# Comprehensive Evaluation of Probabilistic Seismic Risk Methodology for Port Structures

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**Abstract:** Ports have long been the gateway for commodities and people to transport into cities and countries. In fact, ports are very important link in the total maritime transportation chain. Past experience has shown that ports are often susceptible to severe damage during earthquakes. So evaluation of direct and indirect consequence of earthquake in ports and harbors is an essential problem. Probabilistic method for this problem is introduced briefly to be used in comprehensive seismic risk management. At first, reliability of ports is evaluated in this methodology through estimation of component direct and induced damage probability. Afterwards direct economic loss of earthquake estimate with damage probability from direct and followed by sequence and consequence analysis for assessment of induced damages. Finally indirect economic impacts of direct loss are estimated using economic links between the harbor and society. Outputs of the methodology can be used in different stages of seismic risk management from risk financing to proposing mitigation measures. Effects of rehabilitation of equipments and structures, prevention and suppression systems as well as management type of mitigation actions can be estimated by this methodology in preparedness, emergency response and recovery phases.
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**Key words:** seismic risk, direct economic loss, indirect economic loss, port structures, probability.

## 1- INTRODUCTION

Seaports are the cornerstone of international trade and have become increasingly important as the trend for globalized production and distribution of goods has grown stronger. Seaports are also an important part of transportation networks because they function both as sources and sinks for the freight traffic that flows through the transportation infrastructure of a country. In the past, ports have suffered serious damages from earthquakes because their location near estuaries and river deltas and their construction on landfills has made them particularly susceptible to liquefaction and ground failure. Damage to port structures that reduces their functionality will limit the port's operational capacity and result not only in monetary losses attributed to the repair and replacement cost of the structures, but will also result in revenue losses due to reduced throughput. The operational capacity of a maritime port after an earthquake is of great concern to the port authority and tenants because port revenues and market share retention depend largely on the continuing operation of the berthing facilities. Moreover, freight movement through the port is important for the local industries and factories. For many regions, a capacity reduction in the port system results in severe economic consequences.

Two recent events demonstrate that an earthquake can severely affect port operations. After the 1989 Loma Prieta, California, earthquake, one of the 8 container terminals of the Port of Oakland sustained heavy damage and had to cease shipping operations completely. It took almost six months to fully restore operations while the repairs continued. Eventually, the port estimates it spent $14 million (in 1989 dollars) and it took 23 months to inspect, analyze, design, bid, and reconstruct 922m of damaged wharf in that terminal [7]. Fortunately, the ship traffic could be diverted to other operating terminals, so no loss of operating revenues was reported. After the Great Hanshin earthquake in Kobe, Japan in 1995, the direct repair cost incurred by the port of Kobe was estimated to be (in 1995 dollars) $5.5 billion and the economic impacts on port dependent industries due to the loss of operations at the port were estimated to be about $6 billion [28]. During the earthquake, the port lost about 80% of its operating capacity due to extensive wharf damage. It was reported [9] that the Port of Kobe had only recovered 80.4% of its monthly amount of exports and imports as compared to before the earthquake. This permanent loss of business occurred even though the port had recovered 75% of its cargo-handling capacity one year later. What is more astonishing in the case of Kobe Port is that, although Japan is a country of earthquakes and during the last 100 years had 185 earthquakes with Richter magnitude bigger than seven, Kobe had not experienced an earthquake of magnitude bigger than seven in the last thousand years. Thus, potential for losses to a port subjected to an earthquake cannot be ignored but should be evaluated based on seismicity of region, and mitigation actions should be pursued. Consequently, when authorities plan and design new ports or evaluate and expand existing ones, it is necessary to examine the possible repercussion of potential failures due to such extreme events and account for them in their capital allocation program.

In this paper, a probabilistic methodology for evaluation of holistic seismic risk in port structures is introduced. The results of the model contain the probability of unsafe situations and economic impacts of damages in all levels. The effect of secondary hazards on damages and losses is estimated through probabilistic framework as well.

## 2- TYPES OF SEISMIC RISK AT PORT AND LITRETURES REVIEW

Risk is associated with the impact a disaster has on society and can be described in terms of the following metrics: casualties, damage to civil infrastructure, and downtime loss. This risk may either be deterministically or probabilistically assessed under the influence of controlling event(s).

