DOI: https://doi.org/10.14256/JCE.1242.2015

Primljen / Received: 11.2.2015.
Ispravljen / Corrected: 6.9.2016.
Prihvaćen / Accepted: 24.10.2016.
Dostupno online / Available online: 10.8.2017.

Estimated loss and rating of earthquake risk in eastern Turkey

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Subject review

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Loss Estimation and seismic risk assessment in Eastern Turkey

The seismic risk to urban building stock in Turkey is gaining in importance due to very high seismic hazard combined with its vulnerable and densely populated building stock. The research oriented on the eastern part of Turkey, where seismic sources and the level of seismic hazard are different, is presented in the paper. The results of the research show that the seismic safety of civil buildings is highly compromised even in this part of the country, and that expected losses are high and attain the level of "non-tolerable" losses. Economic losses and fatalities are also estimated in the paper, in case of realization of some of the expected scenarios.

Key words:
urban area, earthquake risk, earthquake scenario, loss estimation

Pregledni rad

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Procjena gubitka i ocjena potresnog rizika u istočnoj Turskoj

Potresni rizik urbanog građevnog fonda u Turskoj dobiva na sve većoj važnosti zbog vrlo visoke potresne opasnosti kombinirane s vjerojatno oštećenim i gusto naseljenim građevnim fondom. U radu je prikazano istraživanje usmjereno na istočni dio Turske gdje su seizmički izvori kao i stupanj potresne opasnosti drugačiji. Rezultati istraživanja pokazuju da je potresna sigurnost civilnih građevina i u ovim dijelovima znatno ugrožena te da su očekivani gubici visoki i na razini "ne prihvatljivosti". U radu je dana i procjena ekonomskih gubitaka i smrtnosti, ako se ostvari neki od očekivanih potresnih scenarija.

Ključne riječi:
urbano područje, potresni rizik, potresni scenarij, procjena gubitka

Übersichtsarbeit

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Einschätzung des Verlustes und Beurteilung des Erdbebenrisikos in der Osttürkei

Das Erdbebenrisiko des städtischen Baufonds in der Türkei gewinnt wegen der sehr hohen Erdbebengefahr kombiniert mit den wahrscheinlich beschädigten und dem dicht besiedelten Baufond zunehmend an Bedeutung. In der Abhandlung wird eine Untersuchung angeführt, die auf den östlichen Teil der Türkei ausgerichtet ist, in dem die seismischen Quellen sowie der Grad der Erdbebengefahr anders sind. Die Ergebnisse der Untersuchung zeigen, dass die Erdbebensicherheit der zivilen Gebäude auch in diesen Teilen erheblich beeinträchtigt ist, und dass die erwarteten Verluste hoch und auf dem Niveau von "nicht akzeptabel" sind. In der Abhandlung wurde auch eine Einschätzung der wirtschaftlichen Verluste und der Sterberate angegeben, sollten einige der erwarteten Erdbebenszenarien eintreten.

Schlüsselwörter:
Stadtgebiet, Erdbebenrisiko, Erdbebenszenario, Einschätzung des Verlustes

1. Introduction

Despite catastrophic seismic events that occurred in the past in Eastern Turkey, most of the loss estimation and seismic risk assessment studies have focused on the North Western part of the country because of the higher concentration of population [1-6]. This fact however should still not underestimate the very high monetary and life risks in the less populated regions of the country. 2011 earthquakes in the city of Van [7, 8], adjoining the city of Bitlis, have shown once again that the urban building stock is under serious seismic risk, posing a high threat to the society. The fairly frequent mid- to large-magnitude earthquakes that strike the region provide useful insights into the inherent vulnerability of the building stock in the region. This paper is an attempt to investigate the historically important large magnitude earthquakes in the area of Lake Van Basin, together with the two recent earthquakes of Tabanlı ($M_w = 7.2$) and Edremit ($M_w = 5.6$), specifically in the area of Bitlis, which is a relatively small town of 67K population.

The seismic risk to building stock is of growing interest to scientific community and decision makers, due to an increasing urbanization and concentration of population in earthquake-prone and thus highly vulnerable areas. Turkey, especially since 1999, is known as one of the most earthquake-prone regions in the world. This may be considered true as most of the country is in fact under earthquake threat. Frequent mid- to large-magnitude earthquakes strike not only the western cities but the rest of the country as well. This paper aims to stress that in case one of large magnitude earthquakes, similar to those that occurred in the past, hits the region, the death toll could rise to dramatic proportions. It should be noted that recent Van earthquakes from the year 2011 caused 641 human casualties in the city of Van and in the surrounding area.

The area of the city of Van, as well as the city of Bitlis, which is on the other side of Lake Van, is prone to destructive earthquakes. An overall seismic risk to the urban building stock is investigated in this paper. Reinforced-concrete buildings are considered in the calculation of expected losses. Scenario earthquakes, created by repeating past events, are used in loss calculations. In order to estimate losses, a relatively straightforward approach based on six different scenarios is used. Thus, six deterministic loss estimations are conducted. The scenarios used originate from the earthquake catalogue of the region. The idea is basically to get a good insight about the level of vulnerability of the City of Bitlis, being the subject of a case study selected to represent the eastern part of Turkey, under a very probable and realistic shaking scenario. The results are presented in terms of fatalities and economic losses. The Mean Damage Ratio (MDR), explained below in greater detail, provides a simple indication of direct economic losses, and is calculated for each scenario. This ratio is obtained by dividing the expenditure needed for compensation of direct damage to buildings (structural or non-structural repair or strengthening activities), with the funding required to rebuild these buildings. The MDR is calculated as a single scaled number, and it offers appropriate clues about the level of damage.

2. Seismicity of city of Bitlis

The city of Bitlis is located in the Lake Van basin, lying on the Bitlis Thrust Zone that is actually a collapsed tectonic basin [9]. The Lake Van basin was formed about 100.000 years ago when the lava from the Nemrut volcano blocked the outward drainage of water in the Muş Basin [10]. A geological map of the Lake Van Basin is given in Figure 1.

