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Fleeing to Fault Zones: Incorporating Syrian Refugees into Earthquake Risk Analysis along the East Anatolian and Dead Sea Rift Fault Zones

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geography

by

Bradley Steven Wilson Colorado School of Mines Bachelor of Science in Geophysical Engineering, 2015

December 2016 University of Arkansas

This thesis is approved for recommendation to the Graduate Council

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ABSTRACT

The influx of millions of Syrian refugees into Turkey has rapidly changed the population distribution along the Dead Sea Rift and East Anatolian Fault zones. In contrast to other countries in the Middle East where refugees are accommodated in camp environments, the majority of displaced individuals in Turkey are integrated into local cities, towns, and villages—placing stress on urban settings and increasing potential exposure to strong earthquake shaking. Yet, displaced populations are not traditionally captured in data sources used in earthquake risk analysis or loss estimations. Accordingly, this study presents a district-level analysis assessing the spatial overlap of earthquake hazards and refugee locations in southeastern Turkey, in hopes of determining how migration patterns are altering seismic risk in the region.

Using migration estimates from the U.S. Humanitarian Information Unit, district-level population scenarios that combine official population statistics with camped and non-camped refugee population bounds were created. Probabilistic seismic hazard analysis was performed alongside these scenarios to map spatial variations in seismic risk between 2011 and 2015. Results show a relative southward increase of seismic risk for this period due to refugee migration. Additionally, earthquake fatalities were calculated using a semi-empirical loss estimation technique on five faults to determine degree of under-estimation resulting from forgoing migration data in loss modeling. It was found that refugee populations increase casualties by 11-12% using median population estimates, and upwards of 20% using high population estimates. These findings communicate the ongoing importance of placing environmental hazards in their appropriate regional context which unites physical, political, cultural, and socio-economic landscapes.

Keywords: Earthquakes, Hazards, Loss-Estimation, Syrian Crisis, Migration, Refugees

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DEDICATION

To those affected by the conflict in Syria—may you be able to return home soon.

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1: INTRODUCTION

In late 2010, a series of protests calling for regime change erupted across the Middle East, now referred to as the Arab Spring. Protestors seeking non-violent and peaceful transition of power were met with varying responses from governments at large. In early 2011, the Arab Spring uprisings reached the Arab Republic of Syria. The situation escalated from marches and demonstrations into a full-blown civil war after the Syrian government, led by president Bashar al-Assad, attempted to nullify protests with force. As the Islamic State of Iraq and the Levant (ISIL) concurrently expanded their regional influence, Syria devolved into a territorial battle between government soldiers, rebel opposition, and ISIL forces. The conflict, currently in its fifth year, has displaced over eleven million individuals since its onset in 2011 (UNHCR, 2015). 6.6 million Syrians remain internally displaced, driven away from their homes in avoidance of conflict (MPC, 2016). 4.8 million refugees have been granted formal refugee status in neighboring countries, with just over half (2.5 million) settling in the Republic of Turkey (MPC, 2016).

In an effort to gain distance from areas of internal conflict and ISIL control, many Syrians have fled northward and westward into Turkey as well as settling in unofficial tent camps along the border region. This pattern of migration reflects the locations of conflict zones and active border crossings. However, these settlement locations also lie in a complex tectonic convergence zone between the African, Arabian, Eurasian, and Anatolian tectonic plates, linked together by two large active fault systems, the Dead Sea Fault zone and the East Anatolian Fault zone. The Dead Sea Fault zone extends up through the Hatay province into Kahramanmaraş, where it connects with the East Anatolian Fault zone, extending northeast across its namesake geographic region, Eastern Anatolia. These fault zones have been repeatedly struck by large earthquakes, including several of the deadliest earthquakes in recorded history (Ambraseys, 2009, Sbeinati et al.,

2005).

Earthquakes and mass migration are typically linked in a reversed context, where individuals are forced to move away from areas damaged in earthquake shaking. This study takes a novel approach by doing the opposite—analyzing how mass migration can increase earthquake risk prior to an event's occurrence. The influx of millions of Syrian refugees into Turkey is rapidly changing the population and demographic distribution of earthquake prone regions, thereby increasing the number of individuals potentially exposed to earthquake shaking. Properly assessing these earthquake risks and estimating potential casualties depends on reliable population statistics (Guha-Sapir and Vos, 2011). Yet, displaced persons estimates are not traditionally captured in data sources used in earthquake risk analysis or loss estimations.

Assessing the spatial overlap of refugee migration and earthquake activity forms the foundation for this research. However, the refugee situation in Turkey is demonstrably unique in several ways that contribute to seismic risk concerns. In contrast to other countries in the Middle East, the majority of the Syrian refugees in Turkey are not located in refugee camps (3RP, 2015)—stressing local cities through increased urbanization. Currently, 25% of refugee populations in southern provinces live in makeshift or rubble housing (3RP, 2015). The sheer number of buildings required to adequately house refugee populations creates a serious challenge for local communities. In the past, high rates of urbanization and industrialization in Turkey have contributed to the Turkish government's failure to regulate seismic building codes (Erdik, 2001). When combined with dense populations, inadequate housing and the inability to enforce building codes are particularly problematic because virtually all earthquake deaths follow from building collapse.

Risk perceptions and social attitudes help drive the under-enforcement of earthquake-

resistant construction practices. Risk perception studies consistently find that individuals with no earthquake experience or non-damaging earthquake experience are more likely to underestimate future earthquake impacts and ignore earthquake warnings (Solberg et al., 2010). Accordingly, the recent respite in earthquake activity in southern Turkey (Ambraseys, 1989, Meghraoui et al., 2003) likely contributes to under-preparedness. Eraybar et al. (2010) found that individuals in Istanbul professed beliefs that their houses were adequately constructed for earthquake behavior, despite historical evidence for the contrary (Erdik, 2001, Ilki and Celep, 2012).

The Kocaeli Earthquake of 1999 spotlighted the deadly combination of densely populated areas, poorly constructed buildings, and minimally adjusted persons. The earthquake ruptured several portions of the North Anatolian Fault outside Istanbul, officially killing over 17,000 persons and injuring another 40,000 persons (unofficial death totals place casualties closer to 40,000) (Ganapati, 2009). The earthquake struck a region of rapid population growth on fault segments known to have accumulated enough stress to rupture in a large earthquake (Erdik, 2001). Yet, the widespread extent of building collapse indicated significant noncompliance to Turkish seismic building codes designed to protect structures in areas of high hazard. Furthermore, Erdik (2001) argues that the Turkish government's "legal obligation to replace or repair damaged housing after an earthquake provided discouragement for insurance and implicit encouragement and rewards for inexpensive housing with poor earthquake performance," (18). As refugee migration increases population density in vulnerable urban settings, the 1999 Kocaeli earthquake remains a stark reminder of the scale of potential consequences.

With approximately 1.4 million refugees migrated into this research's study area, the increases in population due to Syrian migration are staggering. As of the end of 2015, refugees constitute nearly twenty percent of the total population. The rate of population change from refugees

far outpaces that of internal migration. As such, refugee migration is increasing seismic risk and potential earthquake consequences along the Turkey-Syria border region. However, the spatial distribution of refugees in uncertain. The U.S. Humanitarian Information Unit tracks provincial estimates of displaced persons, but with large error bounds. In Turkey, the categorical breakdown of refugees by province are grouped into less than 1000, 1,000 to 10,000, 10,000 to 100,000, and 100,000 to 500,000 individuals (HIU, 2016). Following that refugee populations represent a sizable portion of this region's population but are not typically incorporated into earthquake risk analyses, this research seeks to accomplish two major tasks: (1) map the spatial variations in seismic risk at the district level in 2011 and early 2015 to show the impacts of refugee migration; (2) calculate the magnitude of earthquake casualty under-estimation resulting from forgoing inclusion of migration data in loss modeling.

This study represents a necessary step forward in working to properly characterize earthquake risk in regions of the world experiencing rapid population change. Identifying the challenges associated with natural hazard policy and risk mitigation steps in varying social and political contexts is the first step in designing regional solutions. While the Syrian refugee crisis certainly presents more immediate budgetary issues than long-period earthquake mitigation, this work stresses why ongoing natural hazards work in the Middle East needs to consider displaced populations in modeling projects. Additionally, the refugee crisis provides a compelling narrative for communicating earthquake risk and the urgent need to continue developing low cost earthquake-resistant construction for the developing world. These conclusions, combined with stark visualizations of the changes in seismic risk in a four year period, represent a essential first step in drawing connections between mass migration and earthquake risk.

2: STUDY SITE

As the temporary home of over half of the Syrian conflict's refugees, Turkey has accommodated more Syrian refugees than any other country in the Middle East (UNHCR, 2015, MPC, 2016). Additionally, many of the six and a half million internally displaced Syrians are settled along the border between Turkey and Syria. As displaced persons flee Syria, they experience geographic shifts in addition to cultural, societal, and lifestyle changes. Relevant to this research is a notable change in tectonics from broad Syrian plateaus on the northern end of the Arabian plate to Turkish fault zones that mark the convergence of the Arabian, Anatolian, Eurasian, and African Plates. Many refugees have migrated away from relatively stable continental settings and settled on top of active fault zones with long histories of earthquake activity. This chapter uses cartographic techniques to explore areas of overlap between displaced populations and active fault zones. Additionally, this chapter provides an overview of the geologic setting, historical seismicity, and migration history of the area—three factors that frame the importance of linking displaced persons to natural hazards.

2.1 Geographic and Administrative Boundaries

Turkey is subdivided into both geographic and statistical regions. The 1941 First Geography Congress subdivided Turkey into seven geographic regions, seen below in Figure 2.1, according to climatic and geographic boundaries: Marmara, Black Sea, Aegean, Mediterranean, Central Anatolia, Eastern Anatolia, and Southeastern Anatolia. This research's examines the area bounded between 35E, 35N, and 40E, 40N (shown in Figure 2.2), incorporating portions of four geographic regions: Southeastern Anatolia, Central Anatolia, Mediterranean, and Eastern Anatolia. As a candidate country for entry into the European Union, Turkey is also divided into twelve, twenty-six and eighty one statistical regions, subregions and provinces, respectively, according to the Nomenclature of Territorial Units for Statistics (NUTS) system. Each NUTS province is also subdivided into districts. In 2013, Turkey underwent a local government reorganization that defined new metropolitan municipality system. Provinces with over 750,000 individuals are designated as metropolitan municipalities, the largest municipality designation. The thirty provinces designated as metropolitan municipalities cover 50% of Turkey's land area and include 73% of Turkey's population (Akilli and Akilli, 2014). The rest of Turkey's population resides in smaller district or town level municipalities. This process of reorganization into metropolitan districts dissolved many smaller scale municipalities and villages into neighborhoods with no formal administrative entity (Akilli and Akilli, 2014). These changes do not have



Figure 2.1: This map represents the seven geographic regions of Turkey, as defined by the 1941 First Geography Congress. (Cartography by Bradley Wilson).

direct impacts on the earthquake analysis in this research, but are important for larger discussions on risk and hazard policy.



Figure 2.2: This map shows the location of the study site in reference to Turkey and surrounding countries (Cartography by Bradley Wilson).

The boundaries for this research (above: Figure 2.2, below: Figure 2.3) were chosen to incorporate provinces accommodating over 10,000 displaced persons in close proximity to the East Anatolian and Dead Sea Rift fault zones. Most portions of the North Anatolian Fault system were not included because refugee migration significantly decreases away from the Turkey-Syria border. The majority of the analysis in this study was performed at the district level. Provincial-scale boundaries are too large to capture subtleties within both earthquake shaking and population distribution—two important factors for characterizing earthquake risk. Therefore, the district scale was chosen to allow for earthquake shaking intensity to be spatially averaged and compared to population data. The only data not available at the district level was refugee statistics, which

were collected at the province level. To account for this discrepancy, province level statistics were converted into district level populations by assuming displaced persons are distributed in equal proportion to citizens. This process is described in further detail in Chapter Four.



Figure 2.3: This map shows the provinces, districts, and population centers included in the study area. (Cartography by Bradley Wilson).

2.2 Climate

Three major climatic zones are represented across south central Turkey, as defined by the Köppen climate classification in Chen and Chen (2013). Provinces along the Mediterranean Sea are dominated by dry-summer subtropical climates, colloquially referred to as a Mediterranean climate. These areas are characterized by dry, hot summers and mild, comfortable winters. The Mediterranean Sea helps regulate temperature, resulting in smaller temperature fluctuations compared to inland provinces. Further north in Turkey are zones of cold-semi arid climate, a type of steppe climate. These transitional climatic zones exhibit similar precipitation patterns to Mediterranean climate zones with dry summers and wet winters, but have larger seasonal and daily temperature variations. Cold-semi arid climates are not as hot as hot semi-arid or hot desert climatic zones, but maintain an average temperature in the coldest month of zero degrees Celsius. Turkey transitions even further northward into a temperate continental climate. This climate classification has warm, comfortable summers, with an average warmest month of twenty two degrees Celsius. Conversely, winters tend to be quite cold with frosting periods lasting up to nine months of the year.

2.3 Geology and Tectonics

Southern Turkey and northern Syria are broken up into two main tectonic zones, the Anatolide-Tauride block to the north and the Arabian Platform to the south, seen in Figure 2.5. The geological development of the this region upon is linked to the evolution of the Tethys ocean during the Mesozoic and Cenozoic eras, separating the former continents of Gondwana and Laurasia (Okay, 2008). The Anatolide-Tuaride zone, comprising most of southern Turkey, is defined by three



Figure 2.4: This map shows the distribution of Köppen climate zones for Turkey and Syria. (Cartography by Bradley Wilson).

characteristics: "a late Precambrian crystalline basement, a mixed clastic-carbonate Palaeozoic succession, and a thick Upper Triassic to Upper Cretaceous carbonate sequence," (Okay, 2008) (30). The Anatolide-Taurides are dominated by various forms of metamorphism associated with subduction along the boundaries of the Tethys sea. The Arabian platform, covering the southern most parts of Turkey and Syria, is similarly comprised of a crystalline basement overlain by Palaeozoic to Tertiary sedimentary units (Okay, 2008). Stratigraphic sections of both zones contain crystalline basement overlain by deep marine deposits, metamorphosed carbonates, ophiolitic sequences, and Cenozoic sediments (Chorowicz et al., 1994).

2.3.1 Major Fault Zones

Turkey lies in a complex convergence zone between the African, Arabian, Eurasian, and Anatolian tectonic plates. The two main fault zones included in this study, the East Anatolian Fault (EAF) and the Dead Sea Rift (DSF), constitute the boundaries between these plates. The African and Arabian plates are moving northward with respect to the Eurasian continent, with the difference in motion between them accommodated as left-lateral strike slip motion along the DSF (Chorowicz et al., 1994). The lateral portion of the collision zone between the Arabian plate and the Eurasian plate results in the squeezing out of the Anatolian plate. This motion is accommodated as right lateral strike slip faulting on the North Anatolian Fault and left lateral strike slip faulting along the EAF (Barka and Kadinsky-Cade, 1988). These two faults constitute the northern and southern boundaries of the Anatolian plate.

The EAF system extends for roughly 580 kilometers between south-central Turkey near the city of Kahramanmaraş and eastern Turkey near the city of Karlıova (Duman and Emre, 2013). The EAF zone is Pliocene in age and is characterized by a highly fractured system of breaks,



Figure 2.5: This map highlights the major tectonic features and fault zones in the study area. The East Anatolian and Dead Sea Fault systems are this study's main focus areas. (Cartography by Bradley Wilson).

bends, and stepovers (Barka and Kadinsky-Cade, 1988, Yilmas et al., 2006). Strike-slip, thrusting, and folding features are all present on the EAF. Estimates of the EAF's total displacement vary from 22-27 kilometers with an annual slip rate of half a centimeter per year (Barka and Kadinsky-Cade, 1988), to more recent estimates of 15-17 kilometers with an annual slip rate of one centimeter per year (Duman and Emre, 2013). Many of the individual ruptured sections are poorly constrained in length (Barka and Kadinsky-Cade, 1988). Historical seismicity is valuable for reconstructing fault activity prior to the instrumental seismic record, but the large error windows on most historical earthquakes complicates linking historical events to specific parts of the fault (Ambraseys, 1971).

The DSF connects the 1000 kilometer segment between the northern extent of the Red Sea spreading center at the Gulf of Aqaba to the western end of the East Anatolian Fault system near the town of Kahramanmaraş (Garfunkel et al., 1981). Like the EAF, the primary motion along the DSF is left lateral strike-slip, although both normal and thrust motion has been observed for localized earthquake events. The DSF is seismically active but the rates of slip have been variable throughout time. Garfunkel et al. (1981) found slip rates over the past 1000-1500 years to be 0.15-0.35 centimeters per year, while historical estimates place Pliocene-Pleistocene rates at 0.7-1.0 centimeters per year. Current kinematic models place slip rates for the DSF between 0.04 and 0.07 centimeters per year (Meghraoui et al., 2011). Paleoseismology evidence suggests the DSF displays long-period seismicity on the order of 800 years, and may be overdue for a large earthquake event (Meghraoui et al., 2003).

