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Simulation-Based Catastrophe-Induced Port Loss Estimation

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Abstract

Seaports are critical infrastructure systems in the international economy. They are at the same time vulnerable to various types of natural and man-made catastrophes due to their special coastal and low-lying locations. Traditional catastrophe risk analyses focused more on regions, port cities, and port communities. Limited studies assessed catastrophe risks on ports as a specific system. This paper aims to develop a catastrophe-induced port loss estimation framework, based on a port operation simulation model, actual terminal records and historical hazard records. By using the typhoon hazard and the Port of Shenzhen as a case study, we find that (1) the worst-case scenario of a typhoon impact could cause a total loss of US\$0.91 billion for a terminal with 16 berths; and (2) the annual predicted typhoon-induced loss for the same terminal for the next 5 years will reach approximately US\$64 million, accounting for 19.7% of the terminal net profit in 2015. The results provide useful references for various port stakeholders in catastrophe risk assessment and mitigation.

Key words: *Catastrophe risk, port, worst-case scenario, vulnerability, container terminal loss estimation, simulation*

1. Introduction

Seaports are critical infrastructure systems in global supply chains, whose smooth operations safeguard the movement of around 90% of world trade cargo (Lam and Yip, 2012). Despite the importance, due to their coastal locations, seaports are vulnerable to a number of natural and man-made catastrophes from both sea-side and land-side, such as earthquake, typhoon, tsunami, oil spill, and armed conflicts (Brooke, 2003; Leander and Lin, 2015; Oskin, 2015). Different from daily operational risks, catastrophe risks feature high negative impacts and low probabilities. Once being attacked by catastrophes, seaport structures and equipment (for example, quay walls, quay cranes, gantry cranes, and warehouses) tend to suffer serious physical damages, which may result in long-term port downtime and tremendous port economic losses. Any port inoperability will then propagate along supply chains to the industrial clusters that are served by the port, and thus negatively impact local, regional, and even global economy. One oft-cited example is the 1995 Kobe earthquake. A large portion of the port infrastructures in the Port of Kobe was damaged, causing its world ranking to drop from the sixth (1994 ranking, measured in TEU) to the seventeenth (1997 ranking, after repairs and rebuilds completed) (Chang, 2000). This disaster alone cost the Port of Kobe US\$5.5 billion (in 1995 US dollars) of direct physical damage and over US\$6 billion of economic loss (Na and Shinozuka, 2009).

Previous catastrophe risk analyses focused more on regions, countries, and coastal cities (see Pethick and Crooks, 2000; United Nations Development Program (UNDP), 2004; Cardona, 2005; Dilley, 2005; Hanson et al, 2011; Yu et al., 2015; Kermanshah and Derrible, 2016). Limited studies addressed catastrophe risks occurred in ports. Analyzing catastrophe risks at the port level is a challenging work due to (1) the complexity and confidentiality feature of port operation; and (2) the limitation of publicly available port data on catastrophe hazards. Therefore, this paper aims to address the research gaps and deal with such difficulties by firstly identifying major catastrophe hazards occurred via means of literature review. Subsequently, a catastrophe-induced seaport loss estimation framework is developed, in which direct physical damage loss and direct economic loss are estimated based on actual port operation records and the developed port catastrophe hazard database. To achieve this, a terminal operation simulation model is developed by combining a group of primary

terminal operations, including ship arrival, berth allocation, crane allocation, loading and unloading, as well as ship departure.

Simulation techniques are adopted for its wide use in port and terminal operation planning (Dragovic *et al*, 2016) and its merit in simulating the extreme events that can rarely happen in real life. In this study, the software package of ARENA (Rockwell Automation, 2006) is used for the development of the simulation model. The developed terminal operation model is verified and validated with actual terminal records. The hazard of typhoon is particularly selected because it is a common hazard type threatening seaport safety and its scarcity in the existing literature.

The port of Shenzhen, China is selected for demonstrating the application of the proposed framework due to the large import and export cargo volumes and the consideration of data availability. The major catastrophe hazard threatening the Port of Shenzhen is firstly identified. The results obtained from the framework include the current estimated decreased container throughput, the port physical damage loss and economic loss under various disrupted scenarios, as well as the estimated total historical typhoon-induced port loss and the predicted loss for the next five years. Results show their industrial applicability as useful references for port operators in terms of port catastrophe risk analysis and formulation of port catastrophe risks contingency plans. Outputs can also be useful for other port stakeholders, such as local regulators, carriers, (re)insurance companies, regarding port site selection, route planning, and port catastrophe insurance policy pricing.

The rest of the paper is organized as follows. Section 2 firstly identifies major catastrophe hazards occurred in ports. Subsequently, previous literature is reviewed regarding port loss estimations, with research gaps identified. Section 3 describes the proposed catastrophe-induced port loss estimation framework in detail, which includes the establishment of the terminal operation simulation model, the illustration of hazard-specific disruption inputs, and the method for estimating total losses. By using the Port of Shenzhen and typhoon hazard as an example, Section 4 presents a feasible application of the proposed framework in real-world cases. Results, discussion, and several implications are shown in Section 5. Finally, Section 6 concludes the paper with main contributions.

2. Catastrophes occurred in ports

2.1. Identification of hazards

At the first phase of risk analysis, analysts are required to identify and analyze all types of hazards that have already led to or could potentially lead to consequences to a specific target. Hurricane/typhoon and earthquake are identified as natural catastrophic hazards that can affect ports in this research. As shown in Figure 1, the two hazard types account for around 94 percent of total insured loss among the 10 worst natural catastrophes that caused losses to ports worldwide. Unlike natural catastrophes, the universal metrics for gauging the severity of man-made catastrophes are absent, or of limited application in other cases. Taking reference from catastrophe (re)insurance industry, we only focus on events with insured loss of 19.7 USD millions or above (Swiss Re, 2016). Major fire and explosion, oil spill, and war are recorded to have caused such scale of loss to ports in the past (Allen and Vogel, 1996; History, 2009; History 2010; Swiss Re, 2016).

Fig.1. Insured loss percentage of each natural hazard type affected ports.

Source: Computation by authors, based on Swiss Re (2016)

The list is then validated through interviews with selected maritime experts from worldwide and various port-related fields, whose organization, working location, and job title are listed in Appendix A. It was suggested to remove war from the list in this study, as hostile acts will require different research methods from other unintended consequence events. Thus, the scope of this study is determined as shown in Figure 2.

Fig.2. Types of catastrophes occurred in ports.
Source: Authors

2.2. Literature review on catastrophe-induced port loss estimation

Regarding natural catastrophes, some works attempted to estimate the port economic loss caused by earthquake (Federal Emergency Management Agency (FEMA), 1999; Pachakis, *et al*, 2004; Na and Shinozuka, 2009; Burden *et al*, 2016). They adopted the container terminal operation simulation model and wharf component fragility curve for the estimation of disruption periods and container throughput reduction. The seismic risk reduction methods comparison was carried out by Werner *et al* (1997). Regarding wind hazard, Zhang and Lam (2015) estimated the extreme wind event-induced port economic loss by evaluating the average monthly port disruption period using local weather database and port regulations. With respect to man-made hazards, Ronza *et al* (2009) developed a set of guidelines for evaluation of port damages which considered the loss of human lives and equipment, and environment damages.

