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Probabilistic Seismic Direct Loss Estimation for Ports, Case study: Pars Asaluyeh port

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ABSTRACT

Ports are the main avenue of global freight transport. In the past, experience has shown that ports are vulnerable to earthquakes, which cause evident economic damage. The port at Kobe, Japan, experienced economic losses of about $11 billion after an earthquake in 1995. The present study used the full-probabilistic PEER-PBEE framework to develop a comprehensive seismic risk assessment approach with which to estimate the total direct and indirect economic loss incurred by a port experiencing an earthquake. In the proposed methodology, the extent of direct economic loss due to the cost of repair of port structures in the Pars Asaluyeh port was estimated. Seismic risk density curves (SRDCs) were employed to determine the seismic performance of different port structures and pieces of equipment as well as the overall seismic performance of the port. The SRDCs show that the mooring structures and breakwater of the port showed appropriate seismic performance, while other port structures and equipment showed weak or average seismic performance.

1. Introduction

Earthquakes can cause major economic losses to the infrastructure of a country as well as loss of lives, social-psychological consequences, and environmental damage. The Great Hanshin earthquake in Kobe in 1995 is a good example. It caused $100 billion in direct economic losses, caused 6500 deaths, and injured 43,000 people [1]. Studies on the response of infrastructures, installations and lifelines after this earthquake can improve understanding of the extent of vulnerability of these structures.

The consequences of the Kobe earthquake revealed that ports are vulnerable lifelines. Among the lifelines of Kobe, which included utilities, telecommunications, water, natural gas, railways, highways, and the port, the results indicated that the port required the longest recovery time [2]. The effects from the earthquake included an increase in freight transport costs, reduction in income of a noticeable portion of the community, as well as noticeable a drop in rank of the Port of Kobe as the premier container port globally. Direct economic loss to the port caused by damage was $5.5 billion and economic loss caused by downtime was $6 billion during the year following the earthquake [3].

Studies on the Northridge [1994], Chi-Chi [1999], and Haiti [2010] earthquakes reveal similar results in relation to the high vulnerability of ports. Ports play a major role in national, regional, and global economies. About 90% of total cargo transit is delivered through ports [4]. The importance of ports and their vulnerability to earthquakes make seismic risk assessment and management of interest to researchers.

Pachakis and Kiremdijian [5,6] proposed a methodology for estimating physical damage due to earthquakes and loss due to downtime of a port system. In their model, a port was considered to be a complex of wharves and mooring structures, cargo handling equipment, accessways, warehouses, and infrastructures. Ichii [7] used a seismic risk density curve (SRDC) to evaluate the seismic status of port structures and categorized the structures based on function as having either strong, medium, or weak seismic performance levels.

Warner et al. [8-10] assessed the seismic risk of the port of Auckland and created a framework for seismic risk assessment of the entire port system. They also conducted a project for a seismic risk reduction program for the port of Portland. This included an assessment of acceptable risk which can be used as a guide for determining improvements required in response to seismic activity to increase the seismic performance level of the entire port system.

Na and Shinozuka [11] proposed a methodology for estimating the effect of an earthquake on the performance of a port using fragility curves. They estimated direct losses due to an earthquake and economic loss due to downtime of the port system.

Amirabadi et al. [12] proposed a methodology to assess comprehensive seismic risk in ports that addresses five categories: estimation of life safety risks such as death and injury; direct and indirect economic losses; environmental risks; social, political, and ethical risks; and spiritual and psychological risks.

Burden et al. [13] developed the risk assessment framework proposed by PEER for assessing the seismic risk of ports. In order to consider port service interruption or port downtime, a term was added to the general relation for PEER-PBEE called “repair requirement”.

Lam and Lassa [14] investigated the different risks threatening ports and proposed a method for evaluating them. Port facilities and structures were classified as either buildings, utility systems, or transportation infrastructure. The risks threatening marine transportation, particularly ports, included earthquake, tsunami, climate extremes, environmental risks, economic risks, policy risks, security risks, regular supply risks, and daily operational risks.

Iran is a country with a high risk of earthquake occurrence. The seismic risk status of important ports in Iran are shown in Figure 1. It can be seen that almost all main ports are located in regions with high seismic risk potential and it is imperative for these ports to consider seismic risk assessment.

In order to estimate the effect of earthquakes on ports, a methodology called comprehensive seismic risk assessment (CSRA) of ports has been proposed using the full-probabilistic PEER-PBEE framework. The proposed methodology provides the opportunity to accurately investigate the effects of an earthquake on ports, including the probability of failure of port structures and equipment, of secondary risks from the earthquake, of downtime of the port after the earthquake, the time required for recovery of the port, and direct and indirect economic and environmental losses incurred by the port.

The proposed methodology was used to estimate the direct economic loss due to an earthquake at Pars Asaluyeh port. A seismic risk density curve (SRDC) then was developed for each part of the port. These curves were used to assess the seismic performance of different parts of the port.