The structural relationship between the EAF and DSF is complex and poorly understood. The intersection between the two fault zones is generally believed to occur at a triple junction near the town of Kahramanmaraş (Chorowicz et al., 1994), or slightly further south near Antakya

(Over et al., 2004). Doğan Perinçek and İbrahim Çemen (1990) argued that the two faults can essentialy be considered one large fault system with two distinct zones. Duman and Emre (2013) presented a model where the EAF splits into two strands with the southern portion connecting into the DSF further to the south. Meghraoui et al. (2011) tested various kinematic models for the intersection zone, favoring a model with pure transform motion along the DSF.

2.4 Historical Seismicity

The Middle East has a rich history of documented earthquakes dating back to 2000 B.C.E.. Historical seismicity is reconstructed from a number of sources, including written histories, epigraphs, archaeoseismology, remote sensing analysis, fault trenching, and local on-site geological studies (Ambraseys, 2009). Compiled earthquake catalogs appear as early as the 1458 C.E. with *De Terremuto (The Earthquake)*, the first known earthquake catalog by Italian Giannozzo Manetti. Catalogs from other regions appear shortly after Manetti's De Terremuto, with the first Middle Eastern catalog extending the work of Ibn al-Suyuti in the 9th and 10th centuries through 1588 C.E. (Ambraseys, 2009). Surviving portions of these earthquake catalogs are integrated into the largest modern Mediterranean and Middle Eastern earthquake compendium, *Earthquakes in the Mediterranean and Middle East*, published in 2009 by Nicolas Ambraseys. While the extent to which historical earthquakes' epicenter locations, magnitudes, intensities, and damage are known varies widely by individual event, the cumulative knowledge provided by a comprehensive catalog allow for the identification of earthquake trends, and in some cases, reconstructions of shaking intensity.

The EAF and DSF, like other areas in the Middle East, have repeatedly struck by large earthquakes (Sbeinati et al., 2005, Barka and Kadinsky-Cade, 1988, Garfunkel et al., 1981). The

record of historical seismicity along these fault systems is so strong that the area was considered to have the highest seismic risk of anywhere across the Mediterranean and Middle East 150 years ago, as published in Robert Mallet's 1857 seismic hazard map (Ambraseys, 2009). With a recent quiescence in seismic activity in southeast Turkey (Ambraseys, 1989, Meghraoui et al., 2003), historical seismicity becomes an important tool for understanding the long-term behavior of the fault zones in this area. Historical seismicity helps to estimate earthquake recurrence intervals that that extend past the modern seismic record, which only dates back to the late 1950's (Ambraseys, 1971).

Ambraseys (2009) provides a detailed overview of historical seismicity in the Middle East. Large earthquakes in southern Turkey first appear in the historical records in 148 B.C.E. in the writings of John Malalas, who chronicles the destruction of the city of Antioch due to the 'Wrath of God', a phrase often used to describe earthquake events. Less than one hundred years later, sometime between 69 B.C.E. and 66 B.C.E., a large earthquake shakes several Syrian cities, killing 170,000 according to third century writer Justin, who first mentions the quake. It is unknown precisely where this earthquake struck or how large it was, but later records indicate it was likely near Antioch or along the Crimean Peninsula. These two earthquake represent the beginning of the repeated destruction and rebuilding of the city of Antioch. Antioch, located in the Hatay province of modern day Turkey, is shaken again over forty times before 1900 C.E.. The earthquakes that destroyed Antioch in 115 C.E. and 526 C.E. are estimated to have killed 250,000 or more individuals each. If these numbers are correct, both of these earthquakes fall into the top ten most deadly earthquakes of all time (Musson, 2001) (the death estimates may be exaggerated, but are generally considered to be plausible (Ambraseys, 2009)).

From a historical perspective, both the 115 C.E. and 528 C.E. earthquakes are worth ex-

amining. The 115 C.E. earthquake strikes in the morning of December 13th, leveling Antioch and the surrounding area— already the third time Antioch had been destroyed. Ambraseys (2009) describes the damage:

"People standing in the open were thrown down and trees were uprooted and toppled. Almost all structures in Antioch were damaged, and three quarters of the city collapsed, killing a large number of people..." (122).

These descriptions are useful for reconstructing the intensity of the earthquake, estimated at extreme on the Modified Mercalli Intensity scale (XI). The Roman emperor at the time, Trajan, happened to be in Antioch during the 115 C.E. earthquake and initiated a large scale reconstruction of the city that was completed by his successor, Hadrian. Details from the 115 C.E. earthquake are thoroughly chronicled in the writings of Malalas, Eusebius, Dio Cassius, Orosius, and others (Ambraseys, 2009, Sbeinati et al., 2005). The 526 C.E. earthquake struck on the 29th of May, Ascension Day, marking the fifth time the city has been completely or partially destroyed. This death totals for this earthquake (250,000 - 300,000) were likely amplified by the influx of visitors into the city (Ambraseys, 2009). Additionally, the earthquake facilitated the spread of large fires that had started before the earthquake struck. Unlike the 115 C.E. earthquake, the 526 C.E. earthquake:

"does not seem to have been an event of large magnitude, but rather a shock of medium size in the close vicinity of a large and densely populated city, most of which was built on a vulnerable alluvial site," (Ambraseys, 2009) (185).

These types of descriptions help portray the foundational concept of earthquake risk—that earthquake shaking interacts with vulnerable people, places, and structures to produce disasters. Damaging earthquakes can be caused by large earthquakes, as recounted in descriptions of the 115 C.E. earthquake, estimated at a surface wave magnitude of 7.5. However, smaller magnitude earthquakes like that of the 526 C.E. event, can also produce disasters when they rupture near densely populated areas in geologic environments that amplify shaking. While these two earthquakes illustrate exemplify the concepts behind seismic risk, they represent only a small fraction of the damaging earthquakes in this region. The greater Aleppo area was destroyed in 1138 C.E. in an event also attributed as one of the top ten most damaging earthquakes—or earthquake sequences—of all time (Musson, 2001). Over 60,000 people died in the Kingdom of Cilicia (modern day Adana) in 1268 C.E.. An earthquake shook the city of Erzincan in 1939 C.E. that resulted in 30,000-40,000 deaths (Ranguelov and Bernaerts, 1999). The list continues, with virtually every city in the greater Syrian region experiences has experienced some level of earthquake shaking in the past 2000 years, seen in Figures 2.6 and 2.7.

2.5 Human Geography

2.5.1 Turkey

The area encompassed by the modern boundaries of Turkey and Syria is home to rich history, culture, and diversity. Located at the crossroads between Europe and Asia, Turkey has represented an area of strategic conquest for many civilizations including the Greeks, Romans, Byzantines, and the Ottomans before transitioning into modern Turkey under the leadership of Mustafa Atatürk in 1923. While the Syrian landmass was included under many similar empires, its modern history shares greater similarity with other Levantine countries, formed as a French state after the Sykes-Picot agreement of 1915-1916. Understanding the history of these two nations is important for capturing the region's diverse demography, a factor that complicates hazards policy development and amplifies hazard relief and recovery—two factors that contribute to earthquakes becoming natural disasters. Earthquakes do not adhere to administrative bound-



Figure 2.6: This map shows historical seismicity in the study area. Earthquakes are classified into three estimated magnitude ranges according to the parametric catalog from Ambraseys (2009). (Cartography by Bradley Wilson).



Figure 2.7: This map visualizes the SHARE v3.3 European earthquake catalog, including earthquakes from 1000 C.E. - 2006 C.E.. Most of the earthquakes displayed are from the instrumental seismic record (Cartography by Bradley Wilson).

aries; an earthquake in this region will affect a broad range of ethnicities, religious identities, and political groups, and likely overlap with groups in conflict.

The Republic of Turkey was officially recognized on October 29, 1923 following the signing of the Treaty of Lausanne at the close of the Turkish War of Independence. This designation formally dissolved the remaining portions of the Ottoman empire and ceded claims to areas outside the boundaries of modern Turkey. The Kurdish people, residing in a significant portion of eastern Turkey, were not granted an independent Kurdish state as was proposed in the earlier Treaty of Sevres. The Kurdish people remain a geographically dispersed ethnic group today, and tensions between ethnic Turks and Kurds continue to persist. The Turkish Statistical Institute does not collect demographic data as part of the official census, however, estimates place the Kurdish minority population around 18% (CIA, 2016). The Kurdish population in Turkey is heavily concentrated in the Eastern Anatolia and Southeastern Anatolia Regions. Over half of of the provinces in this study contain significant Kurdish populations.

While Turkey does not collect any racial data as part of their census process, they do collect a wide variety of other statistics. This research uses population data from the 2011 Turkish Census, as well as 2015 population estimates from the Address Based Population Registration System (ABPRS) that tracks yearly population changes. Because the Turkish census was taken prior to the onset of mass migration from the conflict in Syria, the census data provides baseline population statistics to compare post-migration data to. As of 2011, the Turkish population is 74.52 million individuals (TSI, 2011) with 12.98 million individuals or 17% of the total contained within provinces included in this study. Figures 2.8 and 2.9 show the population breakdown at the province and district level, using data from the 2011 census. Figure 2.10 shows the internal population flux between the 2011 census and the 2015 ABPRS population estimates. In

general, populations have transitioned from rural districts to urban districts between 2011 and 2015.

The ABPRS system does not include any significant refugee immigration, as it is designed to track Turkish citizens. The total Syrian population within the ABPRS for 2015 is listed at 76,413 (Turkish Statistical Institute (TSI), 2015), a significant underestimate compared to migration data from the U.S. Humanitarian Information Unit and United Nations. Current U.N. and HIU data suggests that several single provinces alone, perhaps even single districts, could be accommodating that many displaced Syrians (U.S. Humanitarian Information Unit (HIU), 2016).

2.5.2 Syria

Syria has been a hotbed for conflict since its modern borders were established in 1920. While modern Syria began as a French mandate, continuous revolts from local rebel groups eventually led to the creation of an independent Syrian republic in the 1930's. Over the next thirty years, Syria saw periods of independence, numerous political coups, and a brief period of unity with Egypt under the banner of the United Arab Republic. The 1961-1963 coups, led by the Ba'athist party began the modern governance led by the Assad family. Under the Assad regime, Syria engaged in a series of conflicts with Lebanon, Israel, and the Kurdish rebel groups. The ongoing civil war, initiated in 2011 in the wake of Arab Spring protests, is the current iteration of long-term religious, ethnic, and inter-governmental conflict within Syria. Unsurprisingly, the demographic composition of Syria is complex and includes interwoven religious and ethic identities. The majority of the population, 90%, is Arab. Syrian Kurds represent 9% of the remaining percentages (CIA, 2016). However, these statistics do not reflect the ethno-religious breakdown of the country. Sunni, Shia, Alawite, Druze, Christian, and Kurdish ethno-religious identities are



Figure 2.8: This map shows the district level population distribution within Turkey. (Cartography by Bradley Wilson).



Figure 2.9: This map shows the district level population distribution within Turkey. (Cartography by Bradley Wilson).



Figure 2.10: This map shows the district level population distribution within Turkey. (Cartography by Bradley Wilson).

all represented in Syria.

The last official Syrian census was taken in 2004. Reliable population estimates are available up until 2011 but have become increasingly difficult following the onset of substantial conflict in 2011. Syrian provinces are not included in this analysis due to the massive uncertainty associated with the current population breakdown. Like Turkey, Syria does not collect official statistics on the exact ethnic and religious breakdown of the country. The 2004 Syrian census provides a population estimate of 17.92 million individuals (Central Bureau of Statistics, Syria (CBS), 2004). 2011 estimates place the population at 21.96 million individuals (Thomas Brinkhoff, 2011). The majority of Syria's population lives in the fertile western half of the country with a minority Kurdish population to the north along the border of Turkey.

2.5.3 Displaced Persons

As stated above, Turkey currently accommodates over 2.5 million Syrian refugees (MPC, 2016). The refugee response plan in Turkey is run by the government, under the Disaster and Emergency Management Agency. However, in an effort to combat the larger regional Syrian refugee crisis, local governments, the United Nations, and non-governmental organizations have developed a regional plan for the Syrian Refugee crisis under the banner '3RP (Regional Refugee and Resilience Plan)'. Turkey, Lebanon, Egypt, Jordan, and Iraq are included in the 3RP plan, which identifies ongoing strategic needs and budgetary breakdowns to provide an cohesive plan for addressing the refugee crisis (3RP, 2015). The 3RP plan provides an outlet for partners to aid local governments in helping address refugee needs. Housing arrangements, health services, food security, and education remain among the largest ongoing concerns for Syrian refugees in Turkey (3RP, 2015).

Both the United Nations High Commissioner for Refugees (UNHCR) and the United States Humanitarian Information Unit (HIU) track the number, location, and demographic statistics of displaced persons, when available (UNHCR, 2015, HIU, 2016). The most recent U.N. estimates indicate over eleven million Syrians are displaced to some degree as of 2016 (UNHCR, 2015). Of the crisis' 2.5 million official refugees, roughly 1.4 million are located in southern and southeastern provinces (3RP, 2015). A choroplethic breakdown of displaced population in this research's study site can be seen in Figure 2.11 below. The southern provinces near the Syrian border have accommodated the most displaced persons, largely due to the locations of government-rebel conflict to the south and ISIL control to the east. These locations overlap with both areas of seismicity (Figures 2.6 and 2.7) and fault zones (Figure 2.5).

As of 2015, Turkey currently has twenty five operating refugee camps operating at full capacity, seen below in Figure 2.12 (3RP, 2015). However, unlike other Middle Eastern countries, the majority of Syrian refugees in Turkey (estimated at 86%) live outside of formal refugee camps. As of December 2015, the camped population remains at 264,191 persons (EADRCC, 2015), while the dispersed refugee population is over 2.2 million persons (3RP, 2015). About half of the refugee camps are located directly on top of major fault zones.

Because the majority of Syrian refugees are not in camped environments, migrated populations represent significant increases in both population and population density. In the context of seismic risk, these populations represent a sort of 'temporary urbanization'. Earthquakes are deadly when strong shaking affects areas of high population in poorly constructed buildings. Even though most refugees claim they would like to return back to Syria after the conflict (3RP, 2015), earthquake consequences in urban districts increase alongside increases in population density. Comparing population data, both official estimates (Figures 2.8 and 2.9) and migration pat-


Figure 2.11: This map shows the number of displaced Syrians in the study region as of the end of 2015. Note the significant increase in and around the Hatay province, an area repeatedly struck by large earthquakes (Cartography by Bradley Wilson).



Figure 2.12: This map shows the location, type, and December 2015 population of the formal refugee camps in Turkey. (Cartography by Bradley Wilson).

terns (Figures 2.10 and 2.11), with the spatial trends of fault zones (Figure 2.5) and earthquake activity (Figures 2.6 and 2.7) highlights overlapping trends centered on the southwestern portion of the study site (Hatay, Osmaniye, Gaziantep, and Adana provinces). Further chapters in this

study will quantitatively analyze the spatial overlap between earthquake hazard and the estimated district-level distribution of migrated population. These variations in seismic hazard, base population, and migrated population provide the framework in which subsequent seismic risk changes are analyzed.

3: LITERATURE REVIEW

This study falls broadly under the category of earthquake risk research, a field with considerable breadth and scope. Researchers across disciplines—geology, geophysics, psychology, geography, economics, public policy—have sought to understand why earthquake events disproportionately affect different areas of the globe. The phrase seismic risk holds a variety of contextual interpretations. In technical literature, seismic risk involves calculating loss estimates from building stock and population density estimates, while geography literature tends to frame risk in the context of concepts like power structures and resource access as limiting factors for communities' ability to cope with natural disasters. This research blends these two approaches in a Middle Eastern context by integrating displaced person population statistics with a classical probabilistic seismic hazard analysis to determine if the ongoing conflict in Syria increasing the consequences of an earthquake in southern Turkey.

While the terms hazard and risk are regularly used interchangeably in colloquial conversation and in the media, making the proper distinction between the two is important. Seismic hazard refers to the "intrinsic natural occurrence of earthquakes and the resulting ground motion and other effects," (Stein and Wysession, 2003) (11). Assessing earthquake risk requires merging seismic hazard assessment with population exposure, impact assessments, and various forms of vulnerability to describe the potential effects an earthquake has on human populations. Because hazard and risk are distinct, geographic areas can hold various magnitude combinations of the two terms. Often, areas of high hazard are also areas of high risk and areas of low hazard are low risk, but this is not always the case. Large portions of the famous 'Ring of Fire' frequently experience earthquakes that have no impact on humans because they rupture in areas with no population. The opposite case, low hazard but high risk, also exist. An infrequent, low moment magni-

tude (5.7 Mw) earthquake struck Agadir Morocco in 1960, resulting in 15,000 casualties and left 25,000 homeless due to poor construction practices and inefficient evacuation procedures (Paradise, 2005). Comparatively, a similar sized earthquake in Los Angeles (Whitter-Narrows 1987) resulted in only eight deaths (Toppozada and Branum, 2004). What drives these differences has been the subject of much discussion in natural hazards literature.

3.1 Earthquake Hazards

Most earthquakes occur at the intersection between Earth's tectonic plates. Earthquakes do occasionally occur on intra-plate faults, although these events are rarer than their inter-plate counterparts. Earth's plates are dynamic, constantly sliding, slipping, and moving with respect to one another. In some areas, plates become 'locked' and start to accumulate stress over time. When accumulated stress exceeds the shear strength of the rock units along a fault surface, energy is rapidly released in an earthquake event. Earthquakes release a remarkable amount of energy; the largest recorded earthquake in 1960 off the coast of Chile released more energy than all nuclear bombs ever set off (Stein and Wysession, 2003).

