DEVELOPMENT OF AN ECONOMIC EVALUATION METHOD FOR SEISMIC DESIGN OF PORT FACILITIES CONSIDERING FREIGHT TRANSPORTATION COST

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ABSTRACT

When performing economic evaluations for seismic design of port facilities, it is essential to consider not only the cost of construction of facilities and reconstructing them damaged by an earthquake, but also the loss of economic activities when damaged. In addition, a stochastic evaluation method must be developed, since economic loss is very dependent on the state of damaged facilities. Thus the objective of this paper is to develop a stochastic evaluation method that can evaluate the economic impact of port facilities considering the cost of the loss of freight transportation, taking gravity-type quay walls as an example of port facilities.

The proposed method is applied to container berths in two sample ports. The results show that the optimal seismic coefficients that are estimated occasionally differ depending on whether or not the cost of the loss of freight transportation was considered.

SOMAAIRE

Lors d'une évaluation économique ayant pour objectif de déterminer le dispositif parasismique le mieux adapté à une installation portuaire, il est nécessaire de prendre en compte non seulement les coûts de construction et de reconstruction en cas de séisme, mais aussi les pertes engendrées par la réduction de l'activité économique du port pendant que celui-ci est endommagé. Ces pertes dépendant de l'état du port après le séisme, et donc du dispositif parasismique choisi lors de sa construction, une évaluation stochastique doit être développée. Par conséquent, l'objectif de cette étude est de développer une méthode d'évaluation stochastique permettant d'évaluer l'impact économique d'un séisme sur des installations portuaires, en prenant en compte les pertes dues à la réduction momentanée du fret. Les quai-poids ont été choisis comme exemple d'installation portuaire.

La méthode proposée a été appliquée à deux terminaux à conteneurs Berth. Les résultats montrent que les coefficients sismiques optimum estimés diffèrent selon que les pertes dues à la réduction des activités de fret ont été prises en compte ou pas.

KEY WORDS : Seismic Design, Gravity Quay-Wall, Economic Evaluation, Freight Transport

1. INTRODUCTION

When performing economic evaluations of infrastructure that must be mitigated or protected from disasters, including quaywalls, breakwaters, and other port facilities, it is essential to consider not only the cost of construction or improvement of facilities and the cost of restoring damaged facilities, but also the loss of economic activities when they are damaged. When a port facility is damaged for example, freight handling function declines and rerouting of freight to other ports inflict economic loss not only around the port but on its hinterland area widely.

When an economic evaluation of the seismic performance of port facilities is done in Japan, in conformity with the Technology Standards and Commentaries for Port Facilities (1999, below simply called "the Technology Standard"), it is stipulated by the present Guideline to the Evaluation of Port Investment (1999 and revised in 2004, below called "the Guideline"). According to the Guideline, the evaluation calculations are performed on the presumption that after an earthquake with scale of a level 1 or less, all port facilities will maintain their functions, while after an earthquake with scale between level 1 and level 2, the functions of seismically retrofitted facilities will maintain their functions but the other facilities will not function fully.

But as the concept of reliability design is introduced to study the revision of technical standards from specification stipulation type standard to performance stipulation type one, it is necessary to introduce stochastic concepts to economic evaluation methods. Economic loss caused by disasters is particularly dependent on the damage level to port facilities, and when a quantitative evaluation of economic loss is attempted, the results differ greatly according to the state of the damage that is hypothesized. To construct a stochastic economic evaluation method is very important challenge

Therefore, this study takes a gravity-type quaywall as a sample port structure to construct an economic loss evaluation method that considers the cost of freight transportation in a case where it is assumed that the damage level is represented stochastically in line with performance stipulation type technical standards This research was conducted as follows. In Chapter 2, concepts concerning seismic performance in past manuals of port facility design and recent research are clarified. In Chapter 3, a stochastic economic value evaluation method for gravity-type quaywalls considering the economic loss of freight is proposed. Then in Chapter 4, economic loss is calculated taking specific ports as examples.

2. Concepts of seismic performance and disaster probability evaluation in the design of port facilities

2.1 Concept of seismic performance in standards and manuals

1) Japanese technical standard (Technology Standards and Commentaries for Port Facilities)

As explained above, the present technical standards uniformly establish seismic performance for retrofitted facilities (particularly important facilities that should have been seismically retrofitted) and for other facilities, as shown in Table 1. In brief, port facilities are designed in order that after a level 1 earthquake, for all facilities, “the facilities’ functions will remain sound” and after an earthquake of level 2, retrofitted facilities will maintain their functions. The judgment whether or not a retrofitted structure maintains its initial functions is, “determined based on an overall consideration of structural stability, functionality, and difficulty of emergency restoration of the facility, but, “at this time, it is difficult to clearly determine the allowable deformation of a quaywall to make such a judgment.”

On the other hand, when designing port facilities, the allowable deformation is calculated by multiplying the regional seismic intensity by a coefficient stipulated according to the importance of the facility and the ground category. The fact that the importance of the facility is considered at the seismic coefficient design as shown in Table 2 is a reflection of tacitly accounting for the social and economic impact of the destruction of port facilities.

Table 1. Earthquake Motion and Considered for Seismic Performance of Port Facilities
(source: Technology Standards and Commentaries for Port Facilities, 1999)

Earthquake motion level	Earthquake motion considered for seismic design	Applicable facility	Seismic performance
Level 1	Earthquake motion with anticipated recurrence frequency of 75 years	All facilities (excluding those stipulated by other standards etc.)	Functions of the facility remain sound
Level 2	Earthquake motion with anticipated recurrence frequency of several hundred years or more, intraplate earthquake motion, or interplate earthquake motion	Seismically retrofitted facilities (seismically retrofitted quaywalls, seawalls that must be seismically retrofitted at disaster prevention locations), and facilities such as bridges, undersea tunnels, and other port facilities that must consider	Maintain initial functions

Table 2. Importance Coefficient for Seismic Design of Port Facilities (same source as Table 1)

Type of structure	Properties of the structure	Importance coefficient
Special	Of the properties of class A structures, important structures in danger of No. 1 or No. 4, those remarkably impacted by No. 2, and those with role No. 3	1.5
Class A	1 Structure that will cause extensive loss of human life and property if it is struck by an earthquake 2 Structure that will devastate social and economic activities if it is struck by an earthquake 3 Structure that plays in important role in earthquake recovery 4 Of structures handling hazardous or dangerous substances, a structure that will cause extensive loss of human life and property if it is struck by an earthquake 5 Structure that will be difficult to restore if it is struck by an earthquake	1.2
Class B	Other than Special, Class A and Class C	1.0
Class C	Structure other than those under Special and Class A that will have a small impact on economic and social activities and will be easily restored if it is struck by an earthquake	0.8

2) Technical standards based on PIANC

While seismic performance of port facilities is set at two levels in Japan as above, the International Navigation Association (PIANC, 2001) has proposed setting the degree of damage (i.e., damage level) at four levels from Degree I to Degree IV, and seismic performance at four grades, S, A, B, and C. Table 3 shows the definitions of each damage level, and Table 4 shows definitions of each seismic performance grade and structures that should be covered by each grade. Seismic performance is defined according to damage level by two earthquake motion level as shown in Table 4. Figure 1 continuously represents the relationship between the scale of earthquake motion and the damage level for each seismic performance. The grade that represents the seismic performance of a structure is continuously defined according to the scale of earthquake motion. In addition, the seismic performance expectedly varies by each structure as the figure shows (for example, structure *a* displays Grade A performance no matter what kind of earthquake motion it receives, but as the earthquake motion striking structure *b* increases, its Grade shifts from S to A or B). This might be one reason that even if the seismic performance of an individual structure is categorized for normal seismic performance design, the damage level obtained as a result fluctuates stochastically. Although the guideline of the PIANC includes degree of importance among Japanese technical standards corresponding to each seismic performance as shown in Table 5, notably that they are not completely equivalent concepts, because the degree of importance in Japanese technical standards does not directly stipulate seismic performance as stated above.

Table 3. Definition of Damage Level by PIANC (2001)

Level of damage	Structural	Operational
Degree Ⅰ: Serviceable	Minor or no damage	Little or no loss of serviceability
Degree Ⅱ: Repairable	Controlled damage**	Short-term loss of serviceability***
Degree Ⅲ: Near collapse	Extensive damage in near collapse	Long-term or complete loss of serviceability
Degree Ⅳ: Collapse****	Complete loss of structure	Complete loss of serviceability

* Considerations: Protection of human life and property, functions as emergency base for transportation, and protection from spilling hazardous materials, if applicable ,should be considered in defining this damage criteria in addition to those shown in this table.
** With limited inelastic response and/or residual deformation.
*** Structure out of service for short to moderate time for repairs.
**** Without significant effects on surroundings.