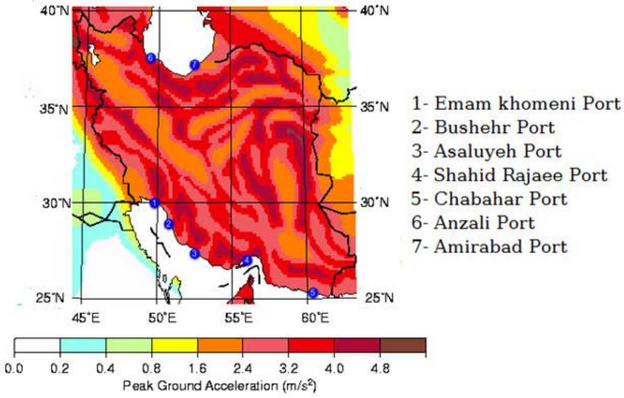

Figure 1. Hazard map showing seven major Iranian ports [15, 16]

The SRDC demonstrates the distribution of the probability density function for seismic risk. It was developed by multiplying the damage incurred by the probability density function of earthquake occurrence. The area below the SRDC represents the expected annual losses. The figure denotes the seismic performance of the structure and equipment. In this case, elliptical risk density curves represent weak seismic performance, hump-shaped risk density curves represent average seismic performance, and sharply-peaked risk density curves represent strong seismic performance [7]. Using the proposed methodology, the cumulative function of economic loss due to an earthquake for each component and the economic loss function for the entire port system was obtained. The SRDC provides an appropriate assessment of seismic performance of each component of the port.

2. Proposed Approach

The effects of earthquakes on ports are classified in the Seismic Guidelines for Ports [17] as being life safety, economic, environmental, political/ethical/aesthetic, and psychological risks. It is not possible to assess any of these risks using the current seismic design standards of port structures. Thus, the risk assessment framework proposed by PEER was developed and combined with the proposed CSRA for ports.

Statistics on recent earthquakes in the USA and Japan indicate that the resulting significant economic losses were beyond expectations. This fundamentally changed the concept of the seismic design of port structures. The most important reason for such changes was the lack of logical descriptions for some of the rules applied by designers and the lack of attention by employers to seismic-resistant retrofitting.

The most important reason for reliance on a performance-based design approach has been to encourage innovation in developing new methods to improve performance. In the seismic design standards for port structures, there exists a concept known as performance-based seismic design. It was developed using a number of performance objectives which enable prediction of performance levels in order to determine the level of risk.

Although advances in development of performance-based seismic design have been remarkable, deficiencies exist. Development of a total probabilistic performance-based seismic risk assessment framework for port systems using the PEER-PBEE framework is an efficient method of comprehensively assessing the seismic risk of such a system. Using this framework, it is possible to correctly assess seismic risks to a port system. The general relation proposed in PEER-PBEE is as follows:

$$P(\mathrm{DV}) = \iiint P(DV|DM).P(DM|EDP).P(EDP|IM).f(IM)\ dDM\ dEDP\ dIM \quad \text{(R-1)}$$

The PEER risk assessment framework equation operates in four stages: hazard analysis, structural analysis, damage analysis, and loss analysis. In hazard analysis, the seismic hazard at a facility is assessed by producing sample ground-motion time histories with an intensity measure (IM) appropriate to different hazard levels. In the structural analysis phase, the response of the facility to a ground motion of given IM is calculated in terms of drift, acceleration, ground failure, stress, strain, and other engineering demand parameters (EDP). In the damage analysis stage, the EDPs are used with component fragility functions to determine the damage measure (DM) to the facility.

Once the DM has been determined, the repair efforts can be evaluated to determine the serviceability, repair costs, repair duration (total cost), and the potential for casualties. These measures are called decision variables (DV) because they can be used to influence stakeholder decisions about future performance [18]. In this study, the damage states were assumed to be discrete. Relation 1 can be rewritten for discrete damage states as follows:

$$P(\mathrm{DV}) = \sum_{i=1}^{NDS_i} \iint P(DV|DM).P_i(DM|EDP).P(EDP|IM).f(IM)\ dEDP\ dIM \quad \text{(R-2)}$$

Using the total probabilistic PEER-PBEE framework for the CSRA of ports, the total economic loss caused by an earthquake to a port can be calculated as the sum of direct economic loss, indirect economic loss, and environmental economic loss. Direct economic loss caused by an earthquake includes the cost of repair and renovation of different parts of a port. Indirect economic loss is damage caused by interruption of port services. In the proposed approach, loss due to death or socio-psychological consequences caused by an earthquake have been included. These cannot be estimated because they were not considered in the overall economic losses in the PEER-PBEE framework, which includes direct and indirect economic and environmental losses.

2.1. Proposed CSRA framework

Figure 2 shows the proposed CSRA framework. The approach is presented in ten steps that are distinguished by different colors. In step 1 (dark red box), the annual average hazard of earthquake occurrence at a port site is estimated. In step 2 (red box), the probability of direct damage due to an earthquake (primary hazard) is estimated using fragility curves. In step 3 (orange box), the performance reliability of the port as it relates to the primary hazard is estimated. Because a port system is composed of several components, the use of FTA is required in order to estimate reliability.

In step 4 (yellow box), the probability of secondary hazards caused by an earthquake, including fire following an earthquake, inundation, falling objects, release of hazardous materials, and explosions have been estimated. In step 5 (light green box), the consequences and damage due to secondary hazards in the port are estimated. In step 6 (green box), the total damage incurred due to primary and secondary hazards is estimated. In step 7 (light blue box), direct economic loss due to damage to structures and equipment at the port and the period required for recovery to resume operation are estimated. In step 8 (blue box), indirect economic loss due to downtime at the port is calculated. In step 9 (dark blue box), environmental, life safety and socio-psychological risks due to an earthquake are estimated. In step 10 (purple box), the total economic loss due to direct and indirect economic losses and environmental economic losses are calculated.

