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SENSITIVITY OF STRUCTURAL DAMAGE TO EARTHQUAKE GROUND MOTION SCENARIOS. THE TORREVIEJA EARTHQUAKE CASE STUDY

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ABSTRACT

Structural damage computation using analytical methods requires the knowledge of the ground motion distribution in the urban area caused by a given earthquake. In this manuscript, the ground motion estimates (i.e. PGA and spectral acceleration values) are obtained through simulation of the 1829 Torrevieja earthquake using the NGA ground motion prediction equations (GMPE). The building stock under consideration has been classified according to the methodology presented in RISK-UE. The computations have been done using the last version of the software SELENA. The epistemic uncertainties of the analysis are accounted for by means of a logic tree computation scheme. The logic tree has two branches for the uncertainty in the earthquake scenario, two branches for the GMPEs and three branches to consider the uncertainties in average shear wave velocity Vs30 (soil conditions). Results indicate large differences derived for the different earthquake loss scenarios (ELE) obtained following each branch of the logic tree.

The greatest structural damages and losses are obtained when the earthquake is located in the Bajo Segura fault zone, using Campbell and Bozorgnia GMPE and for soft soil conditions. This article has allowed us to see how the different possible input parameters for ELE should be carefully analyzed for each case study and the importance of providing ELE results in terms of mean values with corresponding uncertainty ranges.

Keywords: analytical method, earthquake damage, epistemic uncertainty, seismic risk, seismic vulnerability

1 INTRODUCTION

The south of Alicante province (Spain) is characterized by a relatively high seismic activity. In the past, several earthquakes have seriously affected its municipalities. The most important earthquake was the Torrevieja earthquake on March 21, 1829. This event reached a macroseismic intensity X following the EMS-98 intensity scale [1] as reported by Martinez Solares and Mezcua [2]. According to Albini and Rodriguez de la Torre [3], it can be stated that this event represented the mainshock of a seismic sequence of at least 42 events that occurred between 1828 and 1830, with EMS-98 intensities reaching IX–X. It is expected that regional earthquake ground motions were highly amplified by the soft soils covering the areas closest to the Segura River, thereby causing significant structural damage in a wide area.

The city of Guardamar del Segura was also seriously affected by this earthquake. According to Larramendi [4], 397 buildings suffered extensive and complete damage, while 132 buildings experienced moderate damage. With respect to social losses, 8 persons died and 14 suffered injuries of moderate severity. The seismic activity of the Bajo Segura fault zone was studied by Alfaro *et al*. [5] and it was predicted that the maximum moment magnitudes range between 6.6 and 6.8 for individual fault segments and between 6.9 and 7.1 for a complete rupture of the Bajo Segura fault. These values are also consistent with the estimated magnitude of the

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1829 Torrevieja earthquake, which was considered to be in the range between Ms6.3 [6] and Ms6.9 [7]. Additionally, the focal depth was supposed to be shallow (approximately 5 km).

The United Nations Disaster Relief Organization defines the risk connected to a certain hazard as the expected physical damage and connected losses that are computed from the convolution of probability of occurrence of hazardous events and the vulnerability of the exposed elements to this hazard.

For a deterministic analysis, seismic hazard – the first component – refers to the shaking effects at a certain site caused by a scenario earthquake. While the term exposure represents the availability and inventory of buildings, infrastructure facilities and people in the respective study area subjected to a certain seismic event, the structural (i.e. physical) vulnerability stands for the susceptibility of each individual element (building, infrastructure, etc.) to suffer damage given the level of earthquake shaking. This results in structural (and non-structural) damages, which directly implicate economic losses as well as casualties (social losses).

Mena [8] carried out the first global study of vulnerability in various urban areas of Spain by using also Geographic Information System (GIS), using the Italian method [9] and the vulnerability-damage functions proposed by Barbat *et al*. [10] and Yepez [11]. The study was done for the two predominant model building types in the city of Barcelona, i.e. unreinforced masonry and reinforced concrete frame buildings.