The necessity of risk analysis studies for efficient evaluation of planning and design alternatives and for setting the performance requirements for future expansions of ports has been recognized since the late eighties [8]. Some studies of port risk analysis have appeared in the literature since then. To assess the impacts of various emergency events on a complex system such as a port, simulation is often the best option. In particular, De Vries (1990) used a ship maneuvering simulation program to study the risk of naval accidents in the entrance of harbors, while Bruzzone et al. (2000) use simulation to study the environmental risk of oil spills and fires in a port. With respect to natural hazards, Yeend (1997) analyzed the exposure of waterfront and coastal facilities of Canaveral port to hurricanes, tornadoes and tropical storms, and Werner, Taylor, and Ferrito (1999) use Monte Carlo techniques to evaluate the seismic performance of a wharf as part of their seismicrisk determination procedure. In the area of financial risk analysis of ports, Kakimoto and Seneviratne (2000a) and Kakimoto and Seneviratne (2000b) examine the probability of the return on capital investment, adjusted for uncertainty in traffic volume, port tariffs and various costs, to drop below the hurdle rate and for the net present value of an investment to fall below zero given that the return rate is equal to the hurdle rate. In their formulation however, the variable costs from repairs and loss of income due to catastrophes are not included.

After the Kobe (1995) and Loma Prieta (1989) earthquakes, there was considerable interest in the seismic behavior of port structures and as a result, at least four documents with seismic design guidelines for ports appeared. The first (Wittcop and Martin 1990) was a result of an extensive investigation of the Port of Los Angeles to determine the seismic risk of its facilities and to establish state of the art design criteria for its future expansions. The second, edited by Werner (1998), summarized the experience gained from past earthquakes and the current engineering knowledge and proposed guidelines for risk reduction through design, response and recovery actions. Soon after, a study from US Navy was released (Ferritto et al. 1999) with seismic criteria for marine oil terminals. Finally, in 2001 the study by the PIANC (2001) gives a very detailed description of proposed damage criteria and design and analysis methods, specifically for port structures. It has been argued by (Werner, Dikenson, and Taylor), that expected cost due to future earthquakes is not currently considered in the design and construction costs of port facilities and the need for a system performance evaluation and business interruption cost estimation was recognized. To the knowledge of the author, no attempt has yet been made to lay out a methodology for determination of business interruption costs.

Simulation models have been also used extensively in planning and analysis of port operations. Many different simulators exist, varying in complexity and objectives; some studying bulk terminals [24], [18] and others studying container [21], [14], [23], [22] or military terminals [16]. The overall seismic risks to the port system that must be managed in a probabilistic holistic seismic risk evaluation methodology can be categorized as follows: (a) life safety risks: associated with risks of death, injury, or illness due to earthquake damage; (b) economic risks: corresponding to earthquake - induced interruption of port operations and damage repair costs; (c) environmental risks: which relate to the potential for harm to local habitats, ecosystems and species due to the earthquake-induced releases of materials stored or handled at the port into the atmosphere, the ground, or the water; (d) political/ethical/aesthetic risks: which relate to socio-economic impacts of port damage, such as unacceptable modifications of natural and urban environments due to port damage; and (e) psychological risks: of worry, anxiety, loss of confidence in the future, etc. These various types of risk should be considered when establishing port system seismic performance requirements.

## 3- TYPES OF EXPOSURE FROM SESIMIC RISK

As can be understood from the previous sections, ports that are situated in regions of high seismicity are particularly vulnerable. For this purpose, it is important to assess the potential losses resulting from extreme events and consider possible mitigating actions. The types of financial liabilities that can be identified as a result of damage to a port from an earthquake include: direct property loss, net income loss, liability loss to third parties and employees, and indirect loss. It should be noted here that losses due to fire and environmental impacts such as oil spills after an earthquake although important, are beyond of the scope of this article. The different types of losses are further discussed in the following sections.

