Earthquake Vulnerability of Buildings and a Mitigation Strategy: Case of Istanbul

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Background and General Considerations

Turkey ranks high among countries that have suffered centuries of loss of life and property due to earthquakes. In the twentieth century, earthquakes in Turkey caused over 110,000 deaths, 250,000 hospitalized injuries and the destruction of 600,000 housing units.

Following the losses suffered during two major earthquakes in 1999, there is broad recognition among government, non-government and academic organizations that extensive response planning is needed in Turkey. Such planning should be based upon detailed risk analyses of likely seismic hazards in Turkey, particularly in and around Istanbul.

In recent decades, earthquake disaster risk for Turkey's urban centers has increased, mainly due to high rates of urbanization, faulty land-use planning and construction, inadequate infrastructure and services, and environmental degradation. Several studies (Erdik and Aydinoglu, 2002) have shown that the vulnerability of Turkish building stock is higher than that in California, which shares a comparable level of earthquake hazard. Reasons for this high vulnerability can be traced to several reasons. Poor quality residential construction and development is the result of a high (chronic) rate of inflation (leading to a limited mortgage and insurance market, a major impediment to large scale development and industrialization of the construction sector), excessive urbanization (which created the demand for inexpensive housing), ineffective control/supervision of design and construction, regulations with limited enforcement mechanisms, a lack of accountability, and the role of government as a free insurer of earthquake risk.

Another important source of increased risk in Istanbul is the unprecedented increase in the probability of occurrence of a large scale earthquake (with a 65 percent probability in the next 30 years).

The certainty of such a large earthquake in Istanbul means it is essential to put in place preparedness and emergency procedures. It requires the quantification of expected earthquake impacts on the physical and social environment and subsequently, the development of urban earthquake risk mitigation master plans with short and long term strategies.

This paper first summarizes an assessment of building losses in Istanbul in the event of a major earthquake. The study was conducted by the Department of Earthquake Engineering, Bogaziçi University, with support from the American Red Cross (BU-EQE, 2002). The second part of the paper proposes a cost-effective mitigation strategy based on retrofitting. The Metropolitan Municipality of Istanbul recently (October, 2002) signed a memorandum of understanding with Bogaziçi, Istanbul Technical, Middle East Technical and Yildiz Technical Universities to develop a comprehensive earthquake risk mitigation master plan that encompasses technical, legislative, administrative, social and economic issues and strategies of large scale retrofit, renewal and relocation campaigns.

Estimated Building Losses and Casualties in Istanbul

Earthquake Hazard

For Istanbul, a worst-case scenario earthquake of magnitude 7.5 is assumed to take place in the Main Marmara Fault. Figure 1 provides a map of earthquake intensities that would result from the scenario earthquake. Using the damage definitions of 1998 European Macroseismic Scale (EMS), a general picture of damage under exposure to these intensity levels can be gained. For the vulnerability class where the general reinforced concrete multistory building stock in Istanbul is located, EMS-1998 provides the following damage definitions:

Intensity VII: A few buildings sustain moderate damage

Intensity VIII: Many buildings suffer moderate damage; a few receive substantial to heavy damage

Intensity IX: Many buildings suffer substantial to heavy damage; a few sustain very heavy damage

Where “few” describes less than 20 percent and “many” describes 20 percent to 60 percent.

Inventory of Elements at Risk

In urban areas, buildings, populations, lifeline systems and socioeconomic activities constitute the "elements at risk." Buildings and lifeline systems are generally termed "built environment." The building inventory dataset is compiled with information provided by the Istanbul Metropolitan Municipality and the State Statistical Institute. The dataset is complemented with Turkish Telekom analog maps, imagery from helicopter flights and aerial and satellite imagery. Classification of buildings in Istanbul is essential to ensure a uniform interpretation of data and results. Building stock is classified using three basic categories: structural systems, number of stories and year of construction. Each category is further subdivided into groups to yield 24 different building classes. The Istanbul Metropolitan Area was divided into grids of 0.005° x 0.005° (approximately 400 m x 600 m) cells for the aggregation of hazard and physical inventory data. The daytime and nighttime populations of 28 districts were determined then assigned to geo-cells to calculate human losses in the event of a major earthquake. Population and building data for Istanbul were obtained from the State Statistics Institute. To estimate the daytime population, the Istanbul Transportation Master Plan, prepared in 1997 by the Metropolitan Municipality of Istanbul, was utilized.