The European project RISK-UE represented a step forward regarding vulnerability assessment and seismic risk computation in Europe. Under this framework, various damage functions were developed: vulnerability curves for the macroseismic method and capacity and fragility curves for the analytical/mechanical method that could be applied to the typical building types in Europe [12]. Later, two methods were proposed by RISK-UE: the vulnerability index method (VIM) and the Capacity Spectrum Method (CSM) were applied to residential buildings in Barcelona (Spain) in order to evaluate the seismic risk [13–16].

In 2009, Molina *et al*. [17] applied the capacity spectrum method, as implemented in SELENA, in order to compute earthquake loss scenarios for the urban area of Almoradi.

Recently, Serrano-Lanzarote and Temes-Córdovez [18] carried out a seismic vulnerability study of the residential buildings in the Valencia autonomous region using the vulnerability index method. However, the damage and losses were computed assuming a hypothetical earthquake and intensity estimates, so a detailed study should be done to improve their results.

Therefore, the goal of the present study is to conduct detailed earthquake loss estimation scenarios for the city of Guardamar del Segura, which consider not only physical ground motion parameters (i.e PGA and spectral accelerations by simulation a repetition of the 1829 Torrevieja earthquake) but also a detailed vulnerability model (using analytical capacity curves and fragility functions). The computation will be done using the last version of the software SELENA [19]. The epistemic uncertainties of the analysis will be considered by means of a logic tree. We will include two branches of the logic tree for the earthquake source parameter, two branches for the soil conditions represented by Vs_{30} values, and two branches corresponding to the ground motion prediction equations (GMPE) used to simulate the PGA in the city. The most recent Next Generation Attenuation (NGA) relationships ASK14 [20] and CB14 [21] will be used. Therefore, this paper will not only provide a mean ELE and corresponding uncertainties, but also a sensitivity study of the importance of each branch in the seismic risk results.

2 METHODOLOGY

The damage probability for each model building type will be obtained using the analytical methodology implemented in SELENA. The performance of each building typology is represented by its performance point, i.e. the spectral displacement that is experienced by the building typology under the respective seismic demand. This spectral displacement is further connected to a lognormal distribution of damage that the respective building typology will experience, which is, considering the building stock inventory model, computed into absolute values of damage and loss.

The method used to estimate the performance point has been recommended by Eurocode 8 and generally known as N2 method [22].

The process consists of obtaining the appropriate inelastic response, i.e. performance point (defined as point of intersection of idealized SDoF system based capacity curve with the inelastic demand spectrum) for a given earthquake record. Once the performance point has been obtained, the conditional probability of being in, or exceeding a damage state *ds* given by the spectral displacement S_d (or other seismic demand parameter) is defined by the following equation:

$$P\left[ds|S_d\right] = \Phi\left[\frac{1}{\beta_{ds}} ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right] \tag{1}$$

where:

$\bar{S}_{d,ds}$: median value of spectral displacement at which the building reaches the threshold of damage state *ds*; β_{ds}: standard deviation of the natural logarithm of spectral displacement for damage state *ds* and Φ: standard normal cumulative distribution function.

The structural damage is classified into four levels, i.e. slight, moderate, extensive and complete damage states. This damage classification concept was initially provided in the report 'Expected Seismic Performance of Buildings' [23] and later adopted for the HAZUS methodology [24].

In order to apply this methodology, first, the deterministic earthquake is defined. Secondly, the vulnerability model (damage functions in terms of capacity and fragility curves) is proposed, and finally the population distribution and the cost of repair and reconstruction to compute human and economic losses results are presented.

In order to better represent the ground motion in the study area, and to simplify the computation, we have divided the city into ten geographical units (Geounits; Fig. 1), that will be used as a reference unit in terms of computation and representation of damage and loss results.

2.1 Deterministic earthquake scenario parameters

As stated before, our study will simulate the repetition of the 1829 Torrevieja earthquake. We have assumed the fault parameters of the Bajo Segura fault zone and the Torrevieja fault zone given by the active fault catalogue in the Iberian Peninsula QAFI [25] (Table 1). As it can be seen in Fig. 1, two possibilities for the repetition of the earthquake are assumed, each one linked to one of the main faults.