Table 4. Definition of Seismic performance and Corresponding Structures by PIANC (2001)

Performance grade	Design earthquake		Performance Definition based on seismic effects on structures grade	Suggested importance category of port structures in Japanese code
	Level 1 (L1)	Level 2 (L2)		
Grade S	Degree Ⅰ: Serviceable	Degree Ⅰ: Serviceable	1) Critical structures with potential for extensive loss of human life and property upon seimic damage 2) Key structures that are required to be serviceable for recovery from earthquake disaster 3) Critical structures that handle hazardous materials 4) Critical structures that, if desrupted, devastate economic and social activities in the earthquake damage area	Special class
Grade A	Degree Ⅰ: Serviceable	Degree Ⅱ: Repairable	Primary structures having less serious effects for 1) through 4) than Grade S structuers, or 5) structuers that ,if damaged, are difficult to restore	Special class or Class A
Grade B	Degree Ⅰ: Serviceable	Degree Ⅲ: Near collapse	Ordinary structures other than those of Grades S, A and C	Class A or B
Grade C	Degree Ⅱ: Repairable	Degree Ⅳ: Collapse	Small easily restorable structuers	Class B or C

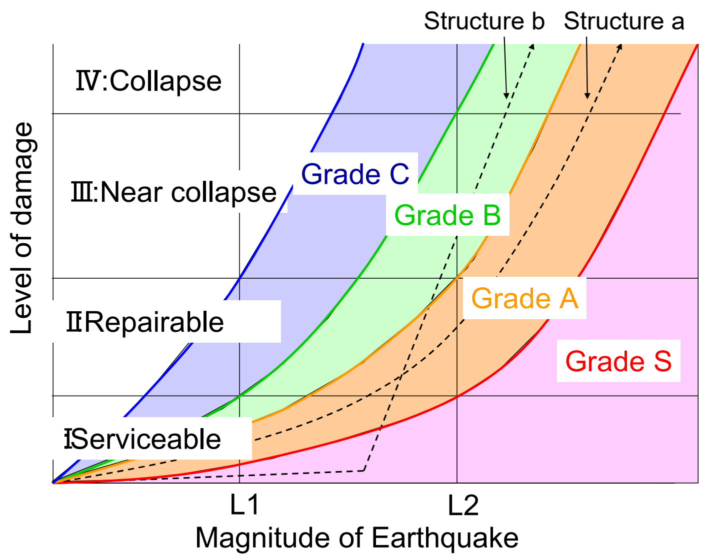

Figure 1. Relationship of Scale of Earthquake Motion with Damage Level (PIANC, 2001)

3) Japanese guideline (Guideline to the Evaluation of Port Investment)

The Guideline prescribes a cost-benefits analysis method for seismically retrofitted facility improvement projects. Here, seismic performance, as stated above, means that after an earthquake with scale of level 1 earthquake motion or less, all port facilities will maintain their functions, while after an earthquake with scale between level 1 and level 2 earthquake motion, the retrofitted facilities will maintain their functions but the other facilities will not function fully, as shown in Figure 2. This assumption in the Guideline presents two problems. The first problem is that the state of the hypothetical damage level is not continuous but is extremely dispersed. The second is that it does not account for the fact that the damage caused by earthquake motion of a single scale fluctuates stochastically.

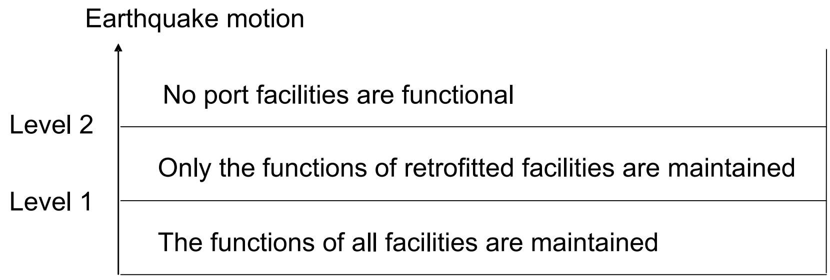

Figure 2. Hypothesis of Seismic Performance in the Guideline to the Evaluation of Port Investment (1999, 2004)

2.2 Past research on seismic design of port facilities

1) Research on the stochastic evaluation of damage to port facilities

The reliability design method that predicts the probability of the collapse and the damage level of a civil engineering structure, and is modeled on reliability engineering that concerns the frequency and intervals between the occurrence of defects in products has been well summarized by Hoshitani and Ishii (1986). In line with this method, Nagao et al. (1998) and Nagao (2001) have studied the level 1 reliability design method for caisson type breakwaters and quaywalls, based the assumption that each design parameter such as load and unit weight fluctuates stochastically.

Another methodology is instead of considering the fluctuation of each parameter, focusing on the fact that damage levels that occur appear stochastically as a result. The probability of the occurrence of each damage level that is represented by the function of external force, which is called a “fragility curve”, is estimated from past actual damage. For example, fragility curves were made for buildings (Yamaguchi and Yamasaki, 2000) or elevated road (ATC-13, 1985 and Tanaka et al., 2000), based on actual damage caused by the Hyogo-ken Nambu Earthquake. Fragility curves are also estimated for port facilities by Ichii (2002), especially for gravity quay-walls, although they were not obtained directly from the actual damage; they were estimated from the results of a Monte Carlo simulation, based on the dispersion of variables estimated from the simple seismic performance evaluation method (Ichii et al. 2002), which is developed by the finite element analysis, inputting a number of design parameters, and based on the actual damage caused by the Hyogo-ken Nanbu Earthquake.

Compared with above two methodologies, the former methodology is preferable at easiness to calculate the optimum seismic performance because it can obtain breakdown probability at any seismic performance. However, because it cannot represent multiple damage levels as long as the calculation is based on the force equilibrium equation, it is difficult to be used for the economic loss calculation of freight transportation that varies widely according to the state of the disaster. On the other hand, the latter methodology is useful for economic evaluations because it can represent multiple damage levels and defines disaster probability continuously according to the scale of the external force, but it often needs many fragility curves for every seismic performance, i.e., the vast number of samples, and reproducibility often cause many problems. Ichii (2002) has overcome the above problems to some degree, because once seismic performance evaluation method has been developed, a Monte Carlo Simulation is performed to obtained fragility curves, although the problem remains that there is small variation of the seismic performance prepared.

2) Research on economic evaluation of port facilities under disaster risk

Research on the economic evaluation of disaster risk of port facilities is broadly classified into two categories. One mainly considers the restoration cost of a facility, from the viewpoint of the facility designer or manager. The other mainly considers the social cost such as damage on physical distribution and loss of private assets from the perspective of public economics.

The former representative researches are Nagao et al. (2002 and 2003) and Ichii (2003). Both have applied damage probability equations for facility structures developed by the authors (Nagao, 2001 and Ichii, 2002) to actual design problems to obtain the optimum design seismic coefficient that will minimize the anticipated cost that is the total of the construction cost and the anticipated restoration cost only. Thus, both of them are called the approach from the facility designer perspective. In addition, Nagao et al. (2002) includes a trial calculation of economic damage to port related industries by the Kushiro Offshore Earthquake. However, it does not adequately consider economic loss, because Yonezawa (1984) that it was based upon was the estimation of the cost of damage based on the results of an interview survey on some discrete port related industries, and the rise of expenditures on port related industries might be theoretically cancelled out in economics.

The latter representative researches that includes public damage are, in addition to Yonezawa (1984) mentioned above, Nagao (1964), Kawakita (1982), Yuzawa and Suda (1989), etc. Of these Nagao (1964) and Kawakita (1982) both calculated the cost-benefits and optimum ground elevation of coastal embankments under flood risk by tidal wave, which was in principle application of the economic evaluation method for river flood control. Yuzawa and Suda (1989) proposed the methodology whether seismic retrofitting of a berth should be designed or not by comparing the costs and benefits, based on the calculation of post-disaster restoration cost and the increase in transportation costs and transportation time by ships to wait before entering the port or rerouting them to other ports. Although they ignore variations of the earthquake scale and occurrence probability and there are several problems when calculating the cost of rerouting, it incorporates many attractive elements; disaster rank according to the quantity of deformation of the berth, differences in freight distribution by type of product, and studies the berth restoration procedure. Although many researches on the economic evaluation of disaster prevention or mitigation facilities in different social infrastructure fields for a variety of risks are performed (for details see study by author, 2002), there are little researches for the port and coastal facilities. Most reliable documents in Japan as reference for economic evaluation methods that include various social-economic effects such as distribution loss, especially against earthquake risk, is the Guideline (1999 and 2004) mentioned above.

