Application of a Scenario-Based Assessment Framework for the Seismic Resilience of Seaports

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ABSTRACT: This study is an application of a previously developed framework for assessing seismic resilience in infrastructure systems. The risk and resilience framework, 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 framework, which as already been applied within a case study for the seismic resilience of a seaport, has been extended to show the utility of and results that can be produced when the methodology is used to compare various infrastructure system mitigation options. This study, which also uses seismic resilience in seaports as a case study, compares two operational mitigation options within the methodology: series repair sequencing post-earthquake versus parallel repair sequencing post-earthquake. Results of this analysis show that for a large earthquake event, repair sequencing done in parallel results in a more resilient infrastructure system than for series repair sequencing. The proposed methodology will allow port stakeholders a means to quantitatively compare mitigation options and their overall effect on the seaport system.

1. INTRODUCTION

The following study applies a scenario-based risk assessment framework to calculate the seismic resilience of seaports with regard to a particular mitigation strategy that can be applied during earthquake disruption. Regarding the several definitions that have been proposed for resilience, this study employs the definition proposed by the Multidisciplinary Center for Earthquake Engineering (MCEER) 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 (Bruneau et al. 2003). Resilience results from this study will be tied with system performance during a particular time period of interest as a comparison of the hypothetical system performance curve (Figure 1) with the effect of the hazard ($HP(t)$), versus the curve without the hazard effects ($BP(t)$), where t is time.

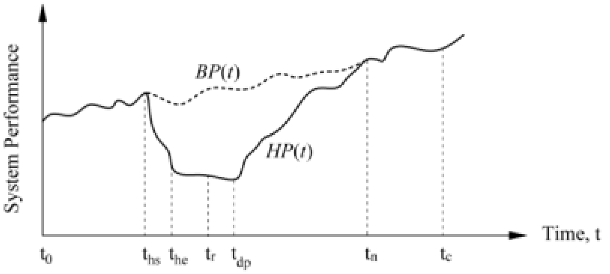


Figure 1 – Idealized resilience results without hazard impact (BP(t)), and with hazard impact (HP(t)).

1.1. Seaports and Earthquake Hazards

Seaports are integral to worldwide trade. Unfortunately, many seaports are vulnerable to earthquake hazards. The Port of Kobe offers one example of this vulnerability since it experienced extensive liquefaction, wharf, and crane damage after the Hyogoken-Nanbu earthquake in 1995. This physical damage cost $5.5 billion dollars to repair, but the indirect costs from business interruption were greater. Shippers who used the Port of Kobe before the earthquake set up operations in other ports during the months that repair took place (Chang, Shinozuka et al. 2000). Unfortunately, many of these shippers never returned, and the Port of Kobe dropped from the 6th largest port in the world to 55th by 2007 (AAPA 2013).

Unfortunately, current seismic management and codes do not address the business interruption losses that result from seismic disruption, and instead rely on arbitrary return periods for individual port components (wharves, cranes, etc.) as standards for building codes. This focus on individual port components neglects the system infrastructure inherent in a seaport. To remedy these problems, a seaport risk analysis framework was created specifically for the NEES Grand Challenge project: Seismic Risk Management in Port Systems and a subsequent resilience calculation was developed in Shafieezadeh and Ivey Burden (2014). This developed methodology enables port stakeholders to probabilistically assess the performance of a port system during future earthquake events with regard to business interruption as well as component performance.

1.2. Risk and Resilience Framework

The seismic risk framework used within this study (Ivey, Rix et al. 2010) integrates multiple research projects (Varun and Assimaki 2008, Kosbab, Jacobs et al. 2009, Shafieezadeh, DesRoches et al. 2009) that were conducted to model various port components and earthquake mitigation options. These component response models were developed specifically for earthquake vulnerable components commonly found in US West Coast ports. The seaport risk analysis framework modifies the risk analysis methodology presented by the Pacific Earthquake Engineering Research Institute (PEER) to account for the system nature of port infrastructure, and instead is used to calculate resilience. Essentially, the framework calculates multiple intensity measures (*IM*), engineering demand parameters (*EDP*), damage measures (*DM*), and corresponding repair requirements (*RR*) that can be used to assess the various components within the port. The repair requirement variable goes beyond the scope of PEER. Since a seaport is a system, loss must be calculated as both dollars and downtime. Therefore, the additional variable is added to the framework to calculate the operational losses on top of the physical losses. This additional step uses the physical damage and corresponding repair periods to estimate the downtime of specific seaport components (See Figure 2).

