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Earthquake vulnerability of school buildings: Probabilistic structural fragility analyses

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ABSTRACT

The study presents probabilistic structural fragility assessment of public school buildings in Istanbul, which were constructed based on a standardized/typical project. The typical structure is a four-story, reinforced concrete shear wall building with moment resisting frames. Derivation of fragility functions rely on nonlinear dynamic analyses through Monte Carlo simulations. Nonlinear dynamic analyses are initially performed for a fully deterministic structural model based on the blueprints of the typical school building project. Uncertainties are introduced in different analysis cases following a modified version of the algorithm presented in Smyth et al. (2004) [21], which considers the effect of the random distribution of the parameters using a Monte Carlo approach. Aleatory uncertainties concerning material properties (i.e. compressive strength of concrete, yield strength of reinforcing steel and concrete density), geometrical characteristics (i.e. span lengths and story heights) and cross sectional dimensions of beams, columns and shear walls as well as epistemic uncertainty in the direction of ground motion excitation are considered. Statistical distributions for the parameters considered are obtained from in-situ measurements and material sampling tests. Fragility functions are produced in terms of peak ground acceleration and velocity as well as of the elastic spectral displacement at the first vibration period of the building. Mean damage ratios are calculated from the derived fragility functions. They are further compared to mean damage ratios calculated for similar building typologies provided in HAZUS-MH technical manual and in Istanbul building inventory.

1. Introduction

Approximately 1.2 billion students are enrolled in primary and secondary schools; of these, 875 million school children live in high seismic risk zones all over the world. Although these children spend up to 50% of their waking hours in school facilities, all too often schools are not constructed or maintained to be disaster resilient [11]. In seismic-prone regions, there always exists a probability of having minor to heavy damage and even collapse of school buildings like many other structures. A school building which is not properly designed to resist earthquake forces can cause loss of lives of hundreds of children. Most recently, a devastating earthquake (M_w=7.0) occurred on 23 October 2011 in eastern Anatolian region of Turkey (near Van city), which caused around 600 fatalities and widespread damage to residential and public buildings (http://www.koeri.boun.edu.tr/News/23%20 October%202011,%20Mw=7.2%20Van,%20Turkey%20Eq._16_204.depmuh). A photo of a primary school building after the strong ground shaking is presented in Fig. 1; fortunately, it was Sunday and there was nobody in the building.

School buildings not only house children for the most of the day but also they serve as emergency shelters in disasters as well as providing storage places for books and technical equipments. Earthquake vulnerability assessment of existing school buildings is a necessary step towards avoiding losses from future events and also increasing the preparedness of the society. In developing countries, assessment is also critical to establish priorities for mitigation strategies and it is also of use to international aid institutions to evaluate the need for financial support. Retrofitting/strengthening of schools or designing them in accordance with the requirements of the earthquake-resistant design codes is considered as a primary objective in earthquake risk reduction strategies due to the high importance of those facilities for the entire community. A document entitled 'The Guidance Notes on Safer School Construction' has been developed by the collaborative effort between the International Network for Education in Emergencies [11] and the Global Facility for Disaster Reduction and

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Fig. 1. Gedikbulak primary school after the M_w=7.0 Van-Turkey Earthquake on 23 October 2011.

Recovery (GFDRR) at the World Bank, in partnership with the Coalition for Global School Safety and Disaster Prevention Education, the IASC Education Cluster and the International Strategy for Disaster Risk Reduction (http://www.unisdr.org/we/inform/publications/11599). This document presents a framework of guiding principles and general steps to develop a context-specific plan for disaster resilient construction and retrofitting of school buildings. One of the aims of ISMEP-Istanbul Seismic Risk Mitigation and Emergency Preparedness Project (2005–2018) is retrofitting or reconstruction of priority public facilities, including schools, hospitals, clinics, administrative buildings, student dormitories and social service facilities (http://www.ipkb.gov.tr/en/Kurumsal/ISMEP-).

Earthquake vulnerability of school buildings can be estimated not only in terms of the need to prevent collapse of the building but also to prevent lesser damage that may cause service interruption. For this reason, a comprehensive seismic vulnerability assessment of existing school buildings is always needed for different damage levels; namely slight, moderate, extensive and complete as described in HAZUS-MH technical manual [9]. Nevertheless, it is not an easy task to achieve especially in developing countries since the quality of construction in these locations tends to be poor, construction materials are scarce and, control mechanisms to implement the standards may not properly work or totally not exist. It is a very often situation that an existing school building may differ rather from the original blueprints of the application project. Therefore, methods that account for the uncertainties are desirable to estimate expected performance of school buildings under earthquake excitations.

This study presents probabilistic structural fragility assessment of public school buildings in Istanbul, which were constructed based on a standardized/typical project (Fig. 2). After developing a three-dimensional finite element model of the typical structure, nonlinear dynamic analyses are performed through Monte Carlo simulations. Uncertainties concerning material properties (i.e. compressive strength of concrete, yield strength of reinforcing steel and concrete density), geometrical characteristics (i.e. span lengths and story heights), cross sectional dimensions of beams, columns and shear walls, and uncertainty in the direction of ground motion excitation are taken into account in different analysis cases wherein the parameter under consideration is randomly changing in each Monte Carlo simulation. Maximum inter-story drift ratios are considered as engineering demand parameters. Fragility functions are produced in terms of peak ground acceleration and velocity as well as of the elastic spectral displacement at the first vibration period of the building (PGA, PGV and $S_d(T_1)$, respectively). Mean damage ratios are calculated from the derived fragility functions. They are further compared to mean damage ratios calculated for similar building typologies provided in Istanbul building stock and HAZUS technical manual.

2. Problem definition

Many school buildings in Istanbul are designed and constructed based on standardized projects. The project chosen in this paper is one of them, which is cited by specific coding, 10403 and/or 10403-YA. To assess vulnerability associated with this specific project, first a three dimensional structural model was formed. A probabilistic procedure was followed to include uncertainties in material properties, geometrical characteristics and direction of ground motion excitation. We look at the importance of uncertainties associated with them and would like to see what parameters affect the vulnerability more than the others. Following six cases were considered for the characterization of aleatory uncertainties associated with material properties, geometrical characteristics and cross sectional dimensions and, epistemic uncertainty in the acting direction of earthquake ground motion:

- *Deterministic Case*: The structure was modeled based on the blueprints of the typical school building project and no uncertainty was considered.
- *Probabilistic Case* I: The structure was the same as the deterministic case. Epistemic uncertainty in the direction of earthquake forces acting on the structure was considered. The direction was selected randomly between 0° and 360° for the application of horizontal acceleration time history.
- *Probabilistic Case* II: The uncertainties in concrete compressive strength (f'_c) and reinforcing steel strength (f_y) were considered. An unconfined concrete model was adopted in the structural model. The randomness in concrete compressive strength is assumed to conform to a normal distribution with a 14.8 MPa mean and 6.6 MPa standard deviation (SD). It was assumed that the reinforcing steel strength also follows a normal distribution with a 220 MPa mean and 22 MPa SD.
- *Probabilistic Case* III: The uncertainties in cross-sectional dimensions were considered in the structural model. It was assumed that shear wall, column and beam dimensions vary