3.1.1 Earthquake Measurement

Magnitude

There are several ways to measure earthquakes. Traditionally, earthquakes are reported on a magnitude scale that specifies the amount of energy released in an earthquake rupture. There are several magnitude scales, each calculating the amount of energy released in a different way. The first magnitude scale, designed by Charles Richter in 1935, was based on the amplitude of oscillations recorded on a local California seismometer after an earthquake event (Spence et al., 1989). The Richter scale is logarithmic, with every point increase representing close to a thirtytwo fold increase in energy. The Richter scale had several problems. First, it was only accurate in a narrow geographic area (within 700km of the earthquake source) due to its reliance on the calibration of a specific instrument. Secondly, earthquake events release two distinct types of energetic waves, body waves and surface waves, each with different properties that were not distinguishable within a single instrumental recording. To fix these problems, two separate magnitude scales, the body wave magnitude (Equation 3.1) and surface wave magnitude (Equation 3.2) were developed (Spence et al., 1989).

$$M_b = \log 10(\frac{A}{T}) + Q(D,h) \tag{3.1}$$

Where A is the amplitude of ground motion (microns), T is the period (seconds), and Q is a correlation function based on distance D between epicenter and station (degrees) and focal depth h (kilometers).

$$M_S = log10(\frac{A}{T}) + 1.66log10(D) + 3.30$$
(3.2)

Where A is the amplitude of ground motion (microns), T is the period (seconds), and D is the distance between epicenter and station (degrees).

Local calibration within both of these equations allowed for magnitude scales nearly consistent in value to Richter's original scale, while simultaneously accounting for differences in the two types of earthquake waves. However, both scales still relied on a measured amplitude to calculated earthquake magnitude. For this reason, Richter, body and surface wave measurements saturated at high magnitudes, resulting in the underestimation of large earthquake events (Spence et al., 1989). As the density of the seismometers across the globe continued to increase, scientists' ability to accurately measure fault geometry and displacement improved significantly. These developments resulted in the creation of a new earthquake scale: the moment magnitude scale (Equation 3.3). The moment magnitude scale relies on calculations of displacement, fault size, and rock sheer strength rather than the recorded amplitude on ground motion recorded on a seismometer. The moment magnitude scale is the most widely used earthquake scale today.

$$M_w = \frac{2}{3} log 10(M_O) - 10.7 \tag{3.3}$$

$$M_O = \mu S \langle d \rangle \tag{3.4}$$

Where M_O is the seismic moment calculated from the shear stress μ , fault area S, and average displacement $\langle d \rangle$.

Intensity

While magnitude describes the amount of energy released in an earthquake event, it does not directly relate to surface ground motions or structural damage. Many factors (soil type, rock type, rupture depth, travel path, etc.) can affect the level of shaking in a particular area. The Mercalli Intensity Scale, later improved into the Modified Mercalli Intensity Scale (MMI), was developed as a descriptive scale to assess perceived shaking. Italian priest and scientist Giuseppe Mercalli developed the originally MMI scale in the late 19th and early 20th century by compiling reports of earthquake shaking across Italy.

MMI and other macroseismic intensity scales (European Macroseismic Intensity (EMI), Medvedev-Sponheuer-Karnik (MSK), etc.) serve two primary purposes. First, they provide a



Figure 3.1: The Modified Mercalli Intensity Scale and its levels of perceived shaking.

scale to assess perceived ground motions. The level of shaking felt at the surface is widely variable, even for earthquakes of the same magnitude. For example, soil resonances in the 1985 8.1 M_s Mexico City earthquake amplified the two second period ground motions by 75 times (Spence et al., 1989). Because stronger shaking generally results in higher building collapse rates, macroseismic intensity is useful for correlating an earthquake event with surface-level impacts. Earthquake magnitude does not incorporate these types of amplification or attenuation effects. Secondly, intensity scales can be used to estimate the size and location of a historical earthquake where the magnitude might not be known. While intensity biases exist, "data provided by historical sources for earthquakes on land are adequate to permit the general location of the epicentral area, particularly for the larger events," concludes Ambraseys (2009) (56). In some cases, surface magnitude estimates can be subsequently derived from historical intensity estimates using Equations 3.5 and 3.6.

$$M_{Si} = -1.54 + 0.65I_i + 0.0029R_i + 2.14log(R_i) + 0.32p$$
(3.5)

$$R_i = (r_i^2 + 9.7^2)^{0.5} \tag{3.6}$$

Where I_i intensity, R_i is the isoseismal radii (calculated using the mean isoseismal radii r_i in kilometers), p is zero for the mean and 1.0 for 84th percentile values (Ambraseys, 2009).

Ground Motion

The third descriptor of earthquake shaking, ground motion, is closely related to both magnitude and intensity. Both body wave and surface wave magnitudes depend on instrumentally measured ground motion values. This was a contributing factor to both of these scales falling out of favor; the relationship between the energy released in an earthquake and recorded ground motion values depends on a number of site-specific variables. As described above, local geology and soil conditions can significantly amplify or attenuate ground motion. However, body wave and surface wave magnitudes are still used in historical earthquakes studies where estimates ground motion are available while the fault length, displacement, and seismic moment are not. Ground motion is most commonly measured as peak ground acceleration, peak ground velocity, or spectral acceleration. Each of these measurements lends itself to particular applications. Peak ground acceleration is frequently used for construction less than seven stories while peak ground velocity and spectral acceleration are used in larger structural designs (USGS, n.d.).

Macroseismic intensity scales (MMI, EMI, MSK) were developed before ground motions were instrumentally recorded. As ground motion databases slowly expanded, empirical relationships connecting macroseismic intensity to ground motion parameters were developed. Trifunac and Brady (1975) used 188 acceleration records to develop relationships between MMI and ground acceleration, velocity, and displacement. This study concluded that the logarithms of all three variables scaled in a linear fashion within an MMI range of III to VIII for acceleration and V to VIII for velocity and displacement. However, the authors also noted uncertainty in calculated coefficient values due to limited ground motion data— especially at the low and high ends of the spectrum. Wald et al. (1999a) presented significant improvements in PGA-PGV-MMI relationships, regressing acceleration and velocity jointly to determine updated coefficients for the conversion equations. This study also found that peak ground acceleration correlated best for MMI less than VII and peak ground velocity less than IX. The equations presented in Wald et al. (1999a) formed the foundation for ShakeMap, a United States Geologic Survey software tool designed to automatically convert instrumental ground motion data into rapid visualizations of shaking intensity (Wald et al., 1999b). New versions of ShakeMap have been released alongside new ground motion studies. Version 3.5 was released in 2010, including updates to address how macroseismic intensity data is handled (Worden et al., 2010).

Ground motion prediction equations were concurrently developed alongside ground motion conversion equations. In contrast to conversion equations that connect instrumental ground motion data to intensity data, ground motion prediction equations seek to forward model ground motion values for future earthquake events. These equations provide coefficients for various site classifications to predict ground motion values for an earthquake of a given set of parameters. Hundreds of different ground motion prediction equations exist, taking into account improved strong motion data sets and classification of local site heterogeneity. A summary of 289 equations from 1964-2010 can be found in Douglas (2011), with best practices for their use in modeling discussed at length in Cua et al. (2010).

3.1.2 Earthquake Frequency

Global and local earthquake frequency follows the Gutenberg-Richter scaling relationship, first published in the 1940's, given by Equation 3.7.

$$logN = a_1 - bM \tag{3.7}$$

Where N is the number of earthquakes occurring above a given magnitude threshold. The values of a_1 and b define a linear relationship with a slope near one. Thus, the Gutenberg-Richter relationship specifies a tenfold decrease in earthquakes for each successive point increase in magnitude. Local variations do exist, but the relationship holds remarkably well (Stein and Wysession, 2003). This relationship equates to roughly one moment M_w eight or greater earthquake per year, ten M_w seven earthquakes, one hundred M_w six earthquakes, continuing down to the thousands and hundreds of thousands of small earthquakes that occur every day. Because the magnitude scale is logarithmic, large events dominate the total annual seismic energy release, as well as the human life and economic losses sustained each year. A common misconception in examining earthquake magnitude frequency relationships is that the frequency of earthquakes is increasing. As more seismic stations are installed across the world, researchers' ability to detect earthquakes is increasing, even with an apparent recent increase in high magnitude earthquakes (Ammon et al., 2010, Shearer and Stark, 2012).

3.1.3 Earthquake Prediction

Earthquake prediction, sometimes called earthquake forecasting, has been a subject of research for over one hundred years. The first major consolidated earthquake prediction program arose in Japan following an earthquake that struck the city of Nobi in 1891 (Hobbs, 1907). The committee's members examined:

"various problems bearing on earthquake prediction, such as earth tiltings and earth pulsations, variation in the elements of terrestrial magnetism, variation in underground temperatures, variation in latitude, secular variation in topography, etc., but satisfactory results were not obtained," (Imamura, 1937) (346).

The earthquake prediction movement regained steam after the installation of the global seismic

network due to the wealth of newly available data on earthquake processes. The 1960s even saw the formation of a United States committee on earthquake prediction (Press, 1975). Earthquake prediction proved to be a double edged sword. On one hand, prediction remained the ultimate goal of the seismology community and was an attractive idea in the public's eye. Yet, earthquake prediction studies continue to indicate that earthquake prediction was too complicated to ever fully understand. The 1970s temporarily brought more optimism, including the claim that long and short-term earthquake prediction could be achieved within a decade (Smith, 1975), but ultimately failed to produce reliable results. After the 1970s, the seismology community largely transitioned towards the idea of earthquake precursors instead of pure prediction. In a review paper on earthquake prediction, Geller (1997) concludes:

"no quantitative physical mechanism links the alleged precursors to earthquakes, statistical evidence for a correlation is lacking and causes unrelated to earthquakes have not been convincingly excluded," (430).

While many individual researchers are still studying possible precursors and prediction methods as the collective understanding of faulting processes develops, earthquakes are largely conventionally deemed unpredictable. The United States Geologic Survey's official stance declares, "Neither the USGS nor any other scientists have ever predicted a major earthquake. They do not know how, and they do not expect to know how any time in the foreseeable future," (HIU, n.d.).

3.1.4 Earthquake Probabilities

Despite a shift away from earthquake prediction, researchers continued to seek to characterize earthquake activity. Estimates of earthquake ground motion are a crucial source of information for seismic zoning—the practice of determining and mapping ground motion levels that buildings should be capable of resisting in different areas. The simplest solution for arriving at these estimates is to determine the maximum possible earthquake magnitude for a given area and calculate the resultant ground motion values in zones of interest. In practice however, incomplete information and irregularities between magnitude and ground motion complicate the choice of deterministic values (Baker, 2008). The alternative approach, probabilistic seismic hazard analysis (PSHA), first developed in Cornell (1975), has been widely favored for its use of probability theory to handle uncertainty (Bommer and Abrahamson, 2006). Baker (2008) provides a succinct outline of the five major steps included in PSHA:

- 1. Define earthquake sources able to cause damaging ground motions;
- 2. Specify the frequency magnitude distribution (of those sources);
- 3. Characterize earthquake source-to-site distance (where earthquakes occur);
- 4. Predict ground motion intensities as function of the above parameters;
- 5. Add uncertainties in earthquake size, location, and ground motion (10).

While PSHA is the most widely used technique for hazard characterization, it has been criticized for overestimating hazard, mostly due to its dependence on variable ground motion prediction equations (Bommer and Abrahamson, 2006). PSHA has also been criticized for its use of Poisson distribution (Equation 3.8) to characterize earthquakes (Anagnos and Kiremidjian, 1984, Wu et al., 1995). Using a Poisson for earthquakes is that time-independence implies that faults don't have any memory of past earthquakes. Earthquake events require time for stress to accumulate along a fault, and instrumental data indicates the rupture probabilities are cyclic in nature (Stein and Wysession, 2003). This has been shown to underestimate hazard in areas with

seismic gaps and characteristic earthquake behavior (Anagnos and Kiremidjian, 1984, Wu et al., 1995).

$$p(n,t,\tau) = \left(\frac{t}{\tau}\right)^n \frac{e^{\frac{-t}{-\tau}}}{n!}$$
(3.8)

Where $1/\tau$ is the number of earthquakes at a given magnitude expected in one year from the Gutenberg-Richter equation (3.7)

Several alternative PSHA approaches, including stochastic (Anagnos and Kiremidjian, 1984), bayesian (Bayraktarli et al., 2011) and modified hybrid Poisson (Wu et al., 1995) have been proposed to improve hazard estimates while reducing uncertainty. However, Cornell and Winterstein (1988) showed that Poisson estimates are sufficient in all but a small percentage of special cases.

3.1.5 Hazard Assessment in Turkey

Several seismic hazard analyses have been completed for Turkey. The first official seismic hazard map produced in 1948 included three zonations, heavy, likely, and zero damage, based on deterministic macro-seismic data (Erdik, 2015). This map was updated in 1972 to include a fourth hazard zone (Erdik, 1985). Erdik (1985) included one of the first national scale PSHAs, estimating maximum intensity values for earthquake recurrence intervals of 225, 475, and 10,000 years. Major collaborative PSHAs including Turkey were published in 1999, 2000, 2008, and 2013 (Erdik, 2015). Post-1999 updates provided shaking estimates in smaller ground motion windows by reevaluating earthquake catalogs, seismic source models, and ground motion prediction equations (Erdik, 2015). The 2013 Seismic Hazard Harmonization in Europe (SHARE)

project incorporated an updated declustered earthquake catalog and the implementation of area source, fault source, and smoothed source fault models (Woessner et al., 2015).

As seen above, the development of new hazard maps is an ongoing process. Most PSHA results are presented in the form of ground motion maps for a 10% exceedance threshold in a 50 year period, equivalent to a 475 return period earthquake. These maps are converted into seismic zonations and standardized to interface with building codes insurance premiums. New Turkish hazard maps specifically developed for the purposes of updating the Turkish building code are being developed as of October, 2015 (Akkar, 2015). In addition to incorporating the most recent earthquake data available, these maps, funded by the Turkish Disaster and Emergency Management Presidency and the Turkish Catastrophe Insurance Pool, will add improvements to the seismic design spectrum (Akkar, 2015).

3.2 Structural Vulnerability

Traditionally, the idea of vulnerability in earthquake literature refers to structural vulnerability. Ambraseys (2009) defines vulnerability as "the degree of structural damage or loss resulting from an earthquake of a given magnitude," (xii). The common adage 'Earthquakes don't kill people, buildings do', is often repeated after deadly earthquakes in poorly constructed regions. The saying has become a ubiquitous message in advocating for seismic building codes and earthquake zoning practices, as ground shaking from earthquake waves alone rarely causes any fatalities. A 2001 study on the great Hanshin-Awaji earthquake in Japan monitored earthquake related deaths for one year after the quake, finding that 95% of earthquake deaths occurred in the first week after the quake and almost all the deaths were related to building collapse (Oskai and Minowa, 2001).

Human-built structures play a dominant role in disparate earthquake mortality rates in the developing versus the developed world. Earthquake resistant structures are both expensive to construct and time consuming to license and verify (Keefer et al., 2011). Retrofitting existing structures is an equally challenging problem. Earthquake resistance in existing structures can be difficult to verify, especially in locations where construction materials and practices are not known. Subtle differences in building materials can make a large difference in shaking resistance, but are difficult to visually verify. Steel-reinforced concrete is not visually distinct from unreinforced concrete (Keefer et al., 2011). Additionally, the clay and straw content of adobe bricks, a central component of earthquake resistant adobe structures, is often unknown (Blondet et al., 2011). Cultural significance presents another challenge for retrofitting existing structures. Popular cultural architectural styles and building materials are often vulnerable to earthquake shaking (Blondet et al., 2011). In countries that do not meticulously track construction, such challenges render building codes ineffective. Moreover, incentivizing the enforcement of building codes is an ongoing challenge. Corrupt payments, bribes, and lack of political incentives all contribute to building codes being underutilized or ignored entirely in many countries (Keefer et al., 2011).

The 2003 Bam, Iran Earthquake highlights how structural vulnerability variables combine to amplify the effects of an earthquake. On December 26, 2003, the historic city of Bam was leveled by a M_w 6.6 earthquake, killing over 25,000 people, injuring 30,000, and displacing over 75,000 (Nadim et al., 2004). Iran had set seismic building regulations in 1989 but they were not enforced in Bam. The majority of buildings in Bam were constructed using traditional mud brick construction practices that left them particularly vulnerable to collapse (Kiyono and Kalantari, 2004). When these mud brick structures collapsed, they injured, trapped, and sealed residents inside with a lack of access to air. Over 90% of Bam's infrastructure was damaged or destroyed in

the earthquake (Kiyono and Kalantari, 2004).