2.2 Soil Conditions and Ground Motion Prediction Equations.

The regional geology of the study area is composed by sedimentary materials, mainly soft soils, which are likely to amplify the seismic ground motion. We have identified two main soil

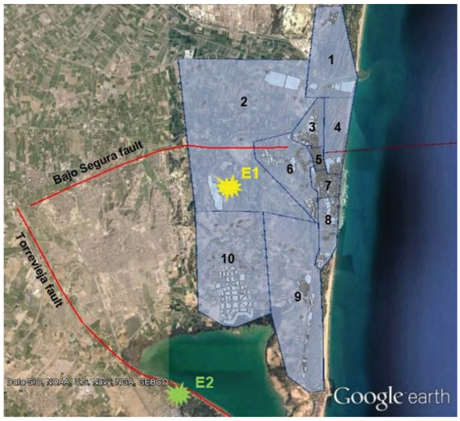

Figure 1: Distribution of geounits and fault traces: the Bajo Segura fault (E1) and the Torrevieja fault (E2).

Table 1: Main source parameters of the earthquake scenarios used as input for SELENA.

Earthquake Scenario:	E1	E2
ID QAFI	ES620	ES616
Fault Name	Bajo Segura (3/3)	Torrevieja
Latitude	38.08	38.03
Longitude	-0.68	-0.7
Focal Depth (km)	5	5
Mw	6.6	6.6
Fault orientation (degrees from North)	77	116
Dip (degrees)	60	90
Fault Mechanism	Reverse	Strike-Slip

types: soil type B (deposits of very dense sands, gravels, or very stiff clays characterized by a gradual increase of mechanical properties with depth and an average $V_{s,30}$ ranging from 360 to 800 m/s) and soil type C (deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters and an average $V_{s,30}$ ranging from 180 to 360 m/s), following the soil classification scheme of EN 1998-1 [26]. It was decided to use soil type B (360–800 m/s), instead of a subdivision as B1 (500–800 m/s) and B2 (360–500 m/s), in order to point out the current uncertainty of the $V_{s,30}$ distribution of the city.

Regarding the selection of GMPEs, we have followed the recommendations of the RISMUR II Project working group that has carried out a revision of the seismic risk in the Murcia Region. They proposed the use of the following GMPEs: ASK [20] and CB14 [21]. Both GMPEs include the soil amplification in the attenuation relationship by means of some terms, which are dependent on the $V_{s,30}$ value. Therefore, all geounits will be assigned three different $V_{s,30}$ values: the lower bound of the Eurocode 8 range, i.e. 360 m/s and 180 m/s, the mean value, i.e. 580 m/s and 270 m/s, and the upper bound, i.e. 800 m/s and 360 m/s for soil types B and C, respectively.

2.3 Vulnerability and Exposure Model

The building stock in Guardamar comprises 4,078 buildings and a residential population of 15,589. This data has been obtained through a thorough analysis of the Spanish Cadastral database (SEC), the Spanish Institute of Statistics (INE), the local council of Guardamar del Segura, the ARGOS website, and several field trips conducted in 2015.

Following previous studies, [17] and [27], the building stock has been classified into model building types taking into consideration the main structural system, primary work materials, year of construction (i.e. the seismic design level), and the building's height range. Each model building type has been assigned a set of capacity and fragility curves [12].

Table 2 shows the model building types observed in Guardamar del Segura. The table contains the ID given in this study, the corresponding label [12], a brief description of the structural system and primary work materials, its height (represented by number of stories), the period of construction used as an indicator of the seismic design level, and the total number of buildings that were assigned to each class. As it can be seen, the city is highly vulnerable because approximately 80% of the building stock was built previously following the provisions of the NCSE-94 [28]. Only 9.5% of the buildings were designed according to NCSE-94 and 10.5 % according to NCSE-02 [29].

Table 2: Classification of the building stock in Guardamar del Segura into model building types (MBT).

