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EVALUTION METHOD OF THE LIFE-CYCLE COST OF QUAY WALLS IN VIEW OF EARTHQUAKE RESISTANCE

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Abstract

This study aims at proposing an evaluation method of the life-cycle cost of quay walls in view of earthquake resistance. Major failure mode of quay walls by earthquake is the occurrence of undesirable amount of residual displacement. Therefore, probabilistic residual displacement of quay walls should be evaluated in the life-cycle cost analysis of quay walls.

As quay walls are earth retaining structures that are subjected to earth pressure, residual displacement of quay walls is generated mainly by the deformation of the foundation soil layers. The problem in the evaluation of the residual displacement of quay walls is the fact that the residual displacement is generated mainly by the deformation in the foundation soil layers and is not easy to be calculated. It is necessary to conduct two-dimensional effective stress finite element earthquake response analysis for the precise evaluation of residual displacement of quay walls. However, as the application of that kind of analysis is time consuming, it is not a practical idea to apply such kind of method for the evaluation of the probabilistic residual displacement of quay walls because designers must conduct the analysis many times in order to evaluate the probabilistic residual displacement.

Authors apply one-dimensional effective stress finite element earthquake response analysis for the evaluation of residual displacement of quay walls whose computational load is much less compared with the two-dimensional analysis. Authors next proposed a method to evaluate the damage cost of quay walls considering both repair cost after earthquake and economic loss cost. As the repair cost varies according to the dimension and residual displacement of quay walls, authors established the equations for the calculation of repair cost considering the dimension and residual displacement of quay walls for each structural type. Authors also established the equations for the calculation of the economic loss cost according to the kind and total amount of cargo for the wharf and the condition of detour route for cargo transportations during the closing period of the wharf. Authors finally showed some examples of the evaluation of life-cycle cost of quay walls by the proposed method.

Keywords: quay wall, seismic hazard, life-cycle cost

1. Introduction

Technical standards for port harbor facilities in Japan has been revised many times to date and the latest version that was published in 2007 sets the target safety level of quay walls against earthquake as the average safety level of those by the old technical standards. That method can be recognized as one of the rational methods for the determination of the target safety level of structures. Another method for deciding the target safety level is to set the target safety level that corresponds to the minimum life- cycle cost by conducting the life-cycle cost analysis.

Major failure mode of quay walls by earthquake is the occurrence of undesirable amount of residual displacement. It is true that yield of structural members should be taken into consideration for sheet pile quay walls and pile supported wharves, however, yield of structural members of such kind of quay walls was caused by the displacement of quay walls and not by resonance. Therefore, probabilistic residual displacement of quay walls should be evaluated in the life-cycle cost analysis of quay walls.

As quay walls are earth retaining structures that are subjected to earth pressure, residual displacement of quay walls is generated mainly by the deformation of the foundation soil layers. Although there are a variety of previous studies on the evaluation of life-cycle cost analysis of structures [1 - 4], little studies have been done on the evaluation of life-cycle cost of structures in view of residual displacement caused by the deformation of the foundation soil layers.

It is necessary to conduct two-dimensional effective stress finite element earthquake response analysis modeling both quay wall and soil layers for the precise evaluation of residual displacement of quay walls. However, as the application of the analysis is time consuming, it is not a practical idea to apply such kind of method for the evaluation of the probabilistic residual displacement of quay walls because designers must conduct the analysis many times in order to evaluate the probabilistic residual displacement.

Authors propose a practical method for the evaluation of the life-cycle cost of quay walls in view of earthquake resistance in this study. The proposed method evaluates residual displacements of quay walls by the one-dimensional effective stress finite element earthquake response analysis. The method evaluates both damage cost and economic loss cost by the earthquake from the residual displacements of quay walls. Authors also show some examples of the evaluation of life-cycle cost of quay walls by the proposed method. Note that structural types of quay walls dealt with in this study are gravity type, sheet pile type and open type wharf.