The general tectonic setting of Eastern Anatolia is mainly characterized by the collision of roughly northerly moving Arabian plate with the Anatolian plate along the deformation zone known as the Bitlis Thrust Zone (Figure 2). The Lake Van basin is a seismically active region as indicated by historical sources. Significant earthquakes that occurred in Bitlis and the surrounding area before the 20th century are summarized in Table 1. According to the Turkish Earthquake Zoning Map, Bitlis lies in the level one seismic zone, which translates into 0.40 PGA in constructing the design spectrum, where the 475-year return period is used.

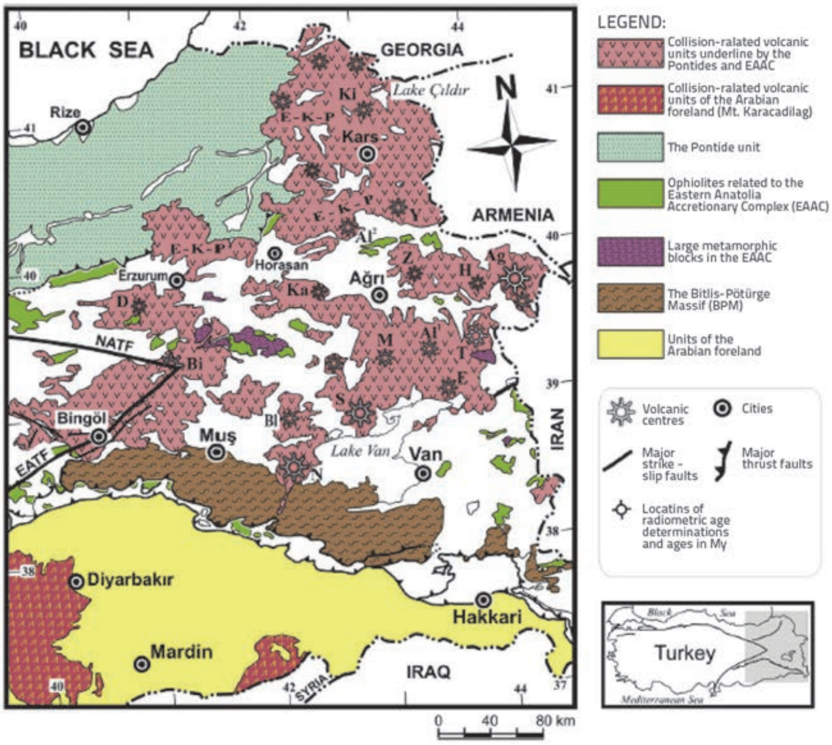

Figure 1. Geological map of the Lake Van region. N – Nemrut Volcano, S – Süphan Volcano in the immediate vicinity of the lake. EATF – East Anatolian Fault; NATF – North Anatolian Fault [11]

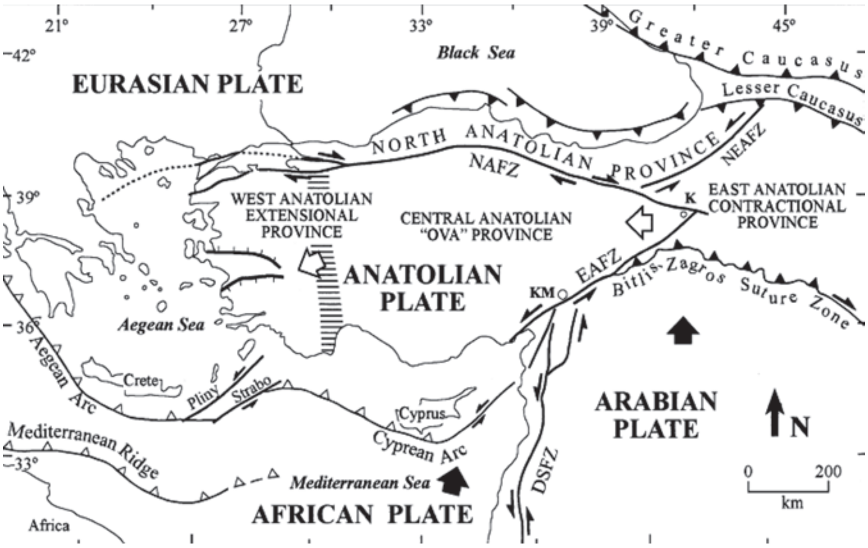

Figure 2.Tectonic map of Turkey with major structural features [12]

Table 1.Significant earthquakes in Bitlis and its vicinity before the 20th century

Year	Location	Mw	I (MMS)	Year	Location	M	I
461	Malazgirt		X	1646	Van and surrounding		VII
1012	Malazgirt		VII	1647	Van - Muş -Bitlis		IX
1101	Bitlis/Van		VI	1648	Van and surrounding	6.7	VIII
1110	Bitlis/Van		VIII	1670	Hizan - Siirt	6.6	
1111	Bitlis/Van		IX	1682	Bitlis		
1208	Bitlis/Van/Muş	6,5		1696	Çaldıran - Bitlis	6.8	X
1245	Bitlis/Van/Muş		VIII	1701	Van and surrounding		VIII
1246	Lake Van		VIII	1704	Van		VII
1275	Bitlis/Van		VII	1705	Bitlis	6.7	IX-X
1276	Bitlis/Van		VIII	1715	Van - Erçiş	6.6	VIII
1282	Bitlis/Van		VII	1869	Bitlis and surrounding		VII
1345	Malazgirt		VIII	1871	Van -Elazığ	5.5	VII
1363	Muş		IX	1881	Van and surrounding	7.3	IX
1415	Lake Van		V	1884	Bitlis - Pervari	6.9	
1439	Nemrut		VI	1891	Elazığ-Bitlis	5.5	VIII
1441	Nemrut		VIII	1892	Elazığ-Muş		VII
1582	Bitlis		VIII				

3. Building inventory used in loss estimations

In order to create the ground motion fields and loss estimations, the provincial centre of Bitlis is divided into 12 regions (Figure 3). Each region represents one sub-district (mahalle). Although resolution of input data is considered to be important in loss calculations [14], the use of sub-districts is found to be sufficient if one is seeking the median loss estimations only. The resolution level of sub-districts or even post-codes (a post-code is generally a smaller geographical unit than sub-district in the Turkish administration system) is considered insufficient, as reported by Bal et al. [14], if the uncertainty of each calculation unit is also required. The sub-district level has been selected in this study, mostly because the soil conditions in the 12 sub-districts, as well as the distribution of buildings, are fairly homogeneous. Furthermore, the results presented here are of median level, while the uncertainty of calculations is considered at every level but is not presented. Thus the use of sub-district as calculation resolution can in this case be considered justified.

