Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

Hüseyin Can ÜNEN, Himmet KARAMAN and Muhammed ŞAHİN, Turkey; Amr S. ELNASHAI, USA

Key words: Risk management, loss assessment, lifelines

SUMMARY

The proposed study considers the interdependency concept on seismic performance analysis of lifeline network systems. Seismic damage estimates of the electric power, potable water, and natural gas networks of the city will be calculated for the expected Marmara earthquake scenario and the results will be utilized to assess the performances of the topological models of the networks. The study will first include collection of lifeline utility network data in GIS format. Seismic damage analysis will be made by defining fragilities of the network components and the ground motions generated by the scenario earthquake. The gathered network datasets will be topologically modeled. The damage estimates will be utilized in the topological model to obtain the post-seismic state of the networks for performance analysis. Two interdependent network performance measures, named connectivity loss and service flow reduction, will be applied to the networks in order to predict the effect of the earthquake on the end users by means of serviceability. By the completion of the proposed study, an analysis tool for use in Turkey will be developed. The model will be validated with the utility lifelines performance in the 1999 Kocaeli earthquake if there is available data in proper format for the analyses; and the seismic performances of the Istanbul networks will be predicted for the expected Marmara earthquake.

FS 2B - SIM Best Practice Applications   1/12
Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

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1. INTRODUCTION

Lifelines provide essential services such as energy, potable water, wastewater treatment, transportation and communication to societies and they are crucial elements of urban systems. As everyday social activities in developed societies get more dependent on the complex body of interconnected lifeline systems, their role gets more crucial. Increasing population and urbanization of societies necessitate using state of the art assessment of seismic vulnerabilities and developing reliable mitigation strategies regarding lifeline systems (Pitilakis et al., 2006). Additionally, because of their critical role on maintenance of public safety, health, and commerce, sustainability of communities rely heavily on lifelines. The study focuses on the use of comprehensive analysis tools and methodologies for electric power, potable water, and natural gas networks of Istanbul.

In order to indicate the importance of seismic performance of lifelines on societies, several examples can be given. 1989 Loma Prieta Earthquake caused extensive damage on viaducts and bridges in the transportation network; broken gas lines in the Marina District caused fire; power outage caused the residents to sit in the dark, network congestion prevented making telephone calls and more than 1,200 leaks and breaks were repaired in the water distribution system (Schiff, 1999). Following the 1994 Northridge Earthquake, a blackout affected the whole city of Los Angeles. There were approximately 1,400 repaired pipeline leaks and breaks on the water system in the epicentral region and about 151,000 outages were reported in the natural gas system (Lund, 1996).

2. LIFELINE PERFORMANCE AFTER 1999 MARMARA EARTHQUAKE

1999 Kocaeli and Düzce Earthquakes had moment magnitudes of 7.4 and 7.2, respectively (Figure 1), and caused damage to structures in Kocaeli, Sakarya, Düzce, Yalova, Bolu, Istanbul, Bursa, Eskişehir, and Bilecik. The earthquakes mainly affected power, transport, and communication systems in the epicentral regions. No power plants of the power networks in the region were reported damaged following both earthquakes. However, damaged substations of the power transmission systems in Kocaeli and Sakarya caused blackouts in northwestern Turkey within minutes following the earthquake and power had not been restored for several days. According to Turkish Electricity Distribution Authority (TEDAŞ) figures, approximately 7% of distribution transformers in the affected urban regions were heavily damaged. Approximately 30% of underground distribution lines and 6% of the towers were also damaged. Water systems in Gölcük (Southern Kocaeli) and Sakarya experienced heavy damage and the water supply was cut off for a long duration due to extensive pipe breaks caused by the fault rupture and liquefaction. Izmit water system, on the other hand,

FS 2B - SIM Best Practice Applications
Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

