Geographic analysis of earthquake damage in Turkey between 1900 and 2012

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ABSTRACT
This study investigates the relationship between fatality and magnitude, energy released, time of earthquake occurrence and building damage, and between building damage and magnitude and energy of earthquakes that occurred in Turkey between 1900 and 2012. Patterns of earthquake occurrence and damage are examined across space and time. Ninety-one per cent and eighty-three per cent of the variation in fatality and building damage are accounted for by the energy released from an earthquake, respectively. Building damage explains 85% of the variation in fatality. Seventy-six per cent of the total death toll is a result of the earthquakes that happened between midnight and 5:22 am. There were two significant clusters of earthquakes in Western Turkey between 1955 and 1965 and between 1969 and 1971. Provinces of Erzincan and Kocaeli emerge as hot spots of fatality and building damage. The location of major earthquakes over 112 years tends to parallel the tectonically active areas of Turkey such as the North and East Anatolian Faults and Western Turkey towards the Aegean Sea. Central, central south, extreme north-western, north-eastern and south-eastern Turkey appears to be void of major earthquakes.

1. Introduction
Earthquakes are natural disasters that affect the landscape physically and cause tremendous economic and social after-effects for communities. Certain regions of the world are more prone to earthquakes depending on tectonic plate activity (Shedlock & Pakiser 1998). One of these regions is Turkey, which lies on a geologically active landscape and it has frequently experienced major earthquakes throughout history. The main reason for this is the interaction among the Arabian, African and Eurasian tectonic plates (figure 1). The Arabian and African plates move northward whereas the Eurasian plate in the north is relatively stable. As a result, much of the country is squeezed westward away from the collision zone between the Arabian and Eurasian plates. This creates a wedge-shaped continental crust known as the Anatolian block, which covers most of the country (McClusky et al. 2000; McClusky et al. 2003; Reilinger & McClusky 2011). The movement on the wedge takes place on two major strike-slip faults: the 1500-km long North Anatolian Fault that extends in the west-east direction along the wedge’s north side terminating in the Aegean and the 550-km long East Anatolian Fault on the south-east side of the wedge (Barka 1992; Straub & Kahle 1995; Reilinger et al. 2006; Chousianitis et al. 2015).

Ninety-three major earthquakes (i.e. with a magnitude equal to or greater than 5 and resulting in either building damage or fatality), which claimed 80,574 lives, occurred during 1900 and 2012 in
Turkey (KOERI 2015). Some of these were devastating catastrophes like the ones that took place in the east and west sections of the North Anatolian Fault. The 1939 Erzincan earthquake in Eastern Turkey with a 7.9 magnitude killed 33,000 people, damaged 117,000 buildings and resulted in a 360-km long surface rupture on five different segments (Barka 1996). The more recent August 1999 Marmara earthquake with the epicentre in the highly industrialized and urbanized north-western province of Kocaeli with a magnitude of 7.8 killed 17,500 people, injured 44,000 people, damaged 73,342 buildings and caused an average surface displacement of about 2.5 m along the central part of the fault line (Toksoz et al. 1999) and a maximum of 5.7 m (Reilinger et al. 2000). Property losses as of 14 September 1999 ranged from $3 to $6.5 billion, which was equivalent to 1.5%—3.3% of the Gross National Product of Turkey at the time (USGS 2000).

Damage resulting from earthquakes is usually reported in terms of direct human suffering like injury, fatality and material damage such as building damage and financial loss. Not surprising, fatality receives the most attention because of its direct impact on human life. Geologic, seismic and site-specific factors determine the damage caused by earthquakes including earthquake magnitude, the depth of the earthquake, seismic wave attenuation, geological structure of the affected area, type and quality of construction, the location of the epicentre of the earthquake and population density. Among these geologic and seismic parameters that characterize ground shaking associated with earthquakes are peak ground acceleration and Arias intensity, which have been analyzed in recent major earthquakes in Italy, Greece and Japan (Del Gaudio & Wasowski 2011; Goda et al. 2013; Chousianitis et al. 2014). Some researchers have also estimated fatality as a function of the time of day the earthquake occurred (Lomnitz 1970), number of completely destroyed houses (Ohta et al. 1983), earthquake magnitude (Oike 1991) and population density (Samardjieva & Badal 2002).