L-G Label	Id	FRAME/ HORIZONTAL STRUCTURE			Period of construction	Nº of stories	Nº of buildings
M3.w_L	UM.w_L	Unreinforced Masonry	Wooden slabs		< 1950	1 – 2	16
M.3v_L	UM.v_L		Masonry vaults		< 1950	1 – 2	490
M.3v_M	UM.v_M				3 – 5	1	
M.3sm_L	UM.sm_L		Composite steel and masonry slabs		1950 – 1970	1 – 2	1191
M.3sm_M	UM.sm_M				3 – 5	99	
RC1_L	RC1.A_L	Reinforced Concrete	Concrete moment frame	PGS – 68	1969 – 1975	1 – 3	92
RC1_M	RC1.A_M					4 – 7	66
RC1_H	RC1.A_H					8+	5
RC1_II_L	RC1.B_L			PDS – 74	1976 – 1995	1 – 3	1097
RC1_II_M	RC1.B_M					4 – 7	305
RC1_I_L	RC1.C_L			NCSE – 94	1996 – 2003	1 – 3	150
RC1_I_M	RC1.C_M					4 – 7	176
RC1_I_L	RC1.D_L			NCSE – 02	2004 – Act.	1 – 3	167
RC1_I_M	RC1.D_M					4 – 7	181
RC1_I_H	RC1.D_H					8+	42

The predominant typology is RC1.B_L, corresponding to low rise (1 to 3 stories) reinforced concrete frame structures built between 1976 and 1994, using the regulations given PGS-68 [30] and PDS-74 [31].

The economic loss model depends on reconstruction values (complete damage) which follow the construction costs for new buildings given by the Spanish cadastral database in Euro/m^2. These construction values depend on the model building type, the quality of the building, the year of construction and the building's use. The cost of repair for extensive, moderate and slight damage will be assumed as 50%, 10% and 2% of the reconstruction cost, respectively [32].

2.4 Accounting for epistemic uncertainties: The logic tree

Figure 2 shows the designed logic tree computation scheme for our study. For example, Branch 1 corresponds to the ELE obtained by using an earthquake located in the Bajo Segura fault zone, using the ASK14 GMPE and assuming that soil types B and C will have the lower bound $V_{s,30}$. At the end this branch will be labelled as E1 – SMIN – ASK. In total, the logic tree has allowed us to obtain 12 ELE scenarios for Guardamar and, after weighting these branches, SELENA will provide a mean value and corresponding standard deviation range.

The weights assigned to each branch of the logic tree are the following: 0.8 to E1 and 0.2 to E2; 0.33 to SMIN, 0.34 to SMED and 0.33 to SMAX; 0.7 to ASK14 and 0.3 to CB14. As we can see, the E1 scenario has been given a higher probability because many authors [5] related it to the 1829 Torrevieja earthquake. Regarding the GMPE, the RISMUR II team [33] carried out a comparison of various GMPE models and they concluded that ASK14 should have a higher weight than CB. The herein assigned weights to the GMPEs follow the recommendations of the RISMUR II team.

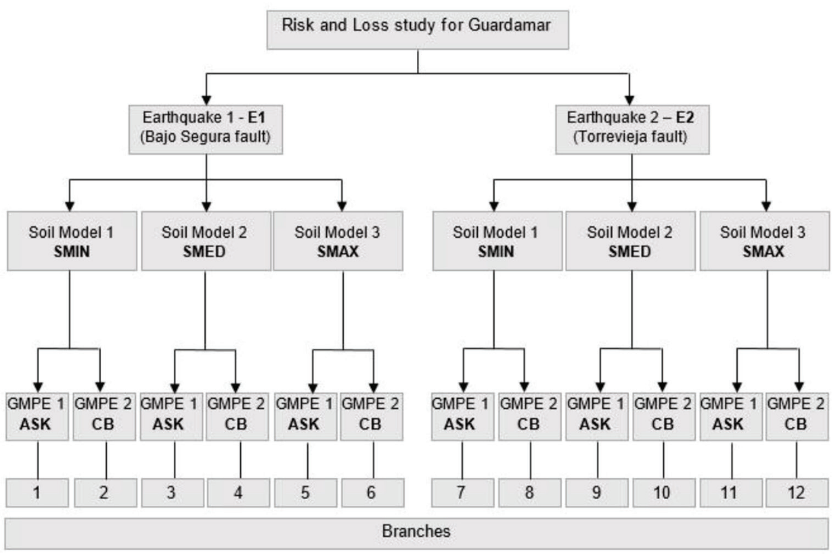

Figure 2: Branches of the logic tree of the ELE for Guardamar.