2/12

experienced minor damage mainly because of the modern steel transmission lines and plants of the city. Although Kocaeli is the junction for the majority of international petroleum and natural gas transmission and major distribution pipelines passing through Turkey; no damage was reported on the major pipeline systems. Also, no severe damage was reported on the city gas distribution network; but on service boxes due to collapsed buildings (Erdik, 2000).
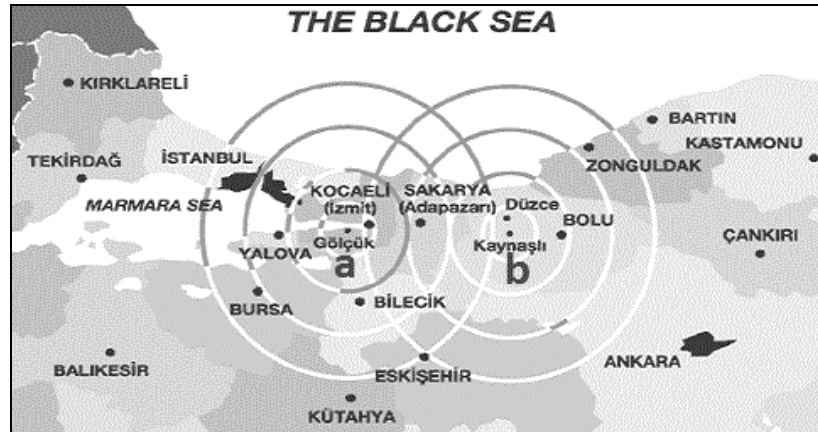

Figure 1. Locations of 1999 Kocaeli (a) and Düzce (b) earthquakes (UNICEF, 2010).

3. NETWORK INTERDEPENDENCY

Given the importance of lifeline systems to the society; reliable seismic assessment of those systems becomes crucial for better preparedness. Modeling the lifelines as a system of networks with proper dependency considerations instead of treating them as independent networks is one approach towards more accurate anticipation of the effects of earthquakes (Kim, 2007). The term interdependency is defined as: "A bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other" (Rinaldi et al., 2001).

Interdependencies among lifeline networks can be described via numerous occurrences. Lifeline networks of San Francisco experienced extensive damage due to the Loma Prieta Earthquake in 1989. Water supply system on the lower zones of the city had failed because of damaged pipes and hydrants. A system wide disruption had been witnessed on the water network due to cascading failures, which lead to the loss of firefighting abilities. Also, an exploding gas transmission line in New York in 1989 that caused power loss for about 5 hours can be given as another example of lifeline interdependency (O'Rourke, 1994). Modeling of network interdependencies is a highly complex task, given the different nature of each physical or spatial connection between systems. Depending on the extent of the study, several disciplines such as civil engineering, mechanical engineering, electrical engineering, computer science, economics and other social sciences may have to get involved. Interdisciplinary work is essential to be able to accurately model losses in one system would affect residents, businesses, and other interacting systems (Shinozuka, 2005).

In his study on interdependent networks, Kim (2007) pointed out the necessity to improve the interdependent failure mechanisms in order to achieve more accurate representations of the

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Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

3/12

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Sydney, Australia, 11-16 April 2010

physical situation of networked systems. The model is formulated over electric power and water network systems with water system being dependent on electric power, based on the fact that electricity is vital for the operation of almost every function in urban societies (Shinozuka, 2005). Each network is built of links and nodes; with links representing power lines or water pipes, nodes representing network facility structures. Nodes are classified as generation, intermediate, or distribution in each network where flow in the network is generated by generation nodes, and is discharged by distribution nodes. The interactions were defined between the networks where water generation nodes are dependent to electric power supplied to the system by power distribution nodes. The failure of a component after an earthquake is linked to two main reasons in the model: Failure due to earthquake damage, and non-functionality of a network component due to power outage. Power outage can be caused by earthquake damage to the distribution facility, or failure of the nodes and links in the power network feeding electric power to the distribution node. Furthermore, although being functional and not affected by interdependency, a network node can still fail by losing its connectivity to the network. This happens when a generation node has no surviving outgoing links, or when a distribution node has no surviving incoming links, thus being isolated from the network (Kim, 2007).