It can be seen that most of the existing literature related to catastrophe-induced port loss focused on the hazard of earthquake. This may result from the extensive research on seismic behavior of hydraulic structures in harbor engineering (for example, Werner, 1998; Atsushi *et al*, 2004; Roeder, *et al*, 2005). However, research on other major catastrophe types that affect ports, such as typhoon, tsunami, especially man-made catastrophes, are limited. Moreover, studies related to wind-induced port loss estimation did not include the worst-case scenario, in which ports are attacked by disasters with extremely high magnitudes or long return periods. Thus, the terminal

operation disrupted period is the only consideration when it comes to the estimation of port losses (Zhang and Lam, 2015). Additionally, the estimation of disruption period is based on the urban wind disaster database, which cannot reflect the actual distance between the wind path and the port. Therefore, in order to enhance the accuracy of estimation, this study not only considers disrupted periods but also longer recovery periods for worst-case scenarios. Also, a more nuanced database for port typhoon events is established, which is described in detail in Section 4.2.1.

3. Method

3.1. Catastrophe-induced seaport loss estimation framework

This section explains in detail the proposed method for catastrophe-induced port loss estimation. As shown in Figure 3, a terminal operation simulation model is firstly established under intact conditions, which is validated through the actual terminal operation records and container throughput. By considering various identified disrupted scenarios, terminal operations under disrupted conditions are then simulated. The decreased container throughput is obtained by comparing container throughput obtained from intact and disrupted scenarios (as shown in the green box), based on which, the container throughput vulnerability surface and the estimation of direct port economic loss are obtained. Direct physical loss is calculated by performing the probabilistic estimates of physical damages and Monte Carlo technique. Finally, the total port direct loss induced by one catastrophe event is estimated as the sum of physical loss and economic loss (shown by the yellow box). Detailed procedures are presented in the following sections, regarding simulation model development (Section 3.2), data acquisition (Section 4.1, 4.2 and 4.3), and finally, the methods for port loss estimation (Section 3.4).

Fig.3. Method flow chart.
Source: Authors

3.2. Terminal operation simulation model

3.2.1. Model development

A typical container terminal mainly consists of structures such as gate, road within terminal, container yard, container freight station (CFS), berth, and cargo handling equipment such as quay crane, gantry crane, as well as fork lift (Talley, 2009). These terminal structures and cargo handling equipment, together with production auxiliary equipment guarantee the smooth operation of a container terminal, which includes loading and unloading, cargo storage, as well as cargo collection (export) and distribution (import). Among these terminal operations, loading and unloading system is considered to be the most critical operation process in determining the throughput of a port (Kim and Park, 2004). Thus, in the development of the terminal operation simulation model, this paper mainly focuses on the process of container loading and unloading.

The first step in developing a simulation model is to identify the simulation procedures, the input information, the output information, and the modeling assumptions. As shown in Figure 4, the simulation starts with ship arrival and ends with ship departure. Once an entity of “ship” is generated, it goes through the procedures of berth allocation, berthing, quay crane allocation, loading and unloading, unberthing in sequence (Dragović *et al*,

2005). The following paragraphs describe each procedure in detail.

Fig.4. Terminal operation simulation flow chart.
Source: Authors

Ship arrival is a queueing system and is implemented by the “Create” module in Arena. The interval time of ship arrival is calculated based on the terminal record. In the real container terminal operation, the ship arrival schedule of liner ships is relatively fixed. Assumed ship arrival distribution is usually adopted by existing literature (Dragović *et al*, 2016). In the present study, actual terminal operation record is collected and used for the benefit of enhancing the accuracy of simulation outputs.

After the ship entity is generated, it is transmitted to the procedure of berth allocation, which includes ship type classification, berth availability checking, and berthing (Dragović *et al*, 2006). In general, berths differ in size and are generally allocated to ships according to ship size. The first-come, first-served rule is adopted here, although in reality, the berth priority could follow the contract. Therefore, in this study, before the ship is allocated with a berth, ship size is classified based on lift per call (LPC, total moves of quay crane trolley per ship call). The probabilities of each LPC category are set in the “Decided” module, based on which the size of arrival ship is assigned. Then,

the available berth will be allocated to the ship according to the ship size. If no berth is available at the moment, the ship will join the queue until there is an available berth. The berth access time is obtained as the difference between actual time of berthing and actual time of arrival.

Once a ship entity finished berthing, the process of quay crane allocation begins. In this paper, quay cranes are allocated based on LPC. The statistical distribution of crane numbers for each LPC category is calculated and is assigned in the “Assign” module. The module of “Decide” checks the availability of quay cranes. If all cranes are occupied, the ship waits in the berth until other ships release cranes. Idle time before, which refers to the time a ship waits for quay crane allocation, is calculated as the difference between loading and unloading commence time and actual time of berthing.

Table 1

Model input	
Port information	Number of berths
	Number of quay cranes
Ship arrival information	Actual time of ship arrival
	Actual time of berthing
	Loading and unloading commence time
	Loading and unloading complete time
	Actual time of ship departure
Quay crane utilization information	Total moves of quay crane trolley per ship call (LPC)
	Number of quay crane allocated per call
Model output	
Ship arrival number	
Container throughput	

Terminal operation model input and output under intact conditions.

Source: Authors

After being allocated with quay cranes, the procedure of loading and unloading starts. The term “berth operation time” is used to refer to the time of loading and unloading, and is obtained as the difference between operation complete time and operation commence time. Likewise, idle time after, referring to the unberthing time for a ship, is calculated as the difference between actual time of departure and operation complete time. The statistical distributions of berth access time, idle time before, berth operation time, and idle time after are obtained through the function of “Input analyzer” and set in “Assign” module. Arena offers a function to record default and customized outputs by using the “Record” module. In this study, ship arrival number and container throughput

are identified as the output of the model. The input information, output information and computing method for various necessary variables are summarized in Table 1.

3.2.2. Model verification and validation

Model verification and validation are critical steps in the development of a simulation model. The process of verification ensures the developed model behaves following model builders' intentions, while validation means the process that ensures the model represents the real system appropriately (Kelton, 2002). Taking the advantage of the animation function Arena, the process of verification is performed. After setting the "Max Arrivals" field in the Create module to "1" and the model running speed to slow, the animation of the ship entity is observed. It is shown that the ship entity goes through each module in sequence without any pauses, and finally disappears in the "Dispose" module. No error message returns during the whole process. Thus, it can be concluded that the built model behaves in the way in accordance with the builders' intentions. Validation is conducted by comparing model outputs, namely, the number of ship arrival and container throughput (in TEU), with actual terminal operational records. An initial replication number is set and is further adjusted by Equation (1) (Kelton, 2002):

$$n \cong n_0 \frac{h_0^2}{h^2} \quad (1)$$

n_0 – the initial replication numbers;

h_0 – the half width of the results obtained from n_0 replications;

h – the ideal half width.

3.2.3. Hazard-specific disruption inputs

Having developed the simulation model under intact operation condition, the hazard-specific disruption inputs are added to obtain the container throughput under disrupted conditions. This process begins with the identification of hazard-specific disrupted scenarios. The worldwide recognized gauges of physical severity of disasters are adopted for a scaling purpose, such as the seismic intensity for earthquake (Medvedev and Sponheuer, 1969), Saffir-Simpson scale (Schott *et al*, 2012) for hurricane/typhoon, spill tonnage (Swiss Re, 2016) for oil spill, and TNT equivalent (Chemical Engineering Progress and American Institute of Chemical Engineers

(CEPAICE), 1967) for explosion. Subsequently, the probabilistic estimate of port physical damage degree as well as the disrupted and recovery period for each scenario is obtained by consultations with port engineers. A detailed illustration for the case of typhoon hazard is carried out in section 4.