3. STOCHASTIC ECONOMIC EVALUATION METHODS FOR GRAVITY QUAYWALLS ACCOUNTING FOR ECONOMIC LOSS OF FREIGHT TRANSPORT

3.1 Outline of the method proposed by this research

This research proposes an economic evaluation method that can serve as a reference to perform design to *individual* port structures under earthquake risk, for example, when selecting the design seismic coefficient for a structure, and deciding whether a seismically retrofitted structure or not. In economic evaluations, ports should be considered as a network, i.e. the seismic coefficient of port facilities should be simultaneously set nationwide or for a region, however, mainly because of its difficulty, in this research, as a first step, the design seismic coefficient of structures other than the targeted will be treated as a given with present conditions.

Figure 3 is a flow chart of the methodology proposed by this research. First, for the port structure to be evaluated, the earthquake occurrence probability by acceleration for each port and the hypothetical section (for example, facility water depth and whether the improved ground or not) are prepared for each design seismic coefficient. Second, the extent of damage by acceleration is simulated by a Monte Carlo simulation based on a fragility curve that provides occurrence probability by acceleration and by damage level, under the given hypothetical sections. Here, the damage level in this process is not based on stochastic calculation but on a Monte Carlo simulation because particularly in a case where a disaster effecting a number of berths or a number of ports is considered, the damage patterns at different berths varies widely so that the economic loss that is calculated also varies greatly. As a result of the simulation, the restoration cost and the economic loss of freight transport are found for each of the obtained damage levels, also with considering the damage level at other ports. Then, the expected cost of the damage caused by an earthquake disaster for each design seismic coefficient can be obtained by multiplying the obtained cost of damage by the occurrence probability of an earthquake at each acceleration and integrating them with acceleration. Thus, in order to minimize the obtained total cost by adding the cost of investment, design seismic coefficient can be finally selected.

The port structure in this study is limited to the gravity-type quaywall, because the fragility curve has been developed only for gravity quaywalls. However, the framework of the methodology that authors will propose is basically unchanged regardless of the structure of each quaywall.

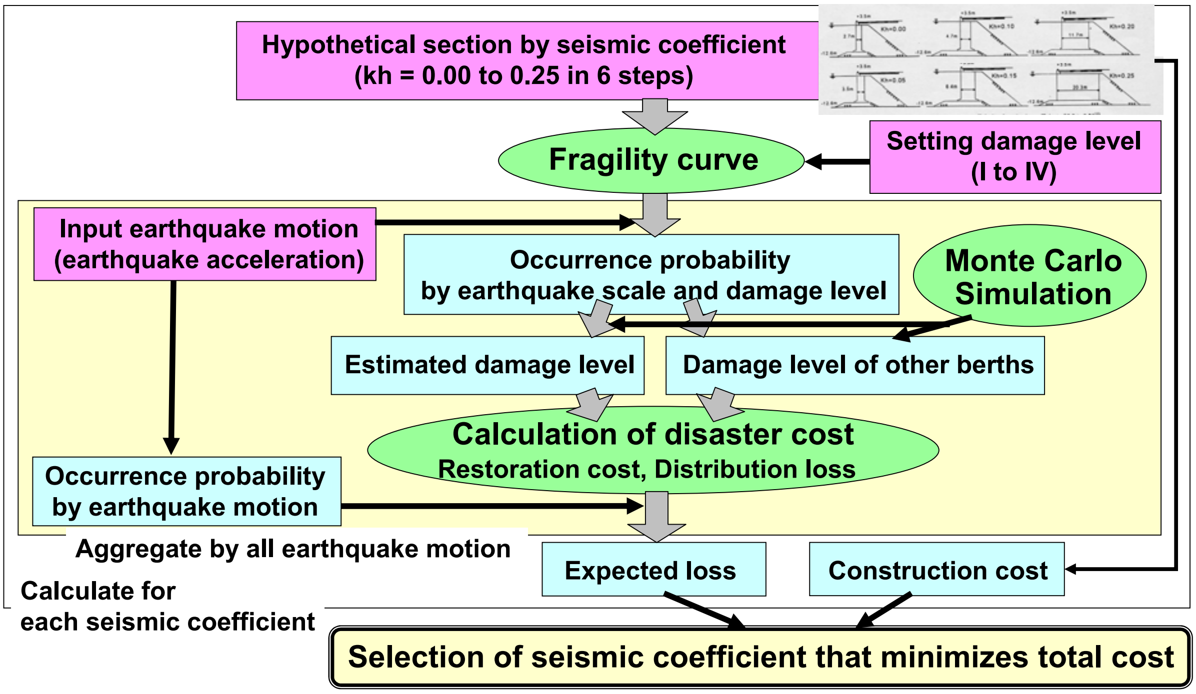

Figure 3. Flow Chart of the Economic Evaluation Methodology Proposed by the Study

3.2 Calculation of the damage probability to a berth

(1) Earthquake occurrence probability

The occurrence frequency equation by corrected maximum acceleration estimated from past disasters for each port by Nozu et al. (1997) was used to obtain the earthquake occurrence probability for each region. This means that the corrected maximum acceleration *x* that occurs in *K*/*N* years is obtained following the Weibull distribution below from the data to the top *N*th samples for *K* years in port *i*.

$$F(x) = 1 - \exp\left[-\left(\frac{x - B_i}{A_i}\right)^{h_i}\right] \qquad (1)$$

Where, A_i, B_i, and h_i are parameters determined for each port *i*. At this time, the probability of the occurrence of Φ(*x*) of an earthquake stronger than corrected maximum acceleration *x* (exceedance probability, inverse of the return period) is represented by the following equation.

$$\phi(x) = \frac{N}{K}\{1 - F(x)\} = \frac{N}{K} \cdot \exp\left[-\left(\frac{x - B}{A}\right)^{h}\right] \qquad (2)$$

Nozu et al. (1997) estimated the parameters A_i, B_i, and h_i when *K*=110 (years) and *N*=20 in major ports throughout Japan.

Regarding this earthquake occurrence probability, utilizing the predicted seismic intensity by expected epicenter is more essential, but above equation was adopted because the occurrence probability of the maximum acceleration for major ports throughout Japan can be easily obtained.

(2) Damage probability by seismic coefficient and damage level

Reflecting the discussion in 2.2(1), in this research, the occurrence probability function by damage level and acceleration (i.e. fragility curve) proposed by Ichii (2002) for a gravity quaywall is adopted. Like many equations for a fragility curve, the damage probability follow a cumulative density distribution of a logarithmic normal distribution with the earthquake acceleration or corrected SL value:

$$G(x, s, k) = \varphi\left[\ln(x / c_{s,k}) \big/ \zeta_{s,k}\right] \qquad (3)$$

Where, *x*: variable that represents the scale of the earthquake motion (adopted SMAC maximum acceleration (Gal)), *s*: damage level, *k*: design seismic coefficient, *φ* cumulative density function of the normal distribution, *c*, *ζ*: characteristic parameter of the structure. According to Ichii (2002), the parameter *c*, ζ of a gravity quaywall is determined based on three factors: ratio of the quaywall width and height (*W*/*H*), presence or absence of ground improvement under the structure, and the equivalent *N* value of the backfill sand. Table 5 shows these *c*, ζ estimated by these elements, and Figure 3 shows examples of fragility curves. In Ichii (2002), the damage level is also hypothetically set at four levels as shown in Table 6, according to the past surveys of damage and the definitions by PIANC (2001), although the definition of category boundaries differ.

For the quaywall depth–height ratio (*W*/*H*) of the above three elements, here, as the hypothesis of Ichii (2002), the standard section for the gravity quaywall shown in Figure 4 is hypothetically set for each design seismic coefficient to apply a feasibility curve that complies with each *W*/*H*. Regarding the section which *W*/*H* is not shown in Table 7, it is estimated based on linear regression by the available value of *W*/*H*. The second element, the ground improvement is regarded as “improved” when *D1*/*H* > 0.5 (here, *D1* is depth of improved ground) and “not improved” in other cases, judging from the section diagram of each berth. The third element, the equivalent *N* value of the backfill sand is assumed to be 15 constantly because variation of *W*/*H* is available only when N=15.