2. EVALUATION OF PROBABILISTIC DISPLACEMENTS OF QUAY WALLS

2.1 Evaluation of Seismic Hazard

Seismic hazard curves at the site of interest can be evaluated by using the method proposed by Nagao et al [5]. Seismic hazard evaluation method based on active faults and fault models is established considering seismic source characteristics, propagation path characteristics and the ground motion amplification characteristics of deep subsurface profiles using the following approach as shown in the conceptual diagram of Fig.1.

The method applies a stochastic Green's function method and ground motions on the seismic bedrock from a subfault are assumed to follow the ω^{-2} model and their Fourier amplitude is evaluated based on the approach proposed by Boore [6]. Using the results of the study of Yamada et al. [7], asperites and rupture starting points are distributed randomly and uniformly on the fault planes. Logic trees are used to estimate the dispersions of the indices unable to be expressed by random dispersions.

Seismic hazard evaluation method based on earthquake catalog data regards the seismic ground motions occurring at the site of interest obtained from earthquake catalog data as background data. Here, background means that authors treat that data without considering the relationship with specific active faults. Seismic source characteristics, propagation path characteristics, and the ground motion amplification characteristics of deep subsurface profiles are estimated through the following procedure as shown in the conceptual diagram of Fig.2.

Assuming that seismic activities are uniform over each earthquake province, authors first distribute seismic sources over the earthquake province of interest. Based on a Gutenberg-Richter's relation and a relational expression between magnitudes and seismic moments, authors then define the sizes of the earthquakes (using the seismic moment M_0). The Fourier amplitude spectra on the seismic bedrocks are calculated assuming the ω^{-2} spectral model. The region-wise Q values that have been proposed in past studies are used to indicate propagation path characteristics. The results of spectral inversion on the site of interest are used for calculating the amplification characteristics of deep subsurface profiles.Fig.3 shows the hazard curve for the port of interest obtained by the method mentioned above.