3.3. Estimation of total catastrophe-induced port loss

Taking reference from HAZUS (FEMA, 1999), catastrophe-induced loss generally constitutes of four parts: direct physical loss, induced physical loss, direct economic loss, and indirect economic loss. Direct physical loss refers to any structural or equipment damages caused by the principle hazard in the hazard chain. While induced physical loss means the damages led by the induced hazards in the hazard chain. In practice, the physical damage loss is commonly evaluated as the repair or replacement fee (Na and Shinozuka, 2009, Ronza *et al*, 2009). Production and income reduction due to the direct physical damage result in direct economic losses. The indirect economic loss is associated with the economic impact of other sectors except for ports, such as, the loss of manufactures in the industrial clusters that served by the affected port. In this paper, only the direct physical damage and economic loss are considered. The total direct catastrophe-induced port loss is estimated as the sum of direct physical and direct economic loss, as shown in Equations (2)-(6).

$$TL = PL + EL. \quad (2)$$

$$PL = \sum_{n=1}^N TLP_n P_n; \quad (3)$$

$$TLP = \sum_{m=1}^M \sum_{k_m=1}^{K_m} L_{mk_m}. \quad (4)$$

$$EL = \sum_{n=1}^N C_n^{load\&unload} T_n^{de}; \quad (5)$$

$$T_n^{de} = T_n^{int} - T_n^{dis}. \quad (6)$$

TL – Total loss of the port caused by one catastrophe event;
 PL – Direct physical loss of the port caused by one catastrophe event;
 EL – Direct economic loss of the port caused by one catastrophe event;
 N – Number of terminals in the study port;
 TLP_n – Total loss potential of the n th terminal;
 P_n – Probability of damage of the n th terminal;
 M – Type of port damaged components;
 K_m – Number of port components of the m th type;
 L_{mk_m} – Loss potential of k th component under the type of m ;
 $C_n^{load\&unload}$ – The loading and unloading charge per TEU at the n th terminal;
 T_n^{de} – Decreased container throughput at the n th terminal;
 T_n^{int} – Container throughput at the n th terminal under intact condition;
 T_n^{dis} – Container throughput at the n th terminal under disrupted scenario.

In detail, terms T_n^{ins} and T_n^{dis} in Equations (6) are obtained as outputs of the established terminal operation simulation model. By simultaneously considering $C_n^{load\&unload}$, EL is estimated. PL is jointly determined by TLP_n and P_n . Through collecting and investigating of port components behaviors during catastrophes, it was found that certain port components show higher vulnerability to certain catastrophe hazards. For example, as shown in Table 2, cranes, vehicles, and navigation aids are more vulnerable to hurricanes/typhoon events. Quay walls, yards, roads, cranes, warehouses and port auxiliary systems are more vulnerable to earthquakes. Therefore, in this study, key vulnerable components are considered in the estimation of TLP_n . Regarding the generation of P_n , one way is by referring to the component's fragility curves developed for wharf structures. When such fragility information is missing, another possible way is through consulting of experienced port operators and engineers. The method of obtaining P_n in this paper is illustrated in Section 4.3.

Table 2

Catastrophe type	Major physical damage mode	Key vulnerable component	Reference
Hurricane/ typhoon	Derailed cranes; collapsed cranes; overturned container trucks; damaged warehouse rooftops; drifted navigation aids	Quay crane; gantry crane; container truck; navigation aids	Lloyd's List, 1999; Nadkarni, 2001; Chambers, 2003; Frittelli, 2005; Wallis, 2009; Hui, 2010; Smythe, 2013; Lam and Lassa, 2017
Earthquake	Fractured quay walls, jetties, yards, and roads; deformation of crane rails; buckling and bending of crane legs; collapsed crane structures; damaged warehouse; bending pipelines and joints; disrupted water, power, natural gas supply and telecommunication; silted channels	Quay wall; jetty; yard; road; quay crane; gantry crane; crane rail; warehouse; auxiliary system; channel	Glass, 1994; Prescott, 1996; Werner, 1997; Coppack, 2002
Major oil spill	Major environmental pollution; polluted oil storage facilities	Oil storage facility	Kelly, 2011; Lin, 2016
Major fire and explosion	Damaged oil refineries, chemical storage facilities, port equipment, warehouses and buildings	Oil refinery; chemical storage facility; building	Lloyd's List, 2000; Leander and Lin, 2015; Osler, 2015

Hazard-specific key vulnerable port components identification.

Source: Compiled by authors

Furthermore, the proposed measurement is expanded for prediction of future catastrophe-induced losses. To achieve this, a port catastrophe database is established in order to analyze the frequencies of a certain type of catastrophe that affected the port under various disrupted scenarios. By considering the yearly adjustment coefficients, future catastrophe-induced losses are estimated by using Equations (7) and (8).

$$TL_{sum} = \sum_{y=1}^Y \sum_{p=1}^P S_p TL_p \alpha_y; \quad (7)$$

$$\alpha_y = T_y / T_{base \ year}. \quad (8)$$

TL_{sum} – The total port loss over predictive period against one type of catastrophe;

Y – Predictive period;

P – Number of disrupted scenarios;

S_p – The frequency of the p th disrupted scenario per year;

TL_p – The expected total loss of the p th disrupted scenario per year;

α_y – The adjustment coefficient of total loss for the y th year;

T_y – The predictive throughput of the port in the y th year.

Primary data are collected from representative ports that have large international influence and at the same time lie in disaster-prone areas. The largest terminal of the Port of Shenzhen is selected, which contains 16 berths, 81 quay cranes, and 222 gantry cranes. The Port of Shenzhen is selected because it is among the largest container ports worldwide, which ranks the third in the 2015 World Shipping Council (WSC) Container Ports Ranking (WSC, 2015). Moreover, as shown in Figure 5, the Port of Shenzhen lies in the South China Sea area, which is among the worldwide major typhoon basins in the northern hemisphere (World Meteorological Organization (WMO), 2015). News reports regarding port closures, operation disruptions are frequent during typhoon seasons (Chambers, 2003; Frittelli, 2005; Wallis, 2009; Smythe, 2013; Lam and Lassa, 2017), however, limited loss quantification methods are found addressing this issue. Thus, the Shenzhen Port and the catastrophic hazard of typhoon are selected as the case study in this work.

4.1. Terminal operation data acquisition and statistical analysis

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typhoon events according to the statics from 1994 to 2015. Thus, the operation data from August onwards are used as inputs. Considering the varied port disrupted periods in each disrupted scenario, different data periods are used for different scenarios. Details are shown in Table 3.

Table 3

Data period	Scenario no.
2016.8	1-5, 8-10, 14-15
2016.8-2016.9	7,19-20
2016.8-2016.10	6
2016.8-2016.11	13, 25
2016.8-2016.12	12, 18, 24
2016.8-2017.2	11, 17, 23
2016.8-2017.3	16
2016.8-2017.4	22
2016.8-2017.5	21

Data periods used for each scenario.