*Direct property loss* includes the repair or replacement costs for the damaged facilities. These facilities are the port's wharves and docks, damaged by liquefied soils, cranes that can topple or collapse from lateral spreading of their legs and buckling, office buildings and warehouses, liquid storage tanks which can sustain loss from collapse or cracking, and failure of utility lines. Moreover, ports sometimes own various types of bridges. Depending on the magnitude of a seismic event and the design characteristics of these facilities, the cost to repair these structures can be excessively high, imposing significant financial difficulties to the port authority.

*Net income loss* accrues due to the reduction in revenues and the increase in operating costs if damaged facilities cause interruption of the port operations. Since most of the revenues of a port come from the transfer of cargo on and off the ships, if the wharves are unusable for a period of time, the revenue loss can be significant. This loss is sometimes also referred to as downtime loss. In the net income loss, one can include the extra expenses that will occur when the operations continue in an emergency mode, e.g., the rental costs for contingency equipment and temporary space.

*Liability loss* occur when port damage causes harm to another party's property or income. An example of such liability is when the power blackout caused by an earthquake results in deterioration of perishable cargo stored in refrigerated containers. Workers' compensation and tenants' loss of revenue could be classified in this category as well.

*Indirect property loss* arises as a result of direct property loss. Indirect loss in this methodology refers to loss of revenue or loss of port owner due to business disruption as a result of stoppage of port operation or reduction of serviceability capacity.

Assessing the risk from market share loss to competitors is considerably more difficult. It is generally admitted that once a ship gets diverted successfully to another port, it rarely comes back. Several scenarios can be considered to evaluate the likelihood that a ship will be diverted under the assumption that the queue is too long and the ship will not wait an extended period of time.

## 4- MANAGEMENT OF SEISMIC RISK

The serious implications that an earthquake can have on port revenues and operations creates a need for a general and comprehensive risk assessment framework for port systems.

Such a framework should be able to describe probabilistically the damage states in which the port components will be after an earthquake event and associate them with the total functionality state of the port. Moreover, it should be able to relate the post-earthquake operations and revenues of the various port terminals with their functionality and provide probabilistic estimates of the incurred loss. If the risk of earthquake related damage to the port can be evaluated in a reliable manner, prudent investment decisions on the seismic upgrading of port facilities can be made and appropriate risk mitigation strategies can be formulated.

The basic steps for conducting comprehensive seismic risk analysis of a port system are Evaluation of seismic hazard, Assessment of damage states of port components, Evaluation of system functionality, downtime and replacement costs, Estimation of difference in revenues and Use the revenue loss process for financial risk analysis and risk management decisions.

In the previous section, various contributors of seismic risk were identified and discussed. The core of the problem lies in that most existing facilities are designed according to older standards and their damage can result not only to direct loss but also to loss of operational capacity. Facilities designed under current standards are also expected to sustain some degree of damage because design criteria are formulated primarily for life safety rather than for different performance requirements. Continued functionality after different size earthquakes, for example has not been considered until recently, as performance-based design criteria became better understood and accepted. Under certain conditions, seismic upgrade of these facilities can cost more than the anticipated loss. Thus, it is necessary for port management to find ways not only to minimize the losses from direct physical damage but also to plan for quick recovery. If mitigation measures are not taken to increase seismic resistance of port facilities, their timely repair after an earthquake requires a significant capital investment. Typically, a combination of mitigation through loss control and risk financing would provide the best approach in reducing overall risk exposure of a port [25].

## 5- PROPOSED APPROACH

Ports have long been the gateway for commodities and people to transport into cities and countries. In fact, ports are very important link in the total maritime transportation chain. Past experience has shown that ports are often susceptible to severe damage during earthquakes. So evaluation of direct and indirect consequence of earthquake in ports and harbors is an essential problem. Probabilistic method for this problem is introduced briefly to be used in comprehensive seismic risk management. At first, reliability of ports is evaluated in this methodology through estimation of component direct and induced damage probability. Afterwards direct economic impacts of earthquake estimate with damage probability from direct and followed by sequence and consequence analysis for assessment of induced damages. Finally indirect economic impacts of direct loss are estimated using economic links between the harbor and society. To fulfill the requirement of risk assessment in port structures, the result of the proposed methodology will evaluate:

1. Probability of direct physical damage.
2. Reliability of structures.
3. The probability of unsafe conditions like probability of leakage of hazardous material or explosion in facility.
4. Probability of induced damage as a result of secondary hazards in facility.
5. Total economic impact of damages including direct, indirect economic.