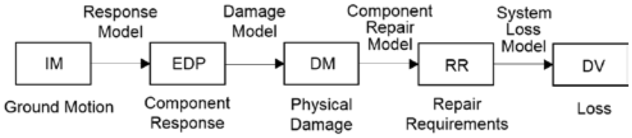


Figure 2 - Seaport Risk Framework Modification of PEER

Resilience can then be calculated probabilistically (to account for the various uncertainties associated with predicting performance prior to a hazard) using the following model conditioned on the distance and magnitude of a scenario earthquake event (Eq. 1):

$$RES(T,R,M) = \int_{SD}\int_{\overline{RR}}\int_{\overline{IM}} Res(T,SD,\overline{RR}) f_{SD} f_{\overline{RR}|\overline{IM}} f_{\overline{IM}|R,M} d_{\overline{IM}} d_{\overline{RR}} d_{SD} \qquad (1)$$

where $f_{\overline{IM}|R,M}$ is the probability density function of ground motion intensity vector ($\overline{IM}$) conditional on the specific values of moment magnitude (M) and distance (R) for the scenario earthquake, $f_{\overline{RR}|\overline{IM}}$ is the probability density function of the vector of repair requirements ($\overline{RR}$) conditional on the intensity measures produced by each earthquake occurrence, f_{SD} is the probability density function for service demand (SD), and

$Res(T, SD, \overline{RR})$ is the resilience of the system given service demand and repair requirements.

Further explanation of the full calculation of resilience and the specific procedures within the risk analysis framework can be found in Shafieezadeh and Ivey Burden (2014).

2. MITIGATION OPTIONS

Using the probabilistic methods described above and including all sources of uncertainty, the risk and resilience framework's greatest asset is that it can be used to evaluate specific mitigation options that could be applied at a seaport to increase resilience. Two distinct types of mitigation options could possibly be examined in the context of a seaport: (1) physical improvements and (2) operational improvements.

Physical improvements would include any upgrades that stakeholders might choose to make on the port components themselves, such as the upgrade of crane or wharf types within the seaport, or the installation of prefabricated drains to reduce liquefaction. Operational improvements would encompass mitigation techniques that would directly impact the rate with which cargo is handled. Mitigation options of this type would be implemented to speed up or slow down the overall throughput of the port.

For the application presented in this paper, one operational mitigation option will be applied to a hypothetical seaport terminal and the resilience with and without the mitigation will be calculated. The mitigation option applied will be to vary the repair sequencing post earthquake, and to calculate resilience when repair is conducted in parallel versus in series.

It is assumed that in real life, a combination of parallel and series repair sequencing takes place after an earthquake. Repair crews will work on as many projects as possible in parallel and sequentially move down a terminal to fix parallel areas of damage in series. However, this is not accounted for within the risk and resilience framework. Instead, the choice is binary, and it is assumed that repair crews will work on repairs for damaged sections of a terminal either simultaneously (in parallel) or one by one (in series). As an example, take the following terminal with the following repair times (t) for each berth and crane (Figure 3):

