SEISMIC RISK MANAGEMENT FOR SEAPORTS

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ABSTRACT :

Earthquake damage to seaports can cause economic losses due to repair costs for individual structures and, more importantly, due to extended downtimes and associated disruption of shipping operations, which can have regional, national, and international consequences. However, no systematic and practical method for assessing and managing these risks currently exists. To fill this gap, the United States Network for Earthquake Engineering Simulation (NEES) is funding a Grand Challenge research project that is currently beginning its fourth year. This paper summarizes the current status and initial findings from this research.

KEYWORDS: seaports, seismic risk management, port system, wharves, cranes, liquefaction

1. INTRODUCTION

Earthquakes pose a significant threat to many large U.S. seaports (Fig. 1) that serve as crucial gateways for international trade. Data from the U.S. Bureau of Transportation Statistics show that forty percent of the value of U.S. international trade passes through these ports, which is more than any other mode. Maritime trade value has more than doubled since 1990 (from $434 billion in 1990 to nearly $900 billion in 2007), and will undoubtedly continue to increase given the expected growth in trade with Asia and Pacific-Rim nations.

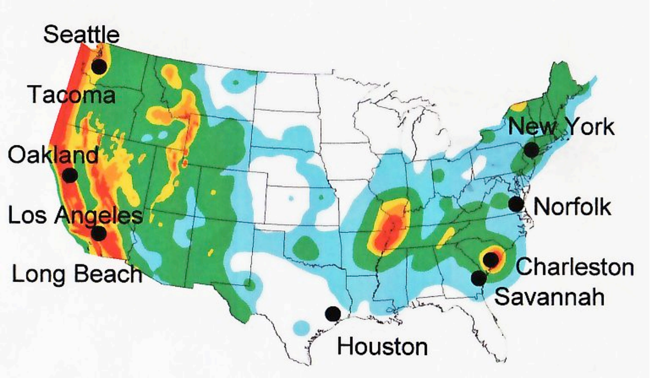


Figure 1. Seismic Risks to U.S. Seaports (PGA with 2% probability of exceedance in 50 years)

Current engineering practice for seismic risk reduction for port facilities is typically based on design or retrofit criteria for individual physical components (e.g., wharf structures) expressed as prescribed levels of force and/or displacement. However, the resilience and continuity of shipping operations at a port after an earthquake depends not only on the performance of these individual components, but on their locations, redundancy, and physical and operational connectivity as well -- that is, on the port system as a whole.

Werner and Taylor (2004) carried out an analysis of the seismic risks to the entire system of wharf structures at the Port of Oakland, in order to assess the effectiveness of various seismic upgrade options in reducing potential economic losses from interruption of shipping operations. However, this is the only known analysis of port-system seismic risks at U.S. seaports, and system seismic risk issues are invariably not considered in U.S. earthquake engineering practice for seaports. This is due in large part to the lack of a practical and technically sound methodology that accounts for the unique physical infrastructure at ports along with their complex operational, planning, and decision-making processes.

To begin to fill this important gap, a five-year Grand Challenge (GC) research project is being performed under the sponsorship of the U.S. National Earthquake Engineering Simulation (NEES) program. This project, which is now starting its fourth year, is addressing the following issues: (a) *earthquake engineering* -- analytical and experimental investigations of soil improvement methods, soil-structure interaction, performance of pile-deck connections, container crane response, and wharf and crane fragility modeling; (b) *port system operations* -- development of models to optimize allocation of incoming ships among available berths, when some of the port's berths have been damaged; and (c) *risk-reduction decision making* -- investigation of stakeholder decision-making processes, including their perceptions of the importance of seismic risks, acceptable levels of these risks, and risk-reduction decision-making processes. Each of these tasks will be important by itself for improving earthquake engineering and post-earthquake operational practices at seaports. In addition, the tasks will collectively be important elements of a port-system risk assessment framework that is being developed under this project to enable seaport decision makers to more effectively manage seismic risks and plan for business continuity. This paper summarizes the current status and future direction of these tasks.

PORT SYSTEM RISK ASSESSMENT FRAMEWORK

The system risk assessment framework being developed under this NEES-GC project is shown in Figure 2. A key feature of this approach is the concept of "acceptable risk". This is based on the premise that, no matter what level of seismic design or upgrade is implemented, there is always some residual risk of earthquake damage (i.e., it is not possible to achieve "zero seismic risk".) An acceptable seismic risk is defined as that point at which the residual risks from earthquakes remain "acceptable", i.e., beyond which the additional cost needed to further reduce these risks is deemed by decision makers to be excessive and unnecessary.