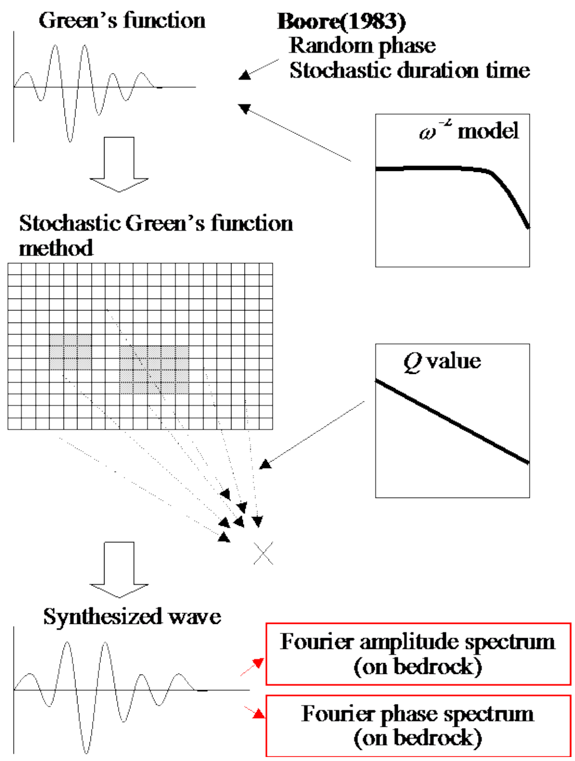


Fig. 1 – Estimation for active fault and fault model

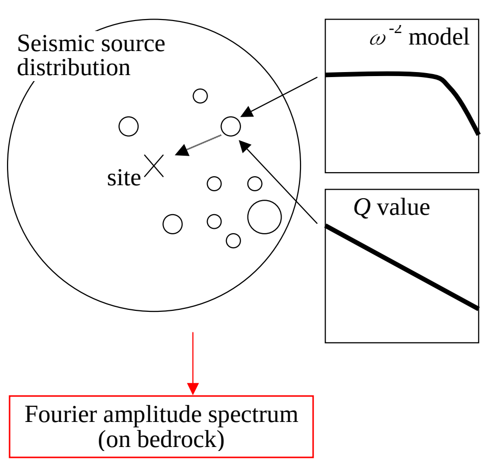


Fig. 2 – Estimation for earthquake catalog data

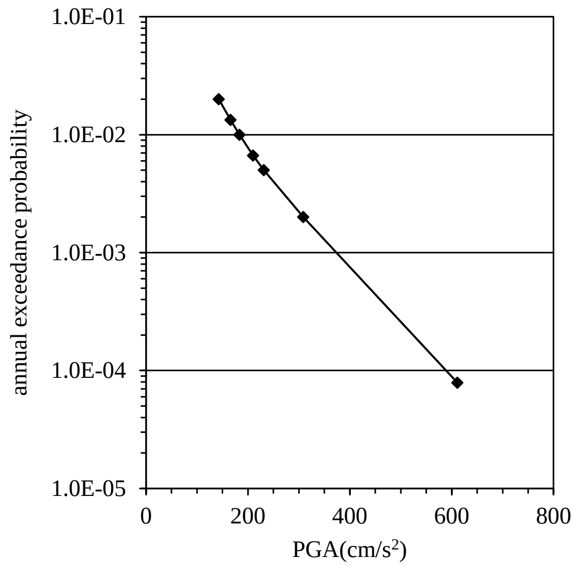


Fig. 3 – Seismic hazard curve

2.2 Evaluation of average displacement of quay walls

As is described above, it is necessary to evaluate probabilistic residual displacement of quay walls for the calculation of life-cycle cost of quay walls. Authors apply one-dimensional effective stress finite element earthquake response analysis for the evaluation of residual displacement of quay walls whose computational load is less compared with the two-dimensional analysis. Yasuda et al. [8] proposed equations for the evaluation of residual displacement of quay walls by the results of one-dimensional effective stress finite element earthquake response analysis modelling only the soil layers behind quay walls. As the proposed method was established by using the 4480 results of two-dimensional analysis and one-dimensional analysis changing design conditions such as ground condition, input seismic wave and design water depth, the method is thought to have high applicability to various design conditions. The proposed equations are as below.

$$D_{est\_g} = 10^{-0.469} k_{hk}^{-0.581} \left(\frac{\alpha_f}{g}\right)^{0.708} P^{1.610} \left(1 + h_{liq1} / h_{liqR}\right)^{0.470} \left(1 + h_{liq2} / h_{liqR}\right)^{0.421} \left(1 + P_{ex1}\right)^{0.753} \left(1 + P_{ex2}\right)^{1.161} \left(\delta_{s1} / \delta_{sR}\right)^{0.281} \left(\delta_{s2} / \delta_{sR}\right)^{0.541} \quad (1)$$

$$D_{est\_s} = 10^{-0.204} k_{hk}^{-0.497} \left(\frac{\alpha_f}{g}\right)^{0.762} P^{1.684} \left(1 + h_{liq1} / h_{liqR}\right)^{0.202} \left(1 + h_{liq2} / h_{liqR}\right)^{0.121} \left(1 + P_{ex1}\right)^{1.930} \left(1 + P_{ex2}\right)^{0.037} \left(\delta_{s1} / \delta_{sR}\right)^{0.128} \left(\delta_{s2} / \delta_{sR}\right)^{0.433} \quad (2)$$

where D_{est_g} is the residual displacement of gravity type quay wall (m), D_{est_s} is residual displacement of sheet pile type quay wall (m), k_{hk} is characteristic value of seismic coefficient, α_f is maximum acceleration, g is gravity acceleration, P is coefficient of effect of duration of earthquake on the displacement of quay walls, h_{liqi} is thickness of liquefiable soil layer(m) ; (i=1;backfill, i=2;in situ ground), H_{liqR} is reference thickness of liquefiable soil layer (=5.0m), P_{exi} is average excess pore water pressure; (i=1;backfill, i=2;in situ ground) , δ_{si} is shear displacement obtained by one-dimensional earthquake response analysis(m); (i=1;backfill, i=2;in situ ground), $\delta_s=\Sigma(h_i \times \gamma_{xy})$, h_i is height of element of earthquake response analysis(m), γ_{xy} is maximum shear strain obtained by one-dimensional earthquake response analysis and δ_{sR} is reference shear displacement(=0.05m).