Given the frequency and destructive nature of earthquakes in Turkey, numerous studies that focused on geophysical, geodetic and seismic characteristics of earthquakes (see additionally; Parsons et al. 2000; Şengör et al. 2005; Gürsoy et al. 2013; Ergintav et al. 2014; Askan et al. 2015) and reports that provide statistics about the damage caused by major earthquakes have been published. Additionally, response systems to estimate earthquake loss (Erdik et al. 2011) and earthquake
hazard in Marmara Region of Turkey have been studied (Erdik et al. 2004). However, there has been no study that has investigated the relationship between fatality and some of the factors mentioned earlier. Moreover, there is no quantitative information whether clusters of earthquake occurrence and the damage caused by the earthquakes exist across space and time. This study will fill a gap in the literature by providing quantitative information about earthquake occurrence and damage at the provincial level in a spatiotemporal context. The results of the study will be useful for two major reasons. First, the results will contribute to our knowledge of earthquake damage and the relationship between damage and some of the factors. Second, the quantitative results will be useful from a policy, city planning and emergency management perspective by providing robust data to be used for the preparation of disaster mitigation plans, allocation of resources to most vulnerable areas and implementation of policies to better prepare for future earthquakes. Specifically, the objectives of this study are

1. to investigate the relationship between fatality and (i) time of earthquake occurrence, (ii) magnitude of earthquakes, (iii) energy released by earthquakes and (iv) building damage from earthquakes in Turkey as well as the relationship between building damage and earthquake magnitude and energy.

2. to identify whether patterns exist in earthquake occurrences and associated damage in Turkey across time and space.

2. Data and methods

2.1. Data and pre-processing

Earthquake data were obtained from the National Earthquake Screening Office of the Kandilli Observatory and Earthquake Research Institute at the Bosphorus University in Istanbul, Turkey (KOERI 2015). Ninety-three earthquakes that occurred between 1900 and 2012 with a magnitude greater than or equal to 5, resulting in either building damage or fatality were included in the analysis (see supplementary material). The coordinates of the reported earthquakes were entered based on the location information provided in the original data-set, the majority of which was at the level of district. The file was converted to a database file and was opened in ArcGIS ArcMap with X-Y display.

Since the energy released by an earthquake is the major factor causing damage, the relationship between the energy released by an earthquake and the resulting fatality and building damage was explored using bivariate maps. The energy released was calculated according to the formula

\[
\log E = 11.8 + 1.5M_s
\]

where \( E \) is the energy released in ergs, and \( M_s \) is the surface magnitude of the earthquake. Unit of energy was converted to terajoules (TJ) for ease of display.

In addition to displaying the raw values of fatality, total fatality resulting from a given earthquake was divided by the population of the province in the year the earthquake took place to better reflect the rate of death toll resulting from earthquakes. Census data were obtained from the Turkish Statistical Institute (TUIK 2015). Population projections between census years were calculated based on the annual growth rate of the province. The fatality rates were reported as percentage values.

Shapefiles of Turkey showing province boundaries and the countries and water bodies in the periphery of Turkey were downloaded from the Global Administrative Areas website (GADM 2015). The point shapefile showing the location of earthquakes was joined to the polygon Turkey
shapefile displaying provinces to represent and analyze the data at the province level. The number of earthquakes and resulting fatality, building damage and fatality rate in each province were summed during the join operation.

2.2. Statistical and spatiotemporal analyses and map generation

The relationships between fatality and magnitude, building damage and total energy released, and between building damage and magnitude and total energy released were examined using linear regression. Since the Richter scale is on logarithmic scale (base 10), fatality and building damage values were log-transformed to obtain linear fits in the magnitude versus fatality and magnitude versus building damage graphs. To check the effect of time of earthquake occurrence on fatality, fatality associated with each earthquake was plotted against time.