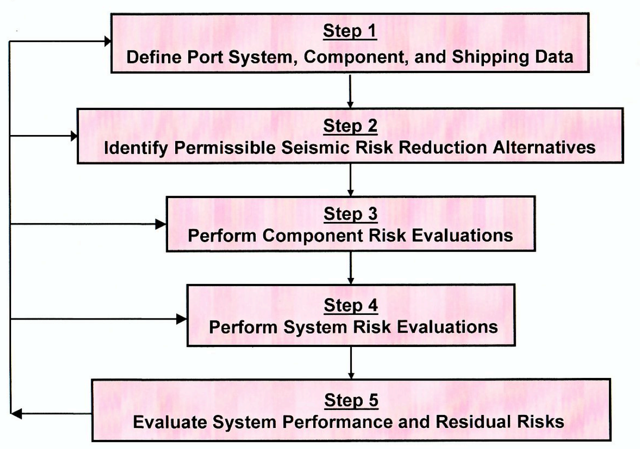


Figure 2. Port System Risk Assessment Framework (Werner and Taylor, 2004)

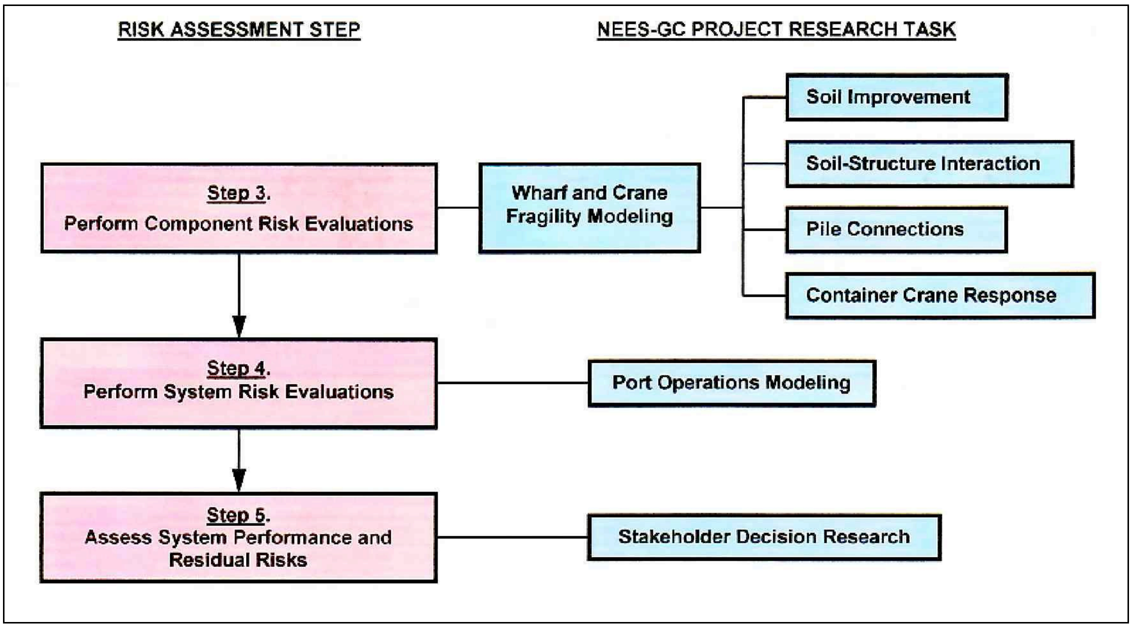


Figure 3. Contributions of Project Research Tasks to Risk Assessment Framework Steps

This risk assessment framework will use geoscience, earthquake engineering, operations research, and risk analysis technologies to evaluate various seismic risk reduction options from a financial risk standpoint. For each risk-reduction option, the following financial costs and losses will be estimated: (a) initial design and construction costs; (b) costs for repair of earthquake damage; and (c) financial losses to the port due to interruption of shipping operations during repair of this damage. To obtain these risk-based results, the approach will synthesize models of: (a) earthquake occurrences over time that represent the surrounding region's seismicity and tectonics; (b) site-specific ground shaking and liquefaction hazards; (c) vulnerabilities of the wharf and crane structures at each berth to these hazards; and (d) the allocation of available (undamaged) wharf structure segments and cranes to incoming ships in order to minimize cargo loading and unloading times. The end results of this approach will usually be probabilistic financial risk information (in which uncertainties in earthquake occurrence, seismic hazard estimation, and structure damage estimation are considered) although deterministic results will also be possible. When assessing various candidate risk reduction options, port officials and stakeholders will be able to consider these financial risks in tandem with any administrative, regulatory, legal and other risks that could be relevant to decision-making. This will provide them with a more rational basis for informed selection of a preferred risk reduction option than has been available in the past.