The year 2000 building census [15] is used for defining the structural data inventory. According to that information, 86 % of the buildings in the provincial centre, which has been adopted as basis for loss calculations, are made of reinforced concrete, 13 % of buildings are made of unreinforced masonry (URM), while about 1 % of buildings are marked as "other". Only the reinforced concrete buildings are considered in this study. Although the DBELA method can be used to estimate the expected losses for URM buildings as well, the visual inventory cross-check conducted in the city revealed that the type of URM used in Bitlis, which is mostly irregular stone masonry, is not covered by DBELA. Thus the loss estimation for this type of URM would not be justified. Despite this simplification, no major changes in the risk estimation are expected, since the RC constitutes 83 % of the building stock. For the sake of simplicity, however, only the RC buildings have been used in final estimations.

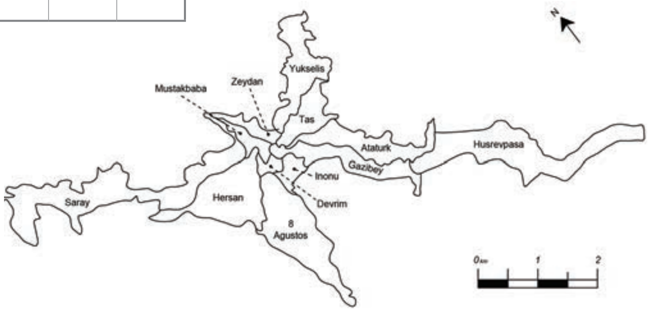

Figure 3. 12 sub-districts (mahalle) of provincial centre of Bitlis, used in loss assessment calculations

Since the year 2000 census does not correspond to the current situation, a visual cross-check on the streets, as well as an inventory study on the municipality footprint maps, have been conducted to find the number and type of buildings located in the 12 sub-districts. The number of reinforced concrete buildings, the number of storeys, construction date, and structural type (i.e. RC-frame, RC-frame-wall, URM, other), have all been recorded in each street. The field and municipality data were combined with the year 2000 census data and so, finally, the inventory dataset to be fed into DBELA was created.

Damage loss estimation was made for 5186RC buildings (present as of 2010) in the total of twelve streets, under six different earthquakes scenarios. The data about additional buildings, built between the 2000 census data and the present time, were obtained from the municipality records as explained above. Each time a scenario event was triggered, 100 ground motion fields with spatial correlation of intra-event uncertainties were created, and the building inventory of each sub-district was calculated. Ground-motion fields were created in the geometric centre of each sub-district, and so the entire building inventory was assumed to be lumped at the centre of each sub-district. This approach has already been investigated and found fairly accurate by Bal et al. [14].

The municipality documents indicate that approximately 15 % of the RC buildings situated in Bitlis as of 2010 were built according to the 1998 seismic code and above, meaning that they are compliant with the ductility and capacity design rules. These buildings are classified as "Good" in DBELA, which means that they are code compliant. A portion of these RC buildings (2 out of 15 %) is found to be RC buildings with proper shear walls, and are also compliant with the 1998 code and above. Visual checks on approximately 8 % of all buildings (visits on 8 % of the buildings in Bitlis) showed that the 5 % of the total pre-code buildings (buildings built before 1998) have shear walls. In summary, 80 % of the existing RC buildings are non-compliant with the relevant code, and do not have shear walls (marked as Poor-Frame-Normal and Poor-Frame-Embedded in DBELA), 5 % of all RC buildings have shear walls (Poor-Dual-Normal and Poor-Dual-Embedded in DBELA), 13 % are code-compatible and are without shear walls (Good-Frame-Normal and Good-Frame-Embedded in DBELA), and 2 % are post-code buildings with shear walls (Good-Dual-Normal and Good-Dual-Embedded in DBELA). This DBELA classification is important since the period-height relationships and the displacement capacity calculations alter from category to category [15]. The percentages of dual, or code-compliant, buildings could be found only for the entire city centre (not separately recorded in the Municipality for every sub-district). Thus building percentages for the post-code or frame wall structures are considered to be homogeneously distributed in the city.

The distinction between "Poor" and "Good" is made in DBELA to denote code non-compliant and code- compliant types of structures, respectively. It should be noted that this type of naming does not a priori define the expected damage level of the building category; it simply identifies the quality of design and construction, as well as code compliance of the building type. The "Normal" and Embedded" are two types that define the beam types used in the RC buildings, where "Normal" denotes emergent beams with typically 10-15 cm slab thickness, and 40-60 cm beam section depth. The term "Embedded" denotes flat beams with a slab, typically with a sectional depth of 30-37 cm for both for the slab and the beam. Finally, "Dual" means frame structures with RC shear walls, while "Frame" means simple frame structures without any RC shear walls. Further details about these classifications are given in Bal et al. [16]. The number of buildings in each sub-district is presented in Table 2. It should be noted that the percentages of the "normal" structural type and the "embedded" structural type are not known, and so the percentages available for Marmara

Table 2. Number of reinforced concrete buildings in 12 sub-districts, used for loss estimations