Two performance measures for the interacting networks are utilized by Duenas-Osorio (2005) in order to quantify the functional loss of a system when some of the components are likely to be dysfunctional: Connectivity Loss (C_L), and Service Flow Reduction (S_{FR}). These measures assess the network performance with metrics depending on the topological settings of the network, or with more detailed metrics depending on supply, demand, and flow patterns additional to the topological settings. Connectivity Loss (C_L) measures the ability of every distribution node to receive flow from generation nodes. Service Flow Reduction (S_{FR}) determines the amount of flow that the system can provide compared to the demand before the disturbance. The effect of network interconnection on post-seismic serviceability is presented in Figure 2.
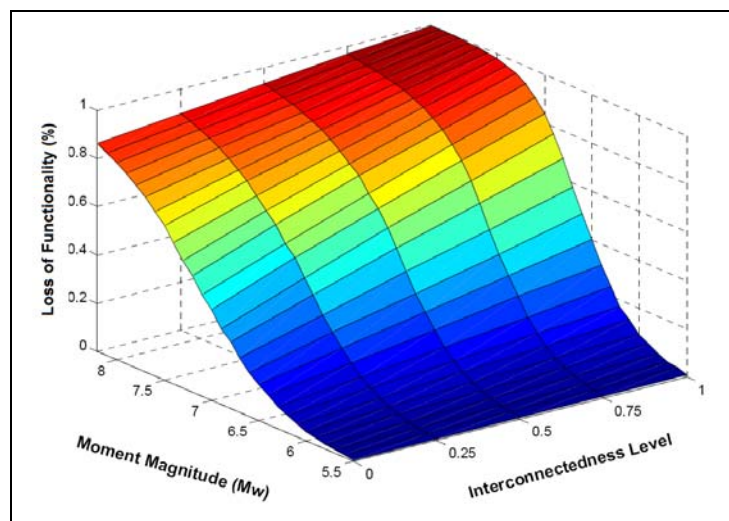

Figure 2. Serviceability loss of networks with changing dependency levels (Kim, 2007).

FS 2B - SIM Best Practice Applications   4/12
Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

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4. INTERDEPENDENT NETWORK ANALYSIS

The Interdependent Network Analysis Tool is developed to model the frequently connected lifeline utility networks via a variety of mechanisms. The methodology is implemented as an analysis tool into MAEviz, seismic loss assessment software of the MAE Center, which provides an extensible, open-source environment enabling incorporation of new data types and analysis modules and further improvements on analysis methodologies (Elnashai, Spencer, Myers, et al., 2008). The model is composed of topological network systems with multiple levels of interdependencies based on spatial proximity. The tool requires both structural and topological modeling of the lifeline network systems. Several fields need to be defined while analyzing datasets, enabling MAEviz to use the information as key values for mapping or as direct inputs to the analysis algorithms. The general structure of the interdependent network analysis process is described in Figure 3. The process can be divided into two as Structural Model where the structural damage is estimated by the inventory, hazard, and fragility information provided; and as Topological Model where the interdependent post earthquake serviceability performances of the networks are simulated based on the structural damage estimates. The analysis inventory should be built in compliance with the requirements of both models.
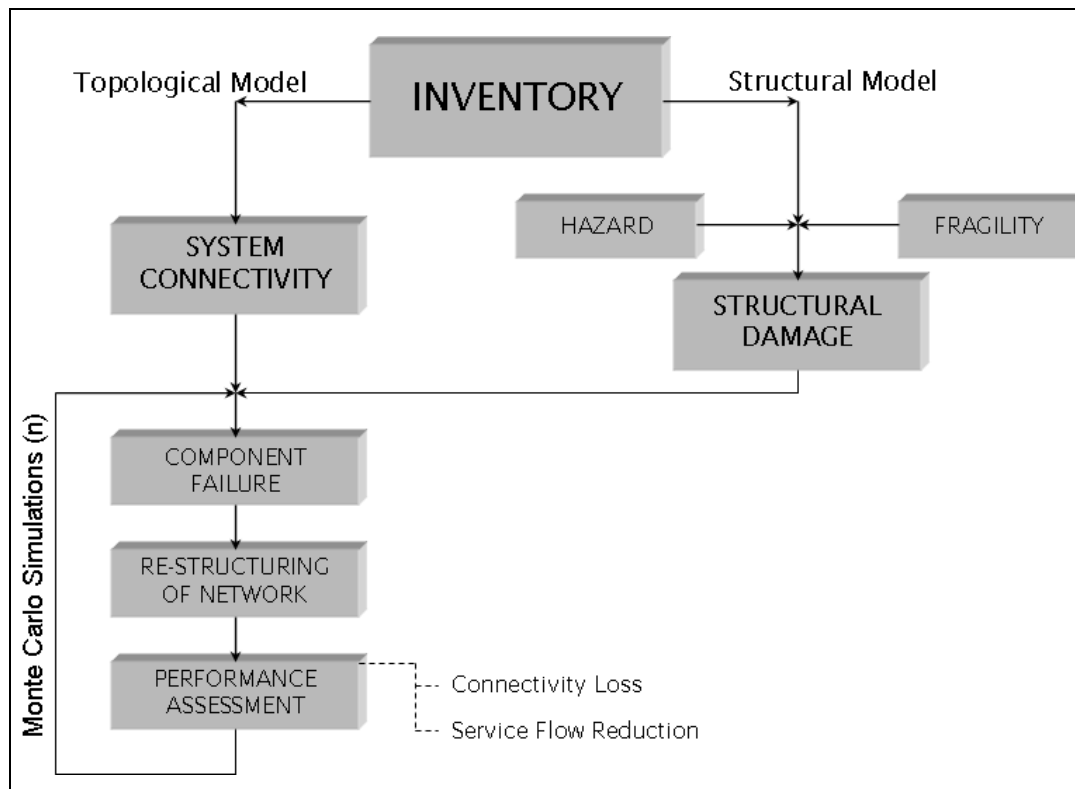