Source: Authors

The operation data from 1st January 2016 to 31st July 2016 are adopted for the validation of the simulation model. As shown in Table 4, it is observed that, during this operation period, the item of quay crane efficiency and most of the functions of LPC category follow Beta distribution, except for the LPC category seven which follows Weibull distribution. Both idle times follow Logitnormal distribution and the interval time of ship arrival follows exponential distribution. By analyzing the collected terminal operation records, the LPC of the Port of Shenzhen is categorized into seven groups, as shown in Table 5. It is seen that the percentage of ship arrival decreases with the increase of LPC. In particular, LPC category of 0-999 makes the maximum proportion, reaching 44.62%.

Table 4

Model Input	Expression
ship arrival	$-0.001 + \text{EXPO}(1.96)$
LPC1	$14 + 985 * \text{BETA}(1.02, 1.32)$
LPC2	$1\text{e}+003 + 999 * \text{BEA}(0.991, 1.15)$
LPC3	$2\text{e}+003 + 992 * \text{BETA}(0.755, 0.974)$
LPC4	$3.01\text{e}+003 + 980 * \text{BETA}(0.886, 1.31)$
LPC5	$4.01\text{e}+003 + 990 * \text{BETA}(0.586, 0.848)$
LPC6	$5.13\text{e}+003 + 827 * \text{BETA}(0.716, 0.953)$
LPC7	$6.01\text{e}+003 + \text{WEIB}(220, 0.474)$
Quay crane efficiency	$-1 + 5.93 * \text{BETA}(43.6, 39)$
IdleTimeBefore	$1 + \text{LOGN}(2.71, 4.62)$
IdleTimeAfter	$\text{LOGN}(0.975, 0.541)$

Model input and statistical distribution.

Source: Authors

Table 5

LPC category	Description	Number of ships	Percentage
1	0-999	1295	44.62%
2	1000-1999	937	32.29%
3	2000-2999	453	15.61%
4	3000-3999	161	5.55%
5	4000-4999	30	1.03%
6	5000-5999	18	0.62%
7	6000-	8	0.28%
Sum		2902	1

LPC classification.

Source: Authors

An initial replication number of 40 was set and then calibrated to 96 after adjustment with the ideal half width set to 0.05. Hence, a final replication number of 100 is adopted. Table 6 shows the comparison between the simulation results and the actual records from 1st January 2016 to 31st July 2016. The simulated results agree well with the actual operation of the Port of Shenzhen.

Table 6

Parameters	Ship arrival number		Container throughput ('000 TEUs)	
	Reality	Simulation	Reality	Simulation
Berths no. 1-16	2902	2899	6519.5	6516.0

Model validation.

Source: Authors

Table 7

Major exposure	Number	Price/unit	Total
Quay crane	81	\$1,700,000	\$137,700,000
Gantry crane	222	\$1,000,000	\$222,000,000
Container truck	200	\$450,000	\$90,000,000
Other equipment			\$2,000,000
Total Potential loss			\$451,700,000

Major typhoon exposures of the case study port.

Source: Authors

As discussed in Section 3.3, cranes, vehicles, and navigation aids are considered as major exposures in the estimation of direct physical loss against typhoon hazard. Table 7 shows the economic values of the major exposures at the Port of Shenzhen, collected via consultation with the port authorities.

4.2. Port typhoon data acquisition and treatment

4.2.1. Establishment of port typhoon database

In this study, we use the database of IBTrACS (Knapp *et al*, 2010) for the hurricane/typhoon center path latitude-longitude coordinates. According to the data availability, the study period is from 1994 to 2015. The port coordinates are retrieved from The World Port Index (National Geospatial-Intelligence Agency (NGIA), 2016). By using Equation (9), the great circle distance between typhoon centers and ports in the same area are calculated. Furthermore, the wind speed at the strike distance (the minimum distance between the typhoon center and the port) are recorded. Thus, a port typhoon database containing the information of past typhoon events attacked the port, the frequencies, the strike distances, and the wind speeds at the strike distances is established.

$$d = r \arccos(\sin(y_1)\sin(y_2) + \cos(y_1)\cos(y_2)\cos(x_2 - x_1)) \quad (9)$$

d – The great circle distance between the geographical latitude and longitude of two points;

$(x_1, y_1), (x_2, y_2)$ – The latitude and longitude of the two points;

r – The radius of the earth.

4.2.2. Determination of disrupted scenarios

To identify the factors that influence typhoon-induced port disruption and recovery periods, records of worldwide typhoon events that caused losses to ports were collected. It is found that the amount of information on typhoon events affecting ports is scarce with fewer details released regarding disrupted periods and recovery periods in the public domain. By making every possible use of valuable information, as shown in Figure 6, it is found that typhoon strike distance and wind speed at the strike distance largely impact port disrupted periods and recovery periods. To be more specific, the shorter the strike distance and the larger the wind speed, the longer the disrupted period and recovery period.

Fig.6. Port recovery periods on given strike distance and wind scale (1998-2015).

Source: Drawn by author, based on Nadkarni, 1998; Chambers, 2003; Sturgis et al., 2014; Liu, 2016

Having identified the major factors of strike distance and wind speed, the next step is to define scopes and scales of these factors. Referring to actual practices of terminal operation, the strike distance is firstly separated as the direct strike distance (0-200km) and the vicinity strike distance (more than 200km) (Zong and Chen, 1999). Considering the largest radius of a Category 5 hurricane is approximately 500 km (Daniels *et al*, 2006), the upper bound of wind speed is set to be 500 km. Thus, a range of 0 to 500 km for the strike distance, with a step size of 100 kilometers is adopted. Regarding the scale of wind speed, the 1 to 5 rating system from the Saffir-Simpson Hurricane Wind Scale (Schott *et al*, 2012) is adopted for its worldwide recognition. Finally, as shown in

Figure 6, 25 disrupted scenarios (indicated by the number in each block) are determined as the basis for typhoon frequency analysis, port physical damage probability analysis, and estimation of port disrupted and recovery periods.

4.3. Analysis of typhoon frequency, determination of physical damage probabilities, disrupted and recovery periods

Based on the identified disrupted scenarios, analysis of past typhoon frequencies in the area of the Port of Shenzhen is carried out. As seen in Appendix B, a total of 30 typhoon events is found to hit the Port of Shenzhen within a strike distance of 500 km in the study period, which equals to an average of 1.43 per year. Among which, 25 cases fall in the scale of Category 1, while 5 cases belong to Category 2. The typhoon events occurred the most in August and September, reaching up to 9 and 10 cases, respectively. The frequencies of typhoon events are shown in Table 8, where the disrupted scenarios 3 and 4 appeared the most, accounting for 8 and 9 cases with frequencies of 0.38 and 0.43, respectively. The most destructive typhoon is Typhoon Vicente in 2012 (a Category 2 typhoon event with a strike distance of 99 km). By using Equation (7) and (8), the typhoon frequencies of each scenario are used as inputs in the past typhoon-induced port loss estimation as well as the future loss prediction, which is illustrated in Section 5 in detail.

