RISK ANALYSIS OF PORT FACILITIES

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SUMMARY

During recent earthquakes, seaports have demonstrated that they can be highly vulnerable to seismic motion and associated ground failures. Poor seismic performance of seaports has resulted in billions of dollars of losses. Seaports are critical nodes in regional transportation networks and have an important impact on the economy of the area. Thus, the need for risk analysis of port facilities is clear. In this paper a general *port seismic risk model* is developed that provides information on potential direct and indirect economic losses from potential failure of facilities and operations at a port. The model is composed of two independent sub-models: the *vulnerability model* and the *port operations model*. The vulnerability model combines seismic hazard analysis with fragility analysis to the individual port components to produce a set of post-event damage states for port components, corresponding repair times and direct repair costs. The main component of the port operations model is a discrete-event simulation that estimates ship waiting times and the number of diverted ships. The operational output data from this model are used to estimate the expected loss of revenue due to downtime (direct loss). The results on direct repair costs and operational losses provide decision-makers with tools that can be used in the development of seismic risk mitigation strategies. Users may adjust the post-event input data set using expert opinion to further take advantage of the model's power and flexibility. For example, decision-makers can compare different reconstruction and repair plans. The intent of the methodology is to help decision-makers take the necessary steps to prevent disasters such as the one experienced in the Port of Kobe in the1995 Kobe, Japan earthquake.

INTRODUCTION

Seaports are the cornerstones of international trade. In the United States, for example, in 1997 the *US Bureau of the Census* valued waterborne international trade at 31.0% of US trade. [Rust, E. and King, P., 1997] These facilities are so vital in fact that, for many regions, a reduction in capacity in the port system carries with it grave economic consequences. According to the 1997 *Economic Benefit Study of California Ports and Harbors*, the closing of even one port or harbor out of California's system of over forty ports and harbors "would overload other ports and harbors and would significantly diminish the Pacific Coast's capacity to move goods and make productive use of ocean resources" [Rust and King, 1997].

Limited redundancy of port systems makes them critical nodes in the transportation networks that connect the coast to points inland. Unlike an intersection between roadways, a port is a major infrastructure investment. The special needs of each mode of transportation that use a port must be accommodated. Seaport activities are therefore often consolidated in one large port area. If that infrastructure becomes damaged and loses capacity, cargo may not simply use an alternate route (as would be the case in the event the roadway intersection were to become damaged). In the case of California, cargo would likely need to be re-routed not only out of the region, but possibly out of the state thereby creating a new set logistical problems for those who are managing the shipment of goods and hurting the local economy of the region in which the port is located.

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Natural disasters can potentially cripple a seaport. Damage to port structures that reduces their functionality will limit the capacity of a port which will result not only in monetary losses attributed to replacement cost of the structures, but will also result in losses due to down-time. Since estuaries and river deltas are often ideal sites for a port (easy connection to inland waterways), many major ports are located in such places. Additionally, many major ports use reclaimed land for seaport facilities. The combination of all these factors makes seaports extremely susceptible to liquefaction and landslides due to seismic events.

In 1999, the Hyogo Prefectural Government reported that the Port of Kobe, which suffered near complete devastation as a result of the 1994 Hanshin-Awaji Earthquake, had only recovered 80.4% of its monthly amount of exports and imports as compared to before the earthquake. [Hyogo Prefectural Government, 1999] This permanent loss of business occurred even though the port had recovered majority of its cargo-handling capacity within one year of the earthquake. The effects of this disaster on the Port of Kobe demonstrate the importance of minimising the risk of damage at major port facilities.

To this end, there is a need for a comprehensive approach for seismic risk assessment of port facilities. Prudent investment decisions on port facilities seismic upgrading and the development of appropriate mitigation strategies can be developed provided the risk of damage and failure of a port is evaluated in a reliable manner. The need for such a systematic approach is also discussed in Werner et al. [1997.]

In this paper, a general framework is presented for seismic risk assessment of port facilities with a particular focus on a methodology for estimating the expected loss of a seaport due to scenario earthquakes. The methodology is divided into two inter-related components: estimating a port's seismic vulnerability, in terms of short-term expected economic loss, and estimating the effects of the damaged port to the regional economy during the recovery period that follows a major earthquake. This paper summarises the short-term economic loss component of the methodology.