Table 5. Estimated Parameters of Fragility Curves (extracted from Ichii, 2002)

Equivalent SPT N values	Aspect ratio *(W/H)*	Normalized thickness of sand deposit *(D1/H)*	Degree Ⅰ		Degree Ⅱ		Degree Ⅲ		Degree Ⅳ	
			c	ξ	c	ξ	c	ξ	c	ξ
15	0.65	0.00	262.7	0.55	429.2	0.35	555.1	0.28	625.8	0.21
15	0.90	0.00	337.5	0.45	505.2	0.25	608.0	0.16	625.3	0.09
15	1.50	0.00	375.4	0.38	547.2	0.22	629.6	0.14	713.9	0.12
15	0.65	1.00	208.1	0.74	378.8	0.41	484.4	0.31	568.8	0.26
15	0.90	1.00	209.6	0.75	392.5	0.42	511.0	0.29	589.9	0.22
15	1.05	1.00	215.5	0.73	400.0	0.41	512.5	0.29	587.5	0.20

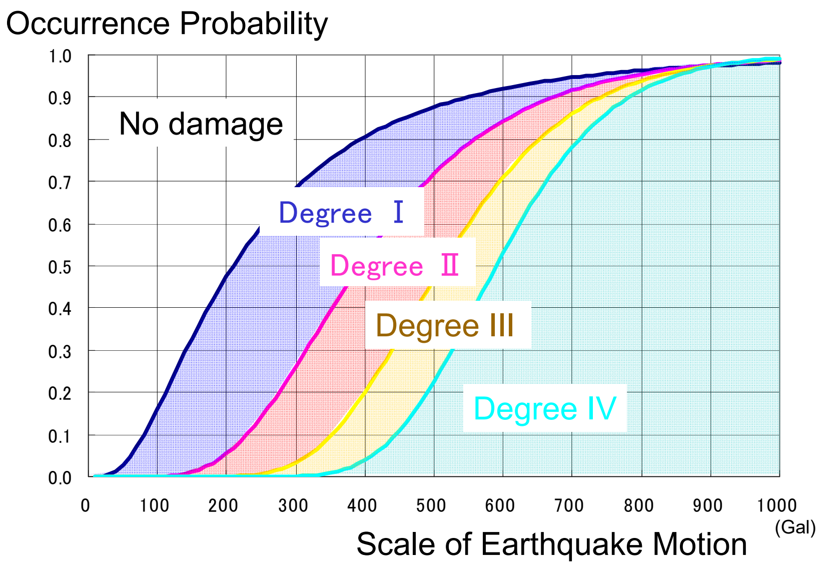

Figure 3. An example of Fragility Curve (Equivalent N value = 15, *W/H* = 0.90, *D1/H* = 1.00)

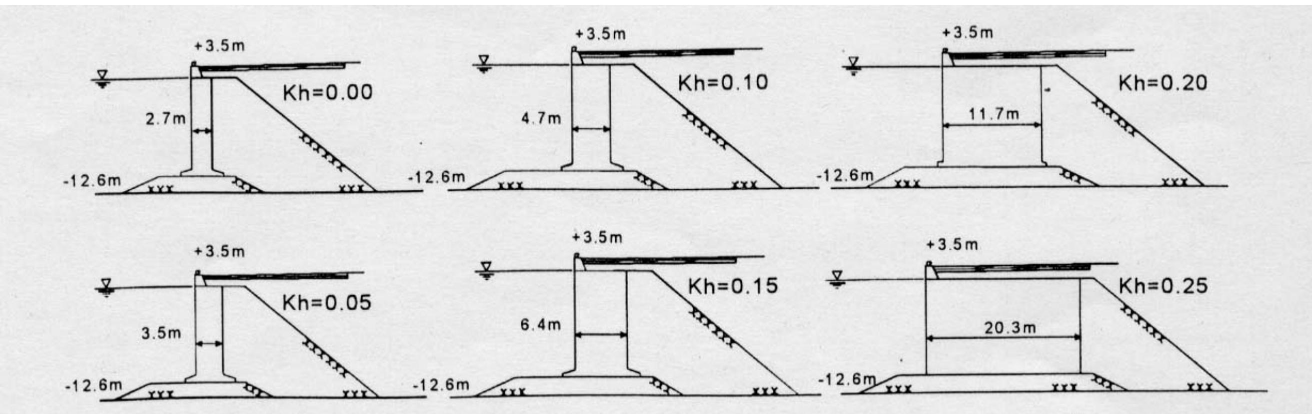

Figure 4. Section of Standard Gravity Quaywalls by Design Seismic Coefficient (Ichii, 2003)

Table 6. Definition of Damage Levels (Ichii, 2002) and Restoration Cost and Period by Level Set in this Study

Damage level	Normalized seaward displacement（*d/H*）	Restoration cost (1,000JPY/m)	Restoration time (days)
Degree Ⅰ	1.5～5%	290	180
Degree Ⅱ	5～10%	166.28x − 112.07	360
Degree Ⅲ	10～15%	193.54x + 28.614	540
Degree Ⅳ	Lager than 15%	10,000	720

*x: the absolute value of the quaywall depth

(3) Consideration of simultaneous multiple berth damage

When there are multiple berths in a single port, how correlate between the damage levels of each berth obtained from the fragility curve under a certain input earthquake motion? One extreme assumption is absolutely no correlation between them that implies the difference of the damage level under the same earthquake motion all attributes to contingent elements. Another extreme case is complete correlation. In reality, both of above two cases would be combined, however, it is very difficult to specify its degree for each port. Thus, in this study the calculation are performed for above two cases respectively, and the results are compared.

Also, damage to multiple ports by a single earthquake should be considered, however, in this study, because the earthquake occurrence probability is provided for each port instead of for each epicenter as above mentioned, it is difficult to predict the scale of earthquake motion for other port, and therefore, multiple ports are assumed not to be damaged simultaneously.

3.3 Calculation of economic loss

In the following calculation, we focus on economic effect on the transportation of international maritime container cargo, considering its larger influence on the economy and data accessibility. For the international maritime container transport, damaged items considered in a calculation of economic loss caused by earthquake damage are 1) restoration cost of damaged facilities and 2) economic loss caused by rerouting land and sea transport which is expressed as the summation of transportation cost and time. Here, the reason why only the rerouting cost is considered as economic loss is that other calculative losses such as the rise of expenditures on port related industries and various economic spill-over effects to other industries or households might be cancelled out on the national accounting, as long as assuming full-employment in line with traditional cost-benefit analysis theory in economics, which is also corresponding to the Guideline.

(1) Restoration cost and period of damaged facilities

The Guideline assumes that the restoration period is uniformly 2 years, but for this research, it needs to hypothesize a different restoration period for each damage level. Thus based on the past restoration work and results of a trial calculation (Nagao et al., 2003), the restoration cost and period are set as shown in Table 6.

(2) Economic loss on the rerouting of the land and sea transport

The economic loss caused by the rerouting of transport is generally calculated according to the Guideline, although several points such as the method of setting the alternate port differ. According to a 1998 survey of international maritime container cargo flow, each port for import / export p can obtain quantity of container cargo, q_{pqr} (freight tons), by overseas counter import /export port q and by production / consuming district r in one month. The economic loss caused by rerouting of transport is calculated by the following procedure based on these data.

a) Conversion to TEU (twenty-foot equivalent unit)

First, in order to divide into 20ft and 40ft containers, in line with the provisions of the Guideline, the dividing ratio is set as 10:6 in terms of weight (in case of multipurpose international terminal). The quantity of cargo per container is, also in line with the Guideline, set to be 18.7 ft per 20ft container and 28.1 ft per 40ft container. Thus, the quantity of freight Q_{pqr} (daily TEU basis) is obtained by the following equation.

$$Q_{pqr} = \left\{ \frac{10}{16} \cdot \frac{q_{pqr}}{18.7} + 2 \cdot \frac{6}{16} \cdot \frac{q_{pqr}}{28.1} \right\} \Big/ 30 = 2.00 \cdot 10^{-3} \cdot q_{pqr} \qquad (4)$$

b) Selecting the alternate port when damaged

The alternate port when a port in question has damaged is assumingly sought by the shortest land transport route from among ports that can handle containers. For the containers on worlds' trunk route such as trans-Pacific and Asia-Europe, alternatives are sorted by closeness among 8 *central* or 8 *core* ports. The reason why alternatives are so limited is capacity (especially for depth) of the berth. Because containerships used for trunk route are very huge, the ports where they can enter are very limited of the world. On the other hand, for them on other routes such as local route within East Asia, the alternate port is selected among *all* ports in Japan that can handle containers. Here, the road network used to search for the shortest routes is developed by authors (Shibasaki et al., 2004) including 46,798 intersections and 76,555 links of all expressways, national highways, and principal regional roads, based on the Road Information Handbook data.