The remainder of this paper summarizes the various NEES-GC project research tasks listed earlier, along with plans for application of the risk assessment framework to a hypothetical port system. Figure 3 illustrates the role of each of these tasks in the risk assessment framework.

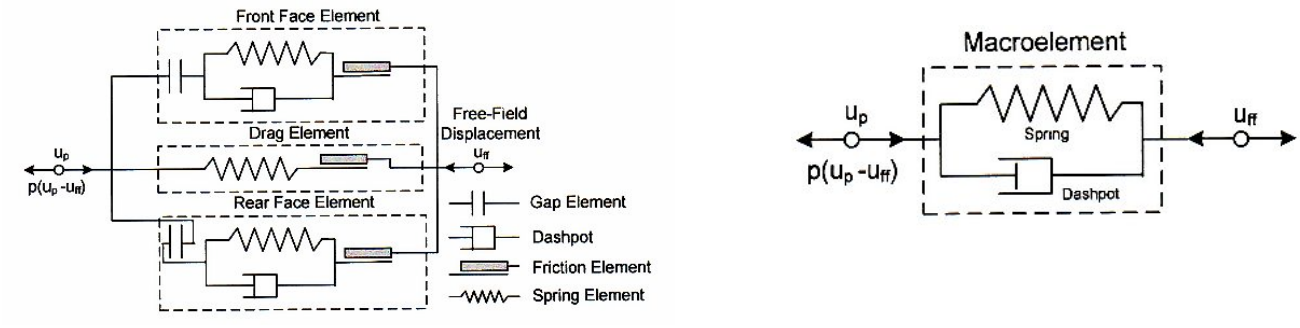
SOIL IMPROVEMENT RESEARCH

This research is investigating two new technologies -- prefabricated vertical drains (PVDs) and colloidal silica gel (CSG) -- that are well suited to remediating liquefiable hydraulic fills at seaports. PVDs for liquefaction remediation are corrugated, perforated, plastic pipe that are encased in a geotextile fabric and can range from 75 to 150 mm in diameter. These relatively large diameters provide the large flow capacity required to drain the soil quickly and rapidly dissipate excess pore pressures. Passive site stabilization using CSG involves slow injection of stabilizing materials at the up-gradient edge of a site and delivery of the stabilizer for the target location using natural or augmented groundwater flow. Upon delivery to the target location, the stabilizer starts to gel or set rapidly at a predetermined time to bind the soil particles and stabilize the soil mass.

The effectiveness of these methods in mitigating liquefaction is being investigated through model-scale centrifuge tests at the NEES/University of California at Davis facilities, full-scale field tests using the NEES-University of Texas large-scale mobile three-dimensional shaker (T-REX), and numerical analysis. Centrifuge tests of untreated saturated sands alongside the same sands treated with PVDs indicated that the drains effectively reduced pore pressures at low shaking levels whereas, at high shaking levels, high pore pressure ratios remained but soil movements were reduced. Reasons for this improved site performance despite high pore pressure ratios are being studied. Centrifuge tests of untreated saturated sands alongside the same sands treated with CSG showed that liquefaction occurred within the untreated sands but not within the treated sands and, in addition, large displacements within the untreated sands were seen to be much lower within the CSG-treated sands. Numerical analyses performed to date have focused on development of preliminary numerical models of the first centrifuge test with PV drains. Analyses using these models appear to capture key aspects of observed response including stabilization of the loose, liquefaction-prone sands by the PV drains and consistent mechanisms of failure within the unimproved soil. Model refinements and complete comparisons of computed and measured response are under development. Full scale testing of these liquefaction mitigation methods at a site in South Carolina was recently performed, and the results of these tests are now being evaluated. Rix et al. (2007) provides further details on the PVD and CSG methods and the above test procedures and results.