3. Case Study: Port of Pars Asaluyeh

The port studied in this research is at Pars Asaluyeh, the location of which is indicated in Figure 1. Pars Asaluyeh is a multipurpose port. Wharves 1, 2, 6, 7, 8, and 9 are for containers, wharves 3 and 4 are for exportation of sulfur and bulk materials, wharf 5 provides services to the installations of South Pars Gas Field, and wharf 10 is for exportation of gas condensate and fueling.

Seismic risk assessment in the Pars Asaluyeh port is important from several aspects. This port is located in a region with high seismic risk potential and is responsible for providing service to one of the largest gas fields in the world (South Pars Gas Field). Figure 4 is plan of the port. The structures are classified into the categories of mooring structures, breakwaters, infrastructures, and cargo handling structures. Classification of the structures and equipment has been based on the proposed methodology as shown in Figure5.

3.1. Probability function of earthquake occurrence at site of port

To estimate direct economic loss for Pars Asaluyeh port using the proposed methodology, the mean annual probability of exceedance was estimated for an earthquake at the site of the port. The probability of earthquake occurrence was considered using the report provided by the Seismic Hazard and Geotechnical Hazard Zonation of Asaluyeh (910 ha) by the IIEES [20]. The curve of the probability of an increase in annual average earthquake risk for Asaluyeh region is provided in Figure 6 in the form of a complementary cumulative distribution function.