If there is only one berth that can handle international maritime containers in the port, when berth has damaged, all containers handled at the port should be rerouted to an alternate port. The alternate port handles the containers that normally passes through plus the shifted containers from the damaged port, up to the limit of its handling capacity. If it cannot handle all of these containers, the part above its capacity would be handled by the next port on the list of alternatives, which is repeated until the containers in excess of capacity is zero. To simplify the calculation, the containers in excess of the capacity of the port are assumingly a fixed percentage regardless of the production / consuming region. The capacity growth of container berths at handling when disaster has happened is, in line with the Guideline, assumed to increase 40% than usual. In sum, where the usual capacity of berth b in port p is cap_b (TEU/day), the quantity of cargo in excess of the capacity of port $Ocap_p$ (TEU/day) is represented as

$$Ocap_p = \left(\sum_q \sum_r Q_{pqr} + Ocap_{p-1} \right) - 1.4 \cdot \sum_{b \in p} cap_b \qquad (5)$$

Where, $\sum_q \sum_r Q_{pqr}$: the quantity of cargo (TEU/day) handled by port p and $Ocap_{p-1}$: quantify of cargo (TEU/day) in excess of the capacity to previous port p - 1. Port 1 means the damaged port and $Ocap_0$= 0. The usual berth capacity of each port is set according to the actual past quantity of container cargo each has handled.

c) Calculation of the increase of transport cost

The increase of transport cost per day L is represented by the following equation.

$$L = \sum_p \left\{ \begin{aligned} &\left(Ocap_{p-1,20} - Ocap_{p,20}\right) \cdot \sum_q \sum_r \cdot \left\{ Q_{pqr,20} \cdot \left(CL_{pr,20} + CM_{pq,20} + Tv_{20} \cdot \left(TL_{pr,20} + TM_{pq,20} \right)\right)\right\} / \sum_q \sum_r Q_{pqr,20} + \\ &\left(Ocap_{p-1,40} - Ocap_{p,40}\right) \cdot \sum_q \sum_r \cdot \left\{ Q_{pqr,40} \cdot \left(CL_{pr,40} + CM_{pq,40} + Tv_{40} \cdot \left(TL_{pr,40} + TM_{pq,40} \right)\right)\right\} / \sum_q \sum_r Q_{pqr,40} \end{aligned} \right\} \qquad (6)$$

Where, CL: cost of land transport (1,000JPY/TEU), CM: cost of sea transport (1,000JPY/TEU), TL: time of land transport (h), TM: time of sea transport (h), and Tv: hourly value of container cargo (1,000JPY/h/TEU), and suffix 20, 40 in the equation means 20ft and 40ft container respectively. These calculation methods and value setting are basically done in compliance with the Guideline.

Regarding the cost of land transport, CL, the functional equation for transport distance and cost is estimated as shown by the following equation, separately for 20ft and 40ft containers.

$$\begin{aligned} CL_{pr,20} &= -0.153 \cdot ld_{pr}^{\ 2} + 380 \cdot ld_{pr} + 26700 \\ CL_{pr,40} &= -0.120 \cdot ld_{pr}^{\ 2} + 279 \cdot ld_{pr} + 21800 \end{aligned} \qquad (7)$$

Where, ld_{pr}: roundtrip distance of the land route between port p and production / consuming region r (km), it is obtained by authors' work (Shibasaki et al., 2004) mentioned above.

The cost of sea transport, CM, follows the transport cost equations by ship type, as shown in the Guideline. Because the types of container ships are not indicated in the source data, the ship size in service on trunk routes is assumed to be 4,000 TEU and that on other routes to be 500 TEU, to apply the equation as shown by the following equation.

$$CM_{pq} = 1885 \cdot \frac{md_{pq} \cdot 24}{vm_t} + 1740 \qquad \text{(case of trunk routes)}$$

$$= 4385 \cdot \frac{md_{pq} \cdot 24}{vm_l} + 3385$$ (case of other routes) (8)

Where, md_{pq}: sea transport distance between the port in Japan p and the overseas port q (NM), vm_t: speed on trunk routes (knot), vm_l: speed on other routes (knot). Here, the cost of sea transport per 1TEU, *CM*, is assumed the same value for both 20ft and 40ft containers. The sea transport distance *md* was obtained from the Japanese Sea Lane Distance Table and so on. The speeds vm_t, vm_l on trunk and other routes was set at 22.7 and 16.2 knots respectively in line with the Guideline. And for this calculation, neither the transshipment ports nor final ports would assume to be changed after a disaster.

The land transport time, *TL*, is represented by the following equation.

$$TL_{pr} = \frac{ld_{pr}}{vl} \qquad (9)$$

Where, *vl*: land transport speed (km/h). The Guideline presents average travel speed by truck on normal roads and expressways, however, since in most cases expressways are not used in Japan because of its expensiveness, the speed was set at *vl* = 34.5km/h assuming that only normal roads are used.

The sea transport time, *TM*, is obtained by the following equation in the same way as equation (8).

$$TM_{pq} = \frac{md_{pq}}{vm_t}$$ (case of trunk routes)

$$= \frac{md_{pq}}{vm_l}$$ (case of other routes) (10)

The value of time of container freight, *Tv* (1,000JPY/h/TEU), in equation (6) is set as follows according to the Guideline.

$Tv_{20} = 2.7$ (case of exported containers)
$= 1.4$ (case of imported containers)
$Tv_{40} = 2.05$ (case of exported containers)
$= 1.05$ (case of imported containers) (11)

3.4 Total cost calculation by seismic coefficient and selection of optimal seismic coefficient

Based on the information obtained as explained above, the total expected cost of reconstruction, rerouting freight and initial construction / improvement cost is obtained for each seismic coefficient. The smallest of these is selected as the optimal seismic coefficient. The following equation represents this calculation.

$$\min_{k_b} TC(k_b)$$

$$TC(k_b) = \sum_{t=1}^{T} \frac{\int_0^\infty \phi'(x)\{R(x,k_b) + L(x,k_b)\}dx}{(1+i_r)^{t-1}} + qd_b \cdot C(k_b) \qquad (12)$$

Where, k_b: seismic coefficient of the berth (below occasionally represented as *k*), *TC*: total cost (1,000JPY), *x*: SMAC maximum earthquake acceleration (Gal),Φ: annual exceedance probability function of the maximum earthquake acceleration, *R*: restoration cost (1,000JPY), *L*: loss caused by rerouting (1,000JPY), *T*: service life (years), i_r: annual reduction rate, *qd*: quaywall length (m), and *C*: construction cost per unit length of the quaywall (1,000JPY/m). The seismic coefficients k_b are as shown in Figure 4, set at six levels from 0.00 to 0.25. The annual exceedance probability function Φ is obtained by equation (2). The service life *T* and annual deduction rate i_r are 50 years and 4% respectively. The construction cost per unit length of the quaywall *C* is set as shown in Table 7 by Ichii(2002)

Table 7. Construction Cost per Unit Quaywall Length by Seismic Coefficient (Ichii, 2002)

Seismic Coefficient	0.00	0.05	0.10	0.15	0.20	0.25
Construction Cost (1,000JPY/m)	4,500	5,000	5,500	6,000	7,000	10,000

Because the restoration and rerouting cost are considered to vary widely according to the damage pattern of berths in a port, they need to be obtained by a Monte Carlo simulation. So the numerator of the first term of equation (12) is rewritten as follows.

$$\int_0^{\infty} \phi'(x)\{R(x,k)+L(x,k)\}dx \approx \sum_{y=\min x/a}^{\max x/a} \{\phi(ay)-\phi(a(y+1))\}\{R(ay,k)+L(ay,k)\} \tag{13}$$

Here,

$$R(x,k)=qd_b \cdot \frac{\sum_{s=0}^{4} n_s(x,k)\cdot R_s}{TN}, \quad L(x,k)=\frac{\sum_{s=0}^{4} n_s(x,k)\cdot RD_s \cdot L_s}{TN} \tag{14}$$

Where, *s*: damage level from 0 (no damage) to 4 (damage level IV), $n_s(x, k)$: frequency of occurrence of damage level *s*, acceleration *x*, and seismic coefficient *k* obtained by a Monte Carlo simulation, *a*: interval between earthquake accelerations in the simulation (Gal), *minx*, *maxx*: minimum and maximum value of *x* in the simulation, *TN*: frequency of the Monte Carlo simulation at acceleration *x* and seismic coefficient *k* (specifically $TN = \sum_{s=0}^{4} n_s$), R_s: restoration cost per unit length of the quaywall by damage level (1,000JPY/m), RD_s: restoration period by damage level (days), L_s: transportation loss caused by rerouting per day by damage level (1,000JPY/day). The frequency of occurrence of damage level *s* by the Monte Carlo simulation n_s can be represented by the following equation.

$$n_s(x,k)=n[TN, G(x,s+1,k)<\lambda \le G(x,s,k)] \tag{15}$$

Where, *n*[.]: number that the equation in [ ] is satisfied by production of random numbers of *TN* times, *G*(*x,s,k*): fragility curve at time of acceleration *x*, damage level *s*, and seismic coefficient *k* (see equation (3)), λ: random number produced by the uniform distribution, $0 \le \lambda \le 1$.