SOIL-STRUCTURE INTERACTION RESEARCH

The use of dynamic nonlinear finite-element/finite-difference (FE/FD) methods to estimate soil-structure interaction (SSI) effects for wharf structures in liquefiable soils is time consuming and complex. To reduce this effort, this research is developing simplified nonlinear Winkler-type mechanical models named macroelements. Two types of macroelements -- a multi-component macroelement (Fig. 4a) and a Bouc-Wen macroelement (Fig. 4b) -- are being developed from numerical FE/FD simulations and experimental (resonant column and centrifuge) test results. The multi-component macroelement contains a front and rear-face (FRF) component and a drag component. The FRF component models the soil resistance on the front and rear faces of the pile through: (a) a gap element to account for possible separation of the pile and the soil; (b) a dashpot to model radiation damping; (c) a spring element to model low-strain soil stiffness; and (d) a friction element, to account for plastic soil deformation. The drag component represents the drag force exerted by the flow of soil around the pile. The Bouc-Wen macroelement uses constitutive equations to model the global SSI behavior, and is derived by stepwise curve fitting with parameters that are linked to measurable physical parameters such as soil properties and foundation geometry. For both types of macroelements, pore pressure effects on the lateral capacity of the pile is modeled by either (a) computation of excess pore-pressure time histories as part of a free-field effective-stress site response analysis; and (b) computation of excess pore pressures within the macroelement while conducting total-stress analyses for free-field conditions (Varun and Assimaki, 2008).

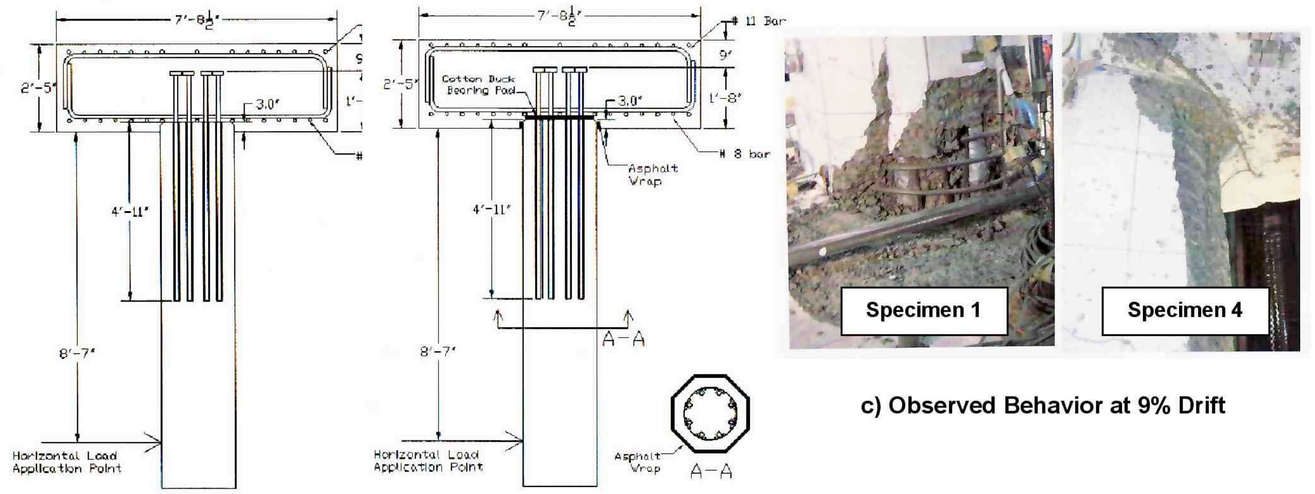


a) Multi-Component **b) Bouc-Wen**

Figure 4. Soil-Structure Interaction Macroelements (Varun and Assimaki, 2008)

PILE-DECK CONNECTION RESEARCH

Experience has shown that connections of piles to wharf decks often suffer severe earthquake damage and rapid deterioration with increasing numbers of excitation cycles. To address this problem, the objectives of this research are to: (a) investigate the seismic response of alternative connection details for vertical concrete piles; (b) use results of these investigations to develop improved seismic design procedures for such connections; (c) identify pile connection damage states (ranging from initial damage to irreparable damage), and corresponding limit-state values of engineering parameters that will be used in the wharf fragility modeling procedure summarized later in this paper to define the onset of each damage state; and (d) establish pile-connection model parameters for use in the development of wharf structure fragility curves. To meet this objective, a limited number of full-scale pile connection tests have been conducted at the University of Washington (UW), and two subsequent full-scale wharf section tests will be carried out at NEES facilities at the University of Illinois (UI). Numerical simulations of these test results will also be performed.