Figure 3. Interdependent network analysis methodology.

In the structural model, damage assessment of the inventory items are carried out based on specified hazard and fragility information. The estimated damage is then used for failure assessment of network components in the succeeding steps of the analysis. Structural analysis

FS 2B - SIM Best Practice Applications
Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

FIG Congress 2010
Facing the Challenges – Building the Capacity
Sydney, Australia, 11-16 April 2010

5/12

gives the direct damage of the network components caused by ground shaking and liquefaction caused by the scenario earthquake. Topological model, on the other hand, is where the networks are modeled based on connectivity and flow relations. Failures of components are determined based on structural damage and interdependency effects for each simulation. Re-structured networks with surviving components are analyzed by applying Monte Carlo Simulations to determine the system performance based on reductions in connectivity and flow. Topological analysis estimates the effects of earthquakes on the users by quantifying the amount of service loss for each individual network.

Since its implementation into MAEviz in 2007, several modifications and improvements on the analysis tool have been performed for the seismic performance analysis of lifeline utility networks of Shelby County, TN and St. Louis, MO as part of the second phase of "New Madrid Seismic Zone Catastrophic Earthquake Response Planning Project", conducted by Mid-America Earthquake Center, funded by FEMA and US Army Corps of Engineers (Elnashai, Cleveland, Jefferson, et al., 2008). The modifications and improvements include: liquefaction induced pipeline damage assessment, interdependent modeling of natural gas networks, and the adoption of a heterogeneous dependency model where each individual interaction is assessed instead of homogeneous, system-wide dependencies.

5. PREVIOUS STUDIES

One of the first efforts for an earthquake oriented disaster management studies in Istanbul is the project conducted by Japan International Cooperation Agency (JICA), contracted by Istanbul Metropolitan Municipality (IMM). The objectives of the study were stated in the final report as to compile seismic microzoning maps which would form a basis for future preparedness and mitigation studies for Istanbul, to develop structural code recommendations for earthquake-resilient urbanization, and to advise on effective planning (JICA, 2002). Loss assessment was performed for damage to potable water pipelines, wastewater pipelines, natural gas pipelines, natural gas service boxes, electric power lines, and fiber-optic telecommunication lines (Figure 4). Damage assessment to network facility structures were excluded from the study. Analysis outcomes suggested that southwestern parts of Istanbul would experience the most severe earthquake damage based on determined worst case earthquake scenario.