The restoration cost per unit of length, R_s, and the restoration period, R_d, are as shown in Table 6 (here, R_0 = RD_0=0). The transport loss caused by rerouting per day by damage level, L_s , is already shown how to estimate in the previous section.

4. EXAMPLES OF SELECTING SEISMIC COEFFICIENT

This chapter studies the evaluation methodology proposed in the previous chapter applied to actual ports for the international maritime container transport.

4.1 Example 1: Case of port A with only one international container berth

In port A, located rural area in Japan, international maritime containers are handled by one berth on multipurpose international freight terminal underlain a caisson type gravity quaywall with water depth of 13m and length of 260m. Figure 5 is the standard section of the berth. The coefficient of region, ground category, and importance of the berth are 0.1, 1.2, and 1.2 respectively, and the actual seismic coefficient *k**=0.15. In 1998, this container berth handled a total of 15,000 TEU of container cargo including both imports and exports. Although it is not among central and core ports, direct route to North America exists but very low frequency. The parameters for the Monte Carlo simulation, min*x*, max*x*, *a*, and *TN*, in equations (13) and (14) are set at 60 (gal), 1,000 (Gal), 20 (Gal), and 10 (times) respectively.

Figure 6 shows the construction cost, the expected restoration cost, and the cost increase caused by rerouting of containers by seismic coefficient, plus the total cost of them. Also the sum of the construction cost and restoration cost is shown in the figure for comparison. According to the figure, the total cost is minimal at seismic coefficient k = 0.15, and conforms to the present seismic coefficient. In addition, this optimal coefficient is one level *higher* than the optimum seismic coefficient (k=0.10) in a case where the cost increase by rerouting is *not* considered. Please notice that only container cargo is considered in rerouting cost calculation shown here, so if other cargoes than containers handled at a multipurpose berth in question are considered, the optimal seismic coefficient would be higher in some cases.

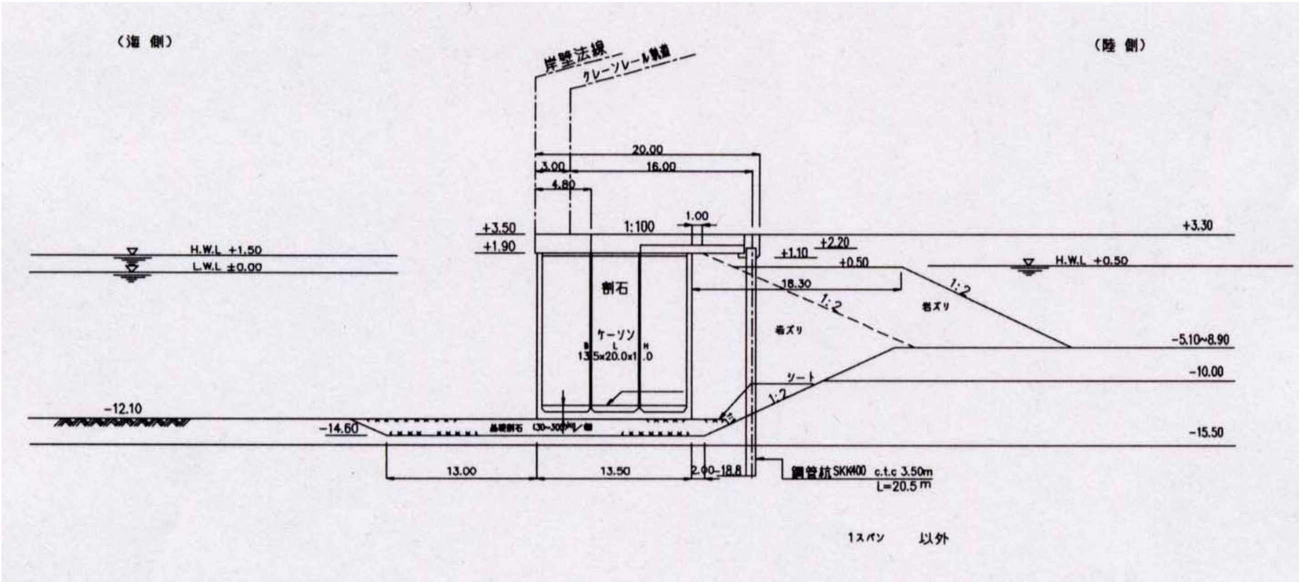

Figure 5. Standard Section of Multipurpose International Freight Terminal in Port A

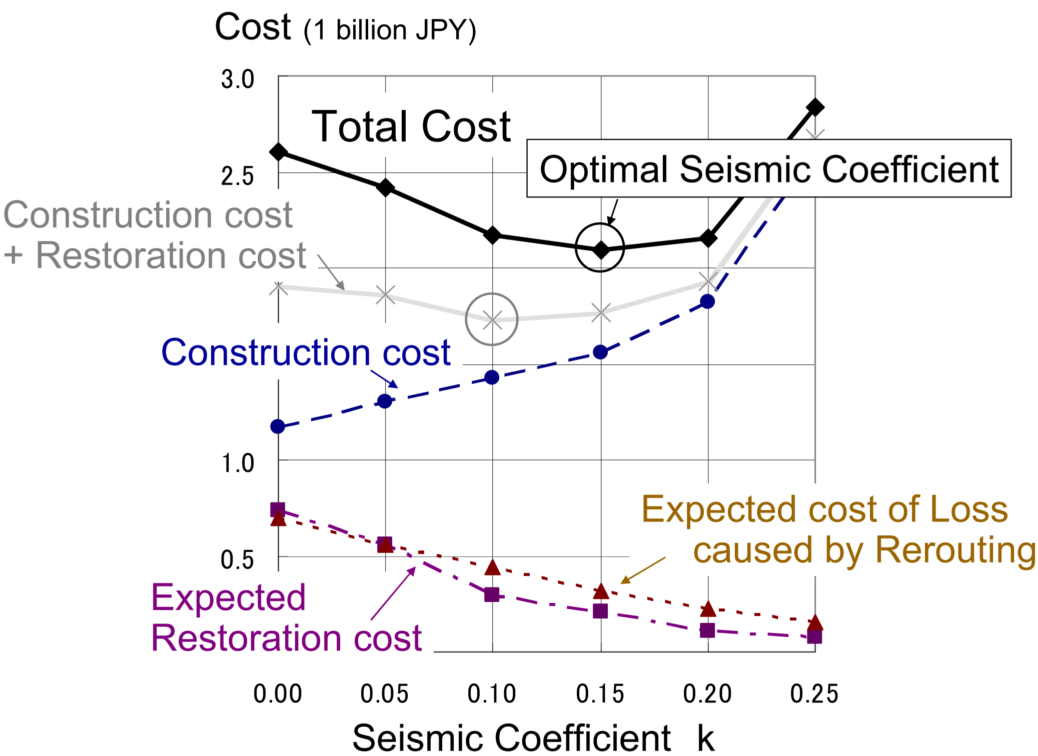

Figure 6. Cost by Seismic Coefficient and Optimum Coefficient in the Container Berth in Part A

4.2 Example 2: Case of port B with multiple international container berths

In port B that is one of core ports in Japan, the five berths shown in Table 8 are all used as public container berths. Although they are all caisson type quaywalls with differing importance coefficients and degrees of seismic retrofitting, as a result, the seismic coefficient k_b*= 0.20 for all quaywalls.