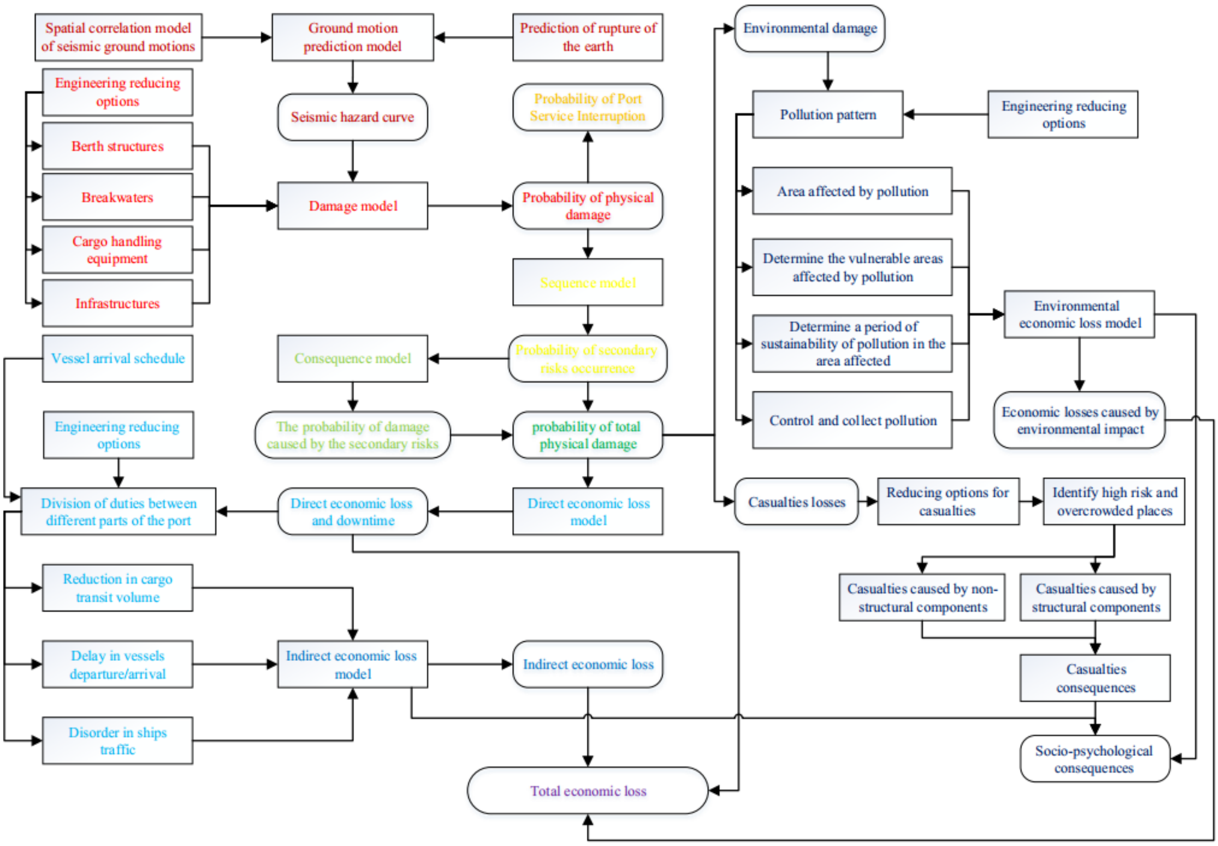

Figure 2. Framework of comprehensive seismic risk assessment of ports

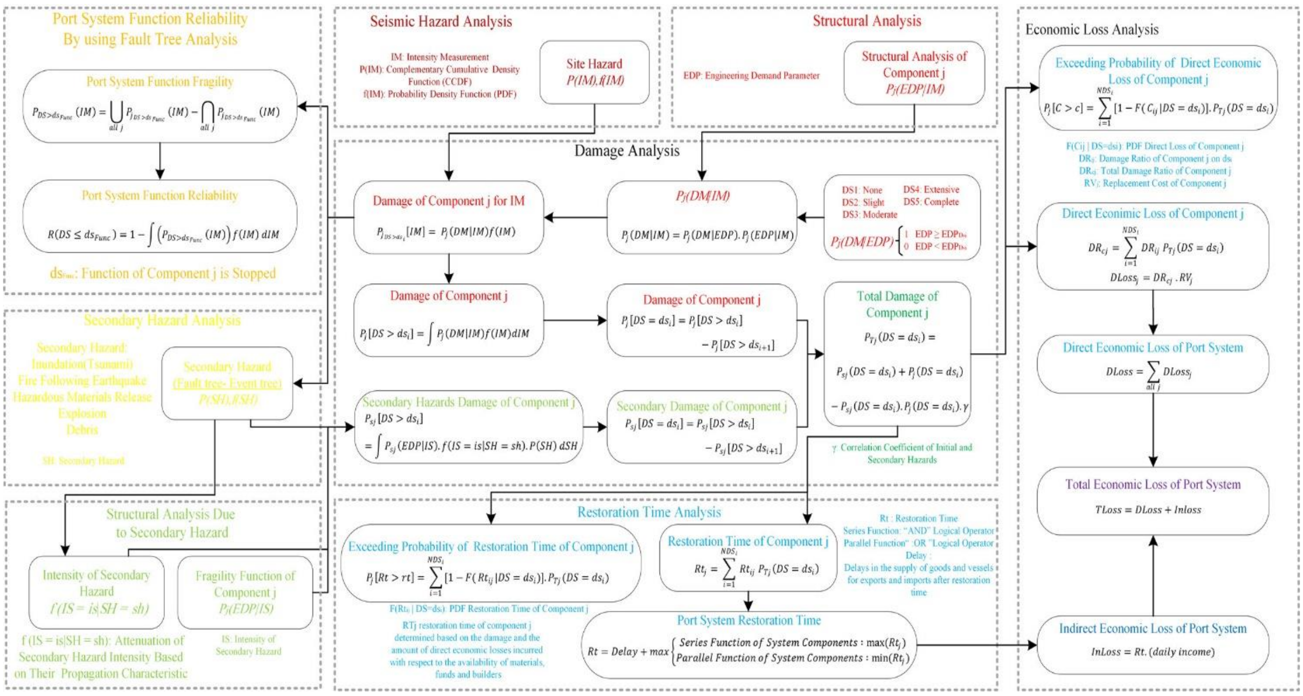

Figure 3. Probabilistic model framework of comprehensive seismic risk assessment of ports

Figure 4. Plan of Pars Asaluyeh port

3.2. Fragility curves for structures at port

After determining the earthquake risk function, the probability of direct damage due to an earthquake for each part and structure in the port should be determined. The development of fragility curves for the port structures were the next step toward estimating direct economic loss. A fragility curve is a logarithmic normal cumulative probability function which represents the probability of an increase in damage from a definite limit in a definite state of earthquake risk. These curves were based on the curves provided in HAZUS for different port structures based on their specifications [21]. The damage states in HAZUS were slight, moderate, extensive, and complete. Table 1 lists the means and standard deviations of the different port structures.