3.3 Earthquake Policy

3.3.1 Building Codes and Zoning

The importance of building material and design led to the creation of seismic building codes all over the world. The origin of seismic building codes dates back to the 1755 Lisbon earthquake, with the creation of prescriptive rules for the construction of common building types (PEER, 2007). The Messina, Italy earthquake in 1909 introduced quantitative structural regulations, requiring that one story buildings be constructed to resist a lateral force of 1/12 their weight (Anderson and Naeim, 2012). This code was amended in 1912 to include two-and three story buildings with 1/8 total weight resistance for the second and third stories. The 1923 Kanto earthquake in Japan prompted the development of a Japanese building code, requiring new construction to be able to resist a ground acceleration of 0.1g (Anderson and Naeim, 2012).

Earthquakes in California have been a consistent motivation for improvements in building codes (PEER, 2007). Surprisingly, California did not implement formal earthquake building codes after the disastrous 1906 San Francisco earthquake. It took two more decades and the 1925 Santa Barbara earthquake for the first institutionalized earthquake-specific building codes to appear in California (University, 2006, PEER, 2007). The first international seismic building code, the Uniform Building Code (UBC), arose out of the 1927 International Conference for Building Officials. The UBC attempted to standardize building codes and was consistently updated until 1997 when it was replaced by the International Building Code (IBC) in 2000 (Anderson and Naeim, 2012). Several years after its initial conception, California modified the UBC into the state's 1933 Field and Riley Acts, which set minimum design standards for schools (Field) and all other buildings (Riley) (Alfred E. Alquist Seismic Safety Commission (AAASC), 2009).

These types of developments became commonplace, with the Structural Engineers Association of California acting as a driving force for seismic design improvements (Alfred E. Alquist Seismic Safety Commission (AAASC), 2009). Modern U.S. zoning practices have their roots in aftermath of the 1971 San Fernando earthquake in California. The Alquist-Priolo Special Studies Zone Act (later renamed the Alquist Priolo Earthquake Fault Zoning Act) of 1972 sought to address surface rupture by preventing most types of occupied structures from being constructed on identified active fault traces (Bryant, 2010). Alquist-Priolo implemented a policy of avoidance the concept that certain hazards are best mitigated by distance (Bryant, 2010). Deficiencies in Alquist-Priolo, namely the lack of hazard identification beyond surface ruptures, were addressed in the Seismic Hazards Mapping Act of 1990 that followed the 1989 Loma Prieta earthquake. This act expanded zoning regulations in California to include areas of secondary hazards: liquefaction, earthquake-induced landslides, and amplified ground shaking (California Geological Survey, 2007).

3.3.2 Turkish Building Codes

Ilki and Celep (2012) and Soyluk and Harmankaya (2012) provide overviews of the evolution of building codes in Turkey. The first seismic building regulations were first implemented in 1940 following the Erzincan earthquake a year earlier. These regulations focused on general construction practices, but also included post-event provisions for those affected in the 1939 earthquake. Between 1944 and 1949, two series of mitigative laws were enacted, requiring buildings to be constructed with specific lateral sheer coefficients. The publication of the 1948 official seismic zonation map prompted the second change that altered coefficients to account for the different zones of hazard and incorporated variations in building height and soil type. After twenty years of urbanization, the codes were updated in 1961 and 1968 and for the first time included soil-structure interactions, specifications on individual building components, including walls, beams, floors, and foundations. Updates in 1975 incorporated the 1972 Turkish seismic zoning map, implemented new structural ductility concepts, and included new provisions for reinforced concrete, high rise buildings, and irregular buildings. Updates in 1997-1998 included several landmark changes; Earthquake recurrence intervals were incorporated into the code for the first time (using 475 year recurrence interval for most buildings) and sheer coefficients were converted to spectral acceleration coefficients.

Only a year later the greater Istanbul region was struck with one of the deadliest earthquakes of the 20th century, the Kocaeli earthquake of 1999. The rate of building collapse in the Kocaeli earthquake was four times the collapse rate of the 1995 Kobe earthquake and twelve times that of the 1994 Northridge earthquake (Erdik, 2001). Erdik (2001) traced the failure rates in buildings to both inadequate enforcement and underestimation of the shaking levels expected in a large earthquake. Rapid urbanization and industrialization were linked to struggles enforcing the building codes (Erdik, 2001). In 2007, the seismic codes were updated in the wake of the 1999 disaster. In addition to introducing performance-based assessment principles that specified different levels of required performance for different building types, the 2007 codes implemented an entirely new chapter on retrofitting existing structures (Ilki and Celep, 2012). Despite these improvements, Ilki and Celep (2012) concluded that the enforcement building codes remain a significant issue for Turkey because buildings cannot be assumed to be up to code regardless of the year and code they were constructed under. Buildings that collapsed in the 2011 Van earth-

quake showed that the 2007 updates had not been implemented (Güney, 2012).

3.3.3 Turkish Catastrophic Insurance Pool

The Turkish Catastrophic Insurance Pool (TCIP) is the other main form of earthquake policy in Turkey. Developed in the wake of the 1999 Kocaeli earthquake, the TCIP seeks to provide affordable earthquake insurance rates while minimizing the government's long term costs (Yazici, 2005). The TCIP also attempts to encourage mitigative construction practices alongside Turkish building codes (Yazici, 2005, Gurenko et al., 2006). According to the World Bank, the TCIP covers 23% of Turkey's total building stock and 40% of buildings constructed in high hazard areas (World Bank, 2011). For urban dwellings within municipality boundaries, participation in the TCIP is compulsory (Gurenko et al., 2006). For an average homeowner, the premiums cost around 62 U.S. dollars per yer with a 2% deductible (World Bank, 2011). The TCIP is run by a board of directors, but the operations of the program are contracted out to insurance or reinsurance providers (Yazici, 2005).

Reception to the TCIP has been mostly positive. As of 2010, the policy has sold 3.5 million premiums (World Bank, 2011). Commenting on the first five years of the program, Gurenko et al. (2006) concludes that "The program has significantly reduced the government's fiscal exposure to [earthquake] risk," adding that "the TCIP transformed itself from an unknown and controversial government-sponsored program to one of the most trusted brand names in the Turkish insurance industry," (xii). However, the TCIP is not without challenges. The system has limited ability to enforce the compulsory policy, only requiring checks when selling or purchasing property within enforcement zones (Yazici, 2005). Additionally, there are concerns that the size of the pool is insufficient to cover a catastrophic earthquake—the same scale of earthquake that incited its own development (Gurenko et al., 2006).

3.4 Risk Perception

"Floods are an act of God, but flood losses are largely an act of man," (White, 1945)

Problems with building codes and hazard policy emphasize an larger question—why do attempts to reduce earthquake risk continuously fail in the presence of known solutions? Underlying economic incentives, e.g. the opportunity cost for some countries is too low (Keefer et al., 2011), presents one explanation. Burton et al. (1978) provide an alternative explanation in *The Environment as Hazard*, arguing that individual attitudes and perceptions on natural hazards influence the likelihood they will take mitigative action. These attitudes vary from denying risk altogether to moving away from hazardous areas. The human-ecological perspective put forth in Burton et al. (1978) stems from the authors' previous research on the nature of the coupled human-environment system. Burton and Kates (1963-1964) connected epistemology to natural hazards, showing how differing belief systems and the probabilistic nature of rare environmental events give rise to unavoidable uncertainties and varying perceptions. Kates (1971) provided a basic flow model on human adjustment to natural hazards—and idea that has since been explored to great lengths in sociology and psychology literature (Solberg et al., 2010).

Broader risk perception research also gained prominence in the late 1970s and 1980s with early work from Daniel Kanehman, Amos Tversky, and Paul Slovic (Kanheman and Tversky, 1979, Slovic et al., 1982, Slovic, 1987). Kanehman and Tversky's seminal behavioral economics paper on prospect theory provided strong evidence that psychological biases impact quantitative decision making. Slovic et al. (1977) analyzed similar principles within natural hazards insur-

ance, showing that individuals tended to favor purchasing insurance for high probability–low loss situations over low probability–high loss situations. However, Slovic is most famous for his work with psychometry. Slovic (1987) asked survey respondents to rank risk behaviors and mapped them on psychometric diagrams using axis of 'dread' vs 'knowledge'. The wide variety in responses showed that the concept of 'risk' varies for different people and among different concepts. This study also judged differences between experts and average citizens, showing that expert's responses closely tied in with mortality rates while average citizens were closer tied to the ideas of controllability and catastrophe.

3.4.1 Social Psychology

Under the banner of social psychology, research in the areas of heuristics, affect, biases, and cultural orientations have been connected to seismic risk perception. Prior experience with hazards, level of education, gender, religious beliefs, and cultural beliefs have all be shown to influence perceptions to earthquake events, although specific conclusions are varied (Solberg et al., 2010). A review of the earthquake related social psychology literature by Solberg et al. (2010) concluded that globally, a vast majority of individuals 'do nothing or very little to adjust to seismic hazards, and when they do take action, it is significantly more likely to be response and recovery-related rather than mitigative," (11).

Anchoring, familiarity, and normalization all contribute to individuals minimizing their own individual risks. Anchoring refers to the tendency of individuals to latch onto information close to them rather than seeking alternate sources. A study by Celsi et al. (2005) found that individuals who had experienced shaking at distant locations underestimated the amount of damage normally caused by an earthquake of the reported magnitude. Familiarity refers to the ten-

dency of individuals to be biased towards circumstances they are familiar with. Survey results from Feygina et al. (2010) showed that even if a person has experienced an earthquake, they are unlikely to heed future warnings. Studies in California have shown that those who do not experience significant losses in earthquake events are less likely to listen to additional warnings due to normalization bias—the attitude that "the first impact didn't affect me negatively, therefore, subsequent impacts will also avoid me," (Mileti and O'Brien, 1992) (53).

3.4.2 Earthquake Fatalism

Earthquakes, unlike other natural disasters, have been strongly associated with religious explanations. Understanding the relationship between earthquakes and religious belief requires going back to the very nature of perception and experience. In 'A Critique of Pure Reason', German philosopher Immanuel Kant brings forth the idea of 'noumenon', something that is abstract, unknowable, and by its very nature incomprehensible (Kant and Smith, 1929). Noumenon is in contrast to phenomenon, something that is able to be experienced directly. Earthquakes, unlike many other natural hazards, arrive without distinct warning signs. The visceral experience of strong shaking without warning lends itself to explanations of divine origin. For centuries, earthquake events were attributed to acts of divine retribution of the Gods, a belief that is still maintained in regions of the Earth today (Paradise, 2005).

This type of religious belief connects with a concept known as 'earthquake fatalism'. First explored quantitatively with the work of Turner et al. (1986), a fatalist view of earthquakes involves the misconceptions that earthquake consequences are uncontrollable and that individuals cannot reduce their own personal risk through behavioral changes. Turner et al. (1986) examined earthquake fatalism in North America, finding that sixty percent of individuals hold fatalist-like

views on the consequences of earthquakes and one in three individuals are fatalist regarding their ability to reduce earthquake risk. Later work by Asgary and Willis (1997) examined earthquake fatalism in Iran, a Muslim majority country, finding that half of respondents in Tehran would do nothing to reduce their earthquake risk, even if informed of an imminent earthquake threat. Work by Paradise (2005) in Morocco helped provide further explanations for why Muslim communities seemed averse to reducing earthquake risk, illuminating the link between the apocalypse scenario in the Qur'an (Surah 99) and survey respondent's attribution of earthquakes to acts of God.

3.4.3 Risk Perception in Turkey

Several risk perception studies have been performed in Turkey. Eraybar et al. (2010) found that increased level of education was correlated strongly with increased awareness of earthquakes, similar to the results found by Paradise (2006) for Morocco. However, the majority of respondents in this study did not plan on taking any mitigative actions because they strongly believed their current houses to be adequate in withstanding future earthquakes. Kundak et al. (2014) compared survey results between 2013 and 2008, finding promise in the increase in percentage of respondents taking mitigative actions and raising awareness, despite the percentages for those who did not take action remaining high. Tekeli-Yeşil et al. (2011) added additional support, showing that most respondents had realistic view of earthquake risk but were limited in their understanding of coping mechanisms. Groups of lower socioeconomic status and education levels scored lower than their counterparts (Tekeli-Yeşil et al., 2011).

Kasapoğu and Ecevit (2004) examined the differences between risk perceptions in the Marmara region of Turkey versus the Bay Area in California. When asked to recall mitigative behaviors, Turkish respondents scored significantly lower than Bay Area respondents in most cat-

egories. Lack of money and God's decree were the two main reasons respondents cited as to why they did not carry out mitigation actions (lack of money was also the highest for Bay Area respondents). The authors concluded that religious and cultural traits "are the main causes of disaster losses and social inequalities (especially improving standards of living) are important factors that differentiate the impact of hazards," (382). Another theme in Turkish risk perception literature is a distrust in state-sponsored relief programs. The state's struggle to respond quickly in the 1999 Kocaeli earthquake resulted in heavy criticism from local citizens (Kasapoğu et al., 2004). Kasapoğu et al. (2004) found a 60% discrepancy in the support expected from the state versus the support they actually received, including failure to rebuild promised houses for disaster survivors.

3.5 Social Vulnerability

3.5.1 Descriptive Models

In 1976, the landmark Nature paper 'Taking the Naturalness out of Natural Disasters', transformed the concept of natural disasters by arguing that natural disasters are primarily a function of socio-economic conditions rather than natural events themselves (O'Keefe et al., 1976). These ideas challenged the standard assumption of the time of a coupled human-environment system. Contrasting the work of Burton et al. (1978), O'Keefe et al. (1976) presented a more radical stance on the driving forces behind disasters by further removing the role of hazards. The paper itself examined the probability of extreme events in different countries. The authors found that while the probability of extreme events has remained constant over time, underdeveloped countries suffered far more 'disasters' than developed countries.

These ideas were expanded upon at great length in Wisner et al. (2004), forming the Pres-

sure and Release model (PAR) that argued lack of access to resources, uneven power structures, and political ideologies constituted the root causes of natural disasters. The PAR model details a progression of risk where root causes combine with dynamic pressures to create the unsafe conditions required to produce natural disasters. In the PAR model, vulnerability ties together the progression from root causes to unsafe conditions. Wisner et al. (2004) explicitly defines vulnerability as "the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard (an extreme natural hazard event or process)," (11). Therefore, vulnerability is not a static metric and is constantly changing over time, both before and after a natural hazard strikes. Natural disasters often have long build up periods and long relief and recovery periods. Variables like rapid population change, urbanization, and a lack of investment in risk reducing behaviors contribute to the development of unsafe conditions in the physical environment, local economy, social relations, and public actions (Wisner et al., 2004). These conditions combined with natural hazards result in natural disasters. The PAR model is descriptive, assuming that many elements contributing to natural hazards risk cannot be quantified. Such assumptions have led to criticism of the model, notably concerning sustainability issues and a failure to provide sufficient detail on hazard sequences (Turner et al., 2003). An alternative vulnerability model built on a coupled humanenvironment system was developed in Turner et al. (2003), addressing the authors' concerns with the PAR model.

3.5.2 Quantitative Models

While the Pressure and Release provides a descriptive tool for highlighting the linkage between social vulnerability and hazards it is not a predictive tool. Therefore, it does not help

quantify which areas or populations are at higher risk compared to others. Social risk indices were developed to help fill this gap. Cutter et al. (2000) introduced a 'Hazards of Place' model in which spatial variability in both biophysical vulnerability and social vulnerability were mapped in Georgetown, South Carolina through a composite index. Cutter et al. (2003) expanded this work with development of the Social Vulnerability Risk Index (SoVI), which used factor analysis on forty two different variables (social and environmental) to construct an index measuring social vulnerability across the United States. This study determined that eleven variables explained 76% of the variance.

Cutter et al. (2003) spearheaded the trend of using quantitative models to assess social vulnerability. Suddenly, anyone with access to historical hazards data and access to demographic data could try and determine how different variables contributed to the 'vulnerability' of an area. Rygel et al. (2006) provided an overview of how different assumptions impact the construction of a social vulnerability index, specifically highlighting the problem of using weighted indices. Borden et al. (2007) added an additional step to the process by calculating separate indices for social vulnerability, built environment vulnerability, and natural hazard vulnerability before creating a composite index. Holand et al. (2011) took a similar approach in constructing a vulnerability index for Norway, splitting social vulnerability and vulnerability of the built environment into two separate indices.

While quantitative approaches are a helpful tool for spatially evaluating estimations of vulnerability, they also have drawbacks. Like any model, vulnerability indices are only as accurate as the data feeding into them. In some countries census data provides a reliable estimation of demographic variables. In other countries however, census data can be unreliable, out of date, or even missing entirely. In a review of earthquake loss estimation techniques, Guha-Sapir and Vos

(2011) found that census data only captured 50%-80% of target populations in area with settlements. In areas experiencing conflict, rapid population change, or rapid urbanization, census data is unlikely to accurately represent the target variables over short periods of time. Additionally, accurate representation of minority racial and ethnic groups has been a contentious issue, even in places like the United States (Anderson and Fienberg, 2000). In Turkey and Syria, ethnic information is not internally tracked at the country level. These factors complicate the use of a quantitative vulnerability model to isolate risk factors in countries where census data is an inaccurate representation of the target variable.