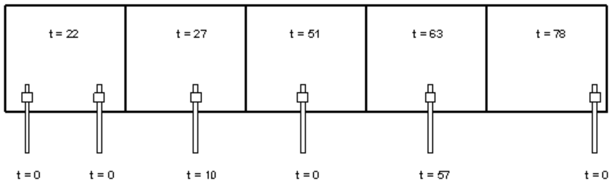


Figure 3 – Terminal Example: Repair Sequencing

In the baseline scenario the total repair time would equal 78 days for the wharf and 57 days for the crane because it is assumed that workers would be making repairs on the entire wharf from day 1. This scenario is actually used for the baseline runs in the overall resilience calculations because it is not unreasonable to assume that workers would repair more than one berth in a terminal at a time. On the other hand, it would be extremely conservative to assume that the workers would work consecutively on only one berth or crane at a time. In that case, the repair time would increase from 78 days to 22+27+51+63+78 = 241 days for the wharf and 57+10 = 67 days for the cranes.

3. APPLICATION OF RESILIENCE FRAMEWORK TO MITIGATION OPTIONS

The repair sequencing mitigation option described in the previous section is a simplistic example of a mitigation option that can be applied to the resilience framework discussed in this study to compare the resilience of a seaport for repairs done in sequence vs. in parallel.

3.1. Hypothetical Port

Concerns about the release of proprietary data prevented the authors from using the risk and resilience framework on an existing west coast port. Instead, a hypothetical port was created to test the framework. The hypothetical port (Figure 4), which is "located" on the coast of Santa Cruz, California, consists of one terminal:

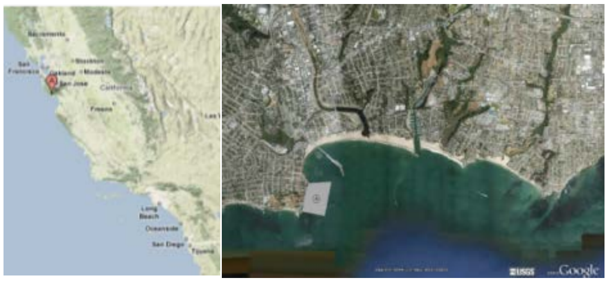


Figure 4 - Location of the hypothetical seaport

The port itself was configured to consist of components and conditions found in modern day ports that are vulnerable to earthquakes. The terminal has four berth sections, each 183 m (600 ft) in length, and is modeled as a seismically vulnerable 1960's style wharf that is commonly used in actual ports today. This style wharf supports a 46 cm thick reinforced concrete deck on prestressed square vertical and battered reinforced concrete piles. (Figure 5) The soil profile in which the terminal is built is assumed to consist of 18.3 m of a hydraulically placed loose sand (G_{max} = 80 MPa and ϕ' = 34°), or a liquefiable soil that is underlain by a 2.6 m layer of dense sand, and a bottom layer of stiff-to-hard clay. Additional details about the hypothetical port can be found in Shafieezadeh and Ivey Burden (2014).

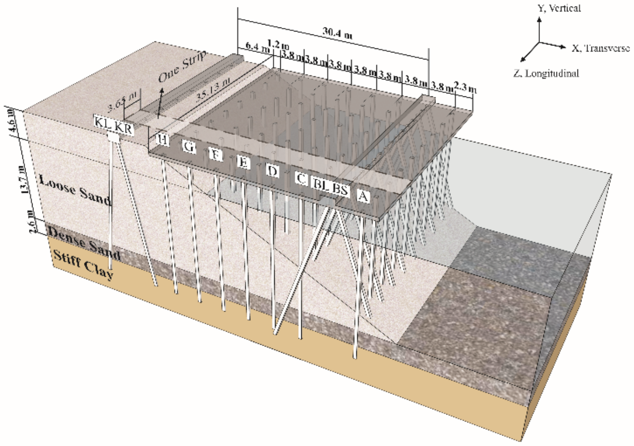


Figure 5 - Transverse view of the wharf configuration and the landside crane rail.

The terminal also contains five Heritage Jumbo Cranes (LD50) that are used for the loading/unloading of ships within the hypothetical port. LD50 cranes are typical of the dated jumbo cranes that are widely used in US seaports today. The terminal length and corresponding number of cranes at the terminal was chosen for the hypothetical port to be consistent with the variety of terminal lengths and corresponding crane numbers typically found in US ports ((Schleiffarth 2008), unpublished data).

