Assessment of Interdependent Lifeline Networks Performance in Earthquake Disaster Management

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ABSTRACT

Several studies and observations regarding past earthquakes such as 1989 Loma Prieta, 1994 Northridge, or 1999 Marmara earthquakes have shown the importance of lifeline systems functionality on response and recovery efforts. The general direction of studies on simulating lifelines seismic performance is towards achieving more accurate models to represent the system behavior. The methodology presented in this paper is a product of research conducted in the Mid-America Earthquake Center. Electric power, potable water, and natural gas networks are modeled as interacting systems where the state of one network is influenced by the state of another network. Interdependent network analysis methodology provides information on operational aspects of lifeline networks in post-seismic conditions in addition to structural damage assessment. These results are achieved by different components of the tool which are classified as structural and topological. The topological component analyzes the post seismic operability of the lifeline networks based on the damage assessment outcome of the structural model. Following an overview of the models, potential utilizations in different phases of disaster management are briefly discussed.

Keywords

Lifeline systems, earthquake engineering, loss assessment, interdependency.

LIFELINES EARTHQUAKE ENGINEERING

Lifeline networks are crucial elements forming the backbone of any society by providing essential services. They play vital roles in response and recovery efforts following disasters, especially earthquakes. 1989 Loma Prieta Earthquake caused serious damage on transportation structures, natural gas and water lines, power systems, and the telecommunication network (Schiff, 1999). Following the 1994 Northridge Earthquake, whole city of Los Angeles experienced a blackout. Within the epicentral region, there were extensive damage on water and natural gas systems (Lund, 1996). 1999 Kocaeli and Düzce Earthquakes caused heavy damage on mainly power, transportation, and communication systems with major fire damage to Tüpraş Oil Refinery and infrastructure damage to approximately 60 km of the Ankara-Istanbul Highway. About 7% of the overall distribution transformers and 25% of the underground distribution cables within the power distribution network were heavily damaged (Erdik, 2001).

The importance of lifeline systems to the society necessitates reliable seismic assessment efforts for better preparedness. Advancing computer technology enables researchers to physically model the network structure of lifeline systems by utilizing network flow and connectivity models (Shinozuka et al., 1992; Hwang et al., 1998). Network models are used to assess the seismic performances of lifeline systems and to recommend rehabilitation measures (Shinozuka et al., 1999). Shinozuka et al. (2007) have also utilized computer simulations to analyze component based progressive failures within lifeline systems. Trying to understand lifelines as systems of multiple interacting networks led Robert (2004) to propose a method to investigate the cascading effects of the networks and potential consequences to other networks. Shinozuka et al. (2005) influenced by this consideration, developed an analysis procedure to evaluate the performance of power and water systems in pre

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and post-earthquake conditions.

LIFELINE INTERDEPENDENCY

Modeling the lifelines as a system of networks with proper dependency considerations 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). Rinaldi et al. (2001) presents a conceptual framework for identification, definition, and modeling of critical infrastructure interdependencies. According to the framework, there exist six dimensions of infrastructure interdependencies intending to define, understand, and model the interdependencies. The six dimensions of infrastructure interdependencies are: type of interdependency, coupling and response behavior, failure type, infrastructure characteristics, and state of operations. Analyzing infrastructure systems with a system-of-systems perspective with interdependency considerations would lead to enhanced validity of analyses and better, more appropriate policies and decisions. In the case of rare extreme events, modeling and simulation efforts are the only possible approaches that would provide information on the consequences given the inadequacy of historical records and experience. Although the stakeholders of infrastructure systems have extensive experience regarding daily small-scale outages and disruptions, the limited experience against major infrastructure failures necessitate the utilization such modeling and simulation efforts which would provide valuable insight for development of mitigation, response and recovery plans (Rinaldi, 2004). Additionally, the possibilities to verify and validate the existing models possess great importance for the development and improvement of existing methodologies.

Duenas-Osorio (2005) developed a model composed of network systems with multiple levels of interdependencies based on spatial proximity. Instead of a macro-level approach to the interacting systems, the model focused on network topology (physical layout) and flow patterns. Duenas-Osorio (2005) also defined three performance measures for functionality characterization of a network: Efficiency, connectivity loss and service flow reduction. These measures assess the network performance with metrics depending on supply, demand, and flow patterns additional to the topological settings. Kim (2007) has proposed a methodology based on the network structure defined by Duenas-Osorio (2005) with further clarification on the probabilistic interdependency model, modified failure models and improved interdependent failure mechanisms. The model is formulated over electric power and water network systems with water system being dependent on electric power.