3.6 Refugee Vulnerability

This research seeks to link earthquake hazards with refugee migration. The PAR model helps illuminate how seismic risk links these two disparate topics. Displaced persons are the quintessential representation of a population group with limited access to power, resources, and structures. Even the small portion of displaced persons who are granted formal refugee status struggle to receive basic needs (3RP, 2015). As a result, persons are forced to flee areas of conflict in search of environments where they have greater access to resources and aid structures. Mass migration into Turkey establishes both rapid population change and rapid urbanization. Turkey has accommodated over two and a half million refugees, with many more IDPs settling along Syrian side of the border region. This represents a massive restructuring of the population density and demographics in the region. Increases in population density have stressed both the social and physical environment in Turkey (3RP, 2015). Furthermore, the refugee crisis has directly contributed to increased populations living in unsafe structures. Even the small percentages of refugees in camped environments are likely to be at risk—Al-Dabbeek and El-Kelani (2008)

found that refugee camps in Palestine were poorly planned, insufficiently constructed, and likely to sustain heavy damages in moderate to strong earthquakes. As a result, unsafe conditions are amplified in the region.

The largest challenge in addressing vulnerability issues concerning refugees in Turkey is data uncertainty. Accurate statistical information for refugees is limited and error windows are large, complicating the use of a place-based quantitative approach like SoVI. Given that persons in the Middle East are likely to believe some degree of earthquake fatalism and have poor seismic adjustment it is reasonable to assume that refugees are likely unprepared for an earthquake, but even well founded assumptions are problematic for quantitative vulnerability modeling. Herein lies the fundamental complication: refugee data is unlikely to be integrated into regional risk analysis, yet large populations of vulnerable people migrating to dense, urban environments in hazardous areas are precisely the reason why an earthquake in this region is likely to be disastrous. With millions of displaced persons unaccounted for in risk models, the standard loss estimation techniques will underestimate the consequences of an earthquake in this region. If relief and recovery estimates are made using Turkish census data, they could underestimate the population in need by hundreds of thousands of individuals. Accordingly, this research fills a needed gap in the literature by performing classical analyses (PSHA and loss estimation) on refugee-inclusive population estimates. These results present the first steps towards quantitatively incorporating vulnerable populations into risk analyses in situations with limited statistical data.

4: METHODOLOGY

4.1 Probabilistic Seismic Hazard Analysis

This study combined earthquake hazard outputs from the Global Earthquake Model's OpenQuake software with population information to assess changes in seismic risk in southern Turkey. OpenQuake is an open source software package that includes tools for hazard, risk, and vulnerability modeling. The OpenQuake hazard modeler's toolkit was used to produce the probabilistic earthquake hazard map presented in this study.

Data from the Seismic Hazard Harmonization in Europe (SHARE) project was used to develop the configuration, source model, and logic tree files necessary for performing probabilistic seismic hazard analysis (PSHA). Four main files are needed to perform PSHA in Open-Quake: a configuration file, a source model, a source model logic tree, and a ground motion logic tree (examples of these files can be found in Appendix B). The configuration file contains all the background information needed to complete PHSA in OpenQuake. This includes observation grid and earthquake rupture discretization, site parameters, output specifications, and directory references to all other necessary files. The source model is an .xml file marked in the natural hazards risk markup language (an OpenQuake format) that delineates fault boundaries, orientations, nodal planes, and frequency-magnitude relationships. If earthquakes in a given fault zone occur with several rupture orientations or nodal planes, multiple orientations are inputted and probabilistically weighted. The final two files, the source model logic tree and ground motion logic tree are .xml files that specify uncertainty weighting values for a given PHSA model.

This study uses a source model, source model logic tree, and ground motion logic tree modified from the SHARE project (Woessner et al., 2015). Both the SHARE area source and fault source models were downloaded as GIS shapefiles and clipped in QGIS to remove sources

outside of the study area (Figure 4.1). These codes assigned to the clipped area and fault sources were used to manually trim the source model .xml files. Area source models are the most commonly used type of source model, especially in regions where detailed fault models are not available (SHARE, 2013a). In an area source model, seismicity has a homogenous probability function across the entire source, signifying that any point in a given polygon is equivalently likely to experience an earthquake. Area sources section off clustered seismicity according to historical patterns and the known faults in the area. A fault source model isolates the occurrence of large earthquakes onto mapped fault planes, while allowing smaller background seismicity to occur in larger area sources (SHARE, 2013b). Accordingly, hazard increases in the near-field areas of fault planes when using a fault source model.



Figure 4.1: This map shows the area sources and fault sources that were used to perform PHSA in OpenQuake. All faults and area sources that intersected with a portion of the study site were included. (Cartography by Bradley Wilson).

The source model logic tree and ground motion trees specify the weighting percentages for the source model and ground motion prediction equations. This study uses a weighting scheme of 80% area source model and 20% fault source model. An area source weighted model helps account for the uncertainty associated with earthquake activity on the East Anatolian and Dead Sea Rift Fault systems, but also potentially increases predicted hazard values in background zones. The ground motion prediction equations (GMPE) weights were not changed from the SHARE project, using a breakdown of four GMPE equations supported by OpenQuake, Akkar-Bommer2010, CauzziFaccioli2008, ChiouYoungs2008, and ZhaoEtAl2006 (these equations can be found in Douglas (2011)), with weights of 35%, 35%, 20%, and 10%, respectively. Mean ground motion values are calculated as a weighted average using these four equations.

The PSHA performed in this study was computed on a .05 degree grid across the entire study area. The python script generatecoords.py (Appendix A) was used to create the coordinate file. Peak ground acceleration (PGA) was selected as the ground motion variable due to its applicability to Turkish building stock. PGA captures the motion experienced at the ground surface, and is therefore usually applied for short buildings (less than seven stories) (USGS, n.d.). The OpenQuake PSHA configuration file was modified to output mean hazard map data, calculating a PGA value at each grid cell location for the specified investigation period and exceedance threshold. The hazard map produced for this study maps shaking intensity at ten percent exceedance likelihood in a 50 year period, nearly equivalent to a 1/475 annual return period. This is a common hazard map exceedance interval as well as the specified threshold in the Turkish building code (Ilki and Celep, 2012). A hazard map for a 50-year interval at a 10% exceedance threshold indicates the PGA values that have a 90% chance of not being exceeded in any given 50 year period.

4.2 **Population Scenarios**

Both the earthquake risk index and earthquake loss modeling portions of this study require the integration of population statistics with hazard information. To account for the full range of internal and external migration, five district-level population scenarios were generated: 2011 census population, 2015 estimated population, 2015 low-bound migration, 2015 median migration, 2015 high-bound migration. District-level data for 2011 and 2015 were downloaded from the Turkish Statistical Institute's central dissemination system (TSI, 2015). The difference between these two datasets was used to track internal migration.

Displaced persons statistics from the end of 2015 at the province level from the U.S. Humanitarian Information Unit were manually transferred from a series of choropleth maps, available from HIU, 2016. These data were aggregated into district-level population scenarios by adding displaced persons to the 2015 population estimates. Several assumptions bounded the construction of these population scenarios. First, the district-level distribution of refugees was set at an equivalent percentage to the natural population distribution. For example, if a district contained 25% of the province's population, 25% of the displaced population was assigned to that district. These percentages can be seen in Figure 4.2. Secondly, all refugee camp populations were incorporated into the population scenarios. This involved forcing known camped populations from EADRCC (2015) into their respective districts while removing those numbers from the total province level estimates distributed across all other districts in the province. Hosting refugee camps did not prevent districts from receiving their proportional percent of non-camped refugees. However, if the total camp population was higher than the lower bound provided on the HIU maps, the total camped population became the lower bound and no additional refugees were distributed into districts. Otherwise, the population estimates were not changed. Three migration population scenarios were created according to this methodology—two using the low and high bounds provided on the choropleth maps, and a third using the median.



Figure 4.2: This map shows how province population is distributed at the district level. These percentages were used to transform province refugee populations into district level data. (Cartography by Bradley Wilson).

4.3 Earthquake Risk Index

Seismic hazard data was integrated with the population scenarios to calculate an exposurebased earthquake risk index. GIS shapefiles containing Turkish administrative boundaries at the province and district level were downloaded from the Global Administrative Area Database (GAA, 2015). These polygons were used in combination with QGIS' native 'Points in Polygon' feature with the mean option selected to spatially average the gridded PGA values from the seismic hazard map. Additionally, the district level shapefile was table joined with the population scenarios and district-level areas. At this point, portions of the shapefile attribute table were exported to a .csv file using the QGIS plug-in MMQGIS, available for free download using the built-in plug-in repository. The resultant .csv files included eight columns: HASC2 (a district identifier code), district area, average PGA value, and each of the five population scenarios.

In Microsoft Excel, changes in population and population density were calculated for each district between 2011-2015, 2015 and each refugee scenario, and the net change including both internal and external migration for each migration scenario. To integrate the hazard data with population information, z-scores were calculated for each variable using equation 4.1. Zscores standardize each variable dataset to have a mean of zero and a standard deviation of one. Thus, for each variable, the z-score provides the deviation from the mean for each data point. This process of standardization allows for the variables of different units to be directly compared. The z-scores for population (both total change and change in population density) were combined with the z-score for PGA in an equal ratio to produce risk scores.

$$z_i = \frac{x_i - \bar{x}}{\sigma} \tag{4.1}$$

where \bar{x} is the mean and σ is the standard deviation.

This type of exposure-based risk index provides a relative measure of seismic risk throughout the study area. Districts with high hazard, but low population and population density will score similarly to districts with high population but low seismic hazard. The highest risk scores will occur in regions that have the highest relative combination of population, population density, and seismic hazard. These risk index scores are useful for comparisons between districts because they rank deviations from a standard value. Additionally, they leverage static hazard values to show the extent to which population changes shifted the locations of highest risk. However, it should be noted that these risk index results require some interpretation and should not be viewed in isolation. Risk changes as shown by the index do not necessarily correspond to regions of high or low risk. Accordingly, risk scores will be discussed in a larger context including the seismic hazard map and earthquake casualty scenarios to provide a framework for interpreting results.

4.4 Earthquake Fatality Scenarios

The third portion of this study uses a semi-empirical approach to estimate fatalities for a series of simulated earthquake ruptures. Fatality estimates are calculated using both pre and post migration population data for each simulated earthquake to assess the degree to which displaced populations affect earthquake losses across the study area. A semi-empirical loss estimation is a hybrid forward modeling approach that determines casualties based on shaking intensity values and estimations of structure types, collapse rates, and fatality rates. The semi-empirical approach as outlined in Jaiswal et al. (2011) is given by:
$$E[L] \approx \sum_{i=1}^{n} \sum_{j=1}^{m} P_i \cdot f_{ij} \cdot CR_j(S_i) \cdot FR_j$$
(4.2)

where n is a grid of intensity values, m is a list of structure types, P_i is the population at grid cell i, f_{ij} contains the fraction of the population at location i in structure type j, $CR_j(S_i)$ gives the collapse rate of structure j at given intensity S_i , and FR_j gives the fatality rate of structure type j if it collapses.

Therefore, for each grid point, Equation 4.2 sums over m structure types and calculates the estimated collapse rates and related fatalities under the intensity value assigned to the corresponding grid point. Summing over n grid points gives the total estimated fatalities for a particular earthquake event. Loss estimations for this study were calculated at the district level. To calculate district averaged intensity values, earthquakes were simulated on five fault segments distributed across the study area. For each fault segment, moment magnitude 5.8, 6.4, and 7.0 ruptures were simulated in OpenQuake, representing moderate, strong, and major earthquakes. OpenQuake earthquake simulations require a rupture configuration file specifying the geometry, magnitude, and hypocenter of the earthquake rupture (Appendix B), and output a gridded series of files containing peak ground acceleration values. For each earthquake, six sets of PGA values were calculated using the ground motion prediction equation specified in Akkar and Bommer (2010). The PGA values from each of the six rupture files were averaged using a mean ground motion MATLAB script (Appendix A). The gridded intensity values were then loaded into QGIS, spatially averaged at the district level, and exported to a .csv file alongside the population scenarios using the same approach detailed above for the hazard map. This process was repeated for each earthquake scenario.

At this stage, the MATLAB script eq_losses.m (Appendix A) applies Equation 4.2 for each formatted data file. This script undergoes the following steps:

- 1. Loads in the formatted data file.
- 2. Specifies the percentage of the population in each building type according to expert estimates of building distribution (Jaiswal and Wald, 2009). These percentages are calculated for both urban and rural populations.
- 3. Defines the collapse rate for each building type at various shaking intensities from estimates in Jaiswal and Wald (2009). World Housing Encyclopedia sub-categories are grouped into four conglomerate categories: woodframe, concrete, unreinforced brick or block, and adobe.
- 4. Specifies the fatality rates for each building category, from Porter et al. (2008)
- Applies the PGA-intensity conversion from Wald et al. (1999a) to each district averaged PGA value. (While this relationship was developed on Californian earthquakes, Erdik (1985) showed that western ground motion equations are a suitable proxy for Turkish earthquakes.)
- 6. Loops through each population scenario calculating each district's estimated fatalities both urban and rural. The average intensity values are used to assign the correct collapse and fatality estimates.
- 7. Outputs results to a .csv file

4.5 Assumptions and Limitations

PHSA is limited by the quality of the earthquake catalog and selection of source models. By using data from the SHARE project, this study utilized the most recent source models and earthquake catalog available. When the Earthquake Model of the Middle East source models are publicly released (the earthquake catalog was released in 2014 in Zare et al. (2014)), a similar analysis for a larger portion of the Middle East could be performed with the same methodology. However, the fault models for Turkey are almost identical between SHARE and EMME. The choice of ground motion prediction equations has been the subject of considerable research (Cua et al., 2010, Bommer and Abrahamson, 2006). This research utilized a weighted average of four equations, weighted more heavily for equations shown to be accurate in the Middle East, to account for uncertainty between individual equations. Source model uncertainty is constantly changing as more earthquake data is acquired. Faults with long recurrence intervals that have not ruptured in the instrumental record are likely to be underestimated in this research. The declustering process required for an earthquake catalog to be used in PHSA eliminates the usability of many historical earthquakes. However, despite this uncertainty, the results of this research match other hazard studies performed in this area (a good overview is available in Erdik (2015)) as well as results from historical earthquakes that have sufficient data to estimate intensity.

The earthquake risk index presented in this research focuses only on exposure measures. Seismic risk is inherently complicated, involving many social, economic, and political factors not included in this analysis. While seismic hazard, exposure, and building stock remain the largest drivers of earthquake loss, other risk factors can complicate the relief and recovery process in addition to impacting mitigation efforts prior to an earthquake. Furthermore, displaced persons are viewed simply as additional numbers in the various population scenarios, assuming they cope equally with that of citizens. This is a best case scenario, as realistically, the ability of displaced persons to reduce their personal risk or recover from an earthquake is lower than that of citizens (Wisner et al., 2004). The 3RP report indicates that many of the refugees still remain with limited access to resources, healthcare, and that 25% still live in makeshift housing 3RP (2015). Therefore, the risk increases due to displaced persons are likely to be minimum estimates. The large uncertainties associated with the migration numbers themselves presents challenges for knowing exactly the extent and location of migration in the area. Concerning location, placing displaced persons at the district level to match the citizen population distribution relies on the assumption that Syrians are heading to population centers to find food, shelter, and work.

Finally, the earthquake fatality estimates have uncertainty associated with each input into the equation. A semi-empirical approach relies on expert estimates of building stock, collapse rates, and fatality rates. The values used in this research are all recent and from USGS or collaborative international sources. Yet, loss estimations should be viewed as 'order of magnitude' estimates rather than exact numbers. An updated Turkish building census data set would vastly improve the accuracy of the earthquake fatality estimates, when available. Local building stock, soil conditions, time of day, geologic setting, and many more variables can vastly alter the damage in a particular earthquake. The fifteen scenarios presented in this work do not represent an exhaustive picture of potential earthquake consequences in the study area.

5: RESULTS & ANALYSIS

This research analyzed the impacts of Syrian migration on earthquake risk in southeastern Turkey using a combination of three techniques: seismic hazard mapping, seismic risk mapping, and earthquake loss estimation. Seismic hazard was broadly characterized through the creation of a localized seismic hazard map for the provinces accommodating the majority of Syrian refugees. This map was used to identify the districts of highest hazard, as defined by probabilistic peak ground acceleration (PGA) values for a 10% exceedance threshold in a 50 year period. Next, ground motion values were spatially averaged at the district level and integrated with five population scenarios to form an exposure-based risk index, designed to assess the overlap between populations and seismic hazard and visualize changes in seismic risk from both internal and external migration. Finally, fatality estimates for fifteen earthquake scenarios (five locations at three different moment magnitudes—5.8, 6.4, 7.0), were calculated pre-migration and post-migration using a semi-empirical loss estimation technique. The difference in fatalities between the premigration and post-migration calculations were assessed to determine the extent that neglecting refugee populations underestimates human casualties in a variety of earthquake events.

5.1 Earthquake Hazard

The probabilistic seismic hazard analysis results for this study are seen below in Figure 5.1, plotted as a filled contour map of PGA values. This map shows PGA values that have a 10% chance of being exceeded in a fifty year period, a close estimation for a 1/475 year return period earthquake. Using the PGA-intensity conversion from Wald et al. (1999a), the color boundaries correspond to macroseismic intensity values of V, shown in dark green, to IX, shown in red. In physical terms, intensity V typically represents moderate shaking and light damage, while inten-



Figure 5.1: This map breaks earthquake hazard results (smoothed from the .05 degree grid) into five peak ground acceleration zones, corresponding to intensity values of V to IV. High peak ground acceleration values follow the major faults in the study area and decay with increasing distance from fault zones. (Cartography by Bradley Wilson).

sity IX typically represents violent shaking and heavy damage.