Sub-district (mahalle)	Total number of RC buildings	Code-compliant frame buildings (GFN and GFE)	Code-compliant dual buildings (GDN and GDE)	Code non-compliant frame buildings (PFN and PFE)	Code non-compliant dual buildings (PDN and PDE)
Hersan	504	66	10	403	25
Saray	313	41	6	250	16
8 Agustos	742	96	15	594	37
Inonu	353	46	7	282	18
Devrim	219	28	4	175	11
Mustakbaba	460	60	9	368	23
Zeydan	272	35	5	218	14
Yukselis	358	47	7	286	18
Tas	456	59	9	365	23
Ataturk	488	63	10	391	24
Gazibey	467	61	9	374	23
Husrevpasa	554	72	11	443	28

PFN: Poor-Frame-Normal, PFE: Poor-Frame-Embedded, GDN: Good-Dual-Normal, GDE: Good-Dual-Embedded, GFN: Good-Frame-Normal, GFE: Good-Frame-Embedded

Table 3. Construction dates of RC buildings in Bitlis [16, 19]

Period Sub-district	Before 1970	1971–1980	1981–1990	1991–2000	2001–2010
Hersan	3 %	11 %	35 %	36 %	15 %
Saray	18 %	23 %	12 %	32 %	15 %
Sekiz Agustos	11 %	22 %	33 %	19 %	15 %
Inonu	17 %	28 %	16 %	24 %	15 %
Devrim	20 %	32 %	22 %	11 %	15 %
Mustakbaba	12 %	25 %	35 %	13 %	15 %
Zeydan	14 %	31 %	22 %	18 %	15 %
Yukselis	10 %	22 %	38 %	15 %	15 %
Tas	15 %	21 %	29 %	20 %	15 %
Ataturk	13 %	22 %	24 %	26 %	15 %
Gazibey	10 %	24 %	31 %	20 %	15 %
Husrevpasa	3 %	5 %	39 %	38 %	15 %
Mean value	**11 %**	**21 %**	**30 %**	**23 %**	**15 %**

Table 4.Number-of-storey percentages for RC buildings in each sub-district

Number of storey Sub-district	1	2	3	4	5	6	7	8	9
Hersan	41 %	23 %	12 %	10 %	5 %	5 %	3 %	1 %	0 %
Saray	35 %	32 %	11 %	8 %	4 %	6 %	2 %	2 %	0 %
8 Agustos	31 %	19 %	15 %	13 %	10 %	4 %	5 %	2 %	1 %
Inonu	27 %	17 %	14 %	12 %	11 %	9 %	5 %	3 %	2 %
Devrim	21 %	18 %	16 %	9 %	12 %	10 %	7 %	4 %	3 %
Mustakbaba	37 %	23 %	18 %	9 %	7 %	3 %	2 %	1 %	0 %
Zeydan	36 %	21 %	17 %	9 %	8 %	4 %	2 %	2 %	1 %
Yukselis	33 %	25 %	13 %	12 %	7 %	5 %	4 %	1 %	0 %
Tas	29 %	17 %	14 %	11 %	9 %	7 %	6 %	4 %	3 %
Ataturk	26 %	16 %	15 %	12 %	9 %	8 %	5 %	5 %	4 %
Gazibey	23 %	20 %	14 %	15 %	12 %	10 %	3 %	2 %	1 %
Husrevpasa	18 %	17 %	11 %	13 %	14 %	8 %	8 %	6 %	5 %
Mean value	**30 %**	**20 %**	**14 %**	**11 %**	**9 %**	**6 %**	**4 %**	**3 %**	**2 %**

Region [16] and Eastern Turkey [17] are used. According to that information, approximately 25 % of the buildings are assumed to have been built with embedded beams.

Construction dates for RC buildings located in each geographical unit in Bitlis are given in Table 3. The year of construction, or simply the construction period, is important in DBELA calculations, because the steel quality used in Turkish building stock changes according to time period [16], which could primarily affect limit state displacement calculations. As stated above, the total number of buildings built between 2001 and 2010 was defined as a lump sum, for the entire city, and distributed evenly to all sub-districts. This is the reason why the building percentage of all sub-districts in the 2001-2010 column in Table 3 amounts to 15 %.

Another important parameter used in loss calculations according to the DBELA method is the number of storeys. This defines the pre-assumed displaced shape of the structure as well as the yield and limit state displacement capacities. Based on available sources [16, 18], the number of stories of all RC buildings in Bitlis is given in Table 4.

4. Estimation of earthquake losses

Loss estimation is an approach devised for estimating the overall quantity and spatial distribution of structural, financial and social losses, either in a post-event case (i.e. by using scenario events) or in a probabilistic fashion, where an earthquake catalogue, representing seismicity of the region of interest, is employed. The methods available may be fully empirical, fragility-curve based, or mechanical-based. Mechanical-based approaches require high level and resolution of data that can adequately represent structural response of the building inventory in question. A detailed discussion on the mechanical-based methods is given in [19]. Loss estimation methods are able to provide direct economic losses and social losses. The indirect losses caused by collateral damage and by business interruption are difficult to correlate with the complex aftermath of a seismic event. The calculation of indirect losses requires a clearer insight into economic impacts of an earthquake, which may spread out for many years [21].

Earthquake loss estimation studies require predictions on the proportion of a building class falling within discrete damage bands from a specified earthquake demand. These predictions should be made using methods that incorporate both computational efficiency and accuracy. The risk or damage maps can be made at the national level following a triggering event, something that is different from the way hazard maps, for example, are prepared.

Earthquake actions should be represented by a parameter that shows good correlation to damage and that accounts for the relationship between the frequency content of the ground motion and the fundamental period of the building; such as the recently proposed approaches to use displacement response spectra [21, 22].

A mechanical-based loss assessment method, previously used for the area of Istanbul [3, 21, 22], is employed in this study. The method is based on principles of structural mechanics and the seismic response of buildings is used to estimate seismic vulnerability of individual classes of buildings. In this procedure, the period of vibration of each building is calculated in the random population using a simplified equation based on the height of the building and building type, whilst the displacement capacity at different limit states is predicted using simple equations which are a function of the randomly simulated geometrical and material properties. The displacement capacity of each building is then compared to the displacement demand obtained from an over-damped displacement spectrum, using its period of vibration; the proportion of buildings, which exceeds each damage state, can thus be estimated (Figure 4).