The flowchart of proposed methodology is shown in Fig.1. First, the seismic hazard is estimated by the site hazard curve. Second, the probability of direct physical damage is computed using relevant vulnerability function in the direct damage module. Third, reliability of port structures and probability of secondary hazards in the port are assessed in sequence module. Fourth, consequences of secondary hazards in terms of physical damage probability of components are anticipated in consequence module. Fifth, total probability of direct and induced physical damages is calculated and used to estimate the direct economic loss and repair time in the direct economic impact modules. In the end, results are utilized to evaluate the indirect loss using indirect loss module. Methodology comprises of two general parts: direct and indirect losses.

## 6- ESTIMATION OF DIRECT ECONOMIC LOSS

The probability of total damage in each component is estimated by aggregating the probability of direct and induced damages employing probability theorem:

$$P_k(D = d_i) = \sum_{all\ j} P_{kj}(D = d_i) - \sum_j \sum_l P_{kj}(D = d_i).P_{kl}(D = d_i).\gamma_{jl} \quad (1)$$

$P_k(D = d_i)$: Probability of damage equal to damage state $d_i$ as a result of direct effect of earthquake and secondary hazards.

$P_{kj}(D = d_i)$: Probability of damage in k$^{th}$ component due to j$^{th}$ hazards (primary or secondary)

$\gamma_{jl}$: correlation coefficient implying the correlation of j$^{th}$ and l$^{th}$ hazards.

In this method, in order to aggregate damage from different sources and due to lack of information, continuous damage state in components are divided to certain damage stats which are described by physical damage measures. This type of damage definition used by many previous studies [4], [20] provides a common base for aggregating probability of damages and assuming financial loss and repair time for each state. Damage states can be identified from different viewpoints. In addition to HAZUS's damage states which are mostly developed for estimation of economic impact of earthquake, damage states can be defined based on safety or process disruption considerations. Experience of previous damages and working condition of components can give valuable clue to identify and describe the damage states in components [13].

### 6-1- DIRECT DAMAGE ESTIMATION

The probability of certain structural response is estimated from total probability theorem. For continuous hazard parameter it can be written as [32]:

$$P[R < r] = F_R(r) = \int F_{R|S}(r;s) f_S(s) ds \quad (2)$$

In which:

$f_S(s)$: Probability Density Function (PDF) of seismic hazard

*R: S*tructural response

$F_{(R|S)}(r;s)$ : Conditional Cumulative Distribution Function (CDF) of response in given ground motion, "s".