Earthquake occurrence data were analyzed between 1900 and 2012 using space—time scan statistics to better characterize the spatiotemporal nature of the data. Retrospective space—time analysis with space—time permutation probability model was conducted to identify clusters with the open source SaTScan software. The space—time permutation only requires case data with spatial location and time information. A cluster in a geographical area is identified if during a specific time period, that area has a higher proportion of its cases in that time period compared to the remaining geographical areas. This is done by comparing the number of observed cases in a cluster to what would have been expected if the spatial and temporal locations of all cases were independent of each other so that there is no space—time interaction. The analysis is carried out by a cylindrical window, in which the circular or elliptical base corresponds to space and the height represents the time period of potential clusters. The cylindrical window is moved in space and time, ensuring that each possible time period is considered for each possible geographical location and size. As a result, infinite number of overlapping cylinders of different size and shape (each of which represents a possible cluster), jointly covering the entire study region are obtained. The significance of identified space—time clusters is determined by the \( p \)-value, which is calculated with Monte Carlo replication. SaTScan performs simulations to generate a number of random replications of the data-set. The null hypothesis that there are no clusters is rejected if the maximum likelihood ratio calculated for the most likely cluster in the data-set is higher than the maximum likelihood ratios calculated for the most likely clusters in the random data-set (Kulldorff 2015).

Spatial patterns in aggregated data at the provincial level were analyzed by spatial statistics. Hot spot analysis test using the Getis-Ord \( G_i^* \) statistic was conducted to identify the location of local clusters for total earthquake occurrence, total fatality, fatality rate and total building damage within each province. In the Getis-Ord \( G_i^* \) method, a local weighted mean around each observation including the observation itself is compared to the mean of the entire data-set (Getis & Ord 1992). In the analysis, spatial relationship of the feature to the neighbouring features and a threshold distance beyond which the adjacent features are ignored are specified. A fixed distance band spatial relationship with Euclidean distance (i.e. straight line distance) and a 60,000 m threshold distance were used in this analysis. The result of the comparison is a \( z \) score, i.e. the Getis-Ord \( G_i^* \) statistic. Positive and negative \( z \) scores indicate clustering of high values (hot spot) and low values (cold spot), respectively. \( Z \) score values of 1.65, 1.96 and 2.58 correspond to 90%, 95% and 99% confidence intervals.

The hot spot analysis was performed in ArcGIS 10.3.1 software and the product is a layer that displays hot and cold spots of the variable of interest with confidences of 90%, 95% and 99% and areas of no significance. Graduated symbols maps representing total fatality, total fatality rate, total building damage and total number of earthquakes within each province with five classes were produced. Class breaks in all of the maps were determined using Jenks natural breaks. These maps were laid over the hot spot analysis layers of the respective factor to generate the maps representing hot spots of fatality, fatality rate, building damage and earthquake occurrence.
3. Results and discussion

3.1. Relationships between earthquake damage and associated factors

Figure 2 displays the relationship between earthquake magnitude and damage. Earthquake magnitude explains only 48% and 43% of the variation in fatality and building damage, respectively (figures 2(a) and (b)) whereas there is strong linear relationship between energy of an earthquake and resulting fatality or building damage.

The relationship between the energy released and resulting damage of earthquakes is shown in Figure 3. Ninety-one per cent and 83% of the variation in fatality and building damage are accounted for by the energy released from an earthquake (figures 3(a) and (b)).

Figure 4 shows the relationship between fatality and building damage. Building damage explains 85% of the variation in fatality resulting from major earthquakes in Turkey between 1900 and 2012 (figure 4).

The time of the day that the earthquake takes place is an important factor for death toll associated with earthquakes in Turkey. This is displayed in figure 5, where 76% of the total death toll is a result of the earthquakes that happened between midnight and 5:22 am. even though the number of earthquakes in the same time period corresponds to less than one quarter of the total earthquake number (figure 5).

These results suggest that improving building quality should be one of the primary objectives in the attempts to reduce fatalities resulting from earthquakes in Turkey since nothing can be done about the time of earthquake occurrence. There have been some advances in building improvements

![Figure 2](image-url)
especially after the 1999 Marmara and Duzce earthquakes. For example, the Turkish Earthquake Code was updated in 2007 to consider the seismic risks more comprehensively in the construction of new buildings. The National Earthquake Strategy and Action Plan for the period between 2012 to 2023 was released in 2015, which aims to mitigate the damage of earthquakes, coordinate the related

Figure 3. The relationship between fatality and energy released by major earthquakes (a); and between building damage and energy released by major earthquakes (b). Fatality and building damage values are in thousands.

