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From a GIS-based hybrid site condition map to an earthquake damage assessment in Iran: Methods and trends

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ABSTRACT

From several decades ago, the average shear wave velocity for the top 30 m (*Vs30*) has been proposed as one of the important factors that reflects the amplification behavior of a site. Most of seismic design standards such as National Earthquake Hazards Reduction Program in the United States and Standard No. 2800 in Iran emphasize on the use of *Vs30* measurements for site classification according to the soil type. As an important step in profound seismic risk reduction to earthquakes, a site effect study was conducted at a nationwide scale. We followed an indirect method to produce *Vs30* map of Iran from geological and topographical data. The outputs indicate that hybrid *Vs30* map has better performance than single topography-based *Vs30* map. The amplitude map deduced from *Vs30* and geology maps then is used for seismic microzonation of Tabriz city and extent of geographical distribution of damage for a possible deterministic scenario ($M=7$) is investigated through considering different fragility curves to describe damaging behavior of ordinary building types in the city.

1. Introduction

Earthquake risk reduction is one of the complex challenges in civil safety prevention, requiring researches from different disciplines working together to solve the complexity of earthquakes. The seismic risk assessment starts with the process of calculating the negative impacts and their likelihood (chance) of experiencing a specific level of seismic hazard in a specific time of exposure [1]. Its input components are: (1) hazard, defined by an earthquake scenario with the earthquake magnitude and the distance from the built-up area and (2) exposure of assets at risk, which is related with public and private buildings in urban areas and (3) vulnerability as the principal component of the assessment, which introduces the quality or state of being exposed to the possibility of being harmed [2]. Risk assessment in urban scale researches contains the information on buildings such number of stories, their material and structural properties. These informations routinely have been used in vulnerability analysis which typically benefits from the concept of fragility curves of a type of buildings, mathematically combined by the intensity of the seismic ground motion of an actual or simulated earthquake [3–8]. The standard outputs from this step are the probable physical damage and direct/indirect economic losses [9]. However as mentioned, vulnerability analysis will not properly be done if outputs of previous steps are not satisfactory. A loss/damage assessment is a chain of procedures and actions from different sources which are almost dependent. As simple as the old proverb “A good beginning makes a good ending…”, this sort of actions (i.e., data collection, taken strategies, modeling methods, etc.) must be followed precisely. Therefore, having a close to real site amplification and ground motion maps results in acceptable loss/damage map at the vulnerability step which itself will be continuation of policy and decision making [3,4,10]. Since our experiences from the past earthquakes often point out considerable structural damage and economical losses, the need to measure the potential of risk and its reduction is necessary. In the last years, several damage assessment tools such as QuiQuake [11], HAZUS [12,13], KHM [4], SELENA [14], and ELER [15] have been developed by different research institutes to deal with impacts of seismic activities and their consequences. Some of them have real time applicability based on webGIS such as QuiQuake. QuiQuake is an online system which uses a combination of amplification capability map (from geomorphological condition) and seismic records to report detailed strong ground motion maps (i.e., PGA, PGV), and seismic intensity after a seismic event in Japanese territory. This system with spatial resolution of 7.5 arc-sec and 11.25 arc-sec in latitude and longitude provides valuable information for a rapid seismic response [11]. However, for example HAZUS (HAZards United States) is working based on scenarios, useful for disaster preparedness. HAZUS has been developed by the Federal Emergency Management Agency (FEMA) for multi-hazards purposes in the US such as earthquakes, storms and

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floods [12,13]. It must be mentioned that each country has its own model for damage assessment based on local fragility. In our study area (Iran), KHM model (Kamnania Hazard Model) was one of the suitable tools for rapid damage assessment of earthquakes [4]. This model connects relational information together to simulate an earthquake with specific characteristics such as magnitude, depth, distance, time and date. Earthquake risk, seismic microzonation, intensity maps, building and population vulnerability maps and number of basic resources are some important outputs of KHM model, reported by applying empirically validated equations and spatial data analysis. However KHM only estimates building damages, human losses and basic resources, and is not able to estimate economic losses or social impacts [3,4]. Despite of the said shortcomings and the complexities that are inherent to simulation modeling, the model can serve as a practical tool to assist decision makers in effective post-disaster management. Furthermore, Karimzadeh et al. [3] also proposed a new combined model from KHM and HAZUS. The method simulates ground shaking map of any earthquake, the vulnerability of buildings, human losses and basic resources for survivors such as number of rescuers, shovels, bread pieces, water bottles, etc., in each city of Iran based on fragility curves, damage functions and relational analyses. The model itself basically is inspired from HAZUS, but there were two differences: (1) HAZUS is multi-hazard software which considers different hazards from earthquakes to storms and basically is designed for the United States. But in Iran, earthquake is the most important issue, accordingly the developed model only focused on earthquakes [3], (2) one of the essential requirements of disaster management in urban scales during, after or even before an earthquake is the provision of a well-enriched geodatabase. Therefore, Karimzadeh et al. [3] have tried to increase the number of influential parameters in microzonation step. Simply put, their model benefits from various factors in comparison with other models. They incorporated many factors from geological conditions to geoid slopes to produce more effective and accurate microzonation map. As well as it is suitable for applying different intensity attenuation relationships in different regions. This increase in number of influential parameters can resolve some uncertainties in the microzonation step, but it also inputs some problems in raster data structure. For instance, the gathered information from various sources and organizations in different scales, have strengths and weaknesses in terms of functionality and representation in GIS. Accordingly, the amplification uncertainties will remain unknown. One method that can be applied is to address the near-surface shear wave velocity between 0 and 30-meter depth (*Vs30*) as a main standard indicator in most of the building codes for mapping seismic site conditions and also as a fundamental parameter of rapid response [16].