c) Observed Behavior at 9% Drift

a) Specimen 1 **b) Specimen 4**

Figure 5. Example Results from UW Pile Connection Tests (Lehman et al., 2008)

At UW, the following four connection specimens were tested: (1) a connection with eight #10 headed bars; (2) same as Connection 1, except that dowels were unbonded for 187 mm in both the pile and the deck; (3) same as Connection 2, except that a cotton duck bearing pad was added to eliminate edge loading and reduce spalling; and (4) same as Connection 3, except that an asphaltic wrap was added at the embedded area of the pile to reduce wrenching behavior. Results of these four tests showed that significant improvement in the seismic performance of pile-deck connections is possible with modest changes in design (Fig. 5). These results, along with the UW test setup and specimens are further described by Lehman et al. (2008). Further study of these results is being used to identify other design improvements and to plan the tests at the NEES-UI facility.

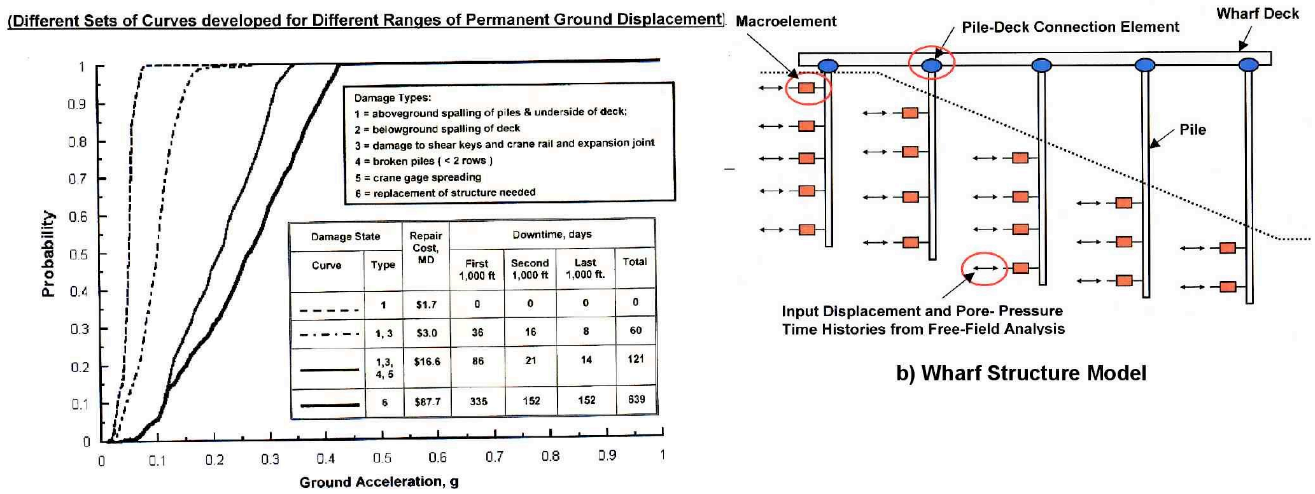
CONTAINER CRANE RESEARCH

Container cranes are essential to shipping operations. However, they are unique and large structures with non-redundant structural systems, and past earthquakes have shown that they are vulnerable to damage from only moderate ground motions and relative movements of non-connected landside and waterside crane rails. Furthermore, replacement of irreparably damaged cranes can take more than a year. Despite these factors, cranes are usually designed as rigid frames with little or no seismic detailing, and their seismic response is not well understood. Furthermore, recent generations of cranes are typically much larger than earlier cranes and, with this increase in mass and size, comes the potential for even greater seismic vulnerability.

This research is addressing these issues by using analytical studies and shake-table tests of crane structures to: (a) develop performance-based seismic design guidelines; and (b) assess the effectiveness of protective systems and other retrofit strategies for reducing earthquake damage. Analytical studies conducted thus far have shown that: (a) modern container cranes can exhibit significant damage at only moderate drift levels; (b) allowing leg uplift can act as a form of isolation that reduces cyclic force demands; (c) inappropriate modeling of boundary conditions (i.e., conditions leading to horizontal displacement of an uplifted leg) can underestimate interface force demands; and (d) prediction of seismic performance of cranes relies on the interaction of model nonlinearities and boundary effects (Kosbab, 2008). In addition to these analytical studies, two phases of shake table tests are being conducted at NEES facilities at the State University of New York at Buffalo. Phase 1 testing of a 1:20 scale container crane has recently been completed, and has focused on study of crane elastic-response and uplift/rocking characteristics. Phase 2, which will be conducted during August 2009, will involve testing of a 1:8 scale structure and will also focus on inelastic response characteristics (Jacobs et al., 2008).