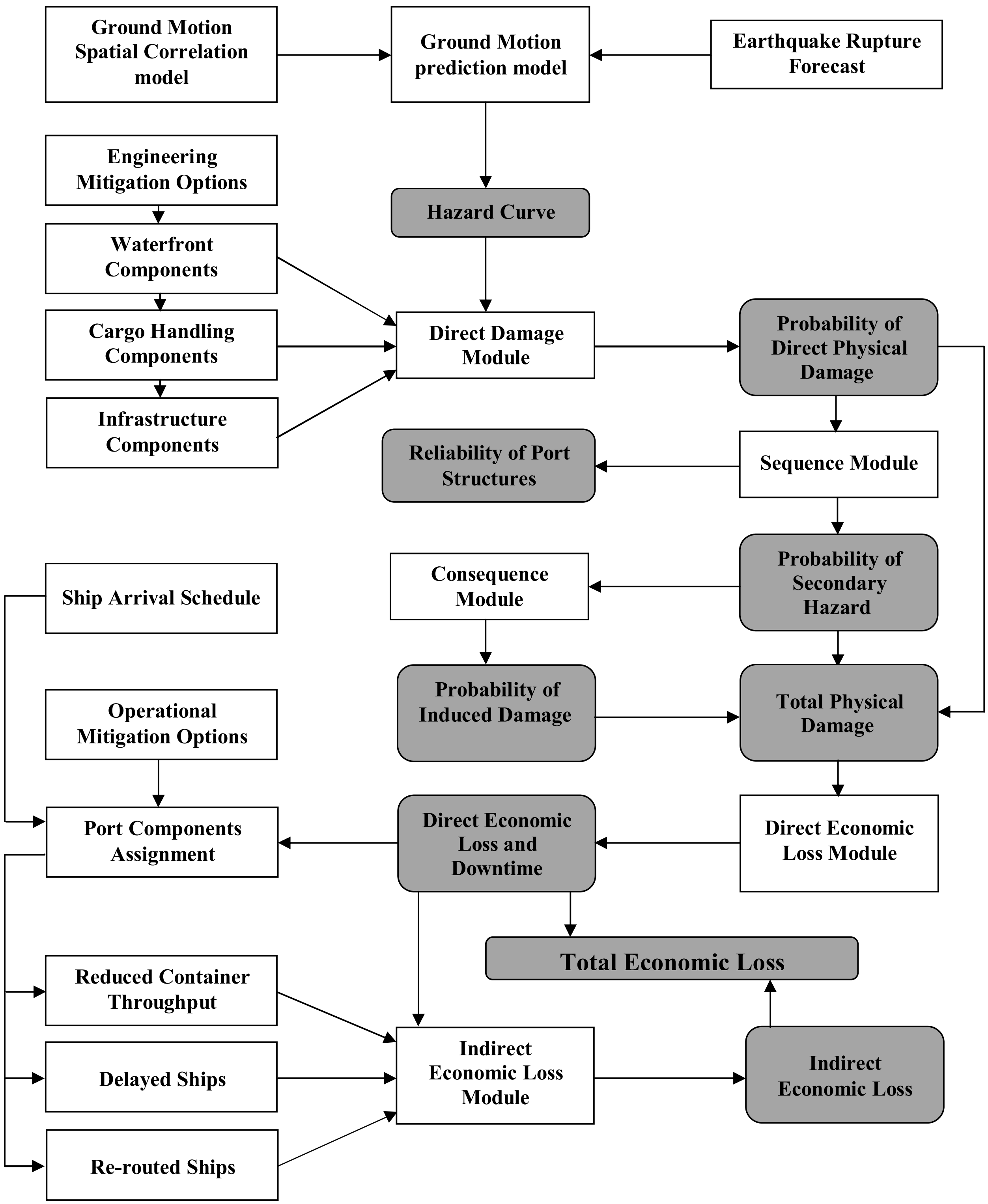
The probability of exceeding damage from a damage state ($d_i$) is derived by replacing damage state in structures instead of structural response:

$$P[D > d_i] = \int F(D > d_i|im).\,|d[P(IM \geq im)]|.\,d(im) \quad (3)$$

Where $P(IM \geq im)$ is hazard curve which estimates the exceeding probability of ground motion Intensity Measure, *IM*, from certain level, "*im*" and $F(D > d_i|im)$ is fragility function which estimates the conditional exceeding probability of damage, *D*, from a damage level, $d_i$, in given "*im*". Equation 2 can be solved either numerically or mathematically. By assuming a power function for hazard curve [10], $P(IM \geq im) = K_0 im^{-k}$ and CDF of log-normal for fragility function [4], $F(D > d_i|im) = \Phi[1/\beta_i.\ln(im/IM_i)]$ in which *k* and $K_0$ are seismic hazard parameters and $IM_i$ and $\beta_i$ are seismic fragility function parameters, closed form solution of Equation 2 can be derived [15]. Probability of damage equal to a damage state can simply estimate:

$$P[D = d_i] = P[D > d_i] - P[D > d_{i+1}] \quad (4)$$

**Fig. 1. Procedure of seismic risk assessment of port structure. Outputs of methodology have shown by shaded objects.**



**6-2- SEQUENCE ANALYSIS**

Damage to one or serious of components could lead to process interruption or secondary hazards initiation. The probability of such incident is estimated in this part. In the present methodology, fault and event tree analyses which have been used conventionally for sequence analysis of port are employed. In practice, it is require to have pre-defined fault and event trees of events formed from damage states of components. The efficiency of prevention and suppression systems can be taken into account in fault and event tree analyses as well.

**6-3- CONSEQUENCE ANALYSIS**

Probability of induce damage is evaluated in probabilistic framework derived from Eq. 2 and total probability theorem:

$$P_{bi}[D > d_i] = \int_{is}\int_{sh} F(D > d_i|IS = is).f(IS = is|SH = sh).f(sh).d(sh) \quad (5)$$

Where:

$f(sh)$: PDF of Secondary Hazards *SH* estimated from sequence analysis.