Vulnerabilities

There are two main approaches to generating vulnerability relationships. The first approach is based on damage data obtained from experiments or from field observations after an earthquake. The second approach is based on numerical analysis of the structure through detailed time-history analysis or simplified methods.

In the earthquake loss scenario developed for the Istanbul building vulnerability assessment, to express the percentage damage for each typified building group and in certain damage classes, the EMS-1998 (European Macroseismic Scale) intensity ranges and spectral displacements have been used. The intensity–based vulnerabilities are empirical in nature and based on damage data from local earthquakes. The spectral displacement-based building vulnerabilities (also called as "fragility curves") relate the probability of being in or exceeding a certain building damage level to a given spectral displacement demand parameter using the methodology developed in HAZUS (http://www.fema.gov/hazus).

The most vulnerable building group is found to be medium-rise (4-7 story) reinforced concrete frame buildings built prior to 1975. These are cast-in-situ reinforced concrete frame buildings with non-reinforced masonry infill walls designed on the basis of outdated codes and generally suffering from reinforcement corrosion problems. In the majority of buildings, ground floor space is reserved for shops and irregular plan shapes are common due to irregular land lots and urban congestion.

Death tolls in earthquakes arise mostly from structural collapses and to a lesser degree from collateral hazards. In this study, casualty per damaged building for a given class of buildings is generated on the basis of data obtained from local earthquakes.

Risk Assessment Methodology

Several methodologies and attendant software (such as, HAZUS, EPEDAT and NHEMATIS) exist for computation of urban earthquake risk using hazard, inventory and vulnerability inputs through a GIS engine for data manipulation and results display. The KOERILoss software developed by the Earthquake Engineering Department of Bogaziçi University, The Kandilli Observatory and Earthquake Research Institute (KOERI), applies a loss estimation methodology (probabilistic vs. deterministic) developed by KOERI to perform analyses for estimating potential losses from earthquakes. To perform building damage and loss analysis, the building inventory stock database should be provided for each geo-cell. The seismic hazard information in terms of intensities for intensity-based analysis and spectral accelerations for spectral displacement-based analysis should also be aggregated at the center of each geo-cell. To compute the damage probability ratios intensity-based vulnerabilities and/or spectral displacement-based fragility curves for each building class type, vulnerabilities should be specified. Economic losses associated with the general building stock are estimated using building damage losses and costs for different structural damage of each building group. To estimate the number and severity of casualties, daytime and nighttime populations for each building type in the geo-cells should be provided together with the casualty rates for each building class and damage grade. The software provides the building damage loss, economic losses and the number of casualties in terms of geo-cells, which can then be integrated into sub-districts (Mahalle) and districts (Ilçe), as MapInfo Output tables.

Building Losses and Casualties

The study culminates with maps depicting the distribution of building losses, lifeline facilities overlaid on intensity maps, the distribution of casualties, temporary shelter needs and expected financial losses due to building damage. Resolution on these maps is the geo-cell (400m by 600m) scale. All digital data, some subject to security classification, will be made available to professional users who will be able to construct data at any scale and with any overlay desired using the GIS software of their choice. Expected building damage, calculated by the intensity-based deterministic approach, is provided in Figure 2. Results indicate that, on the basis of two independent approaches (intensity-based and spectral displacement-based approaches), some 35,000 to 40,000 buildings (about 5 percent of the total building stock) can be expected to be damaged beyond repair (complete damage). Most casualties can be expected in this damage group, especially in a subset of this group where collapse will be in the "pancake" form. In pancaked buildings the floors pile up on top of each other rendering very difficult conditions for search and rescue. The estimate for pancaked buildings is 5,000 to 6,000 buildings.

Furthermore, about 70,000 buildings will receive extensive damage and about 200,000 buildings will be moderately damaged. Both of these damage groups are repairable. Total monetary losses due to building damage caused by the scenario earthquake are estimated to be in the range of US$11 billion (Figure 3). Building damage is mostly concentrated in the densely populated districts located in the southwestern part of Istanbul including Eminönü, Fatih, Zeytinburnu, Bakirköy, Bahçelievler, the southern part of Küçükçekmece and Avcilar, and to a lesser degree, southeastern districts such as Kadiköy, Maltepe and Kartal. Although situated relatively distant from the causative fault, building density and vulnerability conditions could cause the districts of Beyoglu, Eyüp and Bayrampasa to suffer high levels of damage.