Furthermore, as shown in Table 8, the probabilistic estimates of typhoon-induced port physical damages, as well as the disrupted and recovery periods under each scenario for the Port of Shenzhen are obtained by consultation with selected port engineers. The disrupted and recovery period is added to the “Failure data” module under “Resource data” module in order to obtain the container throughput under each disrupted condition, as the term T_n^{dis} in Equation (6). By subtracting the disrupted container throughputs (T_n^{dis}) from the intact container throughputs (T_n^{int}), the decreased container throughputs (T_n^{de}) are obtained. Subsequently, by using Equations (2)-(5), physical and economics losses are obtained. The results are shown in the next section.

Table 8

Typhoon scale	Disrupted input	Strike distance (km)				
		0-100	101-200	201-300	301-400	401-500
Category 1	Scenario	1	2	3	4	5
	Typhoon frequency	0.05	0.14	0.38	0.43	0.19
	Disrupted and recovery period (day)	0-30	0-10	0-7	0-4	0-1
	Physical damage probability (%)	9.6-12.0	7.2-9.6	4.8-7.2	2.4-4.8	0-2.4
Category 2	Scenario	6	7	8	9	10
	Typhoon frequency	0	0	0.1	0.14	0
	Disrupted and recovery period (day)	10-90	10-50	0-20	0-10	0-2
	Physical damage probability (%)	16.8-21	12.6-16.8	8.4-12.6	4.2-8.4	0-4.2
Category 3	Scenario	11	12	13	14	15
	Typhoon frequency	0	0	0	0	0
	Disrupted and recovery period (day)	20-200	10-150	0-100	0-30	0-10
	Physical damage probability (%)	51.2-64	38.4-51.2	25.6-38.4	12.8-25.6	0-12.8
Category 4	Scenario	16	17	18	19	20
	Typhoon frequency	0	0	0	0	0
	Disrupted and recovery period (day)	60-240	50-190	40-140	10-50	0-40
	Physical damage probability (%)	79.2-99	59.4-79.2	39.6-59.4	19.8-39.6	0-19.8
Category 5	Scenario	21	22	23	24	25
	Typhoon frequency	0	0	0	0	0
	Disrupted and recovery period (day)	90-300	80-250	70-200	30-15	0-10
	Physical damage probability (%)	79.2-99	59.4-79.2	39.6-59.4	19.8-39.6	0-19.8

Estimated disrupted and recovery periods of typhoon-induced disruption for the Port of Shenzhen.

Source: Authors

5. Results, discussion, and implications

This section presents the results of catastrophe-induced port loss estimation, performed on the case study of the Port of Shenzhen against typhoon hazard. The main outcomes include the decreased container throughput, the estimated typhoon-induced port direct physical losses and economic losses under various typhoon disrupted scenarios, the annual estimated typhoon-induced loss of the studied terminal from 1994 to 2015 and the predicted loss for the next 5 years. In addition, several applications and implications of the results for various end-users are presented.

Table 9 shows the simulated container throughput reduction for each disrupted scenario as well as the percentage of the reduction in the intact throughput. It can be seen that, for each typhoon scale, the decreased container throughput declines as the strike distance increases, while for each strike distance, the decreased container throughput goes up with the increase of typhoon scale. The lowest container throughput reduction appears when a Category 1 typhoon hits the port at the distance interval of 401-500km, which is 4,158 TEUs. The highest is approximately 1,000 times higher than this value, reaching 4,247,361 TEUs. Such worst case appears when a Category 5 typhoon hit the port at the distance interval of 0-100km. The proportion of decreased throughput in the intact throughput ranges from 0.03% to 34.51%.

Table 9

Typhoon scale	Output	Strike distance (km)				
		0-100	101-200	201-300	301-400	401-500
Category 1	Decreased	432161	140394	89774	47258	4158
	Decreased/Intact	3.47%	1.13%	0.72%	0.38%	0.03%
Category 2	Decreased	1246488	788118	281448	140394	19640
	Decreased/Intact	10.02%	6.34%	2.26%	1.13%	0.16%
Category 3	Decreased	2223579	1917256	1199758	432161	140394
	Decreased/Intact	17.88%	15.42%	9.65%	3.47%	1.13%
Category 4	Decreased	3181954	2626275	2241383	788118	488386
	Decreased/Intact	25.59%	21.12%	18.02%	6.34%	3.93%
Category 5	Decreased	4247361	3661466	2993226	2206839	1199758
	Decreased/Intact	34.15%	29.44%	24.07%	17.74%	9.65%

Simulated typhoon-induced decreased container throughput.

Source: Authors

Figure 7 shows the typhoon-induced throughput vulnerability surface for the terminal under study. This vulnerability surface shows its application in identifying the most frequent typhoon disrupted scenario and its throughput decrease in an intuitive way. In addition, a more precise throughput decrease is generated through interpolation. For the Port of Shenzhen, disrupted scenarios 3 and 4 appeared the most in the past two decades, whose frequencies are 0.38 and 0.43 with a decrease in container throughput of 89,774 TEUs and 47,258 TEUs, respectively. Considering the estimated total loss of US\$38 million and US\$22 million (generated by Equation (2)-(6)), the annual loss induced by these 2 scenarios reaches approximately US\$24 million.

Fig.7. Container throughput vulnerability surface for the case study.
Source: Authors

It should be noted that, in practical terminal operations, when the port is affected without major physical damages, the disrupted period and the recovery period are less significant. A 1 or 2 days' disruption is common for a terminal under study, while the recovery period largely depends on the degree of physical damages. The small amount of container decrease is able to be recovered by speeding up the operation productivity after the port reopens. For example, in the case of a loading port (which means the port's export boxes outnumber the import boxes), container ships that intend to call at the disrupted port may cancel the call, and unload the containers at other available ports along the itineraries. The containers to be loaded in the disrupted terminal would wait in the yard for the next dispatched container ships until the port operation restarts. Similarly, the arriving ships could slow steaming in advance or wait in a sheltered anchorage until the typhoon leaves an unloading port (which means the port's import boxes outnumber the export boxes). However, situations can be quite different when serious physical damages occur. One to two weeks of disruption period and several months' recovery period are found in real cases (Nadkarni, 1998; Frittelli, 2005). The long-term disrupted and recovery period would drive liner shipping companies away temporarily or even permanently to alternative ports in the vicinity. In 2003, after the strike of Typhoon Maemi (disrupted scenario 11: a Category 3 typhoon impacted the Port of Busan at a very near strike distance of 76km), the Port of Busan lost half of its customers. Kwangyang Port and Masan Port are chosen as

alternative ports for carriers and key manufacturers, such as LG Electronics (Flynn, 2003; Lee, 2003). In 2005, Hurricane Katrina (disrupted scenario 11: a Category3 hurricane with an even shorter strike distance at 65km) attacked the Port of New Orleans and other Lower Mississippi ports. Shipping lines serving the affected ports diverted their operations to Houston, Freeport, Pensacola and Port Everglades (Alexander and Irwin, 2005).

Figure 8 shows the estimated physical loss, economic loss and total loss of the port in each strike distance interval. It is observed that for every distance interval, the total loss increases with the rise of the typhoon scale, while the total loss increases with the decrease of the strike distance on each typhoon scale. According to our estimation, the largest typhoon-induced total loss in a single attack reaches 0.91 billion US dollar for a terminal containing 16 berths or terminals of similar size. As the strike distance increases, the average proportion of physical loss becomes smaller, from an average proportion of 54.07% in the case of 0-110 km to 39.48% in the case of 401-500 km. Such a change is consistent with the reality that the closer the strike distance, the higher the probability of structures and equipment damages.