An example of the displacement of quay walls at the port of interest according to the change in the design seismic coefficient is shown in Fig.4. As shown in the figure, displacement increases according to the decrease in design seismic coefficient and annual exceedance of probability of earthquake ground motion. Authors model the probabilistic displacement curve by the logarithmic normal distribution. Parameters of the logarithmic normal distribution are determined as the cumulative value of the distribution becomes 1.0 for the maximum displacement of the quay wall. Annual expected displacement of quay wall for each design condition is obtained by using the probability distribution.

$$P = A \cdot \int_0^x \frac{1}{\sqrt{2}\sigma x} \exp\left\{ -\frac{1}{2} \left(\frac{\ln x - \mu}{\sigma} \right)^2 \right\} dx \tag{3}$$

where P is residual displacement of quay walls(cm), A is coefficient(=5190.0), x is return period, μ is mean value(=11.10) and σ is standard deviation(=2.142).

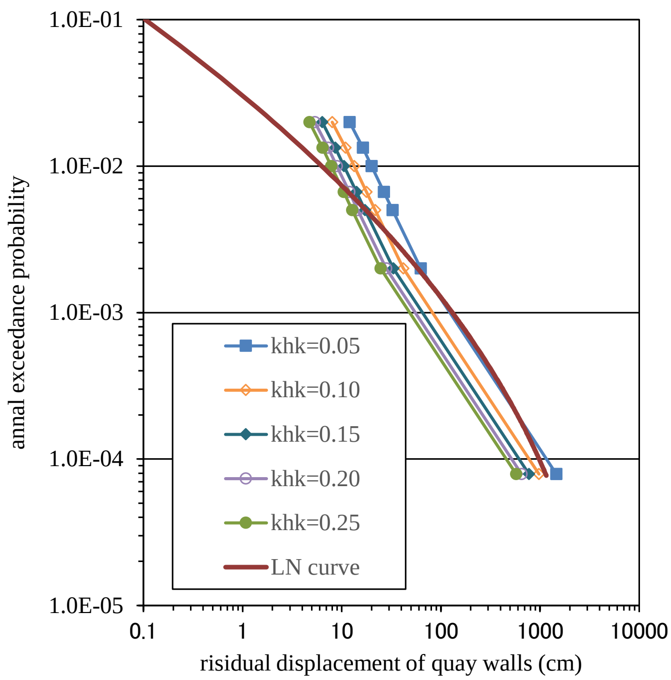


Fig. 4 – An example of the displacement of quay walls

3. EVALUATION OF VARIOUS COST

3.1 Initial construction cost

Authors calculated dimensions of quay walls for each structural type changing both the design seismic coefficient and design water depth according to the technical standards for port and harbor facilities in Japan. Authors next calculated the initial construction cost for each dimension of quay wall considering the standard production rate of construction in Japan. As the results, initial construction cost increases according to the increase in the design seismic coefficient and design water depth. By conducting the regression analysis to the results, authors obtained the equation for the calculation of initial construction cost according to the design seismic coefficient and water depth as below.

$$C_i = A_1 + B_1 \cdot h \cdot k_h^{0.5} \tag{4}$$

where C_{i} is initial construction cost(thousand Japanese yen/m), A_1 and B_1 are coefficients shown in Table 1, h is absolute value of the design water depth(m) and k_{h} is design seismic coefficient.

3.2 Earthquake resistant strengthening cost

Authors applied conventional static seismic coefficient method for the calculation of dimensions of quay walls for each structural type in terms of earthquake resistant strengthening changing the design seismic coefficient increment and design water depth. By conducting the regression analysis to the calculated cost for the earthquake resistant strengthening of quay walls, the design seismic coefficient increment and design water depth, authors obtained the equation for the calculation of cost for earthquake resistant strengthening according to the increment of design seismic coefficient and water depth as below.