3.2. Scenario Earthquake

The scenario earthquake used to calculate resilience in this study corresponds to a large seismic event with magnitude (M) of 7.85 from the North San Andreas Fault. This earthquake was chosen from an earthquake catalogue of all known possible rupture sites within a 200 km radius of the hypothetical port. Since the hypothetical port is located at a known latitude and longitude on the West Coast of California, the earthquake catalogue is compiled using the OpenSHA program: IM_EventSetCalc version 3.0 (Field, Jordan et al. 2009). This program records all earthquake ruptures from the Uniform California Earthquake Rupture Forecast, Version 2 (WGCEP 2008) within 200 km of the terminal site, including background seismicity. In order to capture the uncertainties involved in various modules of the resilience analysis, 1000 samples of the M 7.85 ground motion intensity were generated using ground motion prediction equations for the scenario earthquake. For each of the samples, the downtime of the wharves and cranes in the terminal were probabilistically realized.

3.3. Ship arrival Schedule and Shipping Data

The stochastic modeling of the service demands (*SD*) from the risk and resilience framework requires input to model both the ships that arrive to the hypothetical port and the loads carried by each of these ships. This study uses stochastic models calculated from actual data from current West Coast ports. Ship arrivals are correlated as a non-homogenous Poisson process with frequency determined from terminal lengths using ship arrival and departure logs from the Port of Los Angeles (POLA) and the Port of Long Beach (POLB) during the months of March – August

2008 (Marine Exchange of Southern California 2008).

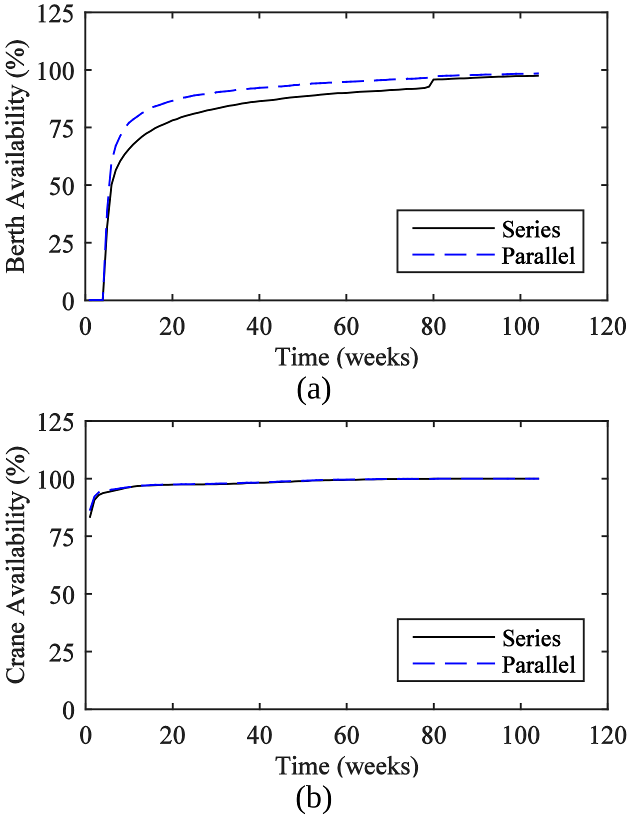
The shipping data to estimate the amount of cargo on each ship was calculated in the form of total twenty-foot equivalent units of cargo (TEUs) loaded and unloaded. The data logs from the Marine Exchange of Southern California (MXSOCAL) do not include information on the total TEUs loaded and unloaded from each ship. They do however keep monthly totals of what was loaded and unloaded at each terminal. These values were compared with the TEU capacities of the ships known to have been serviced at specific terminals in POLA and POLB to create a ratio of TEUs loaded/unloaded to TEU capacity. This ratio was then applied to the TEU capacities of the ships within the ship arrival schedule of the hypothetical port to estimate the total TEUs loaded and unloaded at the hypothetical port.