$f(IS = is\|SH = sh)$ : Conditional PDF function of Intensity of Secondary hazard (*IS*) in given "*sh*" which shows the attenuation of secondary hazard intensity and is derived for four major secondary hazards (fire, explosion, Tsunami and releases of hazardous materials) based on their propagation characteristic.

$F(D > d_i\|IS = is)$ : Conditional probability of exceeding damage from $d_i$ in given "*is*" which is strikingly similar to seismic fragility function.

**6-4- ESTIMATION OF DIRECT ECONOMIC LOSS AND DOWNTIME**

The probability of total direct loss of port is estimated from aggregating loss of individual components in port where direct loss of each component is:

$$P[C_i > c] = \sum_{i=1}^{NDS_i}\left[1 - F\left(C_{ij}\middle|D = d_j\right)\right].P(D = d_j) \quad (6)$$

Where:

$P[C_i > c]$: Exceeding probability of loss in component *i* from *c*

$F\left(C_{ij}\middle|D = d_j\right)$ : Cumulative conditional distribution function of loss in component *i* in given damage state $d_j$ defines by the normal distribution function with mean and deviation of $\ddot{C}_{ij}$ and $\sigma_{ij}$

$P(D = d_j)$: Probability of damage equal to $d_j$ calculated from Equations 1 and 4.

The same formulation can be derived for probability estimation of down time and reconstruction time.

**6-5- UNCERTAINTY MODELING**

Considering uncertainty and randomness of input parameters on the results could help risk managers to make more robust decision by examine all possible consequences. To evaluate the uncertainty of results, numerical simulation is employed. Due to substantial amount of random and uncertain parameters in the methodology, close-formed solutions like FOSM for estimation of uncertainties are not applicable in this stage; therefore Mont-Carlo simulation has been utilized for estimation of loss uncertainty.

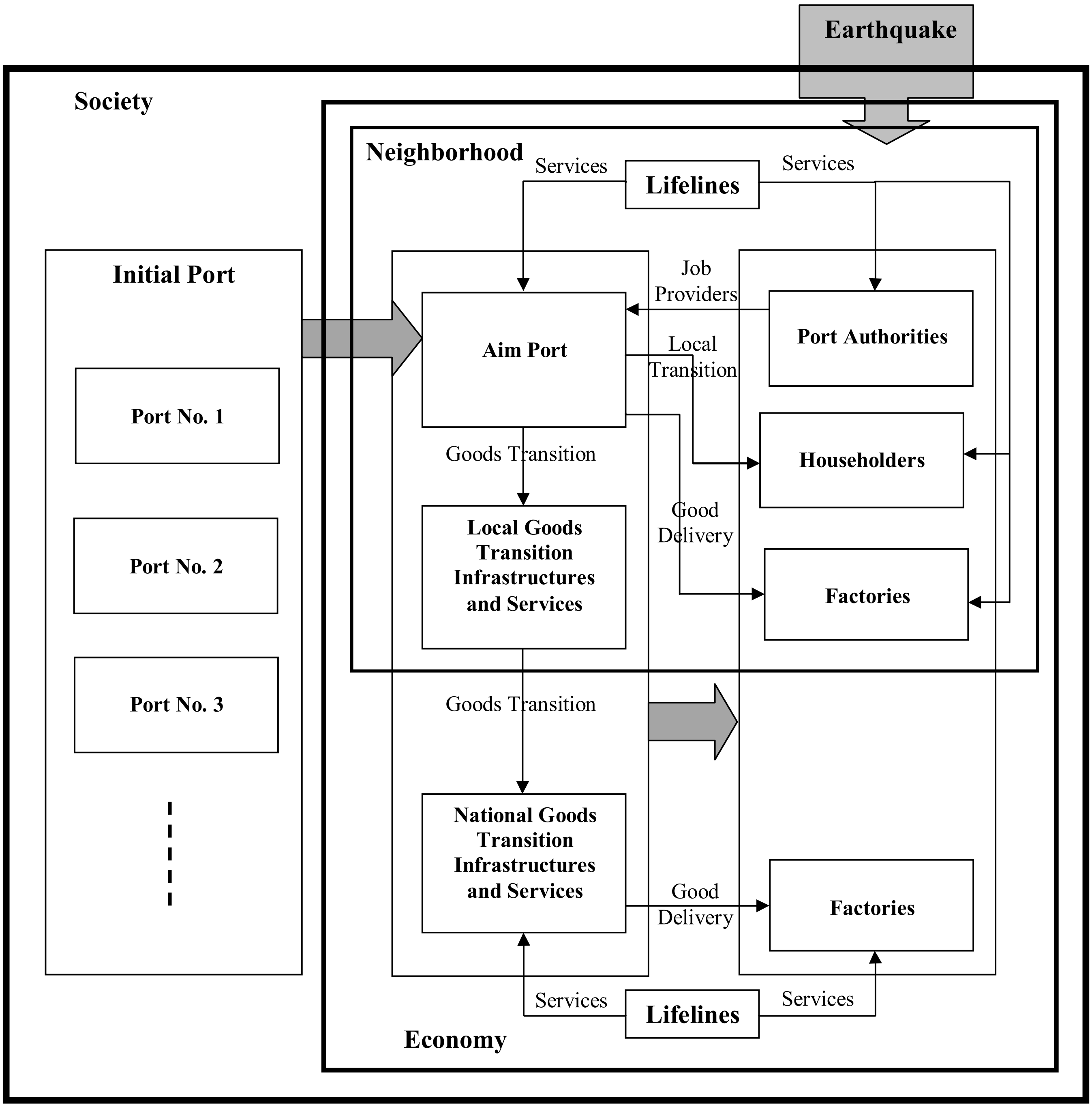
**7- INDIRECT ECONOMIC LOSS ESTIMATION**