Fig.8. Estimated loss for the case study for each strike distance interval.
Source: Authors

Furthermore, we expand the proposed method to calculate the past typhoon-induced port loss as well as to predict the future loss. As shown in Figure 9, from 1994 to 2015, the total estimated typhoon-induced loss for the terminal reaches around US\$0.56 billion (in 2016 US dollar), which equals approximately US\$27 million per year. On a rough estimation, the yearly typhoon-induced loss accounts for 8.3% of the terminal net profit in 2015. It is predicted that for the next 5 years (from 2016 to 2020), the loss will reach approximately US\$0.32 billion, which equals to US\$64 million on a yearly basis, accounting for 19.7% of the terminal net profit. It is seen that, given the same typhoon frequency, the predicted annual average typhoon-induced loss has more than doubled. This implies a higher exposure of the terminal against the hazard of typhoon.

Fig.9. Typhoon-induced port loss (1994-2020).
Source: Authors

Since it is not possible to reduce the frequency of natural disasters, the vulnerability of exposures becomes a vital factor in port typhoon risk management. Lam and Su (2015) proposed several mitigation strategies for port operators in dealing with natural disasters, including the use of warning system in port operation, the establishment of port strategic alliances, updating contingency plans and drills as well as the improvement of port infrastructures. Contingency plans and drills specifically for typhoon are widely adopted by ports facing regular typhoon risks (see contingency plans such as Zhuhai Port Authority, 2011 and Dalian Port 2015). Such plans and drills show their effects to prevent short-term disruption impacts (such as disrupted scenario 2, 3, 4, 5, 9, 10, and 15, in which the longest ports disruption periods are within 10 days). Regarding extreme cases (such as disrupted scenario 11, 16, 21, 22,

and 23, in which the longest port disruption periods have potentials to reach 200 days), port operators are suggested to put more efforts in adopting early warning systems, establishing regional port alliances and strengthening the wind proofing property of port infrastructures and equipment. However, these strategies require time-consuming and high investments, port operators should weigh the pros and cons based on the probability of extreme events occurring in the port area, and the estimated catastrophe-induced port loss. When the probability and the loss exceed some certain thresholds, it is advisable to designate catastrophe emergency coordinators or establish a catastrophe prevention department for ports with high strategic positions. This department should collaborate with the local government, the meteorological department, vicinity port operators, and port users to guarantee the visibility of information among all the related parties. It is also suggested for those regional governments who are located in disaster-prone areas to draft contingency plans specifically for worst cases, where the whole port may lose its functions for a long time.

To test the accuracy of the proposed model, we propose a validation approach by comparing the decreased container throughput obtained from the proposed method with the decreased container throughput estimated by the reported growth-rate. By using the case of 2003 Busan Port and Typhoon Maemi as an example, it is reported that the port's container throughput was expected to have an average growth rate of 22.9% per annum (United Nations, Economic and Social Commission for Asia and the Pacific (UNESCAP), 2005). Thus, the model is able to predict the annual container throughput in 2003 under the intact condition for the Port of Busan. The difference between this predicted value and the actual container throughput in 2003 can thus be used as a benchmark. As shown in Table 10, the decreased container throughput obtained from the proposed method and the benchmark are comparable. This illustrates the accuracy and reliability of the proposed method.

Table 10

Method used	Container throughput_Intact (TEUs)	Container throughput_Disrupted (TEUs)	Container throughput_Deceased (TEUs)
Predicted	11,618,174	10,407,809	1,210,365
Simulated	11,747,732	10,674,611	1,073,121

Method validation by using the case of 2003 Busan Port and Typhoon Maemi.

Source: Authors

It is noteworthy to discuss the factors which affect the accuracy of the proposed method. First of all, as a core of the simulated model, the accuracy of the estimates of physical damage degree under various disrupted scenarios affect the model accuracy. The degree of physical damages is one of the reasons that affect the length of disrupted and recovery periods. It is determined by various factors, such as the frequency and magnitude of the hazard events, and the vulnerability of the port infrastructure and equipment. Thus, to enhance the accuracy of the model, it is suggested that different ports in terms of locations and types estimate the degree of physical damage by simultaneously considering the mentioned factors. Secondly, it is difficult to predict the recovery speed, which is another critical factor that affects the length of the recovery period. The recovery speed is driven by the recovery capability and the degree to which the capability is realized. Thus, it is suggested for the end-users to follow the government policies on post-disaster relief and recovery closely to better estimate the port recovery speed. Thirdly, it is the uncertainty of whether or not the port is able to restore to its original operation level. One assumption in this study is that the container throughput reaches its original level once the recovery period ends. However, not all ports were able to restore to its original level as shown historically. In the case of 1995 Kobe earthquake, after more than ten years, the Port of Kobe's container throughput was still less than the level in 1994 (one year before the disaster) (Na and Shinozuka, 2009). Possible reasons may lie in (1) the decline of Japan's trade volume, and (2) shipping companies once re-routed calls from the Port of Kobe did not call back again. However, in the case of 2003 Typhoon Maemi, the South Korean government invested US\$290 billion (in 2003 US dollars) in the construction of Busan new port. By the year of 2011, 30 new berths were completed (UNESCAP, 2015). Although the development did not restore Busan to its original worldwide container port ranking (3rd among the 2002 rankings), it is able to hold the position of 5th or 6th amid competitions from other ports in the region,

such as Shanghai, Qingdao, and Ningbo. It is seen that governments' investments in port reconstruction plans differ from country to country, which depends heavily on how the government positions the port in the post-disaster era. On all accounts, it is a costly and long journey for ports to recover to their original levels after catastrophes.

6. Conclusion

This study evaluates the catastrophe-induced port loss by adopting simulation model based on actual terminal records. By using the Port of Shenzhen and typhoon hazard as an example, the reduction in container throughputs under various disrupted scenarios are obtained. The physical and economic port losses are estimated using the probabilistic estimates of physical damages and the potential impact on its throughput. We find that (1) the reduction in container throughputs increases with more severe typhoon intensities and shorter strike distances; (2) the proportion of economic losses are greater than physical losses when subject to typhoons of long-distance strikes, while being comparable with short-distance strikes; (3) the worst-case scenario of a typhoon hit could cause a total loss of 0.91 billion USD for a terminal with 16 berths, 81 quay cranes, and 222 gantry cranes; (4) the total typhoon-induced loss for the largest terminal in the Port of Shenzhen reaches US\$0.56 billion since the terminal was firstly put into production (1994), which equals to US\$27 million per year approximately, accounting for 8.3% of the terminal net profit in 2015; (5) the total predicted typhoon-induced loss for the same terminal for the next 5 years (from 2016-2020) reaches US\$0.32 billion, which equals to US\$64 million on a yearly basis, accounting for 19.7% of the terminal net profit in 2015.

This paper makes several contributions to the research and practice on port-related risk modelling and management. Firstly, this study advances knowledge of the scopes and features of port-related catastrophes risks, as well as the components of catastrophe-induced port loss. Secondly, this research addresses the current research gap by evaluating typhoon-induced port loss in terms of physical damage loss and economic loss, with a special focus on the worst-case scenario. Thirdly, the results of this study could be useful references for various port stakeholders such as port operators, engineers, service providers, carriers, and shippers in applications of port catastrophe risk analysis and mitigation, routing planning, port site selection. For (re)insurance companies, the outputs of this research show their attractiveness as a

part of catastrophe risk modelling, and the basis for port-related catastrophe insurance product pricing.