3 RESULTS AND DISCUSSION

3.1 Uncertainty of the structural damage scenarios

Figure 3 represents the structural damage distribution in terms of percentage of the total building stock for the entire city for both scenarios, while concentrating on typology RC1.B_L. As it can be seen, the structural damage is higher in the case of scenario E1 (Bajo Segura fault zone) than in the case of scenario E2 (Torrevieja fault). This is obviously due to the geometry of the fault which is crossing the city and causing a smaller rupture distance.

The higher probability of complete damage is observed for E1 in combination with CB14 GMPE. It ranges from 7% when using upper bound Vs_{30} values and the ASK14 attenuation relationship to 77% when using lower bound $V_{s,30}$ values and the CB14 attenuation relationship. On the other hand, for scenario E2, the probability of complete damage is lower and it ranges from 0% to 17%.

Therefore, again we can observe how the difference in $V_{s,30}$ can lead to important changes in the structural damage, so a detailed microzonation is always recommended when ELE has to be obtained for emergency and management planning.

3.2 Uncertainty in economic losses

As indicated before, the differences in the performance points may be the reason for the differences in structural damage. Therefore, once structural damage is converted into economic losses (Fig. 4), a similar behaviour is expected. Again, the economic losses are higher when scenario E1 and CB14 attenuation relationships are used and when the soil conditions are represented by the lower bound $V_{s,30}$ values. In this case, the total losses are 1,074 million Euro.

Figure 3: Summary of the damage distribution for the entire city: E1 (left); E2 (right). Note that only model building type RC1.B_L is represented.

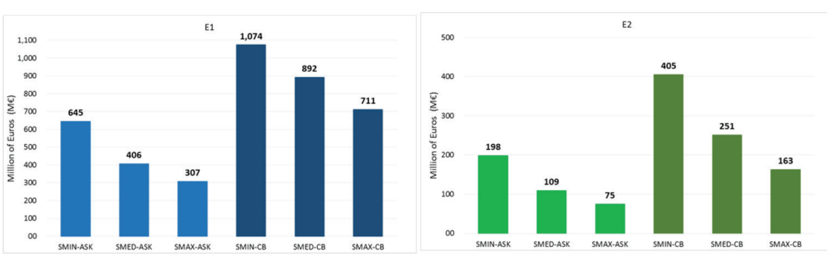

Figure 4: Total economic loss distribution for both scenarios.

However, when using the scenario E2, the upper bound $V_{s,30}$ values and the ASK14 attenuation relationship the economic losses are reduced to 93% approximately. As explained before the economic model used to quantify the repair/reconstruction costs is not very accurate because we have only used general values; therefore, this is only an approximation of the economic losses but it also helps to see how different the losses can be depending on the chosen input parameter.

3.3 Uncertainty in human losses

Figure 5 shows the human losses (injured and deaths) in the city for the two earhquake scenarios and the rest of the branches of the logic tree. The results have been computed assuming a nighttime scenario in which most of the population are inside the residential buildings, thereby serving some sort of a worst-case scenario. The behaviour of the human loss distribution is the same as previously observed with structural damage.

The maximum number of people seriously affected (i.e. heavy injuries and deaths) are 375 for the scenario E1 and 128 for the scenario E2 while the minimum is 63 for the scenario E1 and 9 for the scenario E2. If we add all the people injured, we obtain a maximum of 3165 for the scenario E1 and 1193 for the scenario E2.