Figure 4. The relationship between fatality and building damage of major earthquakes in Turkey between 1900 and 2012. Fatality and building damage values are in thousands.
agencies in the recovery efforts and constitute new earthquake resistant, prepared and sustainable settlements (AFAD 2015). The Action Plan aims to lessen fatality considering the next major earthquake (Mw ≥ 7.0) has a 53% probability of occurrence between 2004 and 2034 in the western end of the North Anatolian Fault beneath the Sea of Marmara. The city of Istanbul is also a hot target with 41% of probability of being affected in the near future (Parsons 2004). Because of the imminent threat to Istanbul, Earthquake Master Plan has been prepared by the Metropolitan Municipality in 2003. However, the risk posed by the presence of large number of damaged buildings is not minor and could contribute to fatality in the next major earthquake. As a result, Istanbul Metropolitan Municipality and the Turkish government initiated urban renewal projects in Istanbul and a few other cities around Turkey to demolish and retrofit some of the damaged buildings that pose a threat to life and safety in certain neighbourhoods. Additionally, training programs to educate teachers, students and citizens about earthquake response and preparation in order to reduce fatality and injury by the government and NGOs reached out to thousands across Turkey in earthquake prone cities.

3.2. Spatiotemporal and spatial analysis of earthquake damage

From a spatiotemporal perspective, several clusters in different parts of Turkey emerged, which are indicated as ellipses of varying sizes in figure 6. Two of these in Western Turkey were significant clusters. One of them covered a two-year period from 1969 to 1971 during which eight earthquakes took place (p < 0.05). The other one represented an 11-year period between 1955 and 1965 during which seven earthquakes occurred (p < 0.10). There were also two large clusters centred on the North Anatolian Fault representing four- (1999–2002) and 15-year (1929 to 1943) periods. Another cluster was located around the confluence of East and North Anatolian Faults representing an eight-year period from 2003 to 2010. There were three smaller clusters in eastern Turkey restricted to one- (2011) and two- (1983 to 1984) year periods. The results of the spatiotemporal analysis reflect the seismic activity in Western and Eastern Turkey and also along the North Anatolian Fault over 112 years.

Hot spot analysis as shown in figure 7 reveals two very significant clusters of fatality (p < 0.001), the provinces of Kocaeli and Erzincan in North-western and Eastern Turkey, respectively. The total number of fatalities in these two provinces account for 63% of the total death toll over the time
period between 1900 and 2012. The high fatality values in these provinces indicate the devastating effects of the earthquakes that took place in them in 1939 and 1999.

Figure 8 shows the percentages of total fatality rates by province population resulting from the major earthquakes and the Getis-Ord Gi’ confidence intervals. The eastern province of Erzincan with 21% fatality rate emerged as a very significant hot spot ($p < 0.01$). This finding reflects the staggering death toll of the earthquake that took place there in 1939. Four provinces in Northern Turkey also have high fatality rates resulting from the earthquakes that took place on the North Anatolian Fault as well as three provinces in Eastern Turkey which sit on the confluence of the North Anatolian and East Anatolian Fault lines. These two maps also indicate that fatality and fatality rates are lower in Western Turkey than in Eastern Turkey.

Figure 9 displays the clusters of building damage and total number of damaged building in each province. Similar to the pattern in fatality, provinces of Erzincan and Kocaeli suffered the greatest building damage over 112 years ($p \leq 0.01$). Additionally, the province of Samsun in the north had significant building damage ($p \leq 0.10$). Together, the building damage in these three provinces account for 41% of the total building damage caused by the earthquakes over 112 years. Some of the same provinces that suffered high fatality rates in north central and Eastern Turkey also have moderately high building damage. One interesting pattern to note in this map is the high rate of building damage in the small province of Duzce to the east of Kocaeli, which had low fatality number according to figure 8. This is probably due to the 7.5 magnitude earthquake that occurred here only three months after the August 1999 Marmara earthquake and many of the buildings that already were seriously damaged and uninhabited collapsed. This map also shows that building damage is more evenly distributed between eastern and western provinces struck by earthquakes compared to fatality.