The short-term expected loss is evaluated by estimating the repair cost of the damaged port facilities and the loss due to loss of functionality of those facilities. The loss estimation model is composed of a Vulnerability Model and a Port Operations Model. The Vulnerability model estimates the hazard at the port site and the resulting loss from damage to the port structures. The Port Operations Model utilises advanced stochastic simulation techniques to track ship arrivals and departures, volume and types of cargo unloaded and loaded, and revenue flow through the port [e.g., Park and Noh, 1987]. The loss model can be used for pre-earthquake event assessment and mitigation planning, and for post-event disaster response and rehabilitation.

PORT OPERATIONS

"A seaport has been defined as a terminal and an area within which ships are loaded with and/or discharged of cargo and includes the usual places where ships wait for their turn or are ordered or obliged to wait for their turn no matter the distance from that area. Usually it has an interface with other forms of transport and in so doing provides connecting services." [Branch, 1986] Figure 1 shows the main components of port operations.

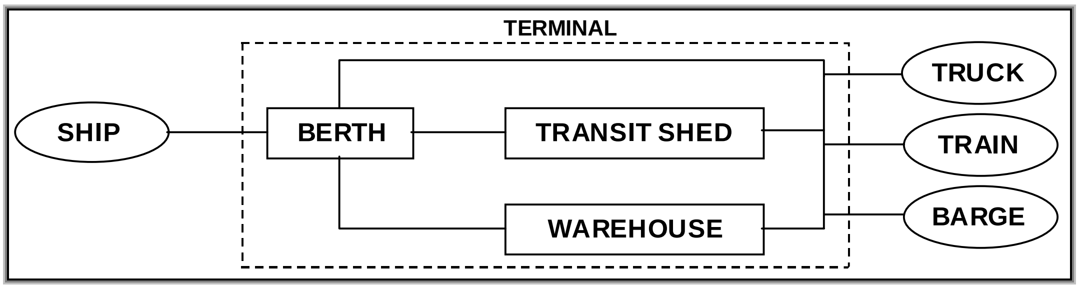

Figure 1: Seaport Operations

Seaports are generally composed of terminals. Each terminal contains a combination of cranes, berths, warehouses, transit sheds, roadways, railways, and administrative buildings. Seaports are nodes at which goods are transferred from one transportation medium to another. These media include, but are not be limited to, ships, trucks, trains, and inland waterway barges.

When a ship arrives to unload cargo, it must first enter a queue in the harbor. Once a desired berth becomes available, the ship may dock. This occurs with the help of tugboats. Cranes help unload the cargo. Modern ports rely heavily on containerised cargo to expedite the loading and unloading process. Not all ships are the same size, and not all berths can accommodate every ship, thus ships are restricted as to which berths they can use. Once off the ship, the cargo is taken to an area referred to as a *transit shed* for temporary storage and sorting. Trucks and trains pick up the cargo from the transit shed directly. *Warehouses* provide a more long-term storage option.

If cargo is loaded onto a train, it leaves the port via rail lines. Barges carry cargo up inland waterways. Trucks use the local highway network to transport goods to their destination. Highway access to the port is therefore imperative. If the transportation network that serves the port experiences a reduction in capacity, it will seriously affect the flow of goods through the port, especially if trucking is the main form of inland transportation.

While the port authority (often a quasi-autonomous government agency as in the case of the Port of Oakland) owns and manages the seaport land, private shipping lines usually operate the terminals. They handle the actual throughput of cargo. Various sources of revenue from the port result from these activities. Among them are cargo-handling fees (per unit of cargo), and cargo storage fees (typically: per unit of cargo per day).

Ports are a throughput for goods. In our model, the operations of the seaport are assumed to be at a steady state under ordinary conditions; i.e. all structures and facilities are operational. A decrease in capacity may not only slow port operations, but the resulting delays may make the port unattractive for existing or potential customers who have the option of using a different port facility (e.g. a seaport elsewhere).

PORT SEISMIC RISK MODEL

The Port Seismic Risk model estimates the short-term expected loss. The model is composed of the *Vulnerability* and *Port Operations Models*. The relationship between these models is shown in Figure 2.