The areas of highest hazard follow the East Anatolian Fault (EAF) system northeasterly, starting from the Maraş Triple Junction located in the center of the map and progressing towards the Karlıova triple junction (located outside the study area), where the EAF connects into the North Anatolian Fault system. Areas of moderate-high hazard extend down the from triple junction along the Dead Sea Fault system through Osmaniye, Gaziantep and Hatay. PGA values also decrease outwards from the EAF system, with moderate-high areas incorporating most of Kahramanmaraş, Malatya, Adıyaman, Elaziğ, Tunceli, and Erzincan. With the exception of one small area of medium-low hazard in Kayseri, all the provinces in the study area located west of the EAF system lie in medium to medium high seismic hazard zones, while seismic hazard drops off to the southeast into Syria.

These hazard results raise significant concerns for poorly constructed buildings in the area. Building collapse starts to occur around intensity VI, colored light green in Figure 5.1, increasing with PGA. Therefore, within any given fifty year interval, these results show every single district contained within the study site is capable of producing some level of building collapse at the 10% exceedance threshold. These results match the large-scale trends in seismic hazard for Turkey presented in the SHARE European seismic hazard maps (Woessner et al., 2015) as well as other seismic hazard studies produced for the country (Erdik, 2015, Grünthal et al., 1999), and Turkey's official earthquake zoning map (Gülkan et al., 1993).

5.2 Population Scenarios



Figure 5.2: This map shows the district-level distribution for the low-bound migration scenario. Districts with refugee camps stand out in the low-bound scenario compared to the median or high bounds scenarios. (Cartography by Bradley Wilson).



Figure 5.3: This map shows the district-level distribution for the median-bound migration scenario. The median bound scenario distributes displaced populations across a wider number of districts compared to the low-bound scenario (Cartography by Bradley Wilson).



Figure 5.4: This map shows the district-level distribution for the high-bound migration scenario. Trends are similar to the median-bound scenario with higher population densities and less influence of refugee camps (Cartography by Bradley Wilson).

Figures 5.2 - 5.4 show the results of integrating low, median, and high bound migration data from U.S. Humanitarian Information Unit (HIU) (2016) and EADRCC (2015) with 2015 Turkish population estimates. These three scenarios were used in all subsequent risk and loss results (differences between 2011 and 2015 estimated populations due to internal migration can be seen in Chapter 2). In the low-bound scenario (Figure 5.2), the distribution of refugees is influenced by the location of refugee camps. This is directly related to the assignment mechanism where districts without camps are not assigned additional population if the camped refugee population surpasses the HIU population estimates. The impact of refugee camps in the median (Figure 5.3) and high-bound (Figure 5.4) scenarios are increasingly diminished, as HIU estimates surpass the known camped population. In these scenarios, districts with previously high populations become increasingly populated, as refugees were assigned in proportion to the natural population breakdown. However, in general, camped and non-camped populations have similar spatial trends. Most refugee camps are located near previously populated areas and are consequently assigned high percentages of refugees in all scenarios.

Similarly, converting province level populations to district populations retained the spatial trends seen at the provincial scale. The southern provinces of Hatay, Adana, Kilis, and Gaziantep contain the highest migrated population, with Osmaniye, Kahramanmaraş and Şanlıurfa following behind. Migrated population strongly decreases away from the Turkey-Syria border. These trends hold across all three population scenarios, but with different magnitudes. The low bound scenario averages an increase of less than thirty persons per square kilometer and peaks at 129 refugees per square kilometer, representing a 3.5% increase in population compared to the 2015 base population. In the median and high estimates, these averages increase to just above 10% and 17%. However, these averages do not reflect the disparity between northern and southern provinces. The ratio comparing migrated population density to base population density at the province-level is seen below in Table 5.1.

| Province | Low-Bound (%) | Median (%) | High-Bound (%) |
|---------------|---------------|------------|----------------|
| Adana | 4.1 | 12.9 | 21.6 |
| Adıyaman | 0.4 | 8.6 | 16.8 |
| Diyarbakır | 0.6 | 3.3 | 6.0 |
| Elaziğ | 0.2 | 1.0 | 1.7 |
| Erzincan | 0.0 | 0.2 | 0.5 |
| Gaziantep | 10.8 | 20.1 | 29.3 |
| Hatay | 7.1 | 19.2 | 31.4 |
| Kilis | 46.7 | 128.3 | 209.9 |
| Kahramanmaraş | 0.3 | 4.0 | 7.8 |
| Kayseri | 0.7 | 4.1 | 7.4 |
| Malatya | 1.6 | 6.9 | 12.2 |
| Osmaniye | 0.7 | 9.4 | 18.1 |
| Şanlıurfa | 7.7 | 17.3 | 26.9 |
| Sivas | 0.2 | 0.9 | 1.6 |
| Tunceli | 0.0 | 0.6 | 1.2 |
| Yozgat | 0.0 | 0.1 | 0.2 |
| Total | 3.5 | 10.4 | 17.2 |

Table 5.1: Migrated population density as percentages of province-level base population density

*Provinces with less than two districts included in study site omitted from Table 5.1.

5.3 Earthquake Risk

Risk index maps visualizing the integration of population and hazard data at the district level are shown in Figures 5.5 - 5.12. The first map, Figure 5.5, shows the risk index calculated using population data from the 2011 census, before mass migration began in the region. In this scenario every district's risk score is between negative one and one. Because the risk index is calculated from equal-weights averaged standard scores, a narrow distribution of scores indicates relatively weak risk variations. No single district or region stands out above the rest as a uniquely high combination of both seismic hazard and population density. Instead, this map reflects more



Figure 5.5: This map shows the distribution of seismic risk across the study area, calculated using the 2011 Turkish census data. Districts with high populations and high population density show increased levels of seismic risk, especially when located in areas of medium to high seismic hazard (Cartography by Bradley Wilson).

general risk trends indicative of the index's component parts. Areas of high risk correspond to districts of (1) high seismic hazard along the EAF and((2) high population density (Adana, An-takaya, Gaziantep, Malatya, Kahramanmaraş). Consequently, areas of high risk are mostly evident in populated districts directly along the EAF and DSF systems. The single highest scoring district is Seyhan, Adana, a district of medium seismic hazard but the most populous district in the study area.

Figure 5.6 shows the difference in risk scores when using 2011 census data compared to 2015 Turkish official population estimates. These scores were mapped to account for natural population changes between 2011 and 2015 in order to isolate the effects of migration. The deviations in scores range from -0.05 to 0.06, indicating that internal migration has not significantly adjusted the relative ranking between districts. Therefore, any calculated changes in the risk index between 2011 and 2015 total populations, including refugees, are overwhelmingly a function of external migration. It is important to note however, that these risk index scores are not indicative of the of the qualitative ways in which continuing internal urbanization trends affects seismic risk.

Figures 5.7 - 5.9 map the risk index changes between 2011 and 2015 for each of the three refugee-inclusive population scenarios, calculated as the difference in risk scores. All three maps show a dramatic southward increase in seismic risk and a corresponding northward decrease. Both types of changes, risk increases and risk decreases, are relative to other areas in the study site. Accordingly, blue districts (decreased risk) are not to be interpreted as low risk areas, but as districts that scored comparatively less on the risk index in 2015 than in 2011. Likewise, red districts (increased risk) should be interpreted as districts that scored comparatively higher on the risk index in 2015 than in 2015. The results strongly mirror the population scenarios themselves,



Figure 5.6: This map shows the distribution of seismic risk across the study area, calculated using the 2011 Turkish census data. Districts with high populations and high population density show increased levels of seismic risk, especially when located in areas of medium to high seismic hazard (Cartography by Bradley Wilson).



Figure 5.7: This map shows the changes in seismic risk index scores, calculated in 2011 and 2015 using the low-bound migration scenario. Note the large increases in refugee camp locations, as dictated by the low-bound migration scenario. (Cartography by Bradley Wilson).



Figure 5.8: This map shows the changes in seismic risk index scores, calculated in 2011 and 2015 using the median migration scenario. Note the similar pattern to the low-bound scenario, but less influence of refugee camp locations and more broad low-level risk changes. (Cartography by Bradley Wilson).



Figure 5.9: This map shows the changes in seismic risk index scores, calculated in 2011 and 2015 using the high-bound migration scenario. Note the continued expansion of low-level risk changes and concentration of risk in districts of southwest provinces. (Cartography by Bradley Wilson).

with almost all risk increases confined to districts within half a degree of the Turkey-Syria border. Kilis and Hatay have increased their risk across the entire province, while Şanlıurfa, Gaziantep, and Adana show increased risk in select districts. With the exception of a few heavily populated districts elsewhere in the study site, every other district has slightly decreased their relative risk index scores. Comparing the magnitude of risk change in from internal migration (Figure 5.6) to external migration (Figures 5.7 - 5.9) further evidences why refugees are a necessary inclusion in population models. The risk score changes from refugee populations, even in a low-bound scenario, dwarf those from natural population flux.

Figures 5.10 - 5.12 show the risk index scores calculated for the 2015 total population. Instead of mapping risk changes, these maps reintegrate the effects of seismic hazard variations. Yet, all three maps show a significant southward increase compared to the equivalently calculated 2011 map (Figure 5.5). In 2011, both population and seismic hazard influenced districts assigned as high risk. In 2015, population deviations far outweighs those of seismic hazard if refugee data is included. This drastically influences the relative risk ranking between districts. Almost all of the high risk districts along the EAF northeast of the Maraş triple junction in 2011 drop to negative risk index scores in 2015. The magnitude and deviation of risk index scores increases several times over between 2011 and 2015, with maximums of 10.3, 12.7, and 13.1 for the low, median, and high bound scenarios compared to 0.95 for the 2011 model. All of the categories in Figure 5.5 are contained within the medium-low and medium color band in the 2015 maps.



Figure 5.10: This map shows the net distribution of seismic risk across the study area, calculated after adding in low-bound refugee estimates to 2011 census data. Seismic risk has increased in southern provinces and decreased along the East Anatolian Fault, as compared to the 2011 map. (Cartography by Bradley Wilson).



Figure 5.11: This map shows the net distribution of seismic risk across the study area, calculated after adding in median refugee estimates to 2011 census data. Seismic risk has increased in southern provinces and decreased along the East Anatolian Fault, as compared to the 2011 map. (Cartography by Bradley Wilson).



Figure 5.12: This map shows the net distribution of seismic risk across the study area, calculated after adding in high-bound refugee estimates to 2011 census data. Seismic risk has increased in southern provinces and decreased along the East Anatolian Fault, as compared to the 2011 map. (Cartography by Bradley Wilson).

Both the 2011 and 2015 maps are important for characterizing seismic risk in this region. Populated districts along the northeastern portion of the EAF remain prone to large earthquake events, but have not experienced the rapid population increases that the southern provinces have. Almost all exposure-related risk changes between 2011 and 2015 have been driven by refugee migration rather than internal migration. Refugee settlement into zones of moderate hazard extending up through Hatay, Osmaniye, Gaziantep, Adana, and Kilis towards the EAF-DSF junction has altered the regional population distribution to such a large degree that that population centers directly along the EAF do not crack the top ten district-level risk index scores in any refugee-inclusive population scenario, when weighted equally against ground motion variations.

5.4 Earthquake Scenarios

Fatality estimates calculated from district averaged shaking intensity are presented in Tables 5.2 - 5.4. In each of these tables, F_i show the fatalities calculated for each population scenario, 2011, 2015, low-bound, median, and high-bound. R_i shows the percentage additional casualties resulting from each population scenario, calculated as the ratio between the additional casualties in the target scenario divided by the casualties estimated using 2011 data (for internal migration) or 2015 data (for external migration). Table 5.5 presents the additional casualty percentages for each refugee migration scenario averaged across all five earthquake locations. Figures 5.13 - 5.15 show the alternative scheme, mapping casualty percentages for each scenario averaged across all magnitude ranges. The size of the coin reflects the total number of earthquake fatalities, while the orange slice reflects the percentage of refugee casualties. Maps showing the gridded ground-motion values for each earthquake scenario can be found in Appendix C.

| Scenario | F_{2011} | F ₂₀₁₅ | FLow | F_{Med} | F _{High} | $R_{Int}(\%)$ | $R_{Low}(\%)$ | $R_{Med}(\%)$ | $R_{High}(\%)$ |
|----------|------------|-------------------|------|-----------|-------------------|---------------|---------------|---------------|----------------|
| 1 | 31 | 25 | 0 | 1 | 2 | -19.4 | 0.0 | 4.0 | 8.0 |
| 2 | 168 | 153 | 0 | 6 | 10 | -8.9 | 0.0 | 3.9 | 6.5 |
| 3 | 2118 | 2209 | 124 | 415 | 704 | 4.3 | 5.6 | 18.8 | 31.9 |
| 4 | 280 | 260 | 0 | 29 | 61 | -7.1 | 0.0 | 11.2 | 23.5 |
| 5 | 3809 | 2952 | 183 | 586 | 987 | -22.5 | 6.2 | 19.9 | 33.4 |

 Table 5.2: Casualties for Earthquake Magnitude: 5.8

 Table 5.3: Casualties for Earthquake Magnitude: 6.4

| Scenario | <i>F</i> ₂₀₁₁ | F ₂₀₁₅ | FLow | F_{Med} | F _{High} | $R_{Int}(\%)$ | $R_{Low}(\%)$ | $R_{Med}(\%)$ | $R_{High}(\%)$ |
|----------|--------------------------|-------------------|------|-----------|-------------------|---------------|---------------|---------------|----------------|
| 1 | 149 | 125 | 0 | 5 | 14 | -16.1 | 0.0 | 4.0 | 11.2 |
| 2 | 1251 | 1331 | 31 | 86 | 138 | 6.4 | 2.3 | 6.5 | 10.4 |
| 3 | 6269 | 6538 | 387 | 1242 | 2098 | 4.1 | 5.9 | 19.0 | 32.1 |
| 4 | 1146 | 1135 | 19 | 123 | 228 | -1.0 | 1.7 | 10.8 | 20.1 |
| 5 | 7907 | 8192 | 374 | 1164 | 1955 | 3.6 | 4.6 | 14.2 | 23.9 |

Table 5.4: Casualties for Earthquake Magnitude: 7.0

| Scenario | F_{2011} | <i>F</i> ₂₀₁₅ | F_{Low} | F_{Med} | F _{High} | $\overline{R}_{Int}(\%)$ | $R_{Low}(\%)$ | $R_{Med}(\%)$ | $R_{High}(\%)$ |
|----------|------------|--------------------------|-----------|-----------|-------------------|--------------------------|---------------|---------------|----------------|
| 1 | 328 | 292 | 0 | 10 | 26 | -11.0 | 0.0 | 3.4 | 8.9 |
| 2 | 2672 | 2870 | 99 | 308 | 517 | 7.4 | 3.4 | 10.7 | 18.0 |
| 3 | 6551 | 6816 | 408 | 1300 | 2193 | 4.0 | 6.0 | 19.1 | 32.2 |
| 4 | 1814 | 1786 | 51 | 231 | 417 | -1.5 | 2.9 | 12.9 | 23.3 |
| 5 | 10134 | 10548 | 454 | 1461 | 2463 | 4.1 | 4.3 | 13.9 | 23.4 |

Table 5.5: Refugee Additional Fatality Percent Averages

| Magnitude | Low-Bound (%) | Median (%) | High-Bound (%) |
|-----------|---------------|------------|----------------|
| 5.8 | 3.3 | 12.0 | 21.2 |
| 6.4 | 2.9 | 10.9 | 19.5 |
| 7.0 | 2.4 | 11.5 | 20.7 |
| All | 2.9 | 11.5 | 20.4 |



Figure 5.13: This map contains the breakdown of earthquake fatality estimates for the low-bound migration scenario at each earthquake scenario location (ruptured faults highlighted in red). The total casualties are shown by the size of the coin while the breakdown shows the percentages associated with Turkish citizens and Syrian refugees. The low, medium, and high casualty ranges are provided for each earthquake magnitude (Cartography by Bradley Wilson).



Figure 5.14: This map contains the breakdown of earthquake fatality estimates for the median migration scenario at each earthquake scenario location (ruptured faults highlighted in red). The total casualties are shown by the size of the coin while the breakdown shows the percentages associated with Turkish citizens and Syrian refugees. The low, medium, and high casualty ranges are provided for each earthquake magnitude (Cartography by Bradley Wilson).



Figure 5.15: This map contains the breakdown of earthquake fatality estimates for the high-bound migration scenario at each earthquake scenario location (ruptured faults highlighted in red). The total casualties are shown by the size of the coin while the breakdown shows the percentages associated with Turkish citizens and Syrian refugees. The low, medium, and high casualty ranges are provided for each earthquake magnitude (Cartography by Bradley Wilson).

