom systems for damage assessment of low-rise building structures subjected to debris flows with given magnitude.

Jakob et al. [9] proposed a debris-flow intensity index equal to the product of maximum expected flow depth and square of maximum flow velocity, as alternative IM to the impact force that was assumed to be correlated with building damage. The latter was lumped in four levels from sedimentation damage to complete destruction, allowing the computation of damage probability matrices for sixty-six case studies in which damage, flow depth and flow velocity were recorded or estimated from global literature.

Mavrouli et al. [10] performed a pioneering analytical work on landslide fragility of single-bay, single-story RC frames with low, medium or high ductility level. Flow-type landslide fragility curves were derived through a hybrid approach based on structural analysis of RC framed buildings and experimental test results on infill panels and openings. Three classes of RC framed structures and five damage levels were considered, whereas the flow velocity was assumed as scalar IM of the landslide.

Zeng et al. [11] carried out a comprehensive analysis of failure modes for RC building columns impacted by debris flows by means of field investigations and historical data. That research was detailed in the case of RC columns constructed in mountainous areas of western China. Critical flow velocities and boulder diameters were obtained for each failure mode using material and structural mechanics approaches.

Kang and Kim [12] derived empirical vulnerability curves for various types of building structures in Korea. The physical characteristics of debris flows were obtained from eleven events occurred in 2011 and damage observed on twenty-five buildings. Those researchers proposed three groups of vulnerability curves as functions of debris flow depth, flow velocity and impact pressure, which were differentiated in relation to RC and non-RC buildings. Four damage levels were considered, i.e. slight damage, moderate damage, extensive damage, and complete destruction.

2.1. Overall assumptions of this study

Two-story, double-bay, two-dimensional (2D) RC frames are considered as subsystems taken out from the overall three-dimensional (3D) framed structure of the building. The latter is supposed to have a shallow stiff foundation, so that a fixed base is assigned to columns of frame models. The structure is assumed to be fixed at the foundation level (i.e. no soil-foundation-structure interaction effects considered) to an immovable and rigid ground (namely, not affected by the flowing and moving mass and/or the landslide mechanism) and is subjected to the loading of soil moving like heavy liquid with a certain velocity.

Several variants of 2D frames were set up to account for structural characteristics and the contribution from infill walls. Therefore, structural systems selected from the following RC building classes were considered:

- Low-rise RC buildings designed only to gravity loads without seismic detailing [13];
- Low-rise RC buildings designed for earthquake resistance according to the high ductility class of Eurocode 8 (EC8) – Part 1 [14].

The former is a pre-code building class, the latter is a high-code building class. It should be noted that considering a whole building class is somewhat different in terms of uncertainty modelling, and that issue is beyond the scope of this paper. Rather, each structure is assumed to be representative of a single building that falls in one of the above-mentioned classes.

On the hazard side, as flow-type landslides such as debris and mud flows are considered (Fig. 1), the impact velocity of the moving mass on the structure was assumed as IM. That assumption was motivated by the high correlation of impact velocity with both non-structural and structural damage [10], thus allowing such physical parameter to be considered a sufficient IM. Debris depth or volume, kinetic energy, kinetic impact pressure, and ground displacement may be selected as alternative IMs for other landslide types such as slow-moving landslides and rockfalls. It should be noted that the expected impact velocity of a landslide on built facilities depends on both predisposing and triggering factors. The former include (i) geological, geomorphological, topographical and hydrological settings of the area, (ii) geotechnical properties of

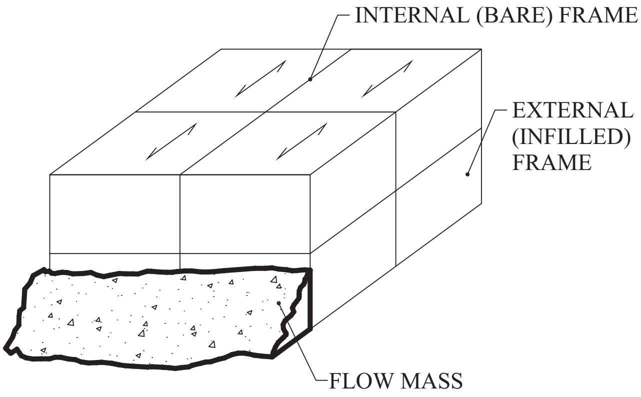

Fig. 1. RC framed building structure impacted by flow-type landslide.

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