Kandilli Observatory and Earthquake Research Institute (KOERI) of Boğaziçi University have conducted a study in 2003 to develop a risk model for the Istanbul metropolitan region based on an earthquake scenario presented in the JICA (2002) study (KOERI, 2003). Scope of the study was to estimate building and infrastructure damage and casualties. Structural damage, similar to JICA (2002) study, was estimated cumulatively for the building and infrastructural stock contained in 500 x 500 meter cells forming a grid along the metropolitan area. Total economic loss was estimated to be approximately 11 billion USD according to the analyses.
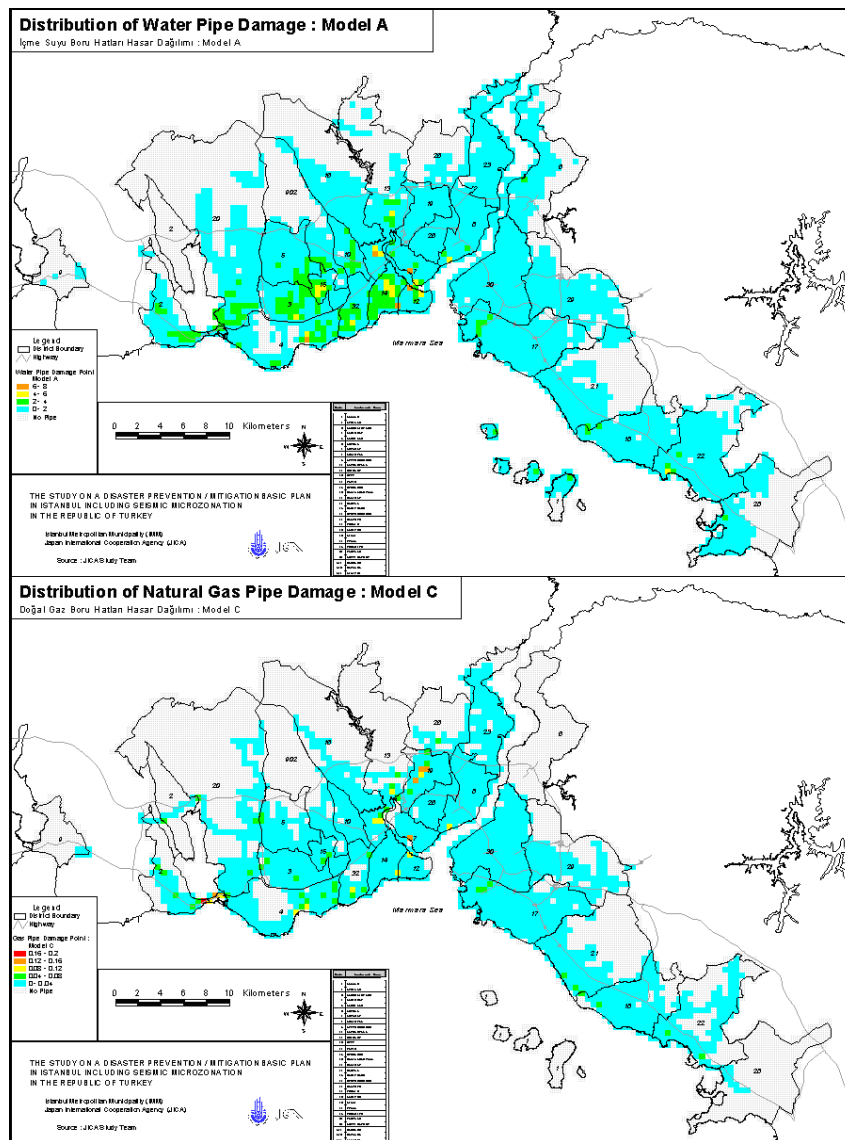
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Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

6/12

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Sydney, Australia, 11-16 April 2010

Figure 4. Expected damage for water and natural gas pipelines (JICA, 2002).