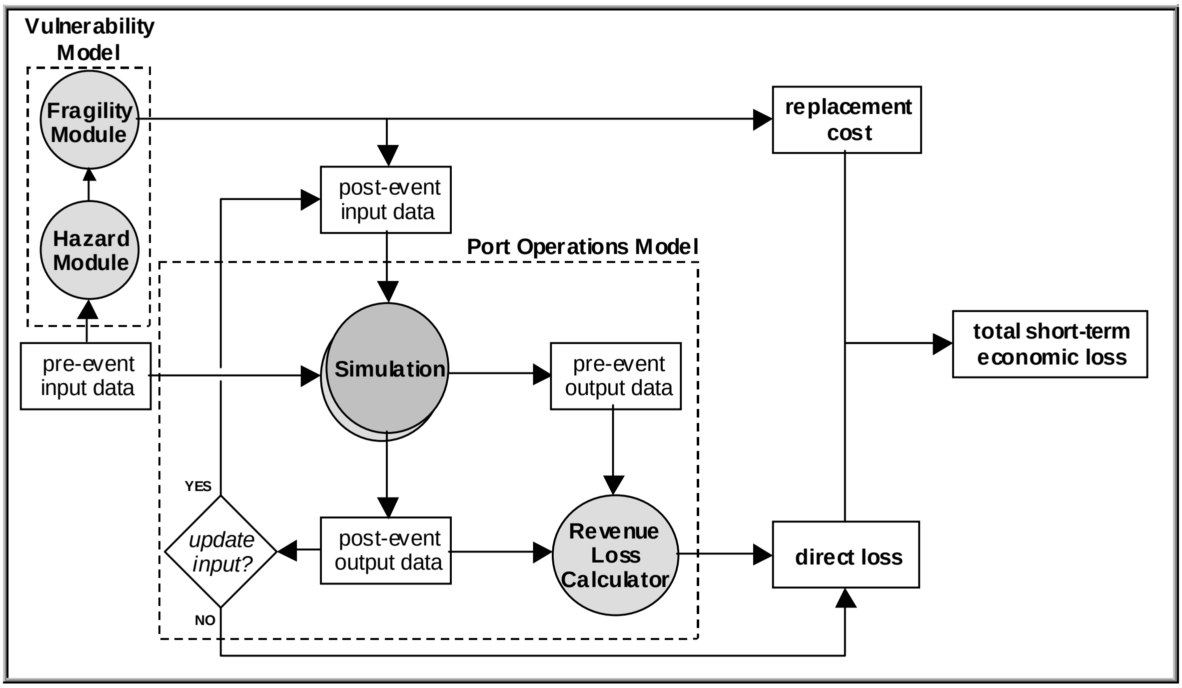

Figure 2: Port Seismic Risk Model

Expected Loss

The *Port Seismic Risk Model* estimates the expected economic loss of a seaport due to a scenario seismic event. The expected overall annual loss is defined as follows:

$$E[L] = E[L_r] + E[L_d] + E[L_i]$$
$$L_r = \text{Replacement Cost}$$
$$L_d = \text{Direct Loss due to down - time} \quad [1]$$
$$L_i = \text{Indirect Loss due to long term economic factors}$$

As mentioned earlier, the *Port Seismic Risk Model* focuses on L_r and L_d. The long term economic loss model, L_i, is currently under development. The expected loss is also given by the annual loss rate calculated as follows:

$$E[L] = \int l\, f_L(l)\, dl = \nu_L = \text{loss rate} \quad [2]$$
$$f_L(l) = \text{probability density function of loss}$$

Vulnerability Model

The *Vulnerability Model* is composed the *Hazard and Fragility Modules.* Figure 3 identifies the inputs and outputs from these modules.