Table 8. Specifications of the Container Berths in Port B

Wharf	Quaywall	Depth (m)	Quaywall length (m)	seismic coefficient	Regional coefficient	Ground-type coefficient	Coefficient of importance	Earthquake resistant quaywall	Remarks
Wharf C	C1	12	220	0.2	0.15	0.8	1.5	○	Multipurpose berth
	C2	12	220	0.2	0.15	0.8	1.5	○	Multipurpose berth
Wharf D	D1	12	240	0.2	0.15	1.0	1.2	×	
	D2	12	240	0.2	0.15	1.0	1.2	×	
	D3	12	240	0.2	0.15	1.0	1.2	×	

(1) Adjustment of the methodology in economic loss calculation by rerouting when multiple berths exist in a port

Unlike port A with only one container berth, for port B with 5 container berths, the calculation method differs according to whether or not the correlation of damage levels of the berths is considered. When it is assumed that the damage level of the berths is completely correlated and that all berths in port B will be equally damaged, only two cases, "all berths in port B are usable," or "no berths in port B are usable," can occur, so the method of calculating the quantity of containers in excess of capacity used in the previous chapter can be applied without modification.

If it is assumed that the damage levels of the berths are completely independent, some of the berths can be used, but other births are unusable. In addition, because the damage level varies between the berths, the number of berths usable varies by restoration stage. Thus, for berths other than the berth in question, the damage level should be calculated according to a random number produced independently of the berth in question, in order to acquire the total capacity of port B for every restoration stage. According to the restoration period for each damage level shown in Table 6, the relationship of the restoration stage with the usable berths is summarized in Table 9.

Table 9. Relationship between Restoration Stage and Useable Berths

Restoration stage	Days after the damage	Useable berths
I	1-180	Only undamaged berths
II	181-360	Above + damage level I berths
III	361-540	Above + damage level Ⅱ berths
IV	541-720	Above + damage level Ⅲberths
V	721	All berths usable (economic loss = 0)

The quantity of containers that cannot be handled by port B, $Ocap_B(t)$ (TEU/day), at restoration stage t. is represented by the following equation

$$Ocap_B(t) = \sum_q \sum_r Q_{Bqr} - Cap_B(t) \qquad (16)$$

Where, $Cap_{B,r}$ is represented by the following equation for the total daily capacity of all container berths in port B at restoration stage t (TEU/day).

$$Cap_B(t) = Cap_B(t-1) + \sum_{b \in B} \{1.4 \cdot cap_b \cdot n[1, G(x, t+1, k_b) < \lambda_b \leq G(x, t, k_b)]\} \quad (17)$$

Here, for the seismic coefficient in berths other than the berth in question is fixed as the present seismic coefficient k_b*.

The restoration cost, *R*, and the loss caused by rerouting, *L*, that are represented by equation (14) can be rewritten as shown by the following equations.

$$R(x,k) = qd_b \cdot \frac{\sum_{s=0}^{4}\left[\left\{\sum_{\mathbf{Sb}} n_{s,\mathbf{Sb}}(G,x,k)\right\} \cdot R_s\right]}{TN},$$

$$L(x,k) = \frac{\sum_{s=0}^{4}\sum_{\mathbf{Sb}} \cdot \left[n_{s,\mathbf{Sb}}(G,x,k) \cdot \sum_{r=1}^{4}\{(RD_r - RD_{r-1}) \cdot L_{s,\mathbf{Sb},r}\}\right]}{TN} \quad (18)$$

Where, Sb= {S1, S2, S3, S4} are vectors that represent the damage levels of other four berths of the port than the berth in question, and $\sum_{\mathbf{s}} = \sum_{s_1}\sum_{s_2}\sum_{s_3}\sum_{s_4}$. In equation of the rerouting loss, *L*, the cost increase by rerouting per day, $L_{s,Sb,r}$, varies according to the damage level and restoration stages of all the berths. Also, the frequency of the damage level obtained from the Monte Carlo simulation, $n_{s,Sb}$, is represented for each damage level of each berth. On the other hand, the restoration cost, *R*, is calculated only for the berth in question.

(2) Results of calculations

The parameters for the Monte Carlo simulation are set as in case of port A. The cost by items and the total cost is shown in Figure 7 for case 1 where there assumes to be absolutely no correlation between the damage level of the berths, and in Figure 8 for case 2 that the damage levels of the berths are completely correlated. The optimal seismic coefficient in case 1 is *k*=0.15 for berths C1 and C2 and *k*=0.20 for the other berths, and in case 2 *k*=0.10 for berth C1 and *k*=0.15 for others. Compared with the total costs of the berths in two cases, the differences between the costs of the berths are greater in case 2, because the damage cost varies widely as once a disaster does occur, all the berths become unusable at that case.

A comparison of the above two cases shows that the optimal seismic coefficient is higher in case 1 (no correlation between the damage levels of the berths), and suggests that if the possibility of simultaneous damage occurring is low, the seismic coefficient must be set higher. This is a result of the fact that the higher the optimal seismic coefficient is, the rapidly smaller the cost increase by rerouting. The reason why so rapid small is considered that as the damage levels of the berths are independently decided, the higher the seismic coefficient the most probable only single berth is damaged, thus the berth itself in question accounts for a large part of the rerouting cost and the seismic coefficient improvement effects would occur more easily.

Moreover, as compared with the case where the rerouting cost is not considered, while the optimal seismic coefficient is one level higher on the average in case 1, it sometimes varies widely and sometimes are the same in case 2, because of small difference between the cost at each seismic coefficient.

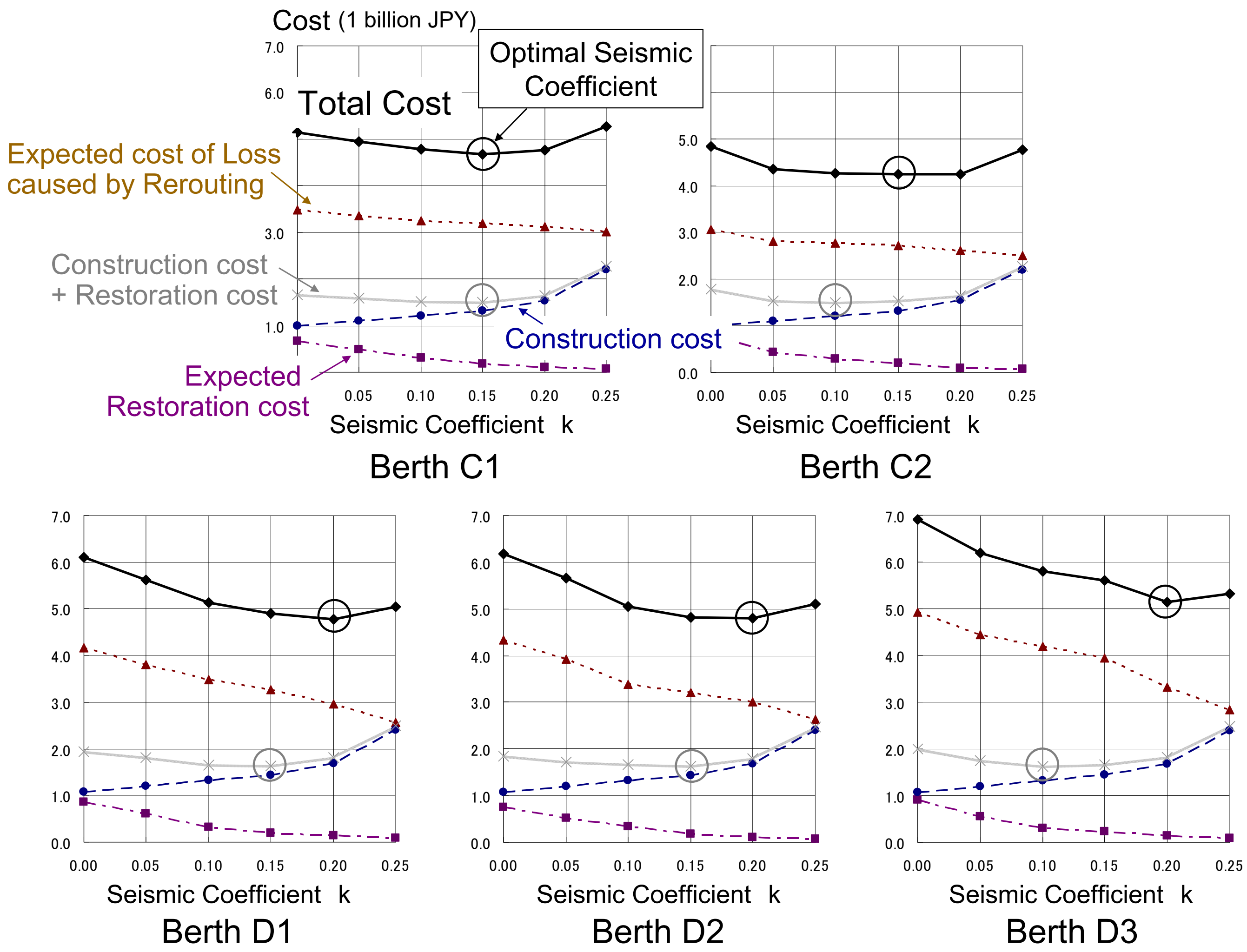

Figure 7. Costs by Seismic Coefficient and Optimal Seismic Coefficient of the Container Berths at Port B
(Case 1: where there assumes absolutely no correlation between the damage levels of the berths)