In this paper, the developed analytical method for seismic damage assessment follows the standard procedure, compatible for Iranian buildings and soil types. The only difference with other models is that the presented model also will use *Vs30* map of the study area to produce a hybrid amplitude map (geology and ASTER topography). The model deals with five major steps: (1) nationwide *Vs30* estimation through a hybrid regression method; (2) production of amplification ratio and amplitude map, useful for feature detection and vulnerability assessment; (3) simulation of an earthquake of magnitude 7 on an specific fault; (4) input building inventory (e.g. materials, structural types); (5) vulnerability modeling associated with the simulated ground shaking map (Fig. 1). Note, in this study the SRTM-based *Vs30* map has been obtained from USGS Global *Vs30* Map Sever (http://earthquake.usgs.gov/hazards/apps/vs30/).

2. Hybrid *Vs30* map

Site condition mapping was initiated by Tinsley and Fumal [17] based on soil type, age and *Vs30* measurements, and continued by studies on the correlation of *Vs30* measurements, topography and geological units [18–22]. Other contributions have focused on smaller scales such as seismic microzonation projects based on geological units and topographical data and intense geophysical and geotechnical measurements [3,4,10] (Fig. 1). The variability in earthquake-related damage is mainly associated with hydrogeological, topographical and local site conditions. For example, flat areas (slope angle $i < 10^{\circ}$) within unconsolidated sediments and ridge positions (slope angle $i < 30^{\circ}$) with crest width have positive impact on seismic wave amplification [23,24]. Although site condition maps contribute in microzonation studies, only a few number of integrated site condition-damage assessment models exist [3,4,12–15]. Wald et al. [19] presented a topo-based site condition mapping that can be used as a proxy for seismic site characterizations. They have developed a methodology for applicable and efficient *Vs30* maps at large scales based on correlation of *Vs30* measurements and mere topographic slope. They found that maps derived from the slope of topography have good correlation with other site condition maps especially in the seismically active regions such as California, Taiwan, etc. Although first-order assessment of seismic site conditions using topographical data is valuable tool for disaster preparedness and extensive actions after a seismic event. The investigations indicate that this method is not intended to supplant real measurements. For instance, the topographic approach does not estimate properly the lower velocities (NEHRP site class E) in Japan and higher velocities (NEHRP site class B) in Iran because of lower logarithmic median which can lead to over- or underestimation of real seismic damages [25]. The main reason of lower correlation is the entity of the *Vs30* measurements used in topo-based estimations. Since most of the measurements in Iran and Japan are from seismic networks, probably the rock locations obscure the trend interpretations. In other words, the purpose of *Vs30* measurements is different and somehow there is a tradeoff between lower-noisy seismic network and precise site condition map [19,24,25]. In addition, Matsuoka et al. [22] have confirmed that the acceptable correlation between slope and 21 geomorphic indicators in Japan can be used for nationwide site amplification zoning. In this study, the trend for production of *Vs30* maps is the combination of geology and slope of topography to assume that there may exist a better correlation between slope and *Vs30* for different geologic units. The key point is that the majority of stations in this study (241 out of 514) fall into B and C NEHRP classes which do not completely follow the NEHRP classification for the slope ranges, but fortunately there is still significant scatter between slope gradient and the rest of measurements. At first, linear regression analysis of *Vs30* measurements of 514 locations of ground motions stations in Iran has been carried out according to NEHRP site classification and topographical data from ASTER sensor (Advanced Spaceborne Thermal Emission and Reflection Radiometer). In this study, both simple and logarithmic correlations of the variables have been investigated. Coefficient correlation between *Vs30* measurements and topographic attributes is lesser than the logarithmic correlation. Particularly the elevation itself, shows considerably smaller correlation with *Vs30*. Slope of topography or gradient for each cell of ASTER data is calculated from the maximum rate of change between each cell and its neighbors. Since we use the logarithmic values of slope of topography, some of the grid cells of ASTER data have elevation of near zero and we assign 1 m as a new value because the log (0) is not defined. The overall trend in both slopes reveals that higher *Vs30* values correlate with higher slopes, indicative of competent materials holding steeper slopes.

The regression model takes the following form:

$$\log(V_{s30}) = a \times (\log(Slope)) + b \quad (1)$$

where a and b are coefficients determined from regression analysis of NEHRP classes. Details of linear regression coefficient obtained from different range of slopes can be found in the Table 1. According to the Table 1, coefficient of determination for the flatter areas is better estimated. This means the database of Wald and Allen [19] was constituted of rather flat sites with relatively lower *Vs30* values. Unlike

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