At all three earthquake magnitudes, scenario five and scenario three resulted in the most earthquake casualties because of their proximity to heavily populated districts. As a general trend, the total number of casualties in each scenario reflects the size of population exposed to strong shaking. These trends extend to refugee populations as well—higher migrated populations result in higher percentages of additional casualties. While the total fatality estimates range from 31 to 12,597, all five earthquake locations are shown to possibly result in hundreds or thousands of casualties under credible earthquake magnitudes. In areas where national building stock averages closely represent local structures, the fatality estimates will have significantly smaller error bounds than those areas that deviate from national averages. Accordingly, the relative comparisons between scenarios are more useful than a single scenario's exact casualty estimates.

Comparing the same scenario at different earthquake magnitudes indicates that casualties do not linearly increase with magnitude, and do not increase in equivalent percentages for each earthquake scenario. The former is explained by non-linear collapse percentages; An increase in shaking intensity does not always result in an equal increase in collapse percentages. For example, Turkish estimates provided in Jaiswal and Wald (2009) indicate a woodframe building's collapse rate quadruples from intensity VI to VIII, but only doubles from VIII to IX. These variations interact with population distribution to explain the second conclusion; the location of an earthquake rupture drives what magnitude earthquake is needed to produce significant casualties. In scenario three, increasing magnitude from 5.8 to 6.4 increases the casualties by 4000 individuals while a subsequent increase to 7.0 increase casualties by 300 individuals. These results are distinct from scenario five where both magnitude increases result in several thousand more casualties. Scenarios two and four match the pattern of three (large increases from 5.8 to 6.4 and small increases from 6.4 to 7.0), while scenario one matches the pattern of earthquake one (large

increase in both cases). These results have implications for earthquake mitigation because the same magnitude earthquakes may affect provinces and districts differently—adding further evidence to support the conclusion that earthquake magnitude is poorly correlated to earthquake casualties.

The ratio results in Table 5.5 indicates that incorporating displaced persons into population scenarios increase estimated casualties by 3%-20%, depending on the scale of migration. Since the low and high-bound scenarios represent the minimum and maximum refugee estimates, the median estimate is most likely to accurately characterize the percentage of additional casualties. Accordingly, average casualties estimates across all scenario locations are between 10.9% and 12.0%, with individual earthquake locations reaching as low as 3.4% in scenario one, magnitude 7.0 and as high as 19.1% in scenario three, magnitude 7.0. Overall, these percentages indicate that using census data for loss estimation of a moderate to strong earthquake in southeastern Turkey will underestimate casualties on the order of tens to several thousand individuals. If the true migration numbers are on the upper end of the HIU estimates, the percentage of additional casualties in a large earthquake could average 20% and reach upwards of 30% in populated districts along the Turkey-Syria border.

6: DISCUSSION

Seismic risk along the Turkey-Syria border has increased since the onset of mass migration in 2011. Significant increases in population density coupled with medium to high probabilistic earthquake hazard creates districts and provinces vulnerable to earthquakes. Mapping tier-changes in an exposure-centric risk index between 2011 and 2015 identifies categorical risk groupings, seen below for the median migration scenario in Figure 6.1. The four classification corners: *high-high* (risk was high and increased post-migration), *low-low* (risk was low and remained low post-migration), *high-low* (risk was high but decreased post-migration), and *lowhigh* (risk was low but increased post-migration), define unique combinations of earthquake risk and risk changes. Excepting low-low districts, the remaining three corner classifications pose unique challenges for earthquake mitigation. The mid-range classifications reflect their corresponding boundary to a lesser degree, e.g. a *low-medium* district is a less severe version of *lowhigh*. These distinctions will be used to frame hazard and risk mitigation discussions.

6.1 High-low districts: The classical challenge

Districts that accommodated fewer refugees generally decreased their risk index score post-migration. Accordingly, districts with a high-low classification scored high on the risk index in 2011, but did not receive significant refugee populations. Regardless, high-low districts remain areas of concern due to their overlap of existing population exposure and seismic hazard. While this study focused on the impacts of the refugee crisis on seismic risk, the fact remains that any populated district in Turkey could be the location of a disastrous earthquake. Despite the existence of formal seismic building codes, existing building stock remains a significant area of concern for Turkey (Ilki and Celep, 2012). Results from the probabilistic seismic hazard assessment



Figure 6.1: This map shows risk group classifications calculated from the change in risk index groupings. Red regions of all tones show high risk districts using 2011 census data, while non-transparent tones of all colors show high risk districts in 2015 after incorporating a median migration estimate (Cartography by Bradley Wilson).

(Figure 5.1) indicate that the majority of the study area is capable of sustaining MMI VII shaking in any 50 year period, with many provinces capable of sustaining Mercalli Intensity of VIII or IX. At Mercalli Intensity VII, an estimated 20%-40% of clay, brick, and block masonry structures will collapse while only 0.3%-2% of moment resisting concrete structures are estimated to collapse (Jaiswal and Wald, 2009). At MMI IX, these differences vary from 5% for shear wall structures to 90% for adobe structures. Expert estimates for Turkey indicate only 10% of Turkey's urban population and none of Turkey's rural population lives in the shear wall structures, the safest building type (Jaiswal and Wald, 2009).

Turkey's building stock, much of which is legally constructed, has not performed well in recent earthquakes Ilki and Celep (2012). Design and construction errors in addition to insufficient inspection practices are the cause of most building failures in Turkey Ilki and Celep (2012). Ilki and Celep (2012) concluded in their 2012 review of the evolution of Turkey's building code that "It is not possible to claim that buildings have been constructed following the codes valid in the time of their construction due to lack of sufficient enforcement of the code," (378). The authors do note that buildings constructed after the 1999 Kocaeli earthquake have a significantly higher likelihood of being up to code. However, without an sufficient building registry, it is difficult to properly characterize the collapse potential across large geographical areas. Seismic building codes are somewhat paradoxical in the mitigation space, as improving building codes appears to be simultaneously the most and least likely actionable step towards reducing seismic risk. Continuously improving building codes is critically important because buildings collapse causes almost all earthquake deaths, but the enforcement of such codes and their nebulous application to areas with aging infrastructure are even larger challenges. Ongoing developments in seismic design codes will continue to falsely increase construction confidence as long as corrup-

tion and bribes remain commonplace. As noted in Kasapoğu and Ecevit (2004), the majority of residents in Istanbul believe their homes are safe, contrary to the reality of most Turkish construction .

6.2 Low-high districts: The unexpected

This study examined rapid changes in population exposure from mass migration, a variable that has not been previously integrated into Turkish seismic risk analysis. Districts with a low-high classification represent areas where drastic migratory population density increases have affected previously low-risk areas. This classification opposes the more common case, high-high, where refugee migration increased population in areas that would have been previously calculated to be high risk given their pre-migration population numbers. All districts in Kilis and several in Şanlıurfa are notable low-high districts. These districts typify areas of unexpected earthquake consequences, especially those in Kilis. In 2011, the entire province of Kilis was home to around 100,000 citizens. Since 2011, Kilis has accommodated an additional 100,000 to 500,000 displaced Syrians— increasing population density by several hundred percent. The hazard estimates for Kilis are medium to low, but seismic risk increases alongside population increases all else held equal.

This scale of population change presents challenges for both scientific modeling and contingency planning. Earthquake mitigation practices are not typically undertaken in areas with low predicted risk. With limited budget allocations to disaster mitigation, relief, and recovery, tools like probabilistic hazard analysis and loss modeling are utilized for the purpose of determining where sparse resources should be invested. This study manually incorporated displaced persons statistics into population models, a step not traditionally taken in risk analyses or loss estimation.

Yet, as seen in the risk index changes and earthquake scenarios, not including refugee populations significantly underestimates casualties. In 2011, Kilis is unlikely to have been a candidate province for a disastrous earthquake. In 2015, an earthquake near Kilis could be among the most deadly of any earthquake in southern Turkey. Refugee-inclusive population models are therefore crucial for earthquake planning purposes, at least in the short-term future.

6.3 High-high districts: The underestimated

The districts of highest concern are those that ranked highly in 2011 and 2015. A high risk index score in 2011 signifies a populated district in an area of medium to high hazard. A high risk index score post-migration in 2015 indicates significant population increases. Accordingly, high-high districts are capable of sustaining high casualties and a high percentage of additional casualties. These districts also possess the unexpectedness trait of low-high districts because their additional populations are likely to be unaccounted for. Yet, their 2011 risk score signifies a larger base population or higher seismic hazard compared to low-high districts. Districts in Hatay, Adana, and Gaziantep exemplify high-high districts. In the earthquake scenarios, Hatay and Adana sustained the highest casualties, with Hatay also sustaining the highest proportion of additional casualties from migration. In Hatay, the features of high-high classification can be seen in records of historical earthquakes. Antioch (modern day Antakya, Hatay) suffered numerous disastrous earthquakes in its early history from both large earthquakes (115 C.E.) and medium earthquakes magnified by population density and migration (526 C.E.).

The underestimation of earthquake loss in high-high districts is amplified by structural vulnerability. Refugees migrating to population centers increases occupancy in urban buildings, likely similar to those that have failed in previous earthquakes. In the 1999 Kocaeli earthquake,

most affected citizens lived in multi-story residential buildings that commonly compromised on construction quality (Erdik, 2001). Erdik (2001) argued that housing needs, bureaucratic red tape, limited accountability, and the government's obligation to reconstruct destroyed buildings under the Turkish compulsory earthquake insurance program all contributed to poor seismic construction in such buildings. Thus, as housing needs and political stresses continue to expand alongside refugee migration, similar buildings likely will continue to be the choice for construction in urban settings. Moreover, if refugee populations are not accommodated in mid-story concrete buildings, the outlook remains the same. More traditional rural Turkish buildings (unreinforced masonry and adobe structures) in the 2011 Van Earthquake did not adhere to any seismic building code and ubiquitously failed to resist earthquake ground motions (11,000 damaged and 6,000 unin-habitable) (Güney, 2012). Given that refugees still require access to basic needs (3RP, 2015), the chances of settlement in seismically resistant construction is extremely low. As a result, the the accommodation of additional populations in poor construction directly contributes to the likelihood of underestimation of earthquake loss.

6.4 Risk Reduction

The findings in this study add to the body of literature challenging the use of census data for rapid earthquake loss estimation. Even if the 2011 Turkish census data or 2015 Turkish population estimations were perfectly accurate, the massive uncertainties associated with post-2011 migration cripples the ability of scientists to provide reliable loss estimations along the Turkey-Syria border. This feedback loop—uncertainty in population statistics creating uncertainty in risk models and loss estimates—can quickly spiral into a self-reinforcing cycle. It becomes increasingly difficult to convince policy makers to implement mitigation practices and improve policies when the impacts of uncertainties, especially those as basic as population numbers, are unknown. The availability of district level migration statistics would vastly improve the ability to characterize losses potential earthquake scenarios. In light of this, the results of this study aimed to provide a framework for discussion by using uncertainty bounds to highlight the best and worst case scenarios. However, showing that refugee migration has broadly increased seismic risk in southern districts relative to northern districts raises a complex question: should disaster reduction budget allocations significantly incorporate individuals of temporary residence?

History indicates the practical answer is—and will continue to be—no. In fact, the refugee crisis likely decreases the chances of seismic mitigation in southern Turkey. Improving construction practices, retrofitting existing buildings, and ensuring access to resources after an earthquake are practices that are effective in reducing earthquake risk, but costly to implement. With the burden of these costs falling almost entirely on governmental institutions, the practice of mortality prevention already depends on calculations of opportunity cost. Keefer et al. (2011) found that countries that are poorer, less-democratic, and amidst political turmoil are less likely to enforce construction standards. As a result, refugees are unlikely to be considered in such calculations, as the rapid influx of 2.7 million displaced persons demands immediate attention on pressing issues like food, shelter, and sanitation. Additionally, mass-migration introduces new cultural issues between refugees and host populations. Anbarci et al. (2005) showed a positive relationship between inequality and disaster mortality, arguing that inequality reduces cooperation between groups. Therefore, current unrest in Middle Eastern geopolitics strongly decreases the chances that mitigating earthquakes with recurrence intervals of several hundred years will be an active part of Turkish political discussions.

These conclusions influence recommendations for working to increase earthquake miti-
gation in this region. At this point, hazard studies for Turkey, including the hazard map produced for this study, are in accordance on the large-scale breakdown of seismic hazard—generally decaying at distance from the East Anatolian Fault, North Anatolian Fault, and Dead Sea Fault zones (Erdik, 2015). Additionally, most of the high risk population centers prior to migration remain high risk population centers post-migration. In an area defined by rapid change, agreements on regions overlap of hazard and exposure should be communicated as key places for improvement. Reducing risk in previously populated districts does not depend on uncertain settlement estimates, but still covers large percentages of the migrated population, provided that a large percentage of displaced persons have integrated into populated areas. Antakya, Seyhan, Kahramanmaraş, and Gaziantep are four candidate districts where improvements would cover large percentages of both Turkish and Syrian populations. As described above, structural improvements are the best step towards reducing earthquake casualties, but challenging to verify. Providing various forms of earthquake education are another way to reduce seismic risk and increase a community's capacity to cope with disaster.

6.4.1 Future Work

This research focused primarily on assessing seismic risk as a function of population variables and seismic hazard and incorporating displaced persons into earthquake loss modeling. In future work, these principles could be expanded in several ways. If large-scale refugee crises continue to affect hazardous areas, research that seeks to identify the ways in which migrated populations are affected differently in natural hazard events is a necessary exploration. Data for this type of analysis is likely to be sparse, but examining the political and legal differences, precise settlement locations, and demographic differences would be a starting point. Using a socio-economic

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vulnerability index could provided the framework needed to compare the two population types. Even without the refugee component, a socio-economic vulnerability analysis in this study region could provide another layer of data for an integrated risk analysis. Understanding the urban-rural differences as well as the provincial variations would help characterize particularly vulnerable areas.

Another question that remains unanswered in this study addresses the effects of an earthquake on the Syrian side of the border. Several faults are capable of rupturing close to Syrian settlements, internally displaced person camps, and large cities. Although population statistics in Syria are hugely uncertain, an earthquake along its western border would impact at minimum thousands of Syrians fleeing conflict zones. Both of the current border crossings between Turkey and Syria are located in areas of active seismicity, and many internally displaced person camps are located near these border crossings. Furthermore, refugees migrating to other neighboring countries, Lebanon, Jordan, and Iraq, are also settling in seismically active areas. While this study focused on a portion of Turkey, it is paramount to understand that these issues are regionalnot local. Earthquakes across most of the fault zones in the Middle East are almost certain to be unexpected and underestimated. In most parts of the world, linking territorial conflict to natural disasters would be a challenging stretch. Yet, As Syrians are expelled from their homes towards fault structures across the Fertile Crescent, such conflicts become an integral part of the evolving risk landscape. Therefore, understanding these previously understudied risk concepts is becoming a crucial part of Middle Eastern earthquake risk analysis practices.

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7: CONCLUSION

This research provided a contextual framework to assess the impacts of post-2011 Syrian migration on earthquake risk along the East Anatolian and Dead Sea Fault zones in Turkey. An updated probabilistic hazard map for a 10% exceedance threshold in a 50 year period was produced using current seismic source models and an updated earthquake catalog. The map produced in this study compares well with similar studies performed nationally for Turkey, showing the highest earthquake hazard along the North and East Anatolian Fault systems. These results are useful for updating seismic zoning maps for earthquake-resistant construction. Seismic hazard was spatially averaged and integrated with pre-migration and post-migration population data to assess seismic risk at the district level. Using an exposure-oriented risk index, it was found that pre-migration seismic risk is highest in populated districts near the two major fault zones. This study revealed that post-migration, seismic risk increased southward towards the Turkey-Syria border, remaining high in districts with high populations while adding new zones of high risk in southern districts with large changes in population. The districts that scored relatively high in both scenarios, the province seats of Hatay, Adana, and Gaziantep, represent areas where mitigation resources should be focused. Future research incorporating socio-economic vulnerability and additional Syrian analysis are logical next steps for extending this work into an integrated regional risk index.

Human casualties were calculated from earthquake scenarios at five locations and three magnitudes using a semi-empirical loss estimation approach. This portion of the study found that casualties non-linearly increase with magnitude and location, indicating that certain locations require smaller earthquakes to sustain high intensity shaking near population areas. Additional work with site-specific ground motion prediction equations would help refine the ability to ac-

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curately predict earthquake shaking given local site conditions. Earthquake scenarios in Hatay and Adana resulted in the most casualties due to their high populations, while Hatay sustained the largest percentage of additional casualties due to migration. The percentage of additional casualties resulting from displaced person migration was between 10.9%-12% using a median refugee population estimate. In some scenarios, the percentages as high as 19.1% and 33.4% using median and high population estimates, respectively. Additional casualty percentages at the district level could be significantly higher depending on the location of an earthquake. These results support the conclusions of the risk index, with risk increasing along the Turkey-Syria border. Casualty estimates in this study rely on two key pieces of information: building stock estimates and population estimates. Improving these two data sources, through accurate building stock documentation and tracking migration settlement more closely, would improve the ability of such analysis to provide accurate loss estimations. Notwithstanding, the casualty tables presented in this study provide an order of magnitude estimate for earthquakes of various sizes.