3.4. Application of Risk and Resilience Framework

The overall performance of an infrastructure system can be measured using any one of a number of metrics that quantify the amount of services provided by a system, or by describing the states of the systems that are required to provide the aforementioned services. For a seaport, the number of berthed ships, the delay time (time in between ship arrival and actual docking), the number of displaced ships (the number of ships in an arrival stream that choose to go to another port due to excessive delay times), and the number of TEUs handled are all metrics that quantify a seaports services. Availability of berths and cranes at a terminal describe the states of the seaport system that are required to provide services. The resilience of each of these system performance metrics was calculated for the M 7.85 scenario earthquake in the hypothetical port assuming parallel and series repair sequencing.

3.4.1. Berth and Crane Availability

The mean performance of the seaport for 1000 realizations of the M 7.85 seismic events in terms of crane and berth availability is shown in Figure 6:



(a)

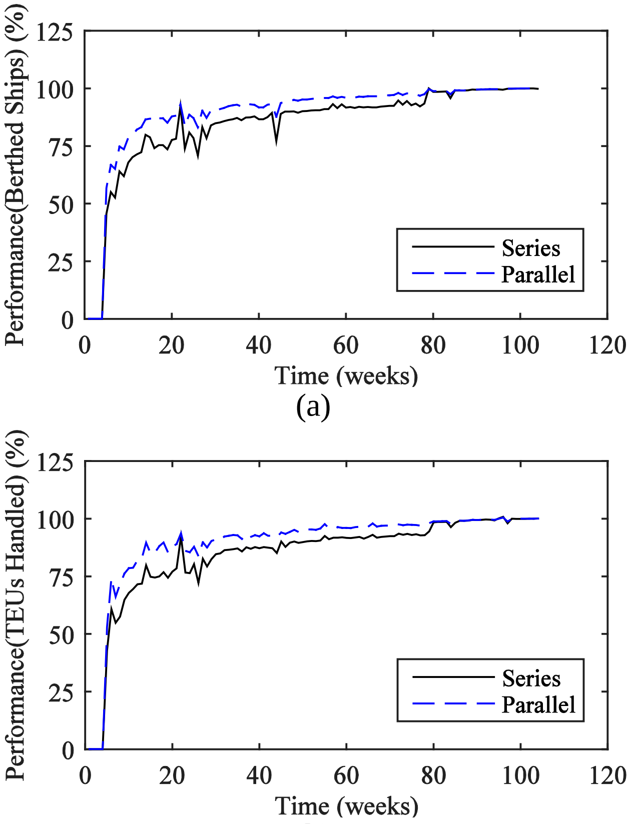
(b)

Figure 6 - Mean performance of terminal in terms of (a) berth availability and (b) crane availability

As expected, in terms of berth availability, less of the berth is available for the series repair sequence than for the parallel repair sequence. Since a longer overall downtime period would be expected for series repair, this result makes sense. The availability for the cranes, however, is nearly identical for both series and parallel repair sequencing. This result can be attributed to the likelihood that there were very few long-term (> 1 week) crane repair times associated with any of the 1000 M 7.85 scenarios. Major damage (i.e. complete collapse or significant structural damage) to LD50 cranes usually only occurs in a very small number of very large magnitude scenarios, and a sample size on the order of 10,000 – 100,000 scenarios would have to be completed to capture this difference in crane availability.

3.4.2. Quantification of Seaport Service Performance Metrics

The mean performance of the seaport for 1000 realizations of the M 7.85 scenario in terms of quantifiable service performance metrics is shown in Figure 7:



(a)

(b)

Figure 7 - Mean Performance of terminal in terms of (a) number of berthed ships, (b) TEUs Handled

Again, the overall performance of the parallel repair sequencing is better than for series sequencing as seen in the number of berthed ships at any given time at the terminal (a), and the number of TEUs handled (b). The series sequencing, however, did not appear to have any effect on the number of ships that had to be displaced from the port itself. Each “run” of the risk and resilience framework (i.e. 1000 earthquake scenarios in series and 1000 earthquake scenarios in parallel) has the same ship arrival schedule applied to the port. For the 1000 earthquake scenarios, the lowered availability of berths within the series run was never so low that additional ships were displaced above the number displaced in the parallel run. However, under a different earthquake scenario, or a different ship arrival schedule, this result could have been different.