In the example given in Figure 4, the demand exceeds the capacity in the 1st limit state only, and so the building is assigned to the 2nd damage state. Four damage states were used to demonstrate this methodology (none to slight, moderate, extensive and complete), as defined in Crowley et al. [22]. A full description of this methodology, in which the entire procedure is demonstrated step-by-step, is presented by Bal et al. [21].

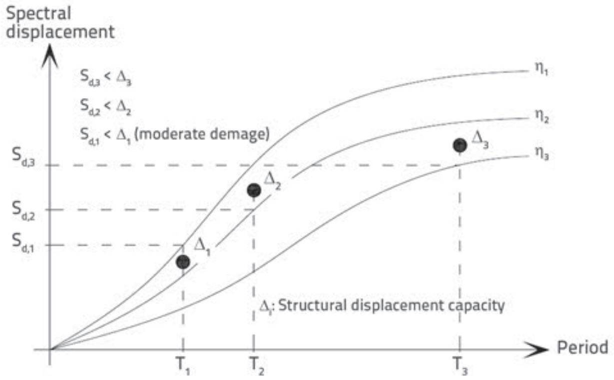

Figure 4. Comparison between capacity for each limit state and associated demand [15]

DBELA method is based on estimating yield and limit state displacements of an equivalent elastic over-damped system. In order to do that, the yield and limit state displacement capacities of the building types are calculated based on structural parameters (i.e. column section depth, reinforcement yield and ultimate strains, beam length, etc.). The yield and limit state capacities are then compared with the displacement demand on the relevant structure.

Priestley and Kowalsky [23] have proved how the yield curvature, f_y, of RC sections is independent of the strength, and thus reinforcement content, but dependent on the yield strain of steel reinforcement and the geometry of the section;

$$\varphi_y = 2.14 \frac{\varepsilon_y}{h_c} \quad \text{for column sections} \tag{1}$$

$$\varphi_y = 1.7 \frac{\varepsilon_y}{h_b} \quad \text{for beam sections} \tag{2}$$

where

h_b - the height of the beam section
h_c - the depth of the column section
ε_y - the steel yield strain.

The most important advantage of this approach is that it is possible to calculate the displacement capacity of RC structures just by using material and geometrical properties of structures, without requiring strength prediction. This is of prime importance for assessment, but especially for loss assessment studies, because of the difficulty in obtaining reliable statistical data for parameters (i.e. concrete quality and reinforcement content of column and beam members) related to the strength of the buildings in the exposure.

One can easily pass from curvature to the tangent yield rotation, q_{ty}, by simply integrating the yield curvature of the column along its height, as shown in Equations (1), (2), and (3). q_{ty} is then increased using empirical factors (1.35 in this example) proposed by Priestley [24] to account for shear and joint deformations.

$$\theta_{ty} = \varphi_y \frac{h_s}{2} = 2.14\frac{\varepsilon_y}{h_c}\frac{h_s}{2} = 1.07\varepsilon_y\frac{h_s}{h_c} \quad (3)$$

$$\theta_y = 1.35\theta_{ty} = 1.44\varepsilon_y\frac{h_s}{h_c} \quad (4)$$

The moment-area technique is then used to find the yield displacement capacity, Δ_y at the top of the column:

$$\Delta_y = \theta_y\frac{2}{3}h_s = 0.96\varepsilon_y\frac{h_s^2}{h_c} \quad (5)$$

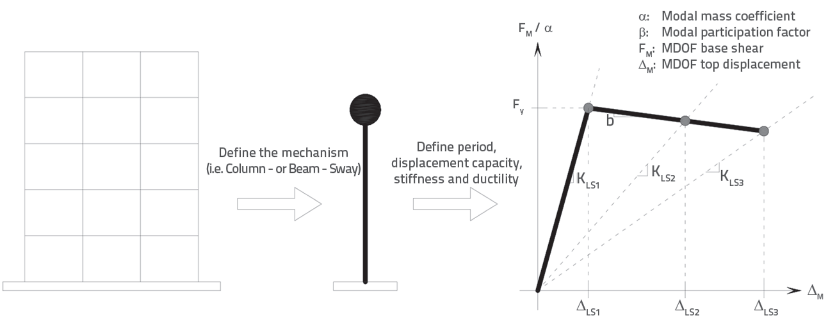

Figure 5. MDOF to SDOF representation of each building and limit states of an equivalent SDOF system

The plastic curvature, ϕ_p, can be found from the difference between the limit state curvature, ϕ_{ls}, and the yield curvature at the base of the column, as shown in Equation (6).

$$\varphi_p = \varphi_{LSi} - \varphi_y = \left(\varepsilon_{C(LSi)} + \varepsilon_{s(LSi)}\right)\frac{1}{h_c} - 2.14\frac{\varepsilon_y}{h_c} = \left(\varepsilon_{C(LSi)} + \varepsilon_{s(LSi)} - 2.14\varepsilon_y\right)/h_c \quad (6)$$

The limit state curvature is approximated by the sum of the limit state strains of concrete and steel at two ends of the section $\varepsilon_{C,LSi}$ and $\varepsilon_{S,LSi}$, respectively, divided by the total depth of the column section. Plastic curvatures are multiplied with the plastic hinge length, l_p, assumed to be half of the section depth, as given in Paulay and Priestley [25], and the plastic rotation capacity is obtained as follows:

$$\theta_p = \varphi_p l_p = \varphi_p 0.5h_c = \left(\varepsilon_{C(LSi)} + \varepsilon_{S(LSi)} - 2.14\varepsilon_y\right)\ 0.5 \quad (7)$$