As analysis was conducted for various structure types, the mid-rise reinforced concrete structures constructed before 1980 were found to constitute the most vulnerable building class. Expected casualties were calculated using both the intensity-based and the spectral displacement-based approaches. Results for both nighttime and daytime populations were obtained for the four levels of casualty severities from the spectral displacement-based approach. Thus, on the basis of these two independent approaches it is estimated that the number of deaths would range from 30,000 to 40,000. The number of casualties in the serious injury class is difficult to estimate since it would depend upon post-earthquake emergency services. If we assume that about one-third would not survive, total deaths could reach 40,000 to 50,000. Death distribution based on intensity approach is presented in Figure 4. With intensity-based analysis, some 600,000 households and with spectral-based analysis, about 430,000 households would be destroyed and their occupants require shelter in the proposed earthquake scenario. This amount constitutes an upper bound limit for expected shelter needs since the conversion of this number to total number of households is subject to further discussion and the vacancy of some dwelling units should also be considered. It should again be noted that these values are the estimates for an Mw=7.5 earthquake at the closest position to Istanbul that one can provide in the absence of detailed building inventory and geotechnical data. Figures for deaths involve great uncertainties since an earthquake's time and day would affect this outcome.

Risk Mitigation

General Mitigation Options

The basic tenets of mitigation are: do not increase existing risk (i.e. build properly); decrease existing risk (i.e. retrofit) and; transfer risk (i.e. buy insurance). The reduction of structural vulnerability, siting and land-use regulations, design and construction regulations, relocation of communities, and public education/awareness programs are viable measures for the mitigation of earthquake risk. Urban settlements can be improved by changing the functional characteristics of settlements through land-use planning and increasing the redundancy of infrastructure, such as building an additional bridge at a strategic crossing.

New buildings in Istanbul are, in general, improvements over the existing building stock. The reasons for this improvement are: application of a new (1998) earthquake-resistant design code; increased public awareness and demand for earthquake safety; various training and education programs for engineers; better zoning regulations and enforcement by municipalities and; control by private construction supervision firms. New legislation (Revision of Law on Engineering and Architecture, Building Design and Construction Control and, Standard Development Regulations for Municipalities) enacted after the 1999 earthquakes helped in this regard. For Istanbul the most important and complex issue in mitigating earthquake casualties is the retrofit of existing buildings.

Retrofit of the Existing Building Stock

The most effective way to reduce human casualties is through the retrofit of existing building stock. Although several assessments and retrofit applications are in place for public and commercial buildings, serious initiatives have yet to be taken for the strengthening of residential building stock. A comprehensive retrofit campaign will be a formidable task that would involve the earthquake performance screening of about 800,000 buildings, prioritization based on the exhibited risk, analysis of options and market study, development of retrofit alternatives; development engineering capacity for retrofit and finally creation of public / private incentives.

The full retrofit (i.e. in compliance with the latest code requirements) of a residential building costs about 40 percent of replacement value and requires that the building be vacated for several months. In addition to this high cost and the inconvenience of moving from residential buildings, there are strong impediments to retrofitting. The retrofit decision is difficult to reach since these buildings are multi-family owned/rented apartments with tenants having different expectations, budgets, and constraints. Due to high residential mobility (desire for better housing in better neighborhoods) people do not want to spend money if they may be moving. Furthermore, there is evidence that retrofitting is an investment without financial return since it does not increase a property's sales value or rental fee. Under these conditions, no conceivable reduction in insurance premium (or property tax) would be sufficient to create an incentive for retrofitting.

Even putting aside the social and legal constraints of retrofit actions to be taken in apartment complexes and the highly distressed real estate market in Istanbul, on average, structural retrofitting is not cost effective. For a mid-rise building in Istanbul, the average loss (mean damage ratio - MDR) in intensity IX region will be 62 percent. For a mid-rise reinforced concrete frame building in Istanbul the average loss (MDR) in an intensity VIII region will be 40 percent (CAR and BU, 2000). If these buildings are retrofitted to fully meet the current earthquake-resistant design code, the MDRs will be 16 percent and 11 percent respectively in intensity IX and VIII regions. Thus retrofitting actions will save 46 percent and 29 percent of the cost of building construction. The average cost of a full retrofit is about 40 percent of the cost of new building construction. For probabilistic earthquake occurrences (even with average return periods as low as 50 years, as is the case for Istanbul) it is almost impossible to be cost effective in full-scale (meeting code criteria) retrofit applications. Only for short-horizon deterministic cases such as 5 years can the breakeven point of cost effectiveness in intensity IX regions be reached. In regions of intensity XIII or less, retrofitting is not cost effective. Thus, if life loss and the other social costs associated with an earthquake are taken out of account, the expected future financial losses are small in comparison with the immediate cost of retrofitting which offers no financial incentives.

