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Scenario-based resilience assessment framework for critical infrastructure systems: Case study for seismic resilience of seaports

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ABSTRACT

A number of metrics in the past have been proposed and numerically implemented to assess the overall performance of large systems during natural disasters and their recovery in the aftermath of the events. Among such performance measures, resilience is a reliable metric. This paper proposes a probabilistic framework for scenario-based resilience assessment of infrastructure systems. The method accounts for uncertainties in the process including the correlation of the earthquake intensity measures, fragility assessment of structural components, estimation of repair requirements, the repair process, and finally the service demands. The proposed method is applied to a hypothetical seaport terminal and the system level performance of the seaport is assessed using various performance metrics. Results of this analysis have shown that medium to large seismic events may significantly disrupt the operation of seaports right after the event and the recovery process may take months. The proposed framework will enable port stakeholders to systematically assess the most-likely performance of the system during expected future earthquake events.

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1. Introduction

Critical infrastructure systems provide the essential physical basis for modern societies, and have multi-dimensional impact on public safety and economic prosperity at regional and national levels. Past experiences have shown that such systems are exposed to various natural and manmade hazards. The resulting damage to the systems may cause human casualties and disrupt the normal day-to-day life of people in the short run. This damage may also impose significant direct and secondary economic losses due to business interruption that may not ever fully recover. The recent events of hurricane Katrina and Sandy, and the earthquakes in Haiti [1,2], Chile [3,4], New Zealand [5,6], and Japan [7,8] have demonstrated the vulnerability of critical infrastructure systems against natural hazards.

Quantification of the effects of such hazards on the performance of systems is a challenging task. A number of frameworks/measures have been proposed and implemented numerically to quantify various aspects of systems response to hazards; among which, system reliability, resilience, flexibility, robustness are some of the proposed metrics. The resilience metric is one of the comprehensive measures that integrates the pre- and post-hazard performance of the system. Resilience is a common term in various research fields; however, the definition of resilience in each field is to some extent different from the others. These definitions in one way or another are conceptually similar to the resilience property of materials that can recover their original shape after being deformed. For instance according to Walker et al. [9], ecological resilience is defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks." Among the several definitions that have been proposed for resilience, this study employs the definition proposed by the Multidisciplinary Center for Earthquake Engineering Research (MCEER). According to this definition, seismic resilience is defined as "the ability of both physical and social systems to withstand earthquake-generated forces and demands and to cope with earthquake impacts through situation assessment, rapid response, and effective recovery strategies," and is composed of four dimensions: robustness, redundancy, resourcefulness, and rapidity [10]. A number of studies have implemented such frameworks to quantify the resilience of various infrastructure systems against natural hazards or the intelligent actions of adversaries. Chang and Shinozuka [11] proposed the probabilistic method that quantifies resilience as the probability of meeting pre-defined robustness

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and rapidity standards. As a case study, the proposed approach was applied to compare the seismic resilience of Memphis water delivery system without retrofit and with two retrofit strategies. Cimellaro et al. [12] extended the resilience assessment framework proposed by Bruneau et al. [10] and explicitly defined resilience as the area beneath the performance curve for a given time period, and demonstrated its application for seismic resilience of a network of hospitals in Memphis, Tennessee. Reed et al. [13] suggested a resilience assessment methodology for subsystems of a multi-system networked infrastructure for extreme natural hazard events. In their proposed method, they combined the resilience measure by Bruneau et al. [10], input-output models, and structural fragilities, and used available data for Hurricane Katrina lifeline damage to illustrate the application of their method. Recently, Ouyang and Dueñas-Osorio [14] introduced a resilience assessment framework that is adequate for both single and multiple hazards, and computed the expected annual resilience of the power transmission grid in Harris County, Texas under random hazards and hurricane hazards. Ouyang [15] provided an extensive review of modeling and simulation approaches of critical interdependent infrastructure systems and compared these methodologies from the overarching perspective of resilience. Other relevant studies in this field can be found in [16–21].