The plastic hinge length does not represent the total extent of plasticity but may be considered a representative length used for mathematical purposes. There are several plastic hinge length considerations, among which one of the most updated ones is the plastic hinge length equation proposed by Priestley et al. [26]. The plastic displacement at the top of the cantilevers is then found by multiplying plastic rotation by the height of the columns:

$$\Delta_p = \theta_p h_s = \left(\varepsilon_{C(LSi)} + \varepsilon_{S(LSi)} - 2.14\varepsilon_y\right)0.5h_s \quad (8)$$

The total limit state displacement capacity given in Equation (9) is finally obtained by adding the yield displacement from Equation (5) to plastic displacement:

$$\Delta_{LSi} = \Delta_y + \Delta_p = 0.96\varepsilon_y\frac{h_s^2}{h_c} + \left(\varepsilon_{C(LSi)} + \varepsilon_{S(LSi)} - 2.14\varepsilon_y\right)0.5h_s \quad (9)$$

The same mechanics principles described above can also be used to calculate the displacement capacity of buildings under strong ground motions. However, it is the capacity of the structure, as opposed to that of separate structural members, that needs to be defined. The displacement demand to the structure is predicted from a displacement spectrum, which gives the response of a SDOF system to a given input of ground shaking. In order to compare this demand to the displacement capacity, the transformation of multi-degree-of-freedom (MDOF) to single-degree-of-freedom (SDOF) is conducted, as shown in Figure 4 and Figure 5.

Capacity estimation for generated buildings, representing structural properties of the building stock, has been explained to this point. Monte Carlo simulation techniques are used for generation of the buildings examined in the scope of loss estimation analyses. For that purpose, the building inventory data [16-18] are used, and statistical properties of these data (i.e. type of distribution the data follow, median, standard deviation, etc.) are employed to generate random building properties. These properties are then used for the calculation of displacement capacities.

The seismic demand is calculated using six deterministic scenario earthquakes, as mentioned before. The scenarios are real events that occurred in the past. According to this, the first earthquake scenario is the magnitude 6.2 Malazgirt Earthquake that occurred in 1903, 87 km away from the city. The second scenario is the event that occurred in 1915, 57 km away from Bitlis, with the magnitude of Mw 5.7. The third scenario is the 1966 Earthquake, with the magnitude of Mw 6.0, and the distance of 99 km. The fourth earthquake scenario, 1705 Bitlis earthquake, had Mw 6.7 magnitude, and the fifth scenario is the 18 May 1881 Bitlis-Nemrut earthquake. The sixth scenario is the recent Van earthquake with the magnitude of M_w7.2.

The city centre of Bitlis, serving as basis for loss estimations, has soil type B according to the NEHRP soil classification [27]. The spectrum for each sub-district is calculated by means of the Akkar and Bommer, attenuation relationship [28]. Although the GMPE used is not up-to-date, it gives the displacement spectrum directly. A GMPE, which provides acceleration spectrum and is more up-to-date, could also be used and the obtained acceleration spectra could be converted to a displacement spectrum. Generating a displacement spectrum however is more accurate only in terms of the associated uncertainties, since it would be erroneous to use an acceleration spectrum GMPE instead, and to assume the uncertainty of the acceleration spectrum equal to that of the displacement spectrum [29]. An intra-event uncertainty component is used in each simulation for the generation of displacement spectra. One hundred ground motion fields are simulated, and the intra-event variability is taken into account using the spatial correlation [30] among different geographical units. It should be noted that the available spatial correlation models are calibrated only for acceleration residuals, and not for displacement residuals. However, the authors had a trade off between using displacement spectra and employing accurate uncertainties, or using acceleration spectra and employing calibrated spatial correlation models. The authors have chosen the former since both options could not be applied simultaneously.

The above steps have been used to create a correlation matrix, by considering the distances among the centres of geographic units (i.e. sub-districts). Finally, an influence matrix is generated using the correlation matrix and the Latin hypercube method, where the epsilon of each simulation is estimated for each geographical unit.

The damage is calculated as the mean-damage-ratio (MDR), an indicator that amalgamates the various damage values into a single parameter. MDR is a convenient parameter that is, in fact, the weighted average of the ratios of the repair and/or strengthening (or replacing, for the collapsed buildings) cost of the structures to their rebuilding cost. Based on the real data from entire Turkey, Bal et al. [17] suggest the MDR of 16 % for the slightly damaged buildings, 31 % for the moderately damaged buildings, 105 % for the severely damaged buildings and, finally, 104 % for the collapsed buildings. Note that reference [17] reports structural properties of the North West Turkey, but the MDR data from that report were also collected in other parts of the country. These ratios are multiplied with the percentages of damaged buildings per sub-district, and a weighted average is calculated per sub-district. The aggregate MDR for the entire region under study (considering all building classes) is determined, i.e. it is defined for each of the one hundred simulated ground-motion fields, and for each of the different levels of spatial resolution, and then the mean aggregate MDR is established. The MDR can then be multiplied with the average reconstruction cost and translated into a total direct loss. The calculation of the MDR is given in Equation (10):

$$MDR = SSR_{LSi,j}\, C_{LSi,j} \tag{10}$$

where $R_{LSi,j}$ is the ratio of the number of buildings with the type number "i" and Limit State "j", and $C_{LSi,j}$ is the repair and/or retrofitting cost ratio of the buildings of type "i" that reached

Table 5. Injury distributions for specific building types, by Spence, 2007 [28]

Building types \ Damage	Complete damage state [%]					
	U_I	I_1	I_2	I_3	I_4	I_5
Masonry (1F)	23.6	50.0	12.0	8.0	0.4	6.0
Masonry (2-3F)	16.5	50.0	15.0	10.0	0.5	8.0
Masonry (≥ 4F)	9.4	50.0	18.0	12.0	0.6	10.0
RC (1F)	32.9	30.0	19.0	3.0	0.2	15.0
RC (2-3F)	20.8	30.0	23.0	4.0	0.2	22.0
RC (≥ 4F)	9.7	30.0	27.0	5.0	0.3	28.0

U_I = uninjured; I_1 = slight injuries; I_2 = moderate injuries; I_3 = serious injuries; I_4 = critical injuries; I_5 = deaths