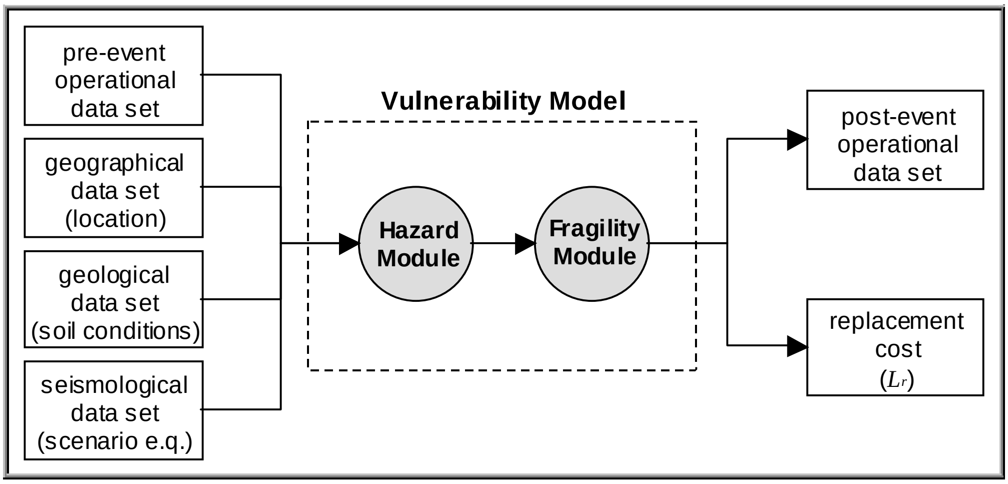

Figure 3: Vulnerability Model

Inputs

The inputs to the *Vulnerability Model* are composed of the following:

- The *pre-event* operational data set.
- The geographical data set.
- The geological data set.
- The seismological data set.

The operational data set contains information describing the physical elements of the port and their attributes. The physical elements are the type and number of facilities (e.g. berths, warehouses, transit sheds). Attributes of each element provide information on the characteristics of each facility such as type of cranes at a particular berth, or the capacity of a warehouse. Operational data such as average number of ships waiting to dock, ship inter-arrival times, ship service times, and revenue sources are also contained in this database. This data set will again be used for the *Port Operations Model.* The "pre-event" qualifier refers to the fact that the information is for the port in its undamaged state.

The geographical data set contains the physical locations of each of the port's facilities. Information describing the soil conditions at the port is stored in the geological database. This information is in the form of maps, soil profiles or borehole data. The seismological data set includes length, depth, location, and type of faults, and magnitudes and frequency of earthquake events.

Hazard Module

The *Hazard Module* focuses on the last three data sets to perform the deterministic seismic hazard analysis on the individual port facilities. The *Hazard Module* can perform probabilistic or deterministic hazard analysis. The probabilistic hazard analysis estimates the annual probability (or annual rate) of exceeding a specified ground motion at the port site. The deterministic hazard analysis estimates the ground motion at the port site for a specified scenario earthquake event. Ground motions are further modified according to the soil conditions at the site of each port facility. Landslide and liquefaction potential and resulting differential ground displacements are also estimated in this module. This paper presents only the results from the deterministic hazard estimation.

Fragility Module

The *Fragility Module* estimates the damage state of each structure or facility at the port, the downtime, and the losses resulting from the damage. The facilities of the port are categorised by structure type (e.g. cranes, berths, and warehouses). A fragility curve, defined as the probability that a facility is in a particular damage state at a specified ground motion or ground deformation level, is developed for each facility type. The module returns two sets of information based on the damage states of facilities. For each facility, the module determines the repair cost and its operational status. The repair cost is defined as the cost to return the facility to its original (pre-earthquake) condition. The operational status is assumed to be binary and a facility is either operational or non-operational. Considerable computational efficiency is gained with this assumption, while still providing reliable results.

The Outputs

The *Hazard* and *Fragility Modules* are combined to produce estimates on the total expected repair cost summed over every facility *i* in every facility type *j*, L_r. For a given damage state and modelling the loss as a random variable, the loss rate is generically represented by the following equation:

$$\nu_{L_r} = E[L_r] = \iiint l \; f_{L|D}(l \mid d)\; f_{D|E}(d \mid E)\; dl\; dd\; dE$$

with $f_{L|D}(l \mid d)$ = p.d.f. of loss given damage d. [3]

and $f_{D|E}(d \mid E)$ = p.d.f of d given event E.