Possible incentives for retrofitting are being discussed all over the world, however. These include: earthquake retrofit grants by government or compulsory insurance agencies; below-market interest rates on loans for earthquake retrofit; insurance premium discounts to policyholders upon completion of the retrofit and; financial incentives to property owners of properties, such as: waiving of building permit fees, city property taxes and easing of siting and geometric regulations.

It should be noted that the direct use of the Turkish Catastrophe Insurance Pool (TCIP) in earthquake risk mitigation, such as the funding of retrofit applications, does not seem to be realistic. Premiums fall far short of meeting actual risks (about 0.2 percent per annum, 2 percent deductible for a flat in Istanbul). These rates should be compared with 0.5 percent premium rates and 10 to15 percent deductibles in San Francisco. In Istanbul, with a cap of about US$17,500, the premium is about US$35. For comparison, premiums in San Francisco average US$600 to US$800. In Istanbul, with such low rates, no risk-based adjustment of this premium can serve as an incentive to structurally upgrade one's property. Market forces require that for retrofitting actions and campaigns to be successful, insurance premiums should be high (or realistic), so that property owners understand that it would be profitable to retrofit their premises rather than wait for damage and reimbursement. As of October 2002, compulsory earthquake insurance in Istanbul had been purchased by 30 percent of those required to do so. The pool has a capacity of about US$1 billion (including US$0.85 billion in reinsurance) for settlement of claims in the event of an earthquake (information from Milli-Re). There is stagnation in the market, however, since the number of new policies issued almost equals the number of non-renewals of existing policies. In the event of a large earthquake, the TCIP today has barely enough money to cover claims (about US$1 billion capacity versus about US$3 billion in insured losses and US$1.5 billion in claims, using a cap of US$17,500 per housing unit for an Istanbul earthquake). Thus at the current financial level, it is not reasonable to use the pool to fund retrofitting.

Although building owners will find future property losses small by comparison with the cost of a full retrofit and cannot visualize the benefit, at the macro scale, society in general will greatly benefit from a retrofit campaign through a reduction in physical, social and societal losses that will eventually have to be covered by the general population. The burden imposed on public finance by the 1999 Kocaeli earthquake was about US$6.2 billion (Erdik, 2001). About US$3.5 billion of this amount was utilized for post-earthquake housing construction. The special earthquake taxes and paid military service scheme introduced by the government generated about US$3 billion in one year after the earthquakes. Foreign finances (World Bank, European Union and others) contributed another US$2.5 billion. Although steps such as the creation of TCIP have been taken, public funds will continue to be used for rehabilitation after earthquake disasters in Turkey. As such, the use of public funds can be justified for retrofit purposes under a strategy that is designed to maximize benefits with well-prioritized and fairly distributed minimum expenditure. Such a strategy can lead to the concept of minimum retrofit.

Prioritization in Retrofit of Residential Buildings

In light of the circumstances and issues discussed above, strengthening and retrofitting the most vulnerable building stock in Istanbul seems to be the most rational course of action. The objective of retrofitting would be the avoidance of total building collapse where fatality ratios could reach 10 percent. The earthquake performance criteria would be the prevention of total collapse and saving lives at minimum cost. The avoidance of total and pancake-type collapses is also important for facilitating search and rescue operations and reducing road closures. However, it should be noted that the boundary between upgrades to "*collapse prevention*" and "*life safety*" performance criteria is fuzzy and more research is needed to assess the amount of retrofit consistent with the objective of saving lives at minimum cost.

The first priority in the use of public funds should be the upgrading of the seismic performance levels of the most vulnerable buildings – those subject to 'pancake' collapse. Somewhat crude screening criteria for the identification of these most vulnerable residential buildings in Istanbul can be set as follows:

Buildings with and greater than five stories, built before 1970 (pre-1975 code, poor concrete quality and corrosion issues), located in zones with PGA >=0.25g or SA (0.2) >= 0.60g or EMS-I >= VIII.