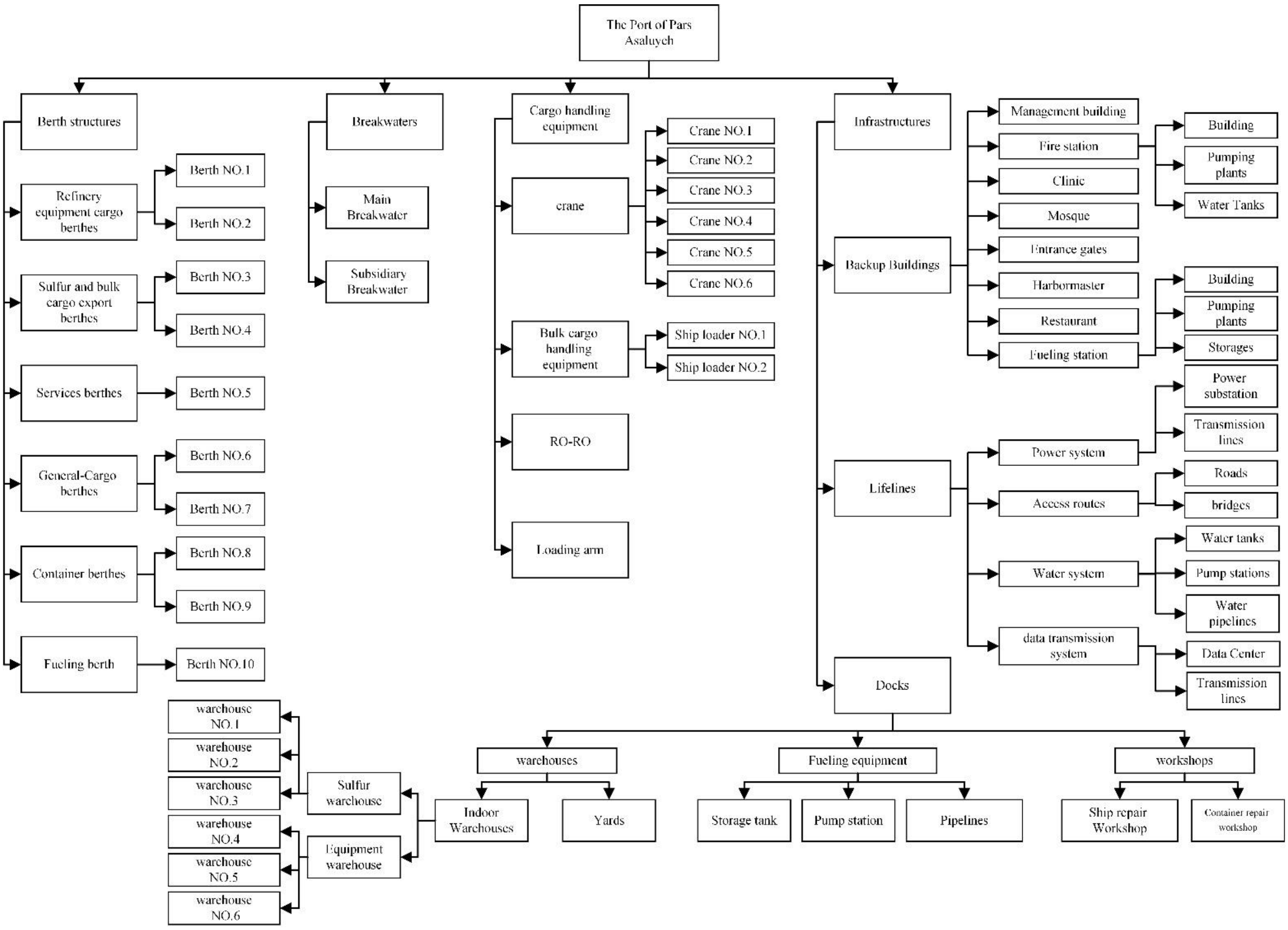

Figure 5. Classification of structures and equipment at port based on CSRA framework

In HAZUS, for structures such as breakwaters and wharves, fragility curves were defined based on permanent ground deformation. For other structures, they were defined based on peak ground acceleration. The method proposed by Saygili [19] was used to unify the differences. The curve of the occurrence of an earthquake in the Asaluyeh region and fragility curves of the port structures were used to estimate the probability of unserviceability of the port. Figures 7 and 8 provide the conditional probability curves for unserviceability of Pars Asaluyeh port based on different applications for the entire port.

3.3. Direct economic loss curves for different port structures

In the next step, in order to estimate the direct economic loss for the port, the damage and repair ratios and recovery costs of the equipment and different structures should be determined. The values proposed in HAZUS were used and provided in Table 2 [21].

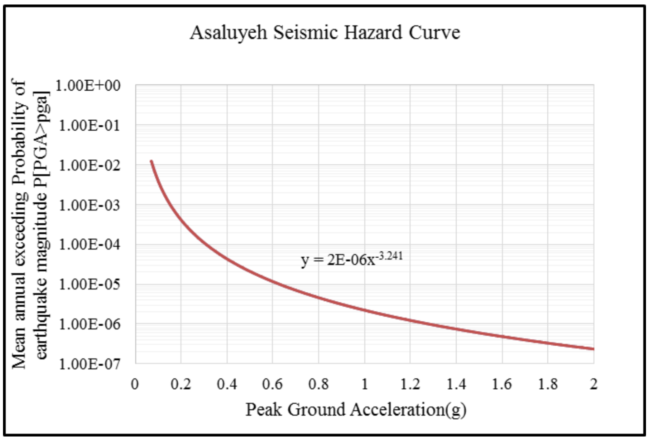

Figure 6. Mean annual probability of exceedance for an earthquake in Asaluyeh region

Table 1. Mean and standard deviations of fragility curves for port structures based on HAZUS

Structure	Slight		Moderate		Extensive		Complete	
	Median	β_i	Median	β_i	Median	β_i	Median	β_i
Wharf type1	20.32 cm	0.6	40.6 cm	0.6	60.9 cm	0.6	152.4 cm	0.6
Wharf type2	12.7 cm	0.6	30.4 cm	0.6	43.18 cm	0.6	109.2 cm	0.6
Breakwater	20.32 cm	0.6	40.6 cm	0.6	60.9 cm	0.6	152.4 cm	0.6
Crane	0.15 g	0.6	0.35 g	0.6	0.8 g	0.7	0.8 g	0.7
RoRo-Trailer	0.3 g	0.6	0.5 g	0.6	1 g	0.7	1 g	0.7
Storage	0.24 g	0.64	0.41 g	0.64	0.76 g	0.64	1.46 g	0.64
Fueling System	0.12 g	0.5	0.27 g	0.5	0.64 g	0.6	1.1 g	0.6
Fuel loading arm	0.15 g	0.6	0.35 g	0.6	0.8 g	0.7	0.8 g	0.7
Substation	0.15 g	0.6	0.25 g	0.5	0.35 g	0.4	0.7 g	0.4
Road	30 cm	0.7	60 cm	0.7	154 cm	0.7	154 cm	0.7
Bridge	10 cm	0.2	10 cm	0.2	10 cm	0.2	35 cm	0.2
Tower Control	0.12 g	0.64	0.23 g	0.64	0.57 g	0.64	1.07 g	0.64