Indirect economic loss in this methodology refers to loss of revenue or loss of port owner due to business interruption as a result of reduced container throughput, delayed ships and re-routed ships. In this study, the indirect economic loss is estimated by equivalent recovery. The restoration time comprise of reconstruction time and delay before, during and after it. Several external and internal parameters are contributing to delay time. For instance in reconstruction stage, shortage of financial sources, leakage of masonry or lack of trained labor after an earthquake which are considered as external factors are increasing the reconstruction time. Furthermore, physical restoration of structures of port does not guarantee the restoration of business interruption and port operation. Business recovery depends on the many external factors such as revert of ships, restoration of lifeline and etc. The substantial amount of contributing agents in the restoration of port operation and their unknown relationships imply a highly complex and dynamic system which should be considered with more detail and consideration.

The conceptual diagram of relationship of port and its relevant agents is shown in Fig.2. Based on the influential factors and the conceptual model of port process, several contributing elements are identified: initial ports, aim port, lifeline services, factories, good transition infrastructures and services port authorities and households which are a source of labors. Two levels of financial relationship between port and society can be explained based on the model. The first level is local level which defines the relationship between the port, household, consumer and lifeline and has effect on indirect loss of port. The second level is the economy level which defines the relationship between different economic sectors and has effect of macroeconomic level.

Based on the conceptual model, a system dynamic approach is employed for developing a probabilistic model of port restoration using detailed conceptual diagram, functional and mathematic model.

**Fig. 2. Conceptual model of port-society relationship is used for developing the indirect and macroeconomic impact model.**



## 8- CONCLUSION

The main objective of this article is to provide a methodology for estimation of probabilistic holistic seismic risk of port structures. Outputs of the model can be used in holistic seismic risk management of port structures from risk financing to hardware (e.g. rehabilitation) and software (e.g. management and preventing) mitigation measures which is a the major advantage of the current method compare to existing ones such as HAZUS. Effects of rehabilitation of equipments and structures, prevention and suppression systems as well as management type of mitigation actions can be estimated by this methodology in preparedness, emergency response and recovery phases.

Since every port is a unique system with its own characteristics in traffic, equipment and hazard conditions, no attempt is made to deduce general conclusions for all ports, rather to identify the key factors influencing the loss estimation and to propose an approach to the problem. Moreover, port characteristics can change rapidly over time and hence any conclusions would correspond to the state of the system at that particular period, giving general results limited applicability.

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