3.4.3. Probability of Exceedance Curves for Resilience

Since resilience is time-dependent, exceedance probabilities are presented in the form of contours in Figure 8. It is seen that the isolines depicting the resilience with certain levels of exceedance probabilities are monotonically increasing with time. For the control times after the time of the minimum performance, the resilience increases and approaches one as the control time increases.

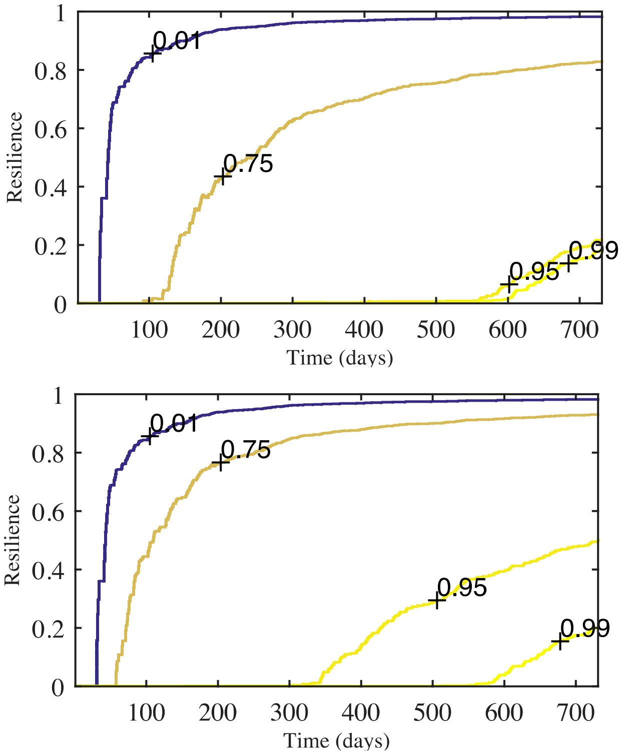


Figure 8 - Probability of exceedance for resilience in terms for (a) series and (b) parallel repair sequencing

As expected, the terminal is more resilience under parallel sequencing as opposed to series sequencing. This is apparent since the respective isolines for 75, 95, and 99% probability of exceedance correspond to higher resilience values and lower recovery times for parallel (bottom) versus series (top) repair. Also of interest is the fact that the 95% probability of exceedance isoline is much closer to the 99% isoline in series repair than in parallel repair. This indicates that for those earthquake scenarios with very rare, highly damaging effects, that recovery time would take significantly longer with series repair sequencing as opposed to parallel repair sequencing. For instance, for a resilience value of 0.2, there is a difference of approximately 330 days (almost 1 year) between the 95% and 99% exceedance curves for parallel repair sequencing, versus a difference of approximately 40 days for series repair sequencing.

4. CONCLUSIONS

The use of the risk and resilience framework should prove to be a very useful tool for port stakeholders in the quantitative evaluation of mitigation techniques within a seaport. The methodology presented here is a vast improvement over the arbitrary return periods for specific port components that comprise the current performance standards used by port stakeholders.

Further study in this area will include a full investigation of possible mitigation options as pertinent to the current case study. In this investigation, a range of mitigation option will be studied and compared, both physical improvements to the port components, as well as a number of operational mitigation options. Physical improvements will include upgrade of the wharves and cranes, and the installation of prefabricated vertical drains to prevent liquefaction in the backfill. Operational mitigation options will include, the implementation of a repair incentive to reduce repair time post-earthquake, varying mobilization times for port repair, varying repair sequencing (as studied in this paper), and implementing a force majeure policy for the entire port post-earthquake.

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