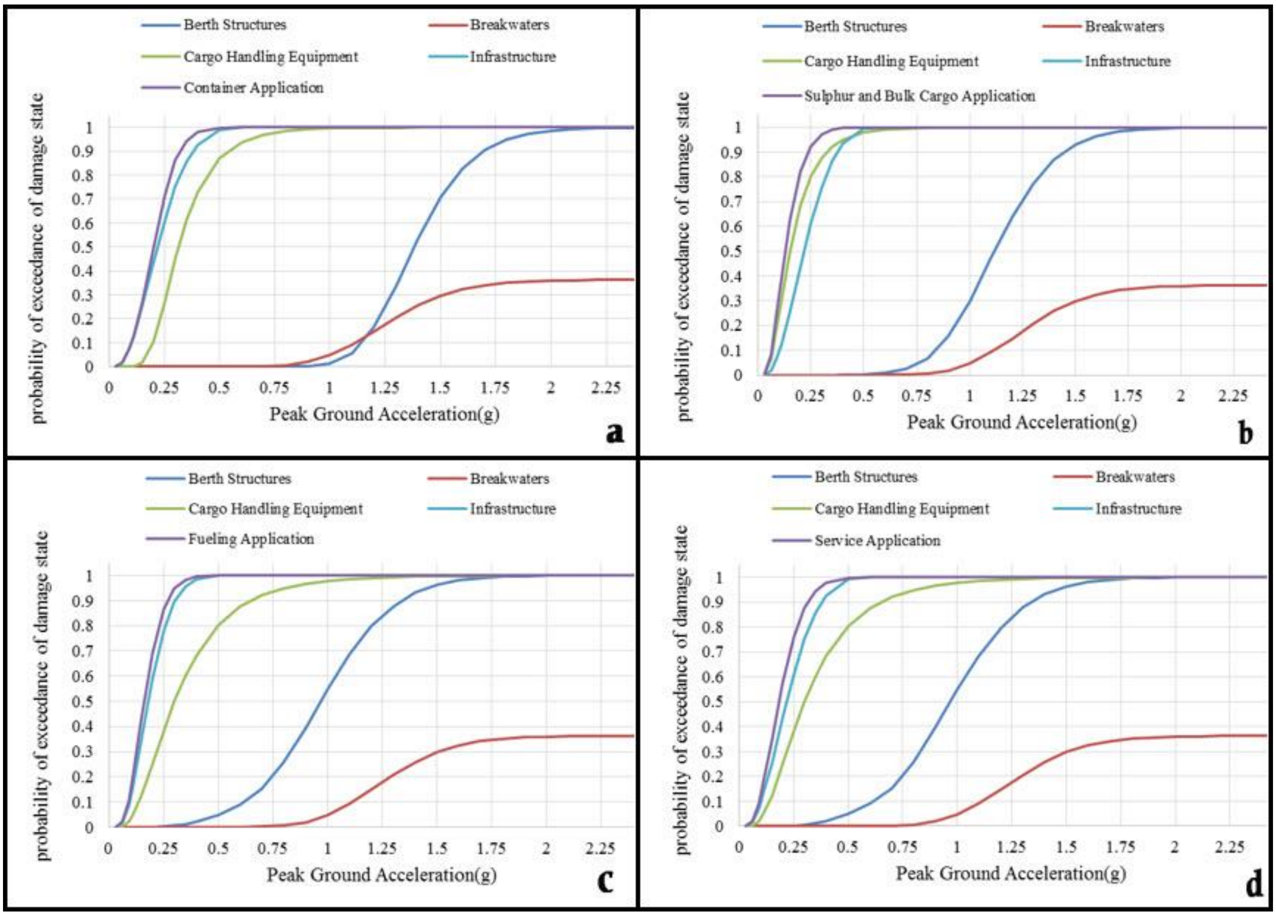

Figure 7. Conditional probability curve for unserviceability of port structures and equipment for Pars Asaluyeh port: (a) containers; (b) sulfur and bulk material exports; (c) fueling; (d) service to South Pars Gas Field.

The data from the fragility functions and damage and cost ratios for repair and recovery of the structures of the port system and direct economic losses for each structure can be estimated for different earthquake intensities or earthquake occurrence probabilities. Figure 9 shows the direct economic loss functions of the port structures and equipment estimated using the proposed methodology. The minimum direct economic loss at low earthquake intensities was for the mooring structures and breakwater of the port. For the high intensities, the minimum direct economic loss was for infrastructures such as the pumping station, power posts, and warehouses. The differences relate to the higher costs of repair and recovery of the mooring structures and breakwater.