Seaports are one of the pivotal nodes in transportation networks and serve as critical gateways for national and international trade. Past experiences have shown that any disruption in the activities of port infrastructure may lead to significant losses from secondary economic effects in addition to direct losses associated with physical port damage [22,23]. A prominent example of the vulnerability of seaports and the consequent effects on business interruption is the seismic damage to the Port of Kobe during the Hygoken Nanbu earthquake (Kobe 1995). Liquefaction and lateral spreading of embankments throughout the port imposed severe damage to waterfront structures [24] leading to $5.5 billion in repair costs and extended business interruption losses due to disruption of cargo throughput [25]. Much of this loss of business has never been recovered by the port, which at the time of the earthquake was the sixth largest port in the world in terms of container cargo throughput and, in the aftermath of the earthquake, is now the 45th largest [26]. The other aspect of the strategic importance of seaports is their role in delivering relief supplies that are essential to the recovery of the surrounding region following a disaster. A poignant example is the 12 January 2010 earthquake in Haiti that severely damaged the major port in Port-au-Prince, the Port de Port-au-Prince (PPAP). During the earthquake, North Wharf of the main port in Port-au-Prince completely collapsed and submerged into the water primarily due to liquefaction of the embankment soil [27,28]. PPAP was Haiti's largest seaport at the time of the earthquake handling most of the commercial waterborne cargo. In addition to direct economic losses and business interruption, damage of PPAP caused major delays in the transport of humanitarian and emergency response cargoes (medical supplies, food, equipment for debris removal, etc.) immediately after the earthquake, as well as cargoes containing equipment and materials needed for the reconstruction of infrastructure and the recovery of Haiti's devastated economy.

Seaports are complex infrastructure systems where physical components such as wharves and cranes work as subsystems to provide services for loading and unloading cargoes and passengers. Despite the significant role of seaports in economic prosperity at regional and national levels, and their strategic importance for immediate emergency response and long-term recovery following a disaster, little attention have been given to holistic performance of seaports following earthquakes. This paper introduces a comprehensive scenario-based resilience assessment framework to evaluate seismic performance of seaports during and after the hazard. The proposed approach decomposes performance assessment of systems to hazard generation considering correlation of hazard intensities, probabilistic repair requirement assessment of structural components, dynamic port operation models, stochastic service demand model, and the recovery plan of the system. This decomposition allows for the proper account of various uncertainties involved in the process of resilience assessment. In particular, consideration of service demands in the form of stochastic processes is quite important, as it may generate scenarios in which the system affected by hazards performs better than the undamaged system for a short period of time. These potential outcomes that go against intuition may occur in reality due to the fact that system operations algorithms have limited knowledge of future service demands. The proposed methodology is general and can be applied to various critical systems.

2. Resilience assessment framework

The concept of resilience is tied with system performance within the period of interest. Fig. 1 shows hypothetical system performance curves with the effects of hazard, $HP(t)$, and without the effects of hazard, $BP(t)$. This figure provides a general overview of time-dependent system performance and illustrates the important times during system response. As expected, system performance under the effects of the hazard degrades from the baseline response. This performance with respect to the time of hazard occurrence can be divided into three mutually exclusive stages: pre-hazard ($t < t_{hs}$), during hazard ($t_{hs} \le t < t_{he}$), and post-hazard ($t \ge t_{he}$) periods. In the pre-hazard stage, the system operates under normal conditions where both the capacity of the system and demand are not affected by the hazard due to causality. This period begins at the reference time, t_0, and ends at the time of hazard occurrence, t_{hs}. In the period between when the hazard hits the infrastructure, t_{hs}, and when the hazard ends, t_{he}, the system operates under the influence of the hazard. During this period, hazard induced force and deformation demands on the physical components of the system may exceed the corresponding capacity of the components for specific damage states; thus, causing a level of damage in structures. The induced damage degrades the functionality of the components. When the damage in all of the components and the role of those components within the system is considered, the performance of the system as a whole in providing various services degrades. It should be noted that occurrence of damage in the system may not be limited to only the duration of the hazard. The degradation of a system or part of a system may result in the cascading failure across the same system or in other interdependent systems which may happen during the post-hazard stage. In a short time following the hazard, restoration and recovery efforts begin. This stage may take a long time compared to the duration of the hazard. System performance starts upgrading under the influence of recovery efforts. With

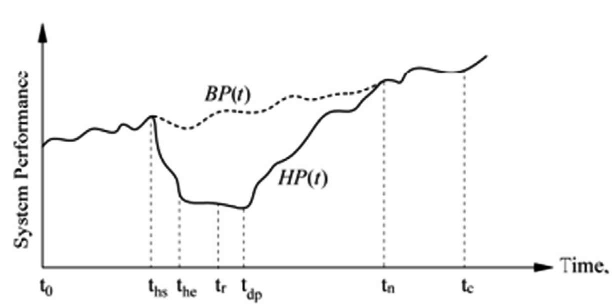

Fig. 1. Schematic of system performance without the impact of hazard, $BP(t)$, and the performance of the system impacted by hazard, $HP(t)$. System resilience is defined as the ratio of the area below $HP(t)$ and $BP(t)$.

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