INTERDEPENDENT NETWORK PERFORMANCE ANALYSIS

Performance assessment of interdependent networks requires utilization of two separate models utilized consecutively: structural model for damage estimation, and the topological model for connectivity and flow analyses based on structural damage assessment output (Figure 1). The inventory datasets must be provided in compliance with the requirements of both models since the output of the structural assessment is used as an input in interdependent performance assessment.

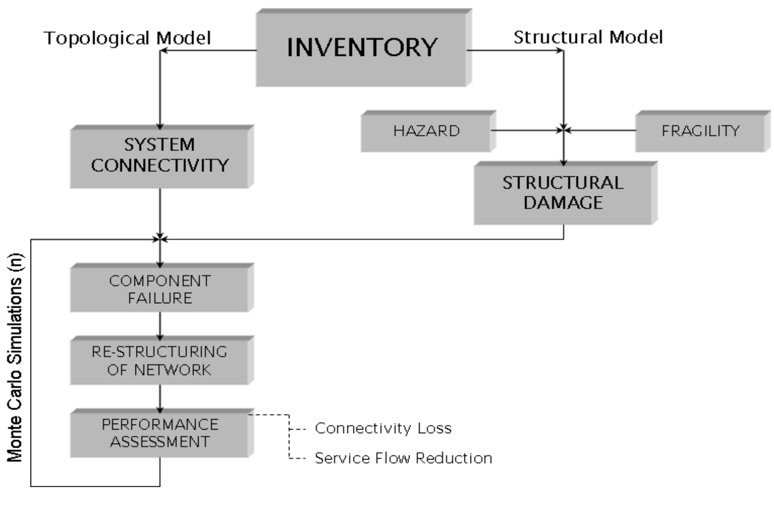

Figure 1. Interdependent Network Performance Analysis flowchart.

Topological model is where the networks are modeled based on connectivity and flow relations. Failures of components are determined based on structural damage and interdependency effects via carrying out numerical simulations. Re-structured networks with their surviving components are analyzed by applying Monte Carlo Simulations to determine the system performance based on reductions in connectivity and flow. System performance is the quantification of the effect of physical damage on the network flow and system serviceability. Topological analysis estimates the effects of earthquakes on the end-users by quantifying the amount of service loss for each individual network.

Structural Model

Structural modeling is the initial step in the performance assessment of interdependent lifeline networks. The essential elements for structural damage assessment are hazard, inventory, and fragility. All three elements are vitally important for the achievement of accurate assessments. The estimated damage calculated in the structural model is used for failure assessment of network components in the succeeding steps of the analysis.

Interdependent network performance analysis inventory is divided in to five classes as electric power network facilities, electric power network lines, water network facilities, natural gas network facilities, and buried pipelines. The classification of the network facilities are made in accordance with HAZUS guidelines specified in the earthquake loss estimation methodology (FEMA, 2003).

Seismic hazard is the quantification of ground motions without any reference to human or structural loss, simply depending on the characteristics of the selected scenario earthquake. Main parameters on hazard estimation are the earthquake magnitude, distance, and site conditions. Based on its definition, seismic hazard differs from seismic risk, which is mainly dependent on the impact of one earthquake on societies or the structural inventory. Quantification of ground shaking is obtained by ground acceleration (PGA, S_a) or ground velocity (PGV) parameters.

Damage functions for buried pipelines are utilized to estimate the number of repairs caused by leaks and ruptures on a unit length of one segment. Results can be obtained in number of repairs per kilometer (O'Rourke & Ayala, 1993; O'Rourke & Jeon, 1999) or number of repairs per 1000 feet (Eidinger, 2001). Damage to pipelines can be induced by ground shaking, ground failure due to liquefaction, landslides, fault rupture, or settlement. Damage predictions for network structures are given in terms of the probability of a structure being in a particular damage state by implementing fragility curves. Four ranges of limit states are utilized to describe the degree of damage to structures: slight (S), moderate (M), extensive (E), and complete (C).

Topological Model

Knowing the physical state of a network is not sufficient to make predictions regarding its operational loss after disruptions. Interdependent performance analysis tools for topological networks are employed to simulate the post-seismic conditions of the analyzed networks by applying connectivity and flow algorithms. With the interdependent approach, lifeline networks are modeled as a mutually dependent system of systems where the state of one network is influenced by another. Three types of nodes are defined for the topological networks in terms of roles in physical networks: generation, intermediary, and distribution.