Similar buildings with added floors (with no engineering services) and buildings that received structural damage in the 1999 Kocaeli earthquake but not retrofitted properly should also be considered.

Initial assessments indicate that about 5,000 buildings fall into this first priority group. The cost of minimum retrofit is estimated to average US$40,000 per building with a total cost of about US$200 million. Upon proper implementation of this retrofit scheme it is expected that 20,000 lives could be saved. On the technical side, intelligent retrofit schemes suitable for general campaign-type applications need to be developed.

A possible mode of operation for this minimum retrofit campaign could be as follows:

After the identification process, municipalities should declare buildings as "*hazardous*" and legally enforce a regulation that unless "*minimum retrofitting*" is done within a prescribed time, the occupancy permit (if any) will be cancelled, tenants evicted and the building will be sold on behalf of the owners. Each household would need to access to credit of about US$5,000 for financing. Such a credit scheme has precedent in Turkey. After the Kocaeli Earthquake, the Turkish government had extended low interest loans of US$5,000. Loans had extended payment periods and were made available to eligible owners of moderately damaged housing units.

The second priority should be the retrofit of the 40,000 buildings assessed to be damaged beyond repair (greater D3 damage level). These are mid-rise, reinforced concrete frame buildings located in zones with EPGA>=0.2g or SA(0.2) >= 0.50g or in zones with EMS-I >= VIII. The retrofit performance criteria will be life safety. The approximate cost of this retrofit would be US$1.6 billion.

Acknowledgements

This study has been partially funded by the American Red Cross Field office in Turkey, Munich-Re and the Bogaziçi University Research Fund. The data in this study came from several sources including the Istanbul Metropolitan Municipality, the Governorate of Istanbul, the State Seismological Institute and Turkish Telekom. I would like to express my sincere gratitude to these agencies.

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Figure 1. Site dependent deterministic intensity distribution.