This equation can be expanded to show the components of the seismic hazard analysis:

$$\nu_{L_r} = \int_L \int_D \int_A \int_R \int_M \sum_{j=1}^{N_s} \sum_{i=1}^{N_j} l_i \; f_{L|D_{ij}}(l \mid d_i)\; f_{D_{ij}|A_{ij}}(d_{ij} \mid A_{ij})\; f_{A_{ij}|M,R}(a_{ij} \mid m, r_{ij})$$
$$f_{R_{ij}|M}(r_{ij} \mid m)\; f_m(m)\, \nu_m \; dm\, dr\, da\, dd\, dl \qquad [4]$$

with N_i = *number of structure types, and* N_j = *number of structures of structure type* i.

$f_{D_i|A}(d_i \mid a) = P[$ *structure of type i will have damage d given that the ground motion at its site is a* $]$

$f_{A|M,R}(a \mid m, r)$ = *p.d.f. of ground shaking given an event of magnitude m and distance r.*

$f_{R|M}(r \mid m)$ = *p.d.f. of r (distance of structure to the ruptured fault segment) given m.*

$f_M(m)$ = *p.d.f. of m (the magnitude of the earthquake).*

The fragility function is given by $f_{D_i|A}(d_i \mid a)$. The repair costs and down time are estimated for the given damage state of the facility. Operational data such as ship inter-arrival time, service times, price charged for storage after an event are modified according to the damage state information on the port facilities. These outputs become the *post-event* operational input set used in the *Port Operations Model* to estimate losses due to reduced level of operation.

Port Operations Model

The *Port Operations Model* is used to estimate the expected loss due to downtime at some or all of the port's facilities. The downtime is the result of loss of cargo-handling capacity that the port experiences because of damage to some of its facilities. In order to model the operation of the port, a stochastic queuing model is formulated. This model tracks ship arrivals and departures, evaluates the amount of cargo loaded and unloaded, counts the number of ships diverted and records the amount of cargo stored and removed from warehouses and holding areas. For simplicity a simulation approach is developed for this model. Figure 4 shows the main components of the simulation procedure.

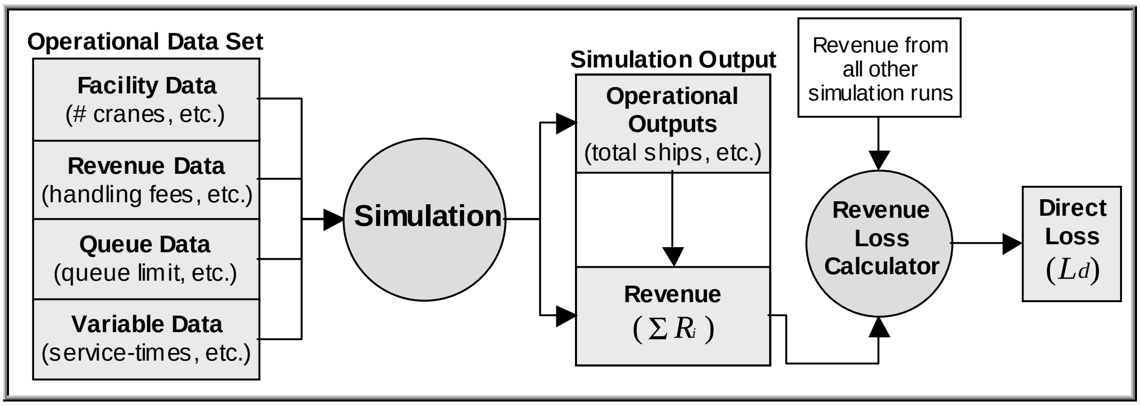

Figure 4: Port Operations Model

Inputs

The *Port Operations Model* takes an *operational data set* as its input. Included in this data set are the port's operational facilities (number of operational warehouses, number of operational berths, etc.), as well as data concerning waiting-lines (ship inter-arrival time data, berth service-time data, etc.). This data set is the same one included in the *Vulnerability Model's* inputs and outputs (*pre-event* and *post-event* operational data set). The *Port Operations Model*, however, employs it in a very different way, relying heavily on the relationships between the different port facilities.