FRAGILITY MODELING RESEARCH

Step 3 of the risk assessment framework evaluates the seismic performance of the port's wharf and crane structures. Wharf and crane fragility models are essential to this step. This section summarizes the procedure for developing wharf fragility models. Similar procedures will be used to develop fragility models for cranes.



Damage Types:
1 = aboveground spalling of piles & underside of deck;
2 = belowground spalling of deck
3 = damage to shear keys and crane rail and expansion joint
4 = broken piles (< 2 rows)
5 = crane gage spreading
6 = replacement of structure needed

Damage State		Repair Cost, MD	Downtime, days			
Curve	Type		First 1,000 ft	Second 1,000 ft	Last 1,000 ft.	Total
- - - - -	1	$1.7	0	0	0	0
- · - · -	1, 3	$3.0	36	16	8	60
———	1,3, 4, 5	$16.6	86	21	14	121
━━━	6	$87.7	335	152	152	639

a) Form of Fragility Curve

b) Wharf Structure Model

Figure 6. Wharf Structure Fragility Modeling

Wharf-structure fragility models define the probability of occurrence of various structure-wide damage states (i.e., extents, types, and locations of structural damage) as a function of the seismic hazards (ground shaking and permanent ground displacement) to which the structure is subjected. Furthermore, because the risk assessment framework focuses on estimation of losses due to interruption of shipping operations, each damage state estimated by the fragility curves must be associated with costs and times to repair the damage (Fig. 6a).

Werner and Rix (2008) describe the methodology that is being developed to obtain wharf fragility models. It contains the following steps: (a) establish a suite of firm-site ground motion time histories that represent the regional seismicity and tectonics and encompass a range of magnitude and distance combinations that could cause various levels of structure damage; (b) estimate site-specific free-field seismic hazards by applying each time history from Step (a) to the base of a finite element model of the soil embankment (with no structure); (c) construct a three-dimensional nonlinear model of the wharf structure with SSI macroelements distributed along the lengths of the piles (Fig. 6b); (d) use this model to obtain engineering demand parameters (EDPs) within the various structural elements due to the seismic hazards from Step (b); (e) compare these EDPs to experience-based and experimentally-based limit-state values of these parameters that represent the onset of each possible type of structural-element damage, in order to develop the overall wharf structure damage state; and (f) use experience-based models for repair of each damage type to estimate costs and times to repair the structural damage identified in Step (d). Then, when Steps (b) to (f) are completed for each firm-site ground motion history from Step (a), their results are aggregated to develop fragility curves of the form shown in Figure 6a.

It remains to assess whether fragility curves should be developed for the coupled wharf-crane structures rather than for the uncoupled structures. In addition, simplifications of the methodology are being studied that would reduce computer times needed to develop the fragility curves for a given wharf structure configuration.

PORT OPERATIONS RESEARCH

The end result of Step 3 of the risk assessment framework is a series of port-wide “system states” that define the ship-handling capacity of each berth throughout the port, in terms of the length of each wharf structure that is available to accommodate a container ship (where the wharf length needed to accommodate a ship will be about 1,000 ft. or more) and the functionality of the various cranes at that berth. These system states will vary over time after an earthquake, because of differences in the damage to the various wharf and crane structures throughout the port, and the rates of repair of these damages that are estimated by the repair models used in the fragility curves. To reflect this, Step 3 develops these system states at several post-earthquake times.

Step 4 of the framework estimates the ability of the overall port system to accommodate its shipping demands at these various post-earthquake times, and the potential for interruption of shipping throughputs and associated economic losses if the port’s ship-handling capacity falls below shipping demands due to earthquake damage. These estimates will be based on an algorithm that is being developed to minimize port-wide ship loading and unloading times at a given post-earthquake time. This algorithm features a sub-optimal allocation of incoming ships to various available berths throughout the port system, as well as the scheduling of crane deployments within a berth or between berths. It accounts for: (a) the rate of ship arrivals and the number of containers to be loaded or unloaded onto/from each ship; (b) the rate of container loading/unloading (which depend on crane type and regional labor practices); (c) each berth’s ship handling capacity, which will depend on the available length of the wharf structures and the number of available cranes; (d) possible blockage of crane movement if a crane located between other cranes is damaged and inoperable; and (e) possible increases in shipping demands and port-wide shipping capacities over time. Special search techniques are used to minimize computer times needed to carry out this simultaneous berth and crane scheduling process (Ak and Erera, 2007).