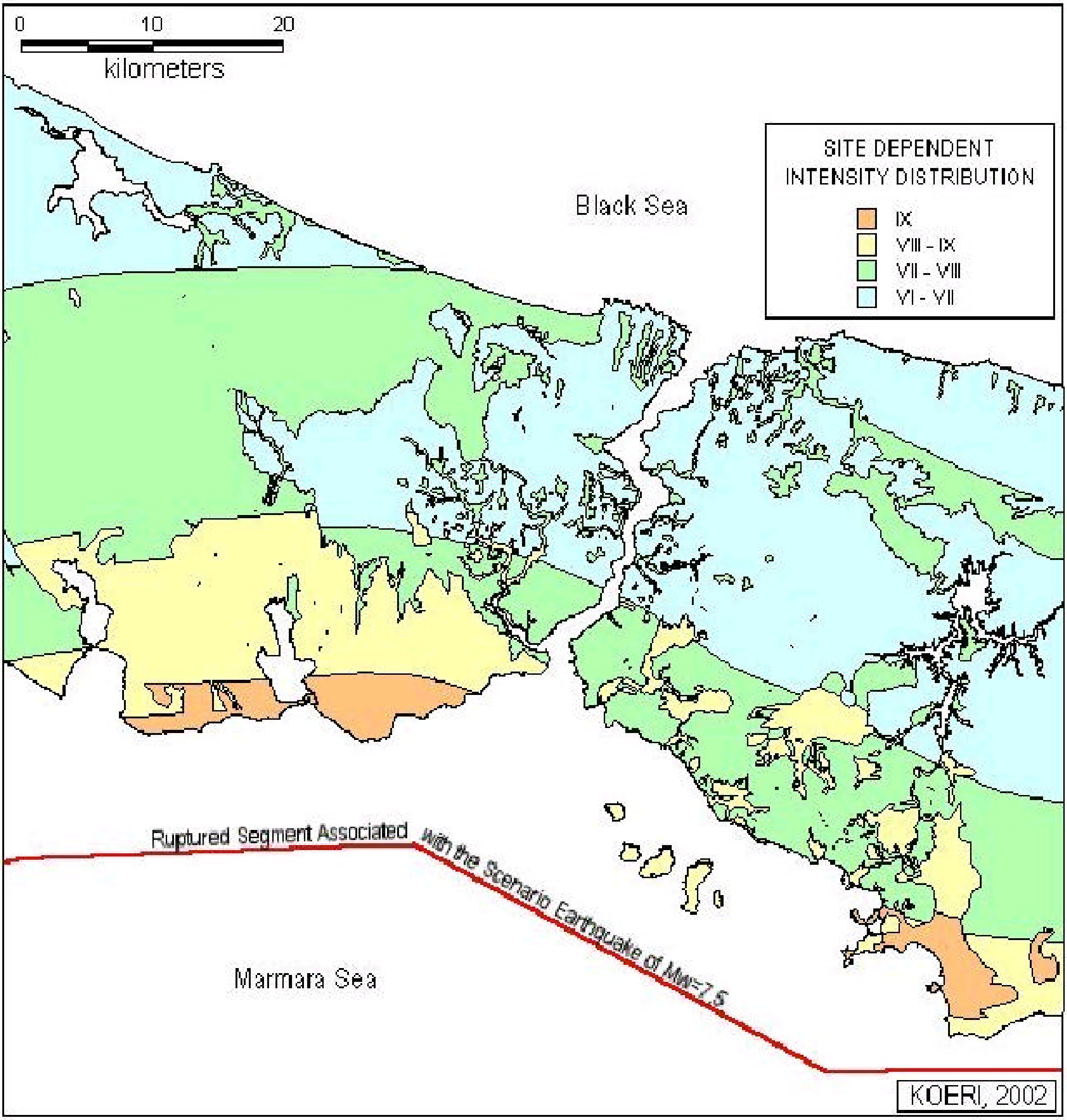

Figure 2. Intensity based distribution of all buildings damaged beyond repair (complete damage).