The proposed framework could be applied to other port-related catastrophe hazards, such as earthquake and tsunami. The multi-hazards catastrophe risk comparison among different seaports can thus be achieved. In the future study, the losses from secondary hazard and the third-order hazard on the hazard chain will be considered in the framework. In addition, various recovery speeds will be studied in the terminal operation simulation model.

References

- ALEXANDER, K. and IRWIN, N., 2005, Port Comes Back Early, Surprisingly. Date of access: 14/9/2016.
<http://www.washingtonpost.com/wpdyn/content/article/2005/09/13/AR2005091302073.html>
- ALLEN, R. L. and VOGEL, P., 1996, The Great WWII Port Chicago Disaster - A Nuclear Blast? Nexus Magazine, June-July.
- ATSUSHI, N., KOJI, I., and TAKAHIRO, S., 2004, Seismic design of port structures. Journal of Japan Association for Earthquake Engineering, 4(3), 195-208.
- BROOKE, J., 2003, Typhoon Hits South Korea Economy. The New York Times, 17 September.
- BURDEN, L. I., RIX, G., and WERNER, S., 2016, Development of a risk framework for forecasting earthquake losses in port systems. Earthquake Spectra, 32(1), 267-284.
- CARDONA, O. D., 2005, Indicators of disaster risk and risk management: program for Latin America and the Caribbean, summary report. Inter-American Development Bank report.
- CHAMBERS, S., 2003, Pusan picks up pieces of typhoon carnage. Lloyd's List. 16 September.
- CHANG, S. E., 2000, Transportation performance, disaster vulnerability, and long-term effects of earthquakes. Second Euro Conference on Global Change and Catastrophic Risk Management, Laxenburg, Austria.
- CHEMICAL ENGINEERING PROGRESS AND AMERICAN INSTITUTE OF CHEMICAL ENGINEERS [CEPAICE]., 1967, Dow's process safety guide (New York, U.S.: American Institute of Chemical Engineers).
- COPPACK, L., 2002, Catastrophe risks threaten transport. Lloyd's List. 17 October.
- DALIAN PORT., 2015, Dalian Port comprehensive emergency contingency plan. Dalian Port report.
- DANIELS, R., KETTL, D., and KUNREUTHER, H., 2006, On risk and disaster: Lessons from Hurricane Katrina (Philadelphia, U.S.: University of Pennsylvania Press).
- DRAGOVIĆ, B., PARK, N. K., RADMILOVIĆ, Z., & MARAŠ, V. 2005, Simulation modelling of ship-berth link with priority service. Maritime Economics & Logistics, 7(4), 316-335.
- DRAGOVIĆ, B., PARK, N. K., & RADMILOVIĆ, Z. 2006, Ship-berth link performance evaluation: simulation and analytical approaches. Maritime Policy & Management, 33(3), 281-299.
- DRAGOVIĆ, B., TZANNATOS, E., and PARK, N. K., 2016, Simulation modelling in ports and container terminals: literature overview and analysis by research field, application area and tool. Flexible Services and Manufacturing Journal, 1-31.

- DILLEY, M., 2005, Natural disaster hotspots: a global risk analysis (Vol. 5). World Bank Publications.
- FEDERAL EMERGENCY MANAGEMENT AGENCY [FEMA]., 1999, HAZUS 99-Technical Manual. Federal Emergency Management Agency.
- FLYNN, M., 2003, Hanjin bullish over box bonanza. Lloyd's List, 29 November.
- FRITTELLI, J., 2005, Hurricane Katrina: Shipping Disruptions. Washington, DC: Congressional Research Service, Library of Congress, RS22257.
- GLASS, J., 1994, Los Angeles rocked by earthquake. Lloyd's List, 18 January.
- HANSON, S., NICHOLLS, R., RANGER, N., HALLEGATTE, S., CORFEE-MORLOT, J., HERWEIJER, C., and CHATEAU, J., 2011, A global ranking of port cities with high exposure to climate extremes. *Climatic change*, 104(1), 89-111.
- HISTORY., 2009, Fertilizer explosion kills 581 in Texas. Date of access: 10/11/2016. <http://www.history.com/this-day-in-history/fertilizer-explosion-kills-581-in-texas>.
- HISTORY., 2010, The Great Halifax Explosion. Date of access: 10/11/2016. <http://www.history.com/this-day-in-history/the-great-halifax-explosion>
- HUI, C., 2010, Ports shut down ahead of typhoon Megi. Lloyd's List, 21 October.
- KELLY, H., 2011, China penalises Dalian port executives for oil spill. Lloyd's List, 25 November.
- KELTON, W. D., 2002, Simulation with ARENA. (New York, U.S.: McGraw-Hill).
- KERMANS SHAH, A., and DERRIBLE, S., 2016, A geographical and multi-criteria vulnerability assessment of transportation networks against extreme earthquakes. *Reliability Engineering & System Safety*, 153, 39-49.
- KIM, K. H., and PARK, Y. M., 2004, A crane scheduling method for port container terminals. *European Journal of operational research*, 156(3), 752-768.
- KNAPP, K. R., M. C. KRUK, D. H. LEVINSON, H. J. DIAMOND, and C. J. NEUMANN, 2010, The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bulletin of the American Meteorological Society*, 91, 363-376.
- LAM, J.S.L. and LASSA, J.A. 2017, Risk assessment framework for exposure of cargo and ports to natural hazards and climate extremes, *Maritime Policy & Management*, 44(1), 1-15.
- LAM, J. S. L., and SU, S., 2015, Disruption risks and mitigation strategies: an analysis of Asian ports. *Maritime Policy & Management*, 42(5), 415-435.
- LAM, J. S. L., and YIP, T. L., 2012, Impact of port disruption on supply chains: A petri net approach. In: *Computational Logistics*, edited by W. B. Jürgen, H. Hu, C. Jahn, X. Shi, R. Stahlbock, and S. Voß. (Springer Berlin Heidelberg), pp. 72-85.
- LEANDER, T., and LIN, T., 2015, Explosions near Tianjin port leave more than 44 dead and disrupt shipping. Lloyd's List, 13 August.
- LEE, I., 2003, Busan Port's Clients Skittish After Typhoon. Date of access: 22/9/2003. http://english.chosun.com/site/data/html_dir/2003/09/22/2003092261018.html
- LIGTERINGEN, H., 1999, Ports and terminals. Date of access: 9/10/2016. <http://repository.tudelft.nl/view/ir/uuid%3Aaa681510-e90c-40ba-b7f6-fa86d242c315/>.
- LIN, T., 2016, Vitol's oil terminal in Tanjung Pelepas reopens after oil spill. Lloyd's List, 26 August.
- LIU X., 2016, After Typhoon Moranti, Kaohsiung Port got severe damaged. Date of access: 15/9/2016. Retrieved from <http://udn.com/news/story/1/1963727>
- LLOYD'S LIST., 1999, India: Cyclone wrecks port of Paradip. Lloyd's List, 2 November.
- LLOYD'S LIST., 2000, Room for all after rebuilding. Lloyd's List, 31 May.