3.4 Mean ELE for the city of Guardamar del Segura.

Finally, as explained before small variations in the input parameters can result into big differences amongst the obtained damage and loss results are depending on small variations in the input parameters. In our case, and after reviewing the literature, we found that both scenarios E1 and E2 could be possible for a repetition of the 1829 Torrevieja earthquake. Additionally, if there is not any detailed information about the $V_{s,30}$ distribution in the city, a first approach using the $V_{s,30}$ ranges provided in Eurocode 8 could be a way of representing the different possibilities. Since no specific attenuation relationships are available for the respective region, two of the NGA have been selected that were initially proposed for the update of the Spanish seismic hazard map. Therefore, we always should provide the local authorities with a mean earthquake loss estimation scenario with corresponding uncertainties.

Regarding the typology RC1.B_L, we have obtained that 276 ± 78 buildings suffer complete damage, 268 ± 35 suffer extensive damage, 193 ± 26 suffer moderate damage and finally 275 ± 58 and 83 ± 45 buildings suffer slight or none damage, respectively. On the other hand, if we add all the different model building types, the damaged number of buildings will increase until 1646 ± 253 building that suffer complete damage, 847 ± 113 suffer extensive

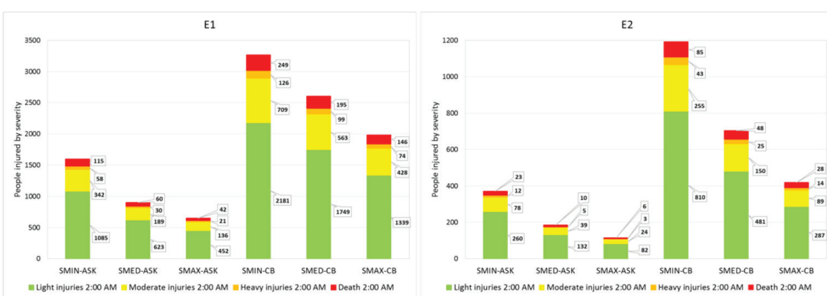

Figure 5: Total human losses distribution for both scenarios.

damage, 648 ± 108 moderated damage and 656 ± 129 and 263 ± 110 buildings suffer slight or none damage, respectively. The mean economic losses due to this structural damage will be 515 ± 79 million Euros and the mean number of people with heavy injuries will be 47 ± 11 and death will be 93 ± 22.

4 CONCLUSIONS

This paper has allowed us to see how the different but possible input parameters that are required to compute an ELE for the city of Guardamar should be carefully analyzed for each case study. In our case, we have developed a logic tree with two different earthquake scenarios, E1 and E2, two different ground motion prediction equations and three different soil conditions. All this branches were assumed to be valid if an ELE is going to be computed for the city, therefore all are realistic.

The obtained results allow us to state the following conclusions:

a) The earthquake scenario source parameters are very important even in a situation like the proposed in this paper where with a similar magnitude but associated a different fault types and mechanism, we obtain structural damage differences up to a 60%.
b) The selection of a correct GMPE is always a difficult task. In our case the CB14 GMPE provides the higher damage that can be up to a 36% when compared with ASK14.
c) Finally, the $V_{s,30}$ conditions in the city also have an important influence on the computed damage. The softer the soil, the higher the damage, usually. In our case, it can be observed differences up to 50% between the damage computed with the minimum and the maximum $V_{s,30}$ values.

Therefore, the steps that we will follow for the next detailed ELE to be computed in the city will be the following: a) First, as the $V_{s,30}$ values provide higher differences, we will carry out a detailed microzonation in order to get a better characterization of the soil behaviour; b) secondly, we will try to analyze if the earthquake scenario can be better defined or complemented with other possibilities; c) thirdly, we will better analyze the behaviour of the attenuation relationships in order to choose those which can simulate our ground motion scenarios in a better way, and d) finally, the vulnerability of Guardamar del Segura's building stock of will be represented through a more detailed vulnerability model [34].

Anyway, the use of the logic tree given in SELENA has been useful in order to obtain a mean ELE scenario, which we consider reliable because all the input parameters are applicable to the case study and with corresponding uncertainties, so stakeholders and local governments can use it in order to establish the first draft of a management and emergency plan for the city.

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