(i) gravity type quay wall and open type wharf with gravity type revetment

$$C_c = A_2 \cdot k_{h0}{}^{0.5} \cdot h \cdot \Delta k_h + B_2 \tag{5}$$

(ii) sheet pile type quay wall and open type wharf with sheet pile type revetment

$$C_c = A_2 \cdot k_{h0}{}^{0.5} \cdot e^{0.14h} \cdot \Delta k_h + B_2 \tag{6}$$

where C_c is cost for earthquake resistant strengthening (thousand Japanese yen/m), A_2 and B_2 are coefficients shown in Table 2, h is absolute value of the design water depth(m), k_{h0} is design seismic coefficient of existing quay wall and $\varDelta k_h$ is seismic coefficient increment for earthquake resistant strengthening.

Table 1 – The coefficient for the calculation of the initial construction cost

	A_1	B_1
gravity type quay wall	848.3	2995.8
sheet pile type quay wall	1385.3	2552.1
open type wharf with gravity type revetment	968.1	2673.0
open type wharf with sheet pile type revetment	924.2	3197.7

Table 2 – The coefficient for the calculation of the cost for earthquake resistant strengthening

	A_2	B_2
gravity type quay wall	10420.0	2932.0
sheet pile type quay wall	23270.0	1155.0
open type wharf with gravity type revetment	5210.0	5966.0
open type wharf with sheet pile type revetment	11635.0	5078.0

3.3 Repair cost

Authors apply the equations for the calculation of repair cost by earthquake proposed by Nagao et al. [9]. The equations calculates the repair cost considering the design seismic coefficient, wall height and displacement of quay wall by the earthquake as

(i) gravity type quay wall

$$C_r = 0.938 \times 10^{-6} \cdot k_h{}^{-2.141} \cdot H^{2.493} \cdot Dx_{\max}{}^{1.682} \tag{7}$$

(ii) sheet pile type quay wall

$$C_r = 2.193 \times 10^{-4} \cdot k_h{}^{-1.262} \cdot H^{0.962} \cdot Dx_{\max}{}^{1.896} \tag{8}$$

(iii) open type wharf

$$C_r = A_3 \cdot DISR^{B_3} \tag{9}$$

where C_r is repair cost(thousand Japanese yen/m), k_h is design seismic coefficient, H is wall height(m), D_{xmax} is displacement by the earthquake(mm), A_3 and B_3 are coefficients shown in Table 3 and $DISR$ is displacement ratio(=lateral residual displacement/height of open type wharf).

Table 3 – The coefficient for the calculation of the repair cost

the pile line number of lateral direction	A_3	B_3
3	206600.0	3.204
4	366300.0	3.295
5	618000.0	3.559

3.4 Detour cost

Economic loss cost arises when a quay wall is damaged by an earthquake and cargo handling service is suspended. As the economic loss cost, authors consider the detour cost that is defined as the difference between transportation cost of cargos after and before earthquake disaster.

It is necessary to estimate the duration of repair work after earthquake disaster because total detour cost depends on the duration of repair work. Authors apply the equations for the calculation of duration of repair work proposed by Nagao et al. [9] as below.

(i) gravity type quay wall

$$rp = 1.544 \cdot L^{0.506} \cdot Cr^{0.326} \tag{10}$$

(ii) sheet pile type quay wall

$$rp = 5.706 \cdot L^{0.503} \cdot Cr^{0.139} \tag{11}$$

(iii) open type wharf

$$rp = 1.149 \cdot L^{0.500} \cdot Cr^{0.321} \tag{12}$$

where rp is duration of repair work (day), L is length of the wharf (m) and C_r is repair cost (thousand Japanese yen/m).