Table 6. Damage distribution (number of buildings) for the Earthquake Scenario # 1 (M_w = 6.7, R = 87 km)

Sub-district \ Damage	Collapsed	Severely damaged	Moderately damaged	Slightly damaged	No damage	Total
Hersan	0	0	2	2	500	504
Saray	0	0	2	2	309	313
8 Agustos	0	0	2	2	738	742
Inonu	0	0	2	2	349	353
Devrim	0	0	2	2	215	219
Mustakbaba	0	0	2	3	455	460
Zeydan	0	0	1	1	270	272
Yukselis	1	1	2	1	353	358
Tas	0	1	1	1	453	456
Ataturk	0	1	1	2	484	488
Gazibey	0	1	2	2	462	467
Husrevpasa	0	0	1	3	550	554
Total	**1**	**4**	**20**	**23**	**5138**	**5186**
Percentage	**0.02 %**	**0.08 %**	**0.39 %**	**0.44 %**	**99.07 %**	**100.00 %**

the damage Limit State 2. An example for the $R_{LSi,j}$ ratio can be "the ratio of the reinforced concrete frame buildings built between 1979 and 1990, between 3 and 5 stories in height, that reached the damage Limit State 1 in the analyses". Please note that this ratio is the ratio to the total number of buildings in the inventory, and the summation of R ratios should be 1. The $C_{LSi,j}$ is the ratio of the cost of returning the structure back to its original functionality to the cost of rebuilding that structure.

Fatalities have been calculated using the model proposed by Spence, 2007 [29]. The details are given in Table 5.Expected injury ratios have been averaged by considering the building types and their distributions in every sub-district. Fatality numbers have been calculated for both cases, event occurring at night or in the daytime (approximately 67 % more population in the buildings at night). The total population of the city is 67.000, spread out in 12 sub-districts studied in this paper. It has been calculated, by means of available statistical data [16], that there are approximately 4.33 persons per floor per building. The results in terms of damage distribution are presented in Table 6 to Table 11.It should be noted that there is a large variability in the values reported in Table 6 to Table 11, which is due to the simulation of several ground motion fields. It is also important to note that these values are the median, and also that there is a large uncertainty associated. The severe damage corresponds

Table 7. Damage distribution (number of buildings) for the Earthquake Scenario # 2 (M_w = 5.7, R = 58 km)

Damage / Sub-district	Collapsed	Severely damaged	Moderately damaged	Slightly damaged	No damage	Total
Hersan	0	0	1	3	500	504
Saray	0	0	1	2	310	313
8 Agustos	0	0	1	2	739	742
Inonu	0	0	2	1	350	353
Devrim	0	0	2	2	215	219
Mustakbaba	0	0	2	3	455	460
Zeydan	0	0	2	3	267	272
Yukselis	0	0	2	2	354	358
Tas	1	1	1	2	451	456
Ataturk	0	0	2	2	484	488
Gazibey	0	0	1	2	464	467
Husrevpasa	0	0	2	3	549	554
Total	**1**	**1**	**19**	**27**	**5138**	**5186**
Percentage	**0.02 %**	**0.02 %**	**0.37 %**	**0.52 %**	**99.07 %**	**100.00 %**

Table 8. Damage distribution (number of buildings) for the Earthquake Scenario # 3 (M_w = 6.0, R = 99 km)

Damage / Sub-district	Collapsed	Severely damaged	Moderately damaged	Slightly damaged	No damage	Total
Hersan	1	1	1	4	497	504
Saray	0	0	1	3	309	313
8 Agustos	0	0	1	6	735	742
Inonu	0	1	2	4	346	353
Devrim	1	1	2	4	211	219
Mustakbaba	0	1	2	4	453	460
Zeydan	0	1	2	4	265	272
Yukselis	1	1	1	4	351	358
Tas	1	1	1	5	448	456
Ataturk	1	1	2	5	479	488
Gazibey	1	1	1	4	460	467
Husrevpasa	0	1	2	6	545	554
Total	**6**	**10**	**18**	**53**	**5099**	**5186**
Percentage	**0.12 %**	**0.19 %**	**0.35 %**	**1.02 %**	**98.32 %**	**100.00 %**

Table 9. Damage distribution (number of buildings) for the Earthquake Scenario # 4 (M_w = 6.7, R = 2 km)

Damage Sub-district	Collapsed	Severely damaged	Moderately damaged	Slightly damaged	No damage	Total
Hersan	31	22	62	79	310	504
Saray	20	15	43	50	185	313
8 Agustos	54	39	106	121	422	742
Inonu	30	22	57	59	185	353
Devrim	22	14	39	38	106	219
Mustakbaba	32	23	61	74	270	460
Zeydan	21	14	38	46	153	272
Yukselis	25	18	52	59	204	358
Tas	37	27	72	76	244	456
Ataturk	38	28	78	81	263	488
Gazibey	34	26	75	81	251	467
Husrevpasa	29	28	85	103	309	554
Total	**373**	**276**	**768**	**867**	**2902**	**5186**
Percentage	**7.19 %**	**5.32 %**	**14.81 %**	**16.72 %**	**55.96 %**	**100.00 %**

Table 10. Damage distribution (number of buildings) for the Earthquake Scenario # 5 (M_w = 6.6, R = 15 km)

Damage Sub-district	Collapsed	Severely damaged	Moderately damaged	Slightly damaged	No damage	Total
Hersan	17	17	53	76	341	504
Saray	12	11	35	50	205	313
8 Agustos	27	30	96	119	470	742
Inonu	14	13	46	60	220	353
Devrim	10	10	31	39	129	219
Mustakbaba	14	16	50	73	307	460
Zeydan	8	10	30	42	182	272
Yukselis	9	11	36	56	246	358
Tas	15	15	55	76	295	456
Ataturk	15	15	55	80	323	488
Gazibey	13	14	54	76	310	467
Husrevpasa	12	15	53	87	387	554
Total	**166**	**177**	**594**	**834**	**3415**	**5186**
Percentage	**3.20 %**	**3.41 %**	**11.45 %**	**16.08 %**	**65.85 %**	**100.00 %**

to a damage state in which the structure is beyond repair. The moderate damage means that the structure does not possess the strength it had before the earthquake, but can be repaired and reused. Slight damage means that there is no significant damage to the main load-bearing system, and that the damage mostly concentrates on the secondary elements, such as infill walls.