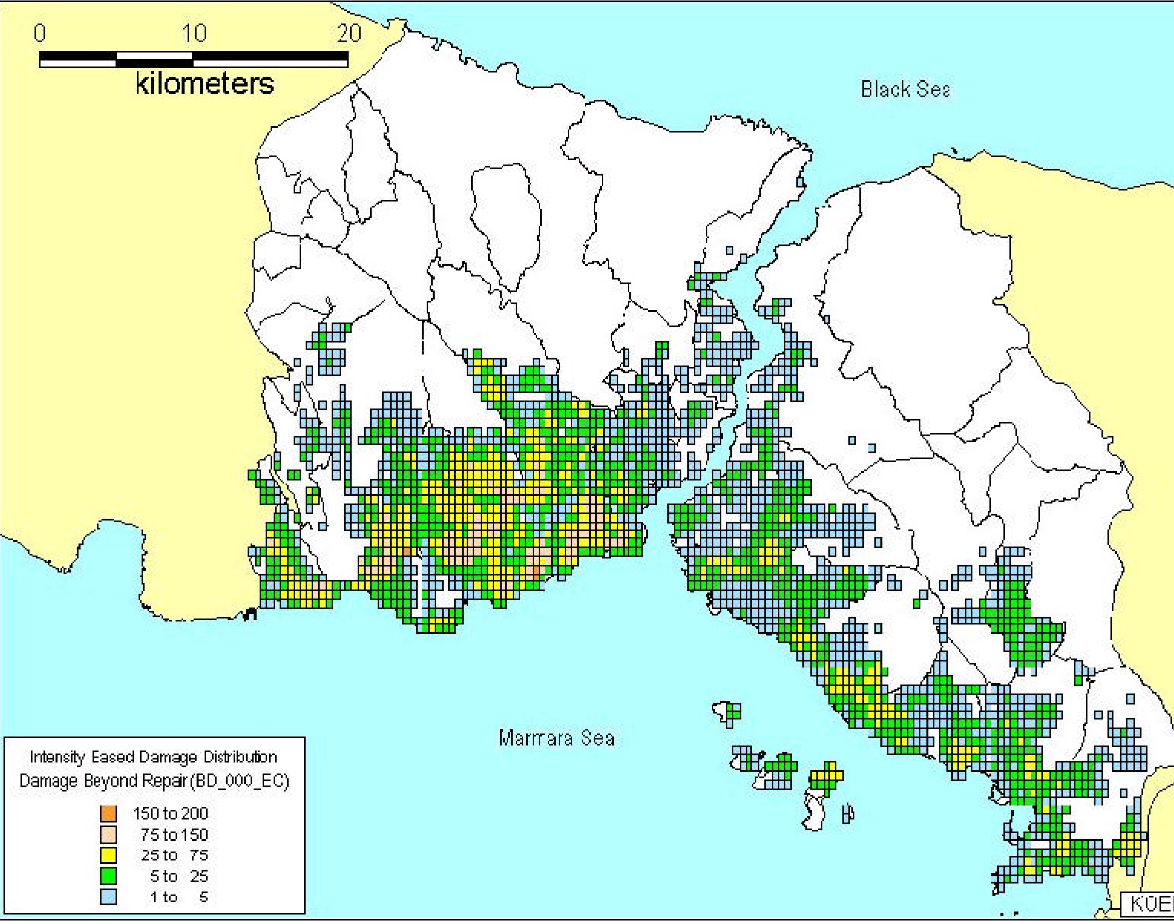

Figure 3. Distribution of Direct Financial Losses due to Building Damage

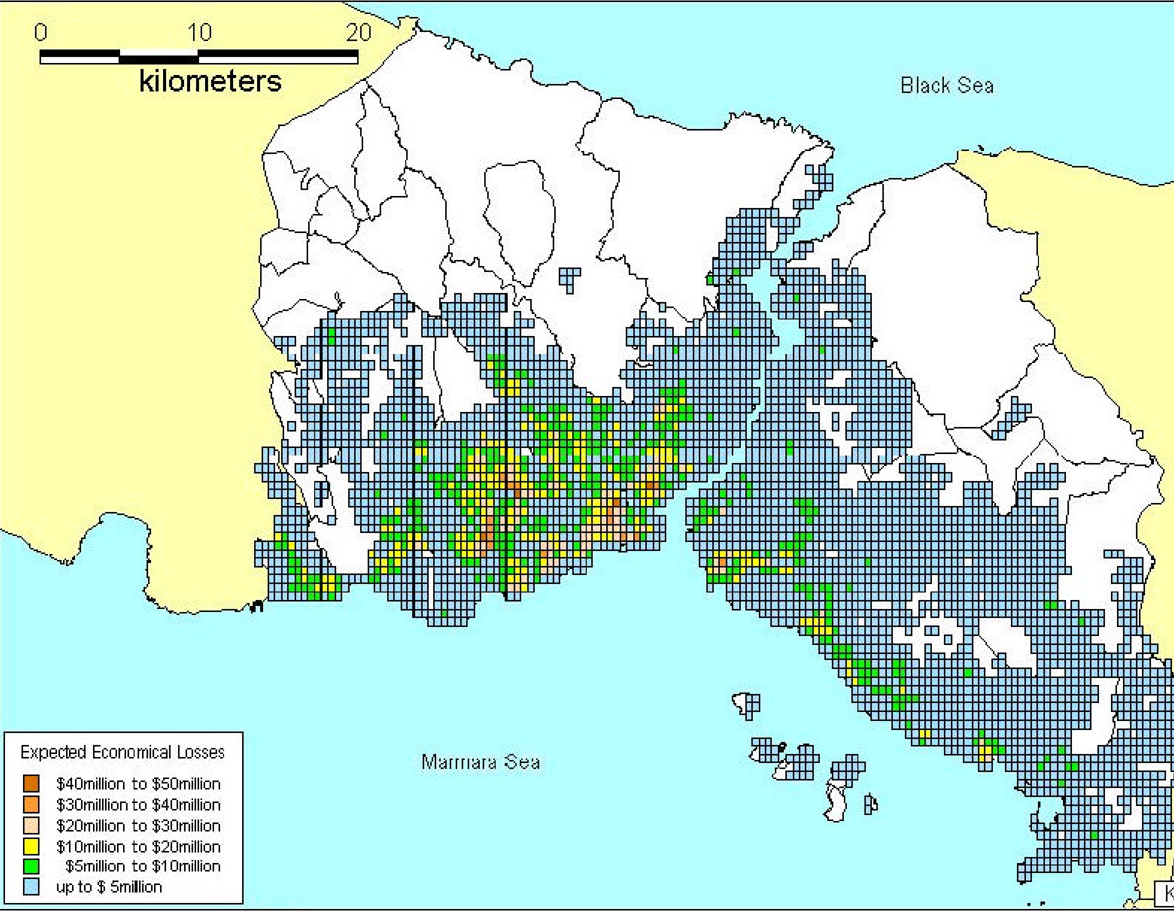

Figure 4. Distribution of Deaths for a Night-Time Scenario Earthquake.