Evaluation of the amount of cargo handling of the wharf in the future is also necessary because detour cost depends on the amount of cargo handling. Authors estimate the amount of cargo handling after ten years according to the procedure shown in Fig.5. First, the gross regional product after ten years is estimated using the ratio of the gross regional product and the gross regional product. The regional shipment value is next estimated from the gross regional product using a relationship between the regional shipment value and the gross regional product. Finally, the amount of cargo handling is estimated from the regional shipment value using a relationship between the amount of cargo handling and the regional shipment value.

In this study, authors assume the design working life of the wharf as fifty years that is standard for Japanese port facilities. Therefore, it is necessary to evaluate the change of the amount of cargo handling of the wharf during fifty years. Considering the economic circumstances in Japan, authors assume that the increase of the total amount of cargo handling from now on to after ten years is equal to that form after ten years to after fifty years.Fig.6 shows an example of the estimation of the change of the amount of cargo handling during fifty years.

In addition to the various evaluations mentioned above, it is necessary to select the alternative port in case of earthquake disaster. Detour cost can be evaluated by using the results of the estimation of the duration of repair work, the amount of cargo handling of the wharf in the future and the location of the alternative port in case of earthquake disaster.

Step1: Estimation of the gross regional product in the future by using the estimation of the gross national product in the future and the ratio of the gross regional product to the gross national product

⇩

Step2: Estimation of the regional shipment value in the future considering the correlation between the regional shipment value and the gross regional product

⇩

Step3: Estimation of the amount of cargo handling of the wharf after ten years considering the correlation between the regional shipment value and the amount of cargo handling of the wharf

Fig. 5 – Flow chart for the estimation of the amount of cargo handling after ten years

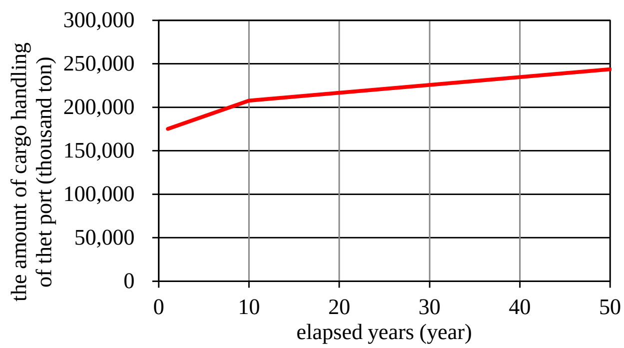


Fig. 6 – Example of the estimation of the change of the amount of cargo handling during fifty years

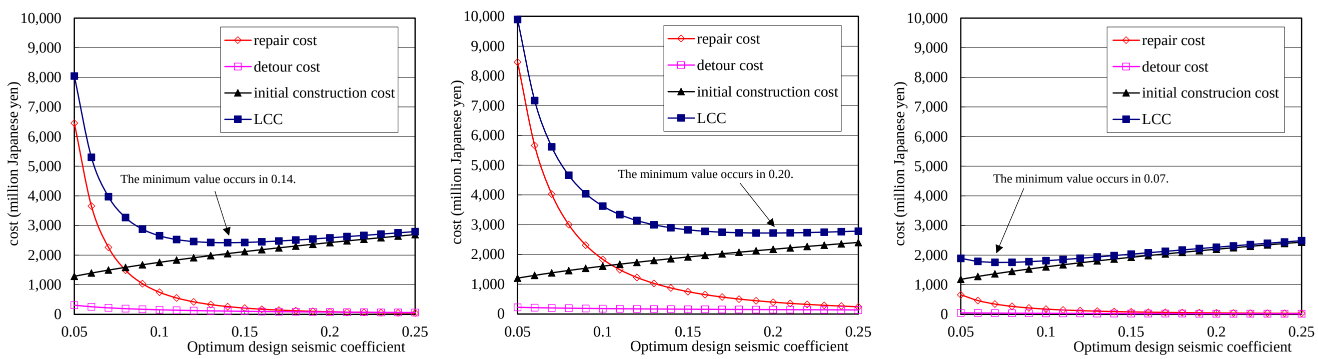
4. EVALUATION OF LIFE-CYCLE COST

The life-cycle cost of quay walls is defined as sum of the initial construction cost, repair cost and detour cost. Authors calculated the life-cycle cost both for wharves for cargo ships with design water depth is -10m and wharves for container ships with design water depth is -14m. Results of the life-cycle cost curves are shown in Fig.7 and Fig.8.