Overall MDR ratios, as well as expected fatalities, are presented in Table 12. The total built area of residential buildings in Bitlis is around 2.1 million m^2. The rebuilding cost is taken from the Turkish Ministry of Environment and Urbanisation for 2015, and it amounts to 650 TL/m^2, or 200 €/m^2. The rebuilding cost is then estimated for all residential buildings in Bitlis, and it amounts to approximately 414 m €.

It has been established in these loss estimations that no buildings would collapse, except for the cases given in scenarios 4 or 5. The scenarios 4 and 5are the earthquakes that occurred very close to the city centre. If these scenarios were to re-occur, it is calculated in this paper that 4.3 % to 9.6 % of existing RC buildings would collapse, 4 %-7 %would be severely damaged, 15 % - 20 % would suffer moderate damage, and 21 %-22 %would be slightly damaged (Table 12).

The 6th scenario examined in this study is the 2011 Van Earthquake. The total of 3 people died in Bitlis during this earthquake, and 4 to 6 buildings were severely damaged (i.e. they were close to collapse). The estimations presented here seem to overestimate the results providing higher losses

Table 11. Damage distribution (number of buildings) for the Earthquake Scenario # 6 (M_w = 7.2, R = 95 km)

Damage / Sub-district	Collapsed	Severely damaged	Moderately damaged	Slightly damaged	No damage	Total
Hersan	0	1	3	4	496	504
Saray	0	1	3	2	307	313
8 Agustos	0	1	3	7	731	742
Inonu	0	1	3	4	345	353
Devrim	0	1	3	4	211	219
Mustakbaba	1	1	1	4	453	460
Zeydan	0	1	3	3	265	272
Yukselis	0	1	3	3	351	358
Tas	0	1	1	5	449	456
Ataturk	0	1	3	7	477	488
Gazibey	0	0	1	6	460	467
Husrevpasa	1	1	2	6	544	554
Total	**2**	**11**	**21**	**55**	**5089**	**5186**
Percentage	**0.05 %**	**0.21 %**	**0.54 %**	**1.06 %**	**98.13 %**	**100.00 %**

Table 12. Loss estimation results for Bitlis, in terms of MDR and fatalities for 6 scenarios

Scenario	M_w	R [km]	Life Losses (day time event)	Life Losses (night time event)	MDR – Median [%]	MDR - CoV [%]	Direct economic losses [m€]
1	6.7	87	4	5	0.3	82	1.2
2	5.7	58	4	5	0.2	66	0.8
3	6.0	99	24	33	0.6	88	2.5
4	6.7	2	1519	1985	20.3	91	84.0
5	6.6	15	676	880	13.0	78	53.8
6	7.2	95	5	7	0.4	41	1.8

CoV – coefficient of variation

compared to real losses in terms of damage and loss of life. However, the lack of ground motion records in the area does not allow the authors to conclude if the overestimation is caused by the method, or by uncertainties associated with ground motions that occurred in the area.

5. Conclusions

A simplified methodology for the earthquake loss estimation based on the DBELA approach is presented in this study concentrating on Bitlis Province. The procedure relies on a probabilistic framework, which takes into account material and geometric uncertainties of the considered building typology, as well as the variability in the ground motion prediction equations. Only reinforced concrete buildings, which constitute 86 % of the total number of buildings in the city, are considered in the case study. The method is then applied to predict damage distributions and fatalities for Bitlis based on six different scenario earthquakes, selected from the earthquake catalogue of the region. Estimated losses that would have been incurred if the old scenarios were to recur,are presented. It was established that two out of six deterministic scenarios are particularly damaging, with3.2 % to 7.2 % of the existing RC buildings experiencing total or partial collapse. Considering the 6 % collapse ratio in Sakarya during the 1999 Golcuk Earthquake, which was the highest ratio of that event, the range of 3.2 % to 7.2 % shows that the results of the scenarios #4 and #5 could be as catastrophic as those of the 1999 Golcuk Earthquake for Bitlis.

Fatality figures are particularly interesting. During the 2011 Van Erciș Earthquake, the death toll reached 604 persons. Here it should be noted that Erciș has a population of 172K, and is a district adjacent to Bitlis. The scenario #4, with the magnitude of M_w=6.7 and the epicentre in the centre of the city, exhibits a total death toll of 1519 if the event should occur during the daytime, or 1985 if it should occur at night.

The Mean Damage Ratio (MDR) is also presented. For instance, the expected 7.4 or 7.6 Istanbul earthquakes in the offshore zone of Adalar District exhibit MDR ratios of approximately 16 % and 18 %, respectively, for the entire city. In the most devastating earthquake scenarios4 and 5, as presented here for the town of Bitlis, the MDR amounts to20.3 % and 13.0 %, respectively.

Several uncertainties are associated with the approach used in the paper. The first level of uncertainty comes from the ground motion prediction equations, and it was accounted for by employing inter- and intra-event variability together with a spatial correlation scheme in creating the ground motion field. A larger level of total uncertainty, however, comes from the field data regarding the building inventory properties and its resolution. All parameters used in generating the building inventory by means of the Monte Carlo simulation present coefficients of variation (CoV) in the range of 25 to 50 %. When all these inventory-related uncertainties are included in the loss assessment formulae, the overall MDR results exhibit the CoV in the range of 41 to 91 %, as presented in this paper. As a result, the presented approach and the results obtained can be useful as an urgent post-event loss estimation tool. However, the associated level of uncertainties makes the approach inappropriate for insurance portfolio calculations. An important improvement to the approach could be made by defining soil properties and inventory data at a higher resolution in the city centre.

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