In summary, this study concludes the following:

- Earthquake hazard is highest along the main SW-NE extent of the East Anatolian Fault, decaying outward. The Dead Sea Fault system is a zone of high hazard, but shaking intensity levels are generally lower than that of the East Anatolian Fault system.
- Using 2011 Turkish Census data, earthquake risk index scores are highest in province seats located in zones with a PGA of at least .18, corresponding to a Mercalli Intensity of VII.
- Combining 2015 Turkish population data with migration estimates shifts risk index scores relatively southward, towards regions of high migration. The provinces of Kilis and Hatay sustain the highest change in risk index scores.

- Highly populated districts in Hatay, Adana, and Gaziantep retain consistent high scores across both scenarios, making them key candidates for additional seismic risk mitigation work.
- Despite increasing seismic risk, refugee migration might have a negative effect on the likelihood of internal risk mitigation by increasing immediate budgetary needs, introducing an additional source of inequality, and adding stress to the political system.

These conclusions lay the groundwork for understanding how ongoing geopolitical conflict in the Middle East shapes earthquake risk outlooks. As of the end of 2015, the massive influx of Syrian refugees into Turkey has created an information gap between official population statistics and actual local populations. Translating these population underestimations into risk models and fatality estimates passes the burden onto the state and international aid agencies who work to adequately respond to earthquake events. While zones of conflict and a tumultuous political climate complicate the data collection process, it is paramount that countries and aid agencies continue to work with scientists to provide access to reliable information. This work reveals and explains why understanding regional setting is an increasingly important consideration for scientists and policymakers working to mitigate earthquake risk across the globe. Despite a recent lull in seismic activity, it is vital to remember that Syrian refugees migrating northwest into Turkey are migrating to areas constructed on the ruins of cities that have been repeatedly destroyed in large earthquakes. The Turkish people have accommodated these displaced individuals into their communities, and it is therefore time to properly accommodate them into risk modeling practices.

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8: APPENDICES

8.1 Appendix A: Scripts

8.1.1 Coordinate Generator

8.1.2 Ground Motion Mean Calculator

```
% Averages a batch of gridded ground motion files
%% Data Load
n = input('Enter number of scenario files: ');
filname = input('Fault Scenario: ');
filepath = input('File Path: ');
f = fullfile(filepath,filname,'SES1/ses1_scenario_%010d.csv');
data = cell(1,n);
filename = cell(1,n);
k = 1;
for i = 0:n-1
    filename{k} = sprintf(f,i);
   k = k+1;
end
for i = 1:n
    data{i} = csvread(filename{i},1,0);
end
%% Average
mean_output = zeros(length(data{1}),3);
```

```
mean_output(:,1) = data{1,1}(:,1);
mean_output(:,2) = data{1,1}(:,2);
for i = 1:n
    mean_output(:,3) = mean_output(:,3)+data{1,n}(:,3);
end
mean_output(:,3) = mean_output(:,3)./n;
```

```
%% Data Write
fo = fullfile(filepath,filname,'SES1/mean_motion.csv');
csvwrite(fo,mean_output);
```

8.1.3 Semi-Empirical Earthquake Fatality Calculator

```
% Calculates estimated fatalities for a Turkish Earthquake
% File Format (.csv, no headerlines):
%
% Column 1: Column 2: Column 3: Column 4: Column 5: Column 6:
  Column:7
% HASC2
            MMI
                      PopSc1 PopSc2 PopSc3
                                                     PopSc4
  PopSc5
%%
clear all;
sc_name = input('Scenario Name: ');
filepath = input('File Path: ');
filename = fullfile(filepath,sc_name);
fileID = fopen(filename);
dat = textscan(fileID, '%s %f %d %d %d %d %d %d', 'Delimiter', ', ', '
  HeaderLines ',1);
fclose(fileID);
%%
%Percent urban and percent rural, national values for Turkey
per_urb = .73; per_rur = .27;
% Distribution of building types (woodframe, concrete,
% clay (Adobe), unreinforced brick or block) for urban and
  rural populations
building_dist = [4,10;
      60,25;
      2,15;
```

34,50]; % Percentage of population in each building type $per_in_BT = zeros(4,2);$ per_in_BT(:,1) = (per_urb.*building_dist(:,1))./100; per_in_BT(:,2) = (per_rur.*building_dist(:,2))./100; %% % Data averaged from Gulkan et al. building spreadsheet % Mean collapse percentages at different intensities (MMI) WF = [20,10,2,0.5]; % Woodframe AD = [90, 70, 40, 10]; % Adobe% Concrete Structures $CS_u = [(40*(40/60) + 45*(8/60) + 15*(5/60) + 5*(5/60) +$ 60*(2/60)), (20*(40/60) + 22*(8/60) + 5*(5/60) + 1*(5/60))32*(2/60)), (2*(40/60) + 2*(8/60) + 0.5*(5/60) + 0.1*(5/60))+ 12*(2/60)), (0.5*(40/60) + 0.5*(8/60) + 0*(5/60) + 0*(5/60))+ 2*(2/60))]; $CS_r = [(40*(25/25) + 45*(0/25) + 15*(0/25) + 5*(0/25))]$ 60*(0/25)), (20*(25/25) + 22*(0/25) + 5*(0/25) + 1*(0/25))+ 32*(0/25)), (2*(25/25) + 2*(0/25) + 0.5*(0/25) + 0.1*(0/25))+ 12*(0/25)), (0.5*(25/25) + 0.5*(0/25) + 0*(0/25) + 0*(0/25))+ 2*(0/25))];% Unreinforced Brick and Block $UB_u = [(80*(4/34) + 72*(25/34) + 65*(5/34)), (50*(4/34) +$ 45*(25/34) + 40*(5/34)), (25*(4/34) + 22*(25/34) + 18*(5/34))(7.5*(4/34) + 7.5*(25/34) + 8*(5/34))]; $UB_r = [(80*(15/50) + 72*(30/50) + 65*(5/50)), (50*(15/50) +$ 45*(30/50) + 40*(5/50)), (25*(15/50) + 22*(15/50) + 18*(5/50))), (7.5*(15/50) + 7.5*(30/50) + 8*(5/50))]; $CR_u = [WF; CS_u; AD; UB_u]./100;$ $CR_r = [WF; CS_r; AD; UB_r]./100;$ %% % Fatality rate for woodframe, concrete, adobe, unreinforced block % (respective) FR = [.0013, .15, .06, .08];%% % Intensity flag: assigns proper collapse percentage for intensity value

```
Iflag = 0;
fatalities = zeros(length(dat{1}),4);
temp_fatal_rur = zeros(length(dat{1}),4); temp_fatal_urb =
  zeros(length(dat{1}),4);
\% Loops through each district, checks the district average PGA
  value and assigns the intensity flag. Then loops through
  each building type and calculates the fatalities in each
  building type given the collapse rate and fatality
  percentage given collapse. Does this for urban and rural,
  summing total fatalities for all building types.
for sn = 1:5 % Population scenario: baseline, migration low,
  migration high
    for i = 1:length(dat{1})
        % Assigns district population urban and rural
          percentages
        pop_urb = dat{sn+2}(i)*per_urb; pop_rur = dat{sn+2}(i)*
           per_rur;
        % Check district average intensity
        if dat{2}(i) > 0.092 && dat{2}(i) <= 0.18
            Iflag = 4;
        elseif dat{2}(i) > 0.18 && dat{2}(i) <= 0.34
            If lag = 3;
        elseif dat{2}(i) > 0.34 && dat{2}(i) <= 0.65
            Iflag = 2;
        elseif dat{2}(i) > 0.65 && dat{2}(i) <= 1.24
            If lag = 1;
        else
            Iflag = 5; %MMI lower than 5.5 unlikely to cause
               collapse
        end
        % j: (1)woodframe, (2)concrete, (3)adobe, (4)
           unreinforced block
        for j = 1:4
            % No fatalities if building doesn't collapse
            if Iflag == 5;
                temp_fatal_urb(i,sn) = 0;
                temp_fatal_rur(i,sn) = 0;
```

```
% Fatalities equation = population * percentage in
           building type *
        % collapse rate @ given intensity * fatality rate given
            collapse
        % Calculated seperately for urban and rural
            temp_fatal_urb(i,sn) = temp_fatal_urb(i,sn) +
               pop_urb * per_in_BT(j,1) * CR_u(j,Iflag) * FR(j)
            temp_fatal_rur(i,sn) = temp_fatal_rur(i,sn) +
               pop_rur * per_in_BT(j,2) * CR_r(j,Iflag) * FR(j)
            end
        end
    end
    % Total fatalities = sum of urban and rural fatalities
    fatalities(:,sn) = temp_fatal_urb(:,sn)+temp_fatal_rur(:,sn
      );
end
%%
% Data output file format: HASC2, Intensity (MMI), Fatalities
  SN 1:3
dat_out = cell(length(dat{1}),7);
dat_out(:,1) = dat{:,1}; dat_out(:,2) = num2cell(dat{2}(:));
dat_out(:,3) = num2cell(fatalities(:,1)); %fatality 2011
dat_out(:,4) = num2cell(fatalities(:,2)); %fatality 2011
dat_out(:,5) = num2cell(fatalities(:,3)); %fatality low
dat_out(:,6) = num2cell(fatalities(:,4)); %fatality med
dat_out(:,7) = num2cell(fatalities(:,5)); %fatality high
sco_name = input('Output Name: ');
fo = fullfile(filepath,sco_name);
cell2csv(fo,dat_out);
```

*Both the average ground motion and loss estimation scripts use Sylvain Fiedler's function cell2csv for data output, available at: https://www.mathworks.com/matlabcentral/fileexchange/7601cell2csv

8.2 Appendix B: Sample OpenQuake Files

8.2.1 Configuration File

```
[general]
description = StudySite
calculation_mode = classical
random_seed = 23
[geometry]
sites_csv=coord_small.csv
[logic_tree]
number_of_logic_tree_samples = 0
[erf]
# km
rupture_mesh_spacing = 2.5
width_of_mfd_bin = 0.1
# km
area_source_discretization = 5
[site_params]
reference_vs30_type = measured
reference_vs30_value = 600.0
reference_depth_to_2pt5km_per_sec = 5.0
reference_depth_to_1pt0km_per_sec = 100.0
[calculation]
source_model_logic_tree_file = source_logic_tree_ts.xml
gsim_logic_tree_file = gmpe_logic_tree_ts.xml
# years
investigation_time = 50.0
intensity_measure_types_and_levels = {"PGA": [0.0009, 0.001,
  0.002, 0.003, 0.004, 0.005, 0.007, 0.0098, 0.0137, 0.0192,
  0.0269, 0.0376, 0.0527, 0.0738, 0.103, 0.145, 0.203, 0.284,
  0.397, 0.556, 0.778, 1.09, 1.52, 2.13, 2.85, 3.45
# km
maximum_distance = 200.0
[output]
export_dir = /output/
```

```
mean_hazard_curves = true
quantile_hazard_curves =
hazard_maps = true
uniform_hazard_spectra = false
```

poes = 0.1

8.2.2 Source Model Logic Tree

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"</pre>
      xmlns="http://openquake.org/xmlns/nrml/0.4">
    <logicTree logicTreeID="lt1">
        <logicTreeBranchingLevel branchingLevelID="bl1">
            <logicTreeBranchSet uncertaintyType="sourceModel"
               branchSetID="bs1">
                <logicTreeBranch branchID="b1">
                    <uncertaintyModel>area_source_model_v2.xml
                       </uncertaintyModel>
                    <uncertaintyWeight>0.8</uncertaintyWeight>
                </logicTreeBranch>
                <logicTreeBranch branchID="b2">
                    <uncertaintyModel>faults_bkgrd_source_ts.
                       xml </ uncertaintyModel >
                    <uncertaintyWeight>0.20</uncertaintyWeight>
                </logicTreeBranch>
            </logicTreeBranchSet>
        </logicTreeBranchingLevel>
```

</logicTree>

8.2.3 Ground Motion Prediction Equation Logic Tree

```
<logicTreeBranch branchID="b1"> <
                   uncertaintyModel >AkkarBommer2010 </
                   uncertaintyModel >
                    <uncertaintyWeight>0.35</uncertaintyWeight>
                </logicTreeBranch>
                <logicTreeBranch branchID="b2"> <
                   uncertaintyModel >CauzziFaccioli2008 </
                   uncertaintyModel >
                    <uncertaintyWeight>0.35</uncertaintyWeight>
                </logicTreeBranch>
                <logicTreeBranch branchID="b3"> <
                   uncertaintyModel > ChiouYoungs2008 </
                   uncertaintyModel >
                    <uncertaintyWeight>0.20</uncertaintyWeight>
                </logicTreeBranch>
                <logicTreeBranch branchID="b4"> <
                   uncertaintyModel >ZhaoEtAl2006Asc </
                   uncertaintyModel >
                    <uncertaintyWeight>0.10</uncertaintyWeight>
                </logicTreeBranch>
            </logicTreeBranchSet>
        </logicTreeBranchingLevel>
    </logicTree>
</nrml>
```

*Full area and fault source models available at: http://www.efehr.org:8080/jetspeed/portal/hazard.psml

8.2.4 Scenario Configuration File

```
[general]
description = Scenario Calculation with Simple Fault Rupture
calculation_mode = scenario
random_seed = 3
[geometry]
sites_csv=coord_small.csv
[erf]
rupture_mesh_spacing = 2.0
[site_params]
reference_vs30_type = measured
reference_vs30_value = 750.0
```

```
reference_depth_to_2pt5km_per_sec = 5.0
reference_depth_to_1pt0km_per_sec = 100.0
[calculation]
rupture_model_file = TRCS339_5.8.xml
intensity_measure_types = PGA
truncation_level = 3.0
maximum_distance = 1000
gsim = AkkarBommer2010
ground_motion_correlation_model = JB2009
ground_motion_correlation_params = {"vs30_clustering": True}
number_of_ground_motion_fields = 6
```

[output]
export_dir = ./output/

8.2.5 Rupture Model Example

```
<?xml version='1.0' encoding='utf-8'?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
     <simpleFaultRupture>
        <magnitude >5.8</magnitude >
        <rake>0.0</rake>
        <hypocenter lat="38.77" lon="38.2" depth="13.2"/>
        <simpleFaultGeometry>
            <gml:LineString>
                <gml:posList>38.734898 38.178427 38.766909
                   38.198474 38.798919 38.21852 38.83093
                   38.238567 38.863602 38.257973 38.896273
                   38.277378 38.928945 38.296784 38.965974
                   38.310586 39.003003 38.324387 39.040032
                   38.338189 39.095567 38.3473 39.151101
                   38.356411
                </gml:posList>
            </gml:LineString>
            <dip>85.0</dip>
            <upperSeismoDepth>0.0</upperSeismoDepth>
            <lowerSeismoDepth>20.0</lowerSeismoDepth>
        </simpleFaultGeometry>
     </simpleFaultRupture>
</nrml>
```



8.3 Appendix C: Earthquake Scenario Ground Motion

Figure 8.1: This map shows the ground motion field calculated for a moment magnitude 5.8 earthquake rupturing the Pütürge fault (Cartography by Bradley Wilson).



Figure 8.2: This map shows the ground motion field calculated for a moment magnitude 6.4 earthquake rupturing the Pütürge fault (Cartography by Bradley Wilson).



Figure 8.3: This map shows the ground motion field calculated for a moment magnitude 7.0 earthquake rupturing the Pütürge fault (Cartography by Bradley Wilson).



Figure 8.4: This map shows the ground motion field calculated for a moment magnitude 5.8 earthquake rupturing the Türkoğlu fault (Cartography by Bradley Wilson).



Figure 8.5: This map shows the ground motion field calculated for a moment magnitude 6.4 earthquake rupturing the Türkoğlu fault (Cartography by Bradley Wilson).



Figure 8.6: This map shows the ground motion field calculated for a moment magnitude 7.0 earthquake rupturing the Türkoğlu fault (Cartography by Bradley Wilson).



Figure 8.7: This map shows the ground motion field calculated for a moment magnitude 5.8 earthquake rupturing the Kırıkhan fault (Cartography by Bradley Wilson).



Figure 8.8: This map shows the ground motion field calculated for a moment magnitude 6.4 earthquake rupturing the Kırıkhan fault (Cartography by Bradley Wilson).



Figure 8.9: This map shows the ground motion field calculated for a moment magnitude 7.0 earthquake rupturing the Kırıkhan fault (Cartography by Bradley Wilson).



Figure 8.10: This map shows the ground motion field calculated for a moment magnitude 5.8 earthquake rupturing the Bozova fault (Cartography by Bradley Wilson).



Figure 8.11: This map shows the ground motion field calculated for a moment magnitude 6.4 earthquake rupturing the Bozova fault (Cartography by Bradley Wilson).



Figure 8.12: This map shows the ground motion field calculated for a moment magnitude 7.0 earthquake rupturing the Bozova fault (Cartography by Bradley Wilson).


Figure 8.13: This map shows the ground motion field calculated for a moment magnitude 5.8 earthquake rupturing the Kozan fault (Cartography by Bradley Wilson).



Figure 8.14: This map shows the ground motion field calculated for a moment magnitude 6.4 earthquake rupturing the Kozan fault (Cartography by Bradley Wilson).



Figure 8.15: This map shows the ground motion field calculated for a moment magnitude 7.0 earthquake rupturing the Kozan fault (Cartography by Bradley Wilson).