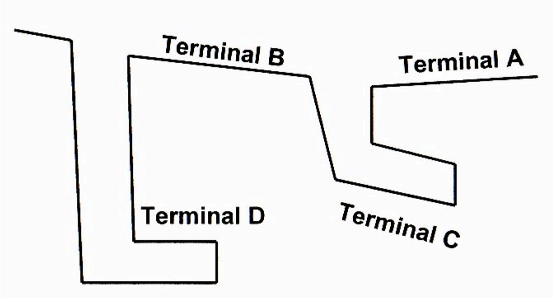
STAKEHOLDER DECISION-MAKING RESEARCH

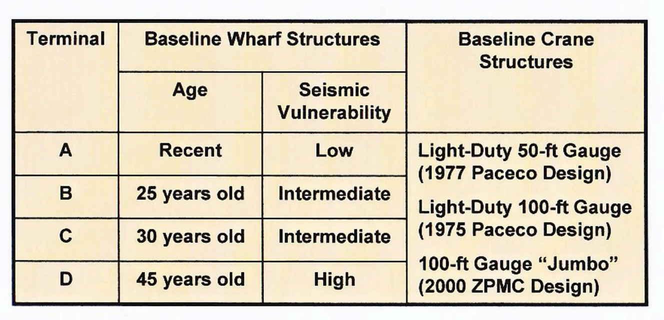
Step 5 of the risk assessment framework involves stakeholder assessment of system performance and residual risks estimated in Steps 3 and 4 for each seismic risk reduction option, and their selection of a preferred option to implement. Research under this project is investigating, how such decisions are made, who makes the decisions, the various factors (i.e., socioeconomic, regulatory, legal, political, institutional, etc.) that may be considered in this decision-making process, and the relative importance of these factors. The research includes structured interviewing of stakeholders at various major seaports along the west coast of the U.S. that addresses such questions as: (a) where do earthquakes rank in perceived importance relative to other risks; (b) what studies have been conducted to characterize seismic risks; (c) what determines an acceptable level of seismic risk; (d) what types of risk mitigation actions are planned; (e) what are the main information needs and planning gaps to be overcome in order to improve the decision making process; and (f) who makes decisions regarding seismic risk mitigation. Initial findings from this investigation are now under development.

DEMONSTRATION APPLICATION

The risk analysis framework will be applied to a hypothetical port located along the central California coast, in order to demonstrate how results from the framework can be used to guide seismic-risk-reduction decision making. The port will contain four berths whose wharf structures are representative of west coast port construction and encompass a range of seismic vulnerability levels. Cranes at the berths will range from light duty structures to the newest jumbo crane configurations. The system's time-dependent shipping/cargo-handling demands will be drawn from shipping data compiled by the Marine Exchange of Southern California.

The framework will estimate seismic risks to the baseline port system (Fig. 7) and also to the system when the following risk reduction options are in place: (a) PVD and CSG soil improvement at selected berths; (b) modified pile connection details that are being investigated under this project; (c) crane retrofit options that will be studied under this project; (d) alternative repair strategies, including "bonus-incentive" strategies of the type used to speed up repairs of severely damaged bridges after the 1994 Northridge Earthquake; and (e) alternative strategies for deploying incoming ships to available berths, including "force majeure" provisions wherein an incoming ship from any shipper can be deployed to any open berth. For each option, implementation costs and reductions in losses due to interruption of shipping operations will be estimated.





Terminal	Baseline Wharf Structures		Baseline Crane Structures
	Age	Seismic Vulnerability	
A	Recent	Low	Light-Duty 50-ft Gauge (1977 Paceco Design) Light-Duty 100-ft Gauge (1975 Paceco Design) 100-ft Gauge "Jumbo" (2000 ZPMC Design)
B	25 years old	Intermediate	
C	30 years old	Intermediate	
D	45 years old	High	

Figure 7. Hypothetical Port System (Baseline Configuration)

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant Nos. CMS-0530478 and CMS-0402490.

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