- MEDVEDEV, S. V., and SPONHEUER, W., 1969, Scale of seismic intensity. Proceedings of IV World Conference of the Earthquake Engineering, Santiago, Chile, January, pp. 143-153
- NA, U. J., and SHINOZUKA, M., 2009, Simulation-based seismic loss estimation of seaport transportation system. *Reliability Engineering and System Safety*, 94(3), 722-731.
- NADKARNI, S., 1998, Partial reopening at Kandla Port. *Lloyd's List*, 27 June.
- NADKARNI, S., 2001, Kandla tallies quake bill. *Lloyd's List*, 17 February.
- NATIONAL GEOSPATIAL-INTELLIGENCE AGENCY [NGIA]., 2015, World Port Index, Date of access: 18/08/2016. http://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&andpubCode=0015.
- OSKIN, B., 2015, Japan Earthquake and Tsunami of 2011: Facts and Information. *Livescience*, 7 May.
- OSLER, D., 2015, Marine insurers face huge Tianjin blast exposure. *Lloyd's List*. 24 August.
- PACHAKIS, D., and KIREMIDJIAN, A. S., 2004, Estimation of downtime-related revenue losses in seaports following scenario earthquakes. *Earthquake Spectra*, 20(2), 427-449.
- PETHICK, J. S., and CROOKS, S., 2000, Development of a coastal vulnerability index: a geomorphological perspective. *Environmental Conservation*, 27(04), 359-367.
- PRESCOTT, J., 1996, Kobe fights for trade one year after quake. *Lloyd's List* 1996, 17 January.
- Bradely, A., 2007, Arena user's guide, Date of access: 8/9/2015. <http://iiesl.utk.edu/Courses/IE406%20S07/Slides/Arena%20User's%20Guide.pdf>.
- ROEDER, C. W., GRAFF, R., SODERSTROM, J., and YOO, J. H., 2005, Seismic performance of pile-wharf connections. *Journal of Structural Engineering*, 131(3), 428-437.
- RONZA, A., LÁZARO-TOUZA, L., CAROL, S., and CASAL, J., 2009, Economic valuation of damages originated by major accidents in port areas. *Journal of Loss Prevention in the Process Industries*, 22(5), 639-648.
- SMYTHE, T. C., 2013, Assessing the impacts of Hurricane Sandy on the Port of New York and New Jersey's Maritime responders and response infrastructure. *Natural Hazards Centre*.
- SWISS RE., 2016, Natural catastrophes and man-made disasters in 2015: Asia suffers substantial losses. *Swiss Re report*.
- TALLEY, W. K., 2009, *Port economics* (London, U.K.: Routledge).
- SCHOTT, T., LANDSEA, C., HAFELE, G., LORENS, J., TAYLOR, A., THURM, H., WARD, B., WILLIS, M., and ZALESKI, W., 2012, The Saffir-Simpson Hurricane Wind Scale, Date of access: 4/5/2016. <http://www.nhc.noaa.gov/pdf/sshws.pdf>
- UNITED NATIONS DEVELOPMENT PROGRAMME [UNDP]., 2004, *Reducing Disaster Risk, A Challenge for Development*.
- UNITED NATIONS, ECONOMIC AND SOCIAL COMMISSION FOR ASIA AND THE PACIFIC [UNESCAP], 2005, *Review of Developments in Transport in Asia and the Pacific 2005*.
- WALLIS, L., 2009, Storm suspends shipping in south China. Date of access: 11/2/2017.
- WERNER, S. D. (Ed.), 1998, *Seismic guidelines for ports* (Boston, U.S.: ASCE Publications).
- WERNER, S. D., DICKENSON, S. E., and TAYLOR, C. E., 1997, Seismic risk reduction at ports: Case studies and acceptable risk evaluation. *Journal of waterway, port, coastal, and ocean engineering*, 123(6), 337-346.
- WORLD METEOROLOGICAL ORGANIZATION [WMO]., 2015, *Typhoon Committee Operational Manual, Meteorological Component*.

WORLD SHIPPING COUNCIL [WSC]., 2015, Top 50 world container ports, Date of access: 3/4/2015. <http://www.worldshipping.org/about-the-industry/global-trade/top-50-world-container-ports>

YU, S., KIM, S. W., OH, C. W., AN, H., and KIM, J. M., 2015, Quantitative assessment of disaster resilience: An empirical study on the importance of post-disaster recovery costs. *Reliability Engineering & System Safety*, 137, 6-17.

ZHANG, Y., and LAM, J. S. L., 2015, Estimating the economic losses of port disruption due to extreme wind events. *Ocean and Coastal Management*, 116, 300-310.

ZHUHAI PORT AUTHORITY, 2011, Zhuhai City port natural disaster contingency plan. Zhuhai Port report.

ZONG, Y., and CHEN, X., 1999, Typhoon hazards in the Shanghai area. *Disasters*, 25(1), 66-80.

Appendices

A. Experts' profile for catastrophe hazards identification validation

Number	Organization	Location	Title
1	International Transport Forum (ITF) at Organization for Economic Co-operation and Development (OECD)	France	Administrator Ports and Shipping
2	Marine Traffic	United Kingdom	Board member
3	World Maritime University	Sweden	Professor
4	University of Manitoba	Canada	Professor
5	Risk Management Solutions, Inc. RMS	United States of America	Model development operations, Vice President
6	Dalian Port	China	Director, the department of safety production
7	Tianjin Port	China	Director, the department of safety production
8	Xiamen Port	China	Director, the department of security
9	Yantian International Container Terminal	China	Terminal manager
10	Guangzhou Port	China	Director, the department of security

Source: Authors

B. Typhoon statistics in area of the Shenzhen Port, 1994-2015

Strike distance	Hurricane scale	Disrupted scenario	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Sum
0-100 km	Category 1	1	0	0	0	1	0	0	0	0	1
	Category 2	6	0	0	0	0	0	0	0	0	0
	Category 3	11	0	0	0	0	0	0	0	0	0
	Category 4	16	0	0	0	0	0	0	0	0	0
	Category 5	21	0	0	0	0	0	0	0	0	0
100-200km	Category 1	2	0	0	0	0	1	2	0	0	3
	Category 2	7	0	0	0	0	0	0	0	0	0
	Category 3	12	0	0	0	0	0	0	0	0	0
	Category 4	17	0	0	0	0	0	0	0	0	0
	Category 5	22	0	0	0	0	0	0	0	0	0
200-300km	Category 1	3	0	0	0	2	3	1	1	1	8
	Category 2	8	0	0	0	0	0	2	0	0	2
	Category 3	13	0	0	0	0	0	0	0	0	0
	Category 4	18	0	0	0	0	0	0	0	0	0
	Category 5	23	0	0	0	0	0	0	0	0	0
300-400km	Category 1	4	2	0	0	0	4	3	0	0	9
	Category 2	9	0	0	0	1	1	1	0	0	3
	Category 3	14	0	0	0	0	0	0	0	0	0
	Category 4	19	0	0	0	0	0	0	0	0	0
	Category 5	24	0	0	0	0	0	0	0	0	0
400-500km	Category 1	5	0	0	0	1	0	1	1	1	4
	Category 2	10	0	0	0	0	0	0	0	0	0
	Category 3	15	0	0	0	0	0	0	0	0	0
	Category 4	20	0	0	0	0	0	0	0	0	0
	Category 5	25	0	0	0	0	0	0	0	0	0
Sum			2	0	0	5	9	10	2	2	30

Source: Authors