In 2007, development of a loss estimation tool that can realize all possible earthquake scenarios for a region of interest and provide the result of the effects and offer reinforcements to mitigate the consequences of a disaster was achieved as a result of a joint study between Istanbul Technical University (ITU) and Mid-America Earthquake (MAE) Center. The resulting product, HAZTURK, was a multipurpose risk assessment tool which comprehensively addressed all aspects of risk management by supporting the integration of physical, social, and economical consequences of earthquakes with decision and public policy making (Karaman, 2008). HAZTURK is a tool utilizing a consequence-based risk management (CRM) approach developed by the MAE Center. The CRM approach is a practical framework to evaluate the dynamic interdisciplinary relations between causes, effects, impacts, and mitigation properties of hazards (Elnashai, Spencer, Hampton, et al., 2008). Based on HAZTURK, damage analyses on building inventory of Istanbul and buried pipeline inventory of Zeytinburnu District (Figure 5) were performed.

FS 2B - SIM Best Practice Applications
Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

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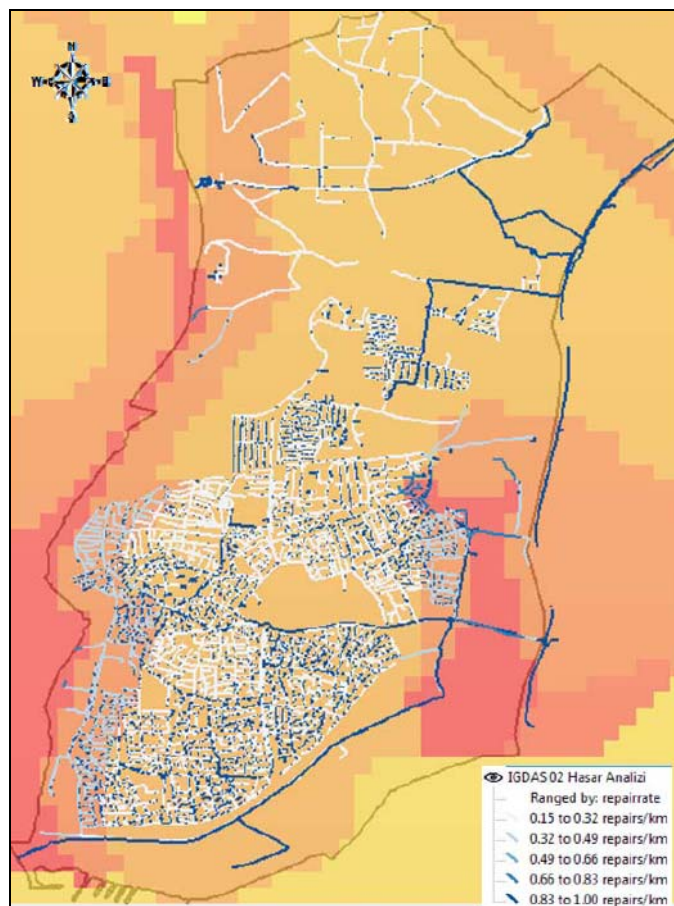Sydney, Australia, 11-16 April 2010

Figure 5. Buried pipeline damage for Zeytinburnu district, Istanbul (Karaman, 2008).

6. PROJECT SCOPE

The proposed study will feature the application of seismic damage and interdependent network performance analysis on topologically modeled electric power, potable water, and natural gas networks of Istanbul based on the expected Marmara earthquake scenarios. Given the added features of liquefaction induced pipeline damage and heterogeneous dependency models into the interdependent network analysis tool, the proposed study will provide an accurate assessment of seismic performance of lifeline networks and local interactions between the networks.

Two different earthquake scenarios will be utilized for the analyses in the proposed study. Fault rupture models of both scenarios were suggested in the JICA (2002) study. The first scenario (Model A) suggests a 120 km rupture at the eastern part of the Marmara segment of the North Anatolian Fault, which would result in an earthquake with a moment magnitude (Mw) of 7.5. Model A was suggested as the most probable rupture model for the next Marmara earthquake.