Methodology

The model is a non-physical discrete-event digital simulation with a multi-channel, multi-phase queuing process. The term "multi-channel" reflects the fact that there can be more than one server (parallel servers), and "multi-phase" means that there can be more than one queue (there can be a series of servers). The model simulates the flow of cargo through the port based on queuing theory, keeping track of various operational parameters along the way. For example, ships wait in line to dock, then the cargo might have to wait to be unloaded into the transit shed where it again waits for a truck to pick it up and take it to its final destination. At the end of the simulation, the model takes that data and calculates many related parameters, such as revenue from cargo-handling fees.

As with most simulations, a clock keeps track of the simulation time. Ship inter-arrival times and server service-times are randomly generated variables, based on statistical distributions derived from the input data (usually normal distributions). The average ship queue length, included in the pre-event operational data set, is used to ensure that the model is properly calibrated. In other words, the average queue length calculated from the set of operational outputs is calculated and compared to the expected average queue length from the inputs to ensure that they match. If they do not, the model is revised and the input data set checks their validity.

The *Port Operation Model* works by taking two sets of inputs and running the simulation with each of them separately but for the same duration. The model then compares the results from each run to determine the effect that the scenario earthquake has had on the port. The goal of the analysis is to measure the effect of the scenario earthquake on the port in terms of loss of revenue (direct loss due to downtime). The loss of revenue is then the difference between the revenue that the port would have collected had there been no earthquake minus the revenue that the port did collect given the occurrence of the seismic event.

$$
\begin{aligned}
&v_{L_d} = E[\text{Revenue} \mid \text{No Event}] - E[\text{Revenue} \mid \text{Event has Occurred}] \\
&E[\text{Revenue}] = \sum R_i \qquad [5] \\
&R_i = \text{Revenue from source } i
\end{aligned}
$$

The time duration of the operations simulation must be the same for both simulation runs in order to preserve the validity of the model. It is assumed that the time duration is such that the capacity of the port remains static throughout its entirety (i.e. the operational status of all facilities remain static). Whatever facilities were operational and whatever facilities were non-operational at the beginning of the simulation maintain their operational status throughout the duration of the simulation. For this reason, port operational data together with expert opinion are used to estimate this static post-event period.

One of the most important values in the input data set is the maximum queue length. It represents the maximum number of ship that will wait in line to dock at the port before being diverted to a different port. Diverted ships potentially represent a permanent loss of business to the port. As it was observed in Kobe, when ports suffer major damage they are the most susceptible to competition to other ports serving the same geographic area.

The true power and flexibility of the *Port Operations Model* lies in the fact that, unlike the *Vulnerability Model*, the simulation of the port operation is run several times. The assumption of a fixed operation time and static facilities configuration is not considered to be a restriction on the model since separate simulations can be run over different operational times. After the initial post-event period, decision makers can test their reconstruction plans by adjusting or updating the model to reflect facilities that have become operational again or new facilities that have been added and determining an period of time during which the port's capacity will remain static. They can test the effectiveness of their strategies by evaluating the operational outputs. Specifically, decision makers can pick a metric that they would like to limit or maximize.

A decision-maker may want to minimise the number of ships that divert to other ports. After running the simulation for the initial post-event period (using the initial pair of input data sets), the decision-maker may decide, for example, to bring another berth back online for a period of three weeks. We then update the *post-event* input data set to reflect the added berth and run the simulation again. Since we define the loss of revenue as the difference between the port revenue under normal (pre-event) conditions and the port revenue under modified conditions, the *pre-event* input data set stays the same, only the duration of its simulation changes. At the end of this second simulation, the decision maker checks to see whether the number of ships diverted per unit of time has increased or decreased and again readjusts the post-event input data set, repeating the previous cycle. Decision-makers may repeat these cycles until the port has regained a desired cargo-handling capacity.

Outputs

The Port Operations Model outputs raw statistical data concerning the operation of the port in general, and its various queues in particular. These include:

- number of ships served
- average ship queue length
- average ship/truck/train/barge inter-arrival and service times
- number of units of cargo handled
- number of units of cargo stored
- average storage time of a unit of cargo

This raw data serves two purposes. First, as mentioned previously, the data are used to verify the assumptions included in the input data set. Second, the data are combined with the revenue source information from the input data set to calculate the total revenue (the desired output) from the various revenue sources (sum of the various sources of revenues: ship berthing fees, cargo handling fees, storage fees, demurrage fees, etc.). Once the model has calculated and summed the revenue from all the sources for the various post-earthquake periods, the *pre-event* revenue and *post-event* revenue are plotted as a function of time. The resulting graph represents the economic recovery function of the port. Plots of this type may in fact be the most useful outputs for decision-makers since it filters out most of the minute statistical data.