Optimum design seismic coefficients corresponding to the minimum life-cycle cost are about 0.15 for the gravity type quay wall, 0.20 for the sheet pile type quay wall and 0.07 for the open type wharf. As life-cycle cost is strongly affected by the repair cost, design seismic coefficients corresponding to the minimum life-cycle cost vary structural type to structural type. Optimum design seismic coefficients become large for structural types with expensive repair cost such as sheet pile type quay wall. On the contrary, optimum design seismic coefficients become small for open type wharf because repair cost is cheap. Although detour costs are much different, authors found that optimum design seismic coefficients are about the same value for wharves for cargo ships and those for container ships.

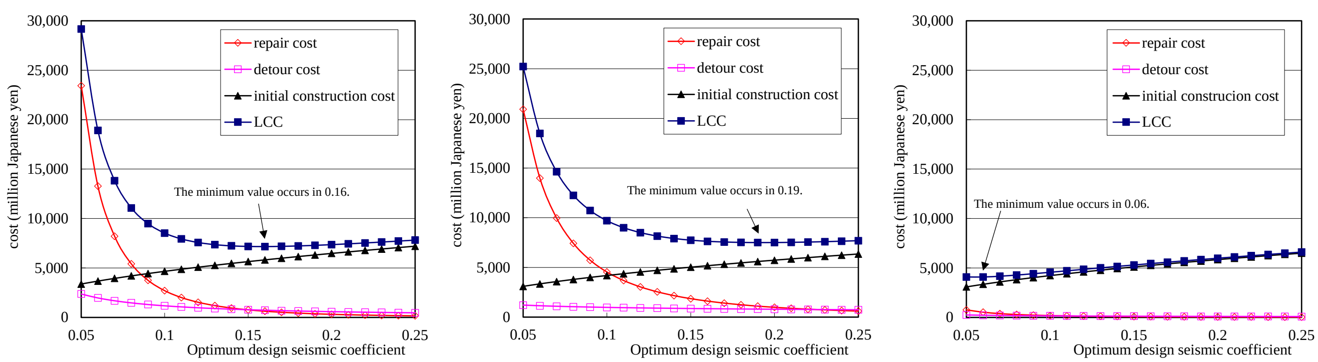
Table 4 – An example of detour cost

	the detour cost (milion Japanese yen/year)
wharf for cargo ships design water depth-10m	307.0
wharf for ccontainer ships design water depth-14m	1376.0



(a) gravity type quay wall (b) sheet pile type quay wall (c) open type wharf with gravity type revetment

Fig. 7 – Examples of life-cycle cost curve (design water depth -10m)



(a) gravity type quay wall (b) sheet pile type quay wall (c) open type wharf with gravity type revetment

Fig. 8 – Examples of life-cycle cost curve (design water depth -14m)

5. CONCLUSION

In this paper authors proposed the evaluation method of the life-cycle cost of quay walls in view of earthquake resistance considering the probabilistic displacement of quay walls and various cost. It necessary to conduct two-dimensional effective stress finite element earthquake response analysis many times in order to evaluate the probabilistic displacement of quay walls precisely. The proposed method uses the result of one-dimensional earthquake response analysis whose computational load is less compared with the two-dimensional analysis. Authors showed some examples of the evaluation of life-cycle cost of quay walls and also showed that life-cycle cost curves according to the design conditions. As the results, it was shown that optimum design seismic coefficients vary structural type to structural type because of the difference in the repair cost.

The idea that setting the target safety level of quay walls against earthquake to that corresponds to the minimum life-cycle cost safety level is a good idea. However, it is not introduced in the technical standards mainly because of the high computational load for the calculation of life-cycle cost of quay walls. Authors hope that the proposed method is to be applied to the practical design in the future.

6. References

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