FS 2B - SIM Best Practice Applications
Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

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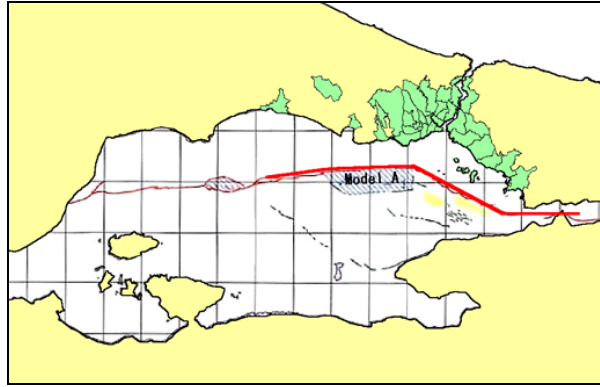Sydney, Australia, 11-16 April 2010

8/12

Figure 6. Model A - Rupture model for the most probable earthquake scenario (JICA, 2002).

The second scenario (Model C) suggests a rupture of 170 km throughout the Marmara Sea that would result in a 7.7-magnitude earthquake (Figure 7). Given that the biggest historical earthquake on the region is a 7.6-magnitude event, Model C is accepted as the worst case scenario for Istanbul (JICA, 2002).
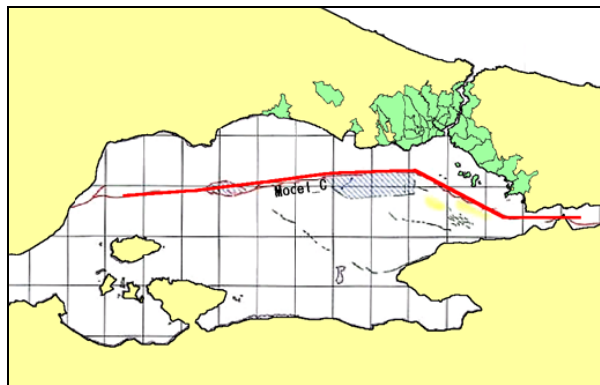

Figure 7. Model C - Rupture model for the worst case earthquake scenario (JICA, 2002).

As part of the project, validation of the interdependent network analysis algorithm developed by Kim (2007) based on the structure defined by Duenas-Osorio (2005) will also be performed. The validation of the model will be sought based on the lifeline network performance after the 1999 Kocaeli earthquake provided that suitable data for the analyses is present and can be obtained from the authorities.

7. CONCLUSION

Modeling the lifelines as a system of networks with proper dependency considerations instead of treating them as independent networks is one approach towards more accurate anticipation of the effects of earthquakes (Kim, 2007). Use of computational sciences integrated with geographic information systems (GIS) enables researchers to carry on more detailed vulnerability analyses and utilize the outcomes in retrofit analyses. It is stated that emphasis on interdependencies over an integrated perspective can help better approaches to the physical infrastructure and this broad extent recommends research and development on geographic information systems, information technologies and remote sensing (O'Rourke, 1994).

FS 2B - SIM Best Practice Applications
Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

9/12

FIG Congress 2010
Facing the Challenges – Building the Capacity
Sydney, Australia, 11-16 April 2010

The proposed study and its integration with the HAZTURK system is going to serve the continuing goal set by Istanbul Technical University to updating potential risks and their consequences as the inventories and analysis methodologies evolve over time. This dynamic behavior of the system enables the earthquake scenarios, analysis methodologies, loss assessments, mitigation, response and recovery plans to be updated continuously when needed. Current research vision ultimately aims to help integration of natural hazard risk management into project planning, assistance programs, and existing structure/infrastructure maintenance to improve Turkey's resilience against seismic hazards.

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FS 2B - SIM Best Practice Applications
Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

10/12

FIG Congress 2010
Facing the Challenges – Building the Capacity
Sydney, Australia, 11-16 April 2010

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Muhammed ŞAHİN:
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FS 2B - SIM Best Practice Applications   11/12
Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

FIG Congress 2010
Facing the Challenges – Building the Capacity
Sydney, Australia, 11-16 April 2010

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Hüseyin Can Ünen, Himmet Karaman, Muhammed Şahin and Amr S. Elnashai
Seismic Performance Analysis of Utility Lifeline Networks in Istanbul, Turkey

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Facing the Challenges – Building the Capacity
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