As with most tools, the *Port Operations Model* and the *Port Seismic Risk Model* as a whole are only as useful as the user makes them. A detailed methodology for modelling ports is not included in this paper; it is crucial, however, to properly model the port in question in order to attain reasonable results. (See references for a more in depth discussion of *port operations* and *simulation*.) Indeed, the power and flexibility of *the Port Seismic Risk Model* lie in the careful assembly of its inputs and the wise application of its outputs.

CONCLUSION

By looking at seaport systems as critical nodes in regional transportation networks and by recognizing their importance to the regional economy, the need for risk analysis of port facilities is clear. Our *Port Seismic Risk Model* takes physical data about the port, its geologic setting, and the nearby seismic sources. It is composed of two independent sub-models: the *Vulnerability Model* and the *Port Operations Model*. The *Vulnerability Model* applies seismic hazard analysis followed by fragility analysis to the individual port facilities to produce a set of post-event inputs and to determine the total repair cost. Both the pre-event and post-event inputs are used to run the port operations simulation. The outputs are operational data that are used to estimate the expected loss of revenue due to downtime (direct loss). The replacement cost and direct loss are summed to calculate the short-term expected economic loss to the port. This result, combined with the operational data outputs, provide decision-makers with tools that help mitigate the seismic risk to ports.

Users may adjust the post-event input data set modified by expert opinion to further take advantage of the model power and flexibility. For example, decision-makers can compare reconstruction and repair plans. Further research in estimating the long-term indirect loss would make the model more robust. Additionally, development of methodology to replace expert opinion (used several times in this model), although not necessary, might make it easier to use by a broader audience. Our methodology will help prevent disasters such as the one experienced by the Port of Kobe in 1995 from ever taking place again, by empowering the decision-makers with the tools necessary to make sure it does not.

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REFERENCES

Basöz, N., and Kiremidjian, A. (1996). *Risk Assessment for Highway Transportation Systems*. Blume Earthquake Engineering Center Report No. 118. Stanford University. Stanford, California.

Bird, J. (1971). *Seaports and Seaport Terminals*. Hutchinson. London.

Branch, A. (1986). *Elements of Port Operation and Management*. Chapman and Hall. London.

Cellineri, L. (1976). *Seaport Dynamics*. Lexington Books. Lexington, Massachusetts.

Hyogo Prefectural Government (1999). *Damage Caused by the Great Hanshin-Awaji Earthquake and the Current Status of the Reconstruction*. 1999 Consular Summit. March 8,1999.

Imakita, J. (1978). *A Techno-Economic Analysis of the Port Transport System*. Saxon House. Farnborough, England.

Kiremidjian, A. (1998). Multiple Earthquake Event Loss Estimation Methodology. Proceedings of the *11th ECEE*, September 6-11, 1998. Paris, France.

Law, A., and Kelton, W. (1991). *Simulation Modeling & Analysis*. 2nd Edition. McGraw-Hill. New York.

National Institute of Building Sciences (1998). *Transportation Lifelines Subcommittee Meeting, Draft Summary Minutes*. April 3, 1998.

Park, C., and Noh, Y. (1987). "A port simulation model for bulk cargo operations." *Simulation* 48:6, 236-246.

Port of Oakland (1999). Web-site http://www.portofoakland.com

Rust, E., and King, P. (1997). "Economic Benefit Study of California Ports and Harbors." *California Marine Affairs and Navigation Conference*. February 28, 1997. West Sacramento, California.

Solomon, S. (1983). *Simulation of Waiting-Line Systems*. Prentice-Hall. Englewood Cliffs, New Jersey.

Werner, S., Dikenson, S., and Taylor, C. (1997). "Seismic Risk Reduction at Ports." *Journal of Waterway, Port, Coastal, and Ocean Engineering*. 123:6, 337-346.