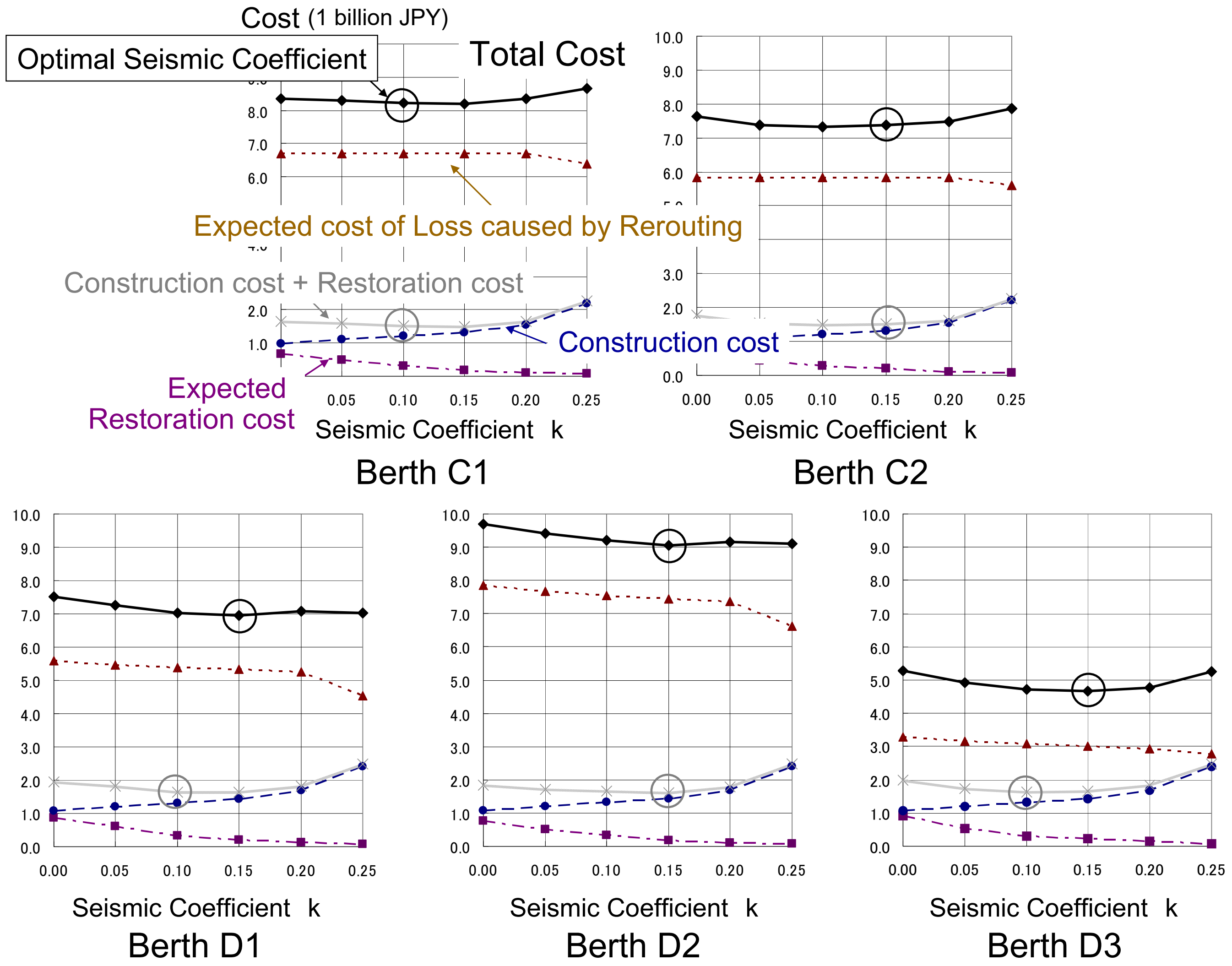

Figure 8. Costs by Seismic Coefficient and Optimal Seismic Coefficient of the Container Berths at Port B
(Case 2: where there assumes complete correlation between the damage levels of the berths)

5. CONCLUSION

The purpose of this research is to construct an economic evaluation methodology for port facilities including the economic loss of freight transport where damage levels appear stochastically in accordance with performance-type technical standards, taking gravity quaywalls as an example from among port facilities. Then, the proposed methodology is applied for a port with one container berth and with multiple container berths as examples, revealing that the optimal design coefficient would sometimes differs according to whether the economic loss by rerouting is considered or not.

This research has completed the foundations for an economic evaluation methodology for port facilities that includes the economic loss of freight transport, but many important challenges remain for future study. The following are the principal challenges that should be studied in the future.

(1) Technical study of the calculation of damage probability of port structures

The first problem is the stochastic variability of damage level or fragility curves can only be prepared for a gravity quaywall. Actually in central and core ports in Japan, most berths are underlain by jetty type or sheet pile type quay wall. A fragility curve or a functional equation equivalent must be prepared for berths with structures other than the gravity quaywall, even if it is a simplified method, especially when studying a concept of the nationwide distribution of various kinds of berths. In addition, although this paper used seismic coefficient as an index representing the performance of the port structures, a more precise methodology of representing the performance of a facility and a damage probability equation corresponding to the proposed one must be studied.

(2) Considering the probability and correlation of simultaneous damage to multiple berths or ports

The second point to improve is clarifying the degree of correlation between levels of damage of berths in a single port. This will require a study from the structural engineering and geotechnical engineering perspectives instead of sensitivity analysis as in this research. In addition, by setting the earthquake occurrence probability of an individual port from the epicenter, the proposed methodology in this research can consider simultaneous damage to multiple ports in contiguous regions.

(3) Application to freight cargo other than containers

It is necessary to calculate economic loss for sea transport and hinterland transport of normal freight other than containers, however, it needs to combine various kinds of data with a number of assumptions due to limitation od available data concerning these matters.

(4) Evaluation of the benefits considering port networks, complementary relationships between ports, and the damage on the hinterland

This research limited freight that causes losses when it must be rerouted according to the damage level. However, after the port of Kobe was damaged by the Hyogo-ken Nanbu Earthquake and its hub functions were once shifted to other hub ports such as Busan, the flow of freight has been changed for the port of Kobe even after full restoration. To quantitatively measure the impact of damage to ports on the flow of freight over wide areas, it is necessary to apply a distribution flow model such as proposed by authors (Shibasaki et al., 2005) that covers the entire East Asian region. In addition, when studying the economics of seismic retrofitting investment of port facilities, it is not enough to evaluate each port or individual berths; the overall network must be evaluated, considering the ports in a single region complement each other's functions. Evaluation indices and methodologies such as application of genetic algorism must be studied. Also, the damage level to a land transport network in a hinterland should be considered for a more precise, comprehensive economic evaluation.

(5) Considering the catastrophic economic loss

The investment evaluation index that is most widely used to choose the level of disaster prevention / mitigation facility, also as adopted in this research, is the expected loss that is represented by the simple product of the cost of damage and the frequency of occurrence. However, the state-of-the-art researches in the field such as Froot (1999) and Kobayashi and Yokomatsu (2002) are pointing out that expected loss is inadequate to deal with the risk of catastrophic damage in particular, proposing to add a risk premium etc. to the cost of loss. Based on the actual provision level of disaster prevention / mitigation facilities, the author (see Shibasaki, 2002) has studied how decision makers evaluate the amount of loss of each risk and the occurrence frequency, also will try a similar study of seismic design problems for port structures under the earthquake risk that dealt with this paper.

Although many challenges related to this research remain to be dealt with in the future as above mentioned, this research is significant in that it has constructed a prototype of a port facility economic evaluation methodology that considers economic loss of freight transport.

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