Based on seismic damage assessment results and interdependency definitions between systems, post seismic states of the networks are obtained and system reliabilities are assessed by utilizing Monte Carlo simulations. In order to measure the functional loss of a system, two performance measures are defined: Connectivity Loss (C_L), and Service Flow Reduction (S_{FR}). These measures assess the network performance with metrics depending on supply, demand, and flow patterns additional to the topological settings. Connectivity loss measures the ability of every distribution node to receive flow from generation nodes (Kim et al., 2008). Service flow reduction determines the amount of flow that the system can provide compared to the demand before the disturbance (Kim et al., 2007).

Significance

While the current study, as part of a Ph.D. research, adopts the methodology of Kim (2007) for the analyses, it also aims to enhance and improve the network analysis methodology. The buried pipeline damage algorithm utilized in the methodology only took damages induced by ground shaking (PGV) into account. However, ground failure and permanent deformations (PGD) also cause significant damage to buried pipelines. There exist methodologies for estimation of combine pipeline damage against PGV and PGD (Honegger & Eguchi, 1992) in the literature, finding applications in loss estimation tools such as HAZUS. One improvement to the methodology was to implement a buried pipeline loss estimation methodology into the interdependent network analysis that would provide combined damage estimates and assess the effect of liquefaction-induced pipeline damage on network performance. One of the issues that Kim (2007) turned his attention was the claim which stated interdependent failure mechanisms needed to be improved to more accurately reflect the physical situation. The existing methodology adopted a system-based approach where the dependency mechanism homogeneously dictates the same behavior in every component throughout analyzed networks. For more accurate representation of the physical situation, a heterogeneous element-based approach was adopted in the dependency model where each component in the network is allowed to behave differently and have different dependency levels to account for possible localized mechanisms which may arise in lifeline networks.

ANALYSES IN DISASTER MANAGEMENT

The disaster management process is generally referred as a continuous cycle of actions revolving around natural disasters. Given the continuum, the preparedness, mitigation, response, and recovery phases are related to each other, but focusing on different aspects regarding a natural disaster. It is possible that the output of the interdependent network analysis can be utilized by disaster managers in different phases of the disaster management process along with other relevant information via information synthesis.

In preparedness phase, response and recovery needs are required to be determined using more detailed hazard, inventory, and fragility information for the selected scenario. Methodology can help researchers to identify regions to focus on where mitigation would be necessary. The analysis outputs may also be utilized in enhancement of response operation planning efforts such as allocation of repair teams, stocked repair tools, or hardware for quick response following a potential hazard. The application of the methodology was performed in a study to assess the impact of New Madrid Seismic Zone earthquakes on Central United States (Elnashai et. al., 2010). The study provided detailed seismic impact analysis on both structural and infrastructural inventory of the region and a comprehensive socio-economic assessment to be utilized in mitigation efforts.

In the presence of more than one risk source, preliminary analysis would identify the most serious risk based on the expected consequences as the hazard scenario to be utilized in further steps of the disaster management process. The analyses would also reveal the most vulnerable components of the systems for increased focus in the mitigation phase.

In the response phase, rapid assessment can be applied to portray components with more likelihood of damage for effective coordination during the early stages of the disaster response. Analyses would provide information on where heavy damage is most likely to be located in or existence of regions of critical importance likely to be experiencing utility service disruptions. This approach would provide the response teams a quick reaction and valuable guidance in the lack of information regarding the actual consequences of the disaster in the early periods of the post-disaster situation.

Prioritization analyses can be carried out in recovery phase based on the observed structural damage inflicted by the earthquake. Determined high priority repairs in the system are expected to focus on the most critical components that are vital for to meet the minimum operational requirements of lifeline services. This approach would prevent poor estimations or decisions based on inadequate information, and expected to help in saving time, money, and lives (Johnson, 2000). Rebuilding schemes can be simulated in the model for verifying whether the system would reach its previous operational state or would it improve. If these activities are carried out simultaneously with the planning and mitigation phases for the next expected disaster, completion of disaster management cycle would also be achieved. Thus, the lifeline systems would be re-planned and rebuilt according to the future risks instead of the one they just experienced.

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 fragility analyses and utilize the outcomes in retrofit analyses. Emphasis on infrastructural interdependencies over an interdisciplinary integrated perspective can help better approaches to modeling the physical infrastructure. The interdependent network performance analysis methodology and the analysis tool provides an environment for researchers and disaster managers to analyze the consequences of potential risks, assess the expected structural damage and operational performance, build retrofitting schemes, and prioritize the repair efforts after disasters. Potential verification of the model with experienced real-life performances of lifeline systems and developing automated tools for the mentioned analysis methodologies would result in more effective and wider utilization of the subject within future studies.

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