![Figure 6. Spatiotemporal clusters of major earthquakes in Turkey between 1900 and 2012.](image)
The total number of earthquakes within each province and hot spots of earthquake occurrence is shown in figure 10. According to the map, several provinces in Eastern and Western Turkey had numerous earthquakes. Like building damage, total earthquake number has an even distribution between eastern and western provinces. The province of Bingol in Eastern Turkey had the greatest number of earthquakes, five, over 112 years and represented a very significant hot cluster ($p < 0.01$). The provinces which experienced four earthquakes from 1900 to 2012 were also hot spots of earthquake occurrence ($p \leq 0.10$).

In addition to the factors causing fatality and building damage considered in this study, there are geologic, seismic and site-specific factors like the depth of the earthquake, seismic wave attenuation, geological structure of the affected area, type and quality of construction, the location of the epicentre of the earthquake and population density, which all play a role in the damage caused by earthquakes. For example, the stronger the building is, the less likely it is to get damaged, lean over or collapse. As a result, there will be fewer fatalities. Even though a quantitative analysis of the effect of building strength was not conducted in this study due to lack of data availability, it is known that Eastern Turkey is a poorer and less developed part of the country where buildings are not built at the same standards as in the more developed western part of the country. The difference in building strength may partially explain the difference between the numbers of fatality in Western versus Eastern Turkey. Greater fatality and building damage will occur if the epicentre is closer to an urban and/or industrial area. This was the case for the 1999 Marmara earthquake. The epicentre was located in one of the most populated and industrialized parts of Turkey (i.e. Kocaeli province), therefore the damage was pronounced despite the occurrence of only one major earthquake in the province over a century.

Figure 7. Hot spots of fatality and total fatality resulting from major earthquakes in each province of Turkey between 1900 and 2012.
It should also be kept in mind that the total building damage or total fatality values displayed on the maps may be slightly overestimated for some of the provinces because some of these earthquakes caused building damage and fatality in the neighbouring provinces such as the 1999 Marmara earthquake. However, the data source utilized in this study does not provide information at that level. Future studies should focus on all data sources to provide more detailed information about earthquake damage. Also, the total number of damaged buildings for each province was not available so normalization was not possible as it was for fatality.

4. Conclusions

In this study, the relationship between fatality and (1) earthquake magnitude, (2) energy released by an earthquake, (3) building damage from an earthquake and (4) time of earthquake occurrence was examined along with the relationship between building damage from an earthquake and magnitude and energy released by the earthquakes in Turkey between 1900 and 2012. Existence of patterns in earthquake occurrence and associated damage in Turkey across time and space was also investigated. The analysis was restricted to earthquakes with magnitude greater than or equal to five and which resulted in either building damage or fatality. The following conclusions can be drawn from the results:

(1) Energy released by an earthquake is more directly and strongly correlated with fatality and building damage than magnitude. It explains 91% and 83% of the variation in fatality and number of damaged buildings.
Building damage accounts for most of the fatality resulting from earthquakes. It accounts for 85% of the variation in fatality.

Earthquakes that occur at night result in higher fatality accounting for 76% of total death toll over 112 years.

Kocaeli province in North-western Turkey and Erzincan province in Eastern Turkey suffered the highest fatality and building damage. They represent hot spots of earthquake damage.

Fatality and fatality rate is higher in Eastern Turkey compared to Western Turkey whereas number of damaged buildings and earthquake occurrence is more evenly distributed between the two parts of the country, and Central Turkey suffered less fatality and building damage overall.

The location of major earthquakes over 112 years tends to parallel the tectonically active areas of Turkey such as the North and East Anatolian Faults and Western Turkey towards the Aegean Sea. Central, central south, extreme north-western, north-eastern and south-eastern Turkey appears to be void of major earthquakes.

These findings improve our spatial understanding of major earthquake distribution and damage in Turkey at province level between 1900 and 2012. They also highlight the importance of focusing efforts on building strength and retrofitting to reduce the damage from the possible major earthquake that is expected to occur in densely populated and urbanized Western Turkey. Overall, the information gained from the study will be useful for the preparation of disaster mitigation plans, allocation of resources to most vulnerable areas and implementation of policies to better prepare for future earthquakes in Turkey.
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Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributor

Kemal Gökçayya is a visiting scholar at the Environmental Change Initiative at the University of Notre Dame. His research interests are in ecology focusing on applications of geospatial technology (remote sensing and geographic information systems) to study forest structure, physiology, natural hazards and biogeochemistry.

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