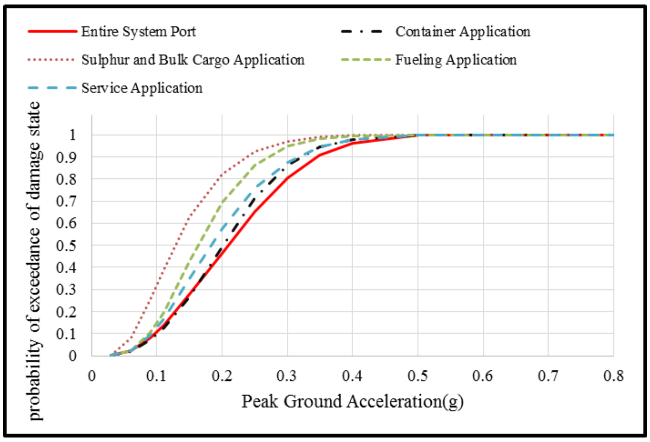

Figure 8. Conditional probability curve for unserviceability of entire system of Pars Asaluyeh port

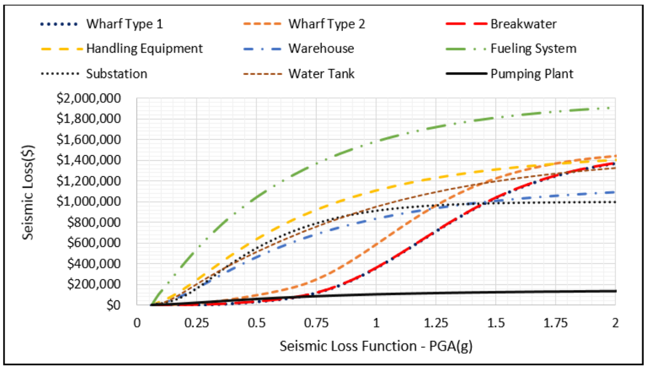

Figure 9. Direct economic loss for port structures vs. earthquake intensity

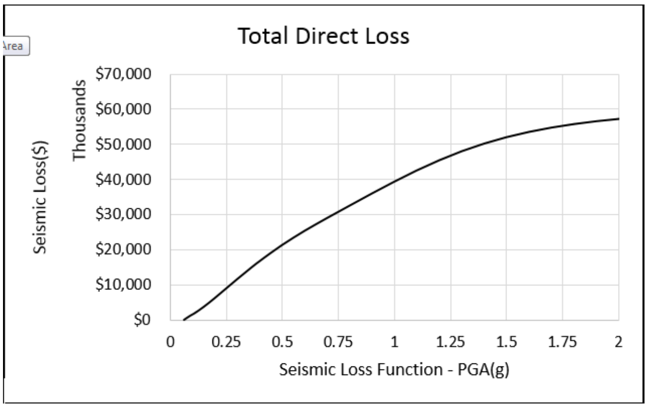

Figure 10. Direct economic loss function for entire port based vs. earthquake intensity

3.4. Direct economic loss curve of entire port system

By combining all direct economic loss functions based on the number and diversity of structures and equipment existing in the port, the total direct economic loss for the port can be calculated as shown in Figure 10. The figure indicates that, for low-intensity earthquakes, the

gradient of economic loss function for the entire port is larger and the gradient decreases with an increase in intensity of the earthquake. The reason for this is that, at lower earthquake intensities, damage increases at a higher rate than at higher earthquake intensities. Seismic retrofitting of port structures to decrease direct economic loss appears to be necessary.

Table 2. Damage, repair and recovery costs of equipment and structures of port based on HAZUS

Structure/equipment	Cost of repair/recovery ($1000)	Damage ratio per damage state			
		Slight	Moderate	Extensive	Complete
Wharf	1500	0.1	0.4	0.8	1
Breakwater	1500	0.1	0.4	0.8	1
Handling QUIP	2000	0.05	0.25	0.75	0.75
Storage	1200	0.1	0.4	0.8	1
Fueling system	2000	0.16	0.39	0.8	1
Substation	10000	0.05	0.11	0.55	1
Water tank	1500	0.2	0.4	0.8	1
Pumping plant	150	0.05	0.38	0.8	1
Control tower	5000	0.1	0.4	0.8	1
Buildings	1.5/m	0.09	0.35	0.73	1

4. SRDC for port structures

Risk density curves were used in order to assess the seismic performance of different port structures. The area below the SRDC represents the annual expected economic losses due to an earthquake. The risk-density curve denotes the annual distribution of risk probability density, which can be calculated using the earthquake risk probability density function for the site and the seismic economic loss function.

The earthquake risk curve can be calculated using the records of past earthquakes and/or active faults near the site. This curve represents the mean annual probability of exceedance of a definite earthquake magnitude. By applying a differential operator to this function, the earthquake risk probability density function can be obtained.

Figure 6 shows the curve for the mean annual exceedance of probability of an earthquake for the region. The loss function indicates the extent of loss incurred due to an earthquake of a specific magnitude. The SRDC function can be obtained by applying a multiplication operator to the probability density function and the economic loss function due to an earthquake.

Figure 6 represents the seismic performance status. The elliptical risk density curves represent weak seismic performance, the hump-shaped risk density curves represent average seismic performance, and the sharply-peaked risk density curve represents strong or high seismic performance. Using the SRDC results for the structures and equipment of the port, their seismic performance status can be assessed. Figure 11 shows the SRDC for structures and port equipment. According to the shape of the curve, engineering judgment can be made about the level of seismic performance.

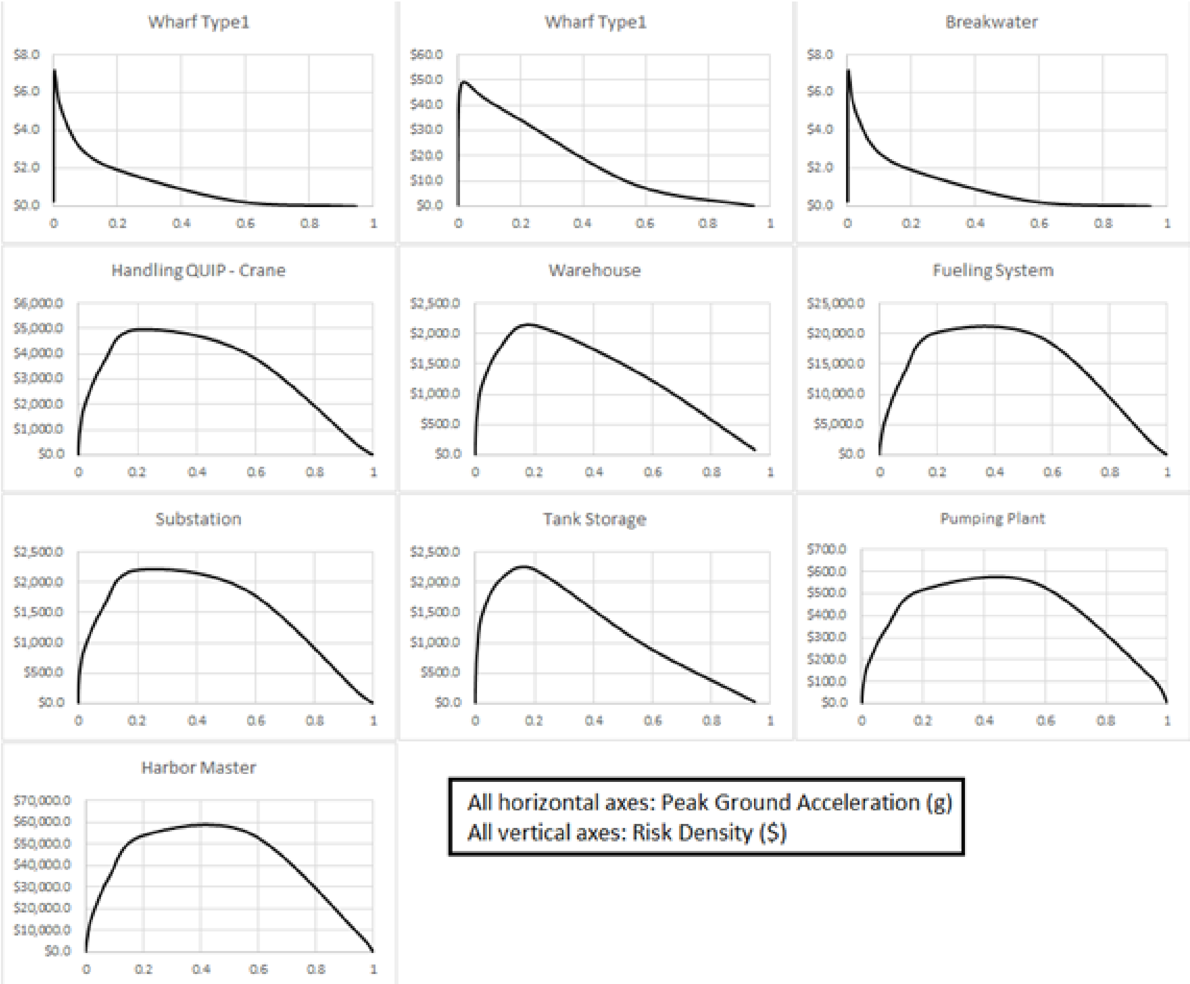

Figure 11: Seismic risk density curves for port equipment

Using the proposed methodology, the SRDCs were provided for different port structures. Because the SRDC curves for the breakwater and mooring structures type 1 and 2 have sharply-peaked risk density curves, they reflect appropriate seismic performance. Infrastructures such as storage tanks for liquids and cargo warehouses have hump-shaped risk density curves that denote average seismic performance. The curves for the pumping station, fueling system, cargo handling equipment, harbor master and power posts have elliptical risk density curves that denote weak seismic performance

5. Conclusion

The proposed methodology of comprehensive seismic risk assessment (CSRA) was used to extract the direct economic loss functions due to an earthquake for structures and equipment Pars Asaluyeh port. Figure 9 indicates that the minimum direct economic loss at low earthquake intensities was for the breakwater and mooring structures. At higher intensities, it was for pumping stations, power posts, and warehouses. It could be concluded that, at high earthquake intensities, the breakwater and mooring structures are more vulnerable than other port structures and will incur a higher cost for repair and recovery.

Seismic risk density curves (SRDCs) were used to accurately determine the seismic performance of the structures and equipment of Pars Asaluyeh port. The shapes of the SRDCs shown in Figure 11 indicate that the breakwater and mooring structures enjoy appropriate seismic performance and that the cargo handling equipment, pumping station, fueling system, harbor master, and power posts show weak seismic performance and require rehabilitation and retrofitting.

The conditional probability curves in Figure 7 for unserviceability of the port indicate that the infrastructure and cargo handling equipment are the cause of unserviceability. This conclusion agrees with engineering judgment in relation to the SRDCs.

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