

ESTIMATION OF EXPECTED REPAIR COST FOR DETACHED BREAKWATER COVERED WITH WAVE-DISSIPATING BLOCK

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ABSTRACT: The expected repair cost for the detached breakwaters covered with wave-dissipating blocks for a target period is estimated. The total repair cost is composed of the cost for repairing the detached breakwater body and the cost equivalent to the amount of damage to the coastal zone behind the detached breakwater. In estimating the cost for repairing the detached breakwater body, the influence of abrasion of the wave-dissipating block is taken into account. The influence of the difference in the reduction rate in size due to abrasion on the lowest total repair cost is also investigated.

KEYWORDS: repair, cost, breakwater

1. INTRODUCTION

An effective repair of coastal structures is very important. The number of coastal structures constructed more than 30 years ago is increasing in Japan. The hydraulic performances of old coastal structures are generally reduced and the maintenance cost for old coastal structures is increased. However, the budget for the maintenance cost and replacing old coastal structures with new structures is very limited. Under these circumstances, the maintenance cost for coastal structures during the lifetime should be minimized because too frequent repair causes a high repair cost; however, infrequent repair may cause a catastrophic damage to coastal structures and surrounding areas. Therefore, the repair criterion at which the repair cost is minimized and at which coastal structures can maintain adequate hydraulic performances should be determined.

Recently, several studies on lifecycle costs for coastal and harbor structures including repair costs have been studied. Matsubuchi and Yokota (1999) investigated the lifecycle cost of berthing facilities.

Nagao and Matsubuchi (1999) investigated the lifecycle cost and allowable failure probability of composite breakwaters. Nanba *et al.* (2003) pointed out the necessity of regular and effective maintenance of coastal structures. Yoshioka and Nagao (2004) proposed a design method of minimizing the life cycle cost. Takayama *et al.* (2007) proposed the procedure for determining the optimum size of armor units by selecting the minimum life cycle cost. The authors have investigated the deformation of rubble mound structures and the change in hydraulic performances of rubble mound structures (Araki *et al.*, 2002; Araki *et al.*, 2004; Araki *et al.*, 2005a). The authors have also estimated the repair cost for rubble mound structures during their lifetime (Araki *et al.*, 2007; Araki *et al.*, 2008).

In this study, the expected repair cost for a detached breakwater covered with wave-dissipating blocks was estimated. From the circumstances that the number of old coastal structures is increasing, the target structure was the existing detached breakwaters, *i.e.*, the initial construction cost was not

included. In estimating the repair cost, the influence of abrasion of tetrapods on the deformation in the detached breakwater body was taken into account.

2. PROCEDURE FOR ESTIMATING OF EXPECTED REPAIR COST

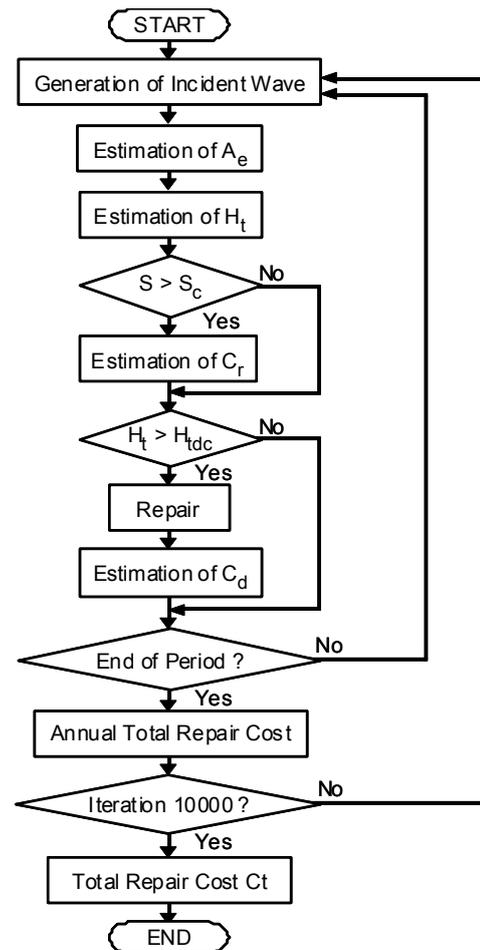
2.1 Overview

Expected total repair cost was estimated by the model based on that proposed by Araki *et al.* (2007). The total repair cost was assumed to be composed of the cost for repairing the detached breakwater body and the cost equivalent to the amount of damage to the coastal zone behind the detached breakwater. The initial construction cost was not included in the total repair cost in this study because the repair cost for the existing breakwaters was estimated. The procedure for estimating the expected repair cost is briefly summarized as follows:

- (i) The probability distribution of the incident wave height is determined by using the annual maximum wave height measured in the ocean.
- (ii) The annual maximum wave height of the incident wave is determined by generating a random number which satisfies the probability distribution.
- (iii) The magnitude of deformation caused by the wave attack of the annual maximum incident wave is estimated.
- (iv) The transmitted wave height behind the deformed detached breakwater is estimated.
- (v) If the criteria for repairing the detached breakwater body are satisfied or if damage occurs to the coastal zone, the cost for repairing the detached breakwater or the cost equivalent to the amount of damage to the coastal zone is estimated.
- (vi) The above procedure, from steps (i) to (v), is performed annually. Therefore, the steps are annually iterated until the end of a target period.

- (vii) The steps (i) to (vi) are iterated with different numbers (Monte Carlo Simulation).

Figure 1 shows the flowchart of the procedure. The probability distribution of occurrence of the incident wave height in Step (i) was determined to be a Weibull distribution with parameters $A=1.87$, $B=4.20$ and $k=2.0$ from the measured wave height.



$H_{1/3}$: Incident Wave Height
A_e	: Eroded Area
H_t	: Transmitted Wave Height
S	: Damage Level ($= A_e / D_n^2$)
S_c	: Non-dimensional Allowable Deformation (Repair Criterion)
C_r	: Cost for Repairing Breakwater Body
H_{tdc}	: Transmitted Wave Height that Represents Threshold of Damage
C_d	: Cost Equivalent to Amount of Damage
C_t	: Total Repair Cost

Figure 1. Flowchart of procedure

2.2 Relationship between Incident Wave Height and Deformation of Breakwater

In order to investigate the relationship between the incident wave height and the deformation of the detached breakwater body, the equation for estimating the stability of tetrapods on a 1:1.5 slope proposed by Van der Meer (1988) was used in this study.

$$\frac{H_{1/3}}{\Delta D_n} = \left(3.75 \frac{N_{od}^{0.5}}{N^{0.25}} + 0.85 \right) s_{om}^{-0.2} \quad (1)$$

where $H_{1/3}$ is the significant wave height in front of the detached breakwater; D_n , the nominal diameter of tetrapods; Δ , relative density ($= \rho / \rho_w - 1$, ρ : the density of tetrapods, ρ_w : density of water); N_{od} , the actual number of displaced tetrapods related to a width of one nominal diameter (The number of locking tetrapods is not included); s_{om} , the wave steepness ($= 2\pi H_{1/3} / gT_m^2$, T_m : mean wave period, g : gravitational acceleration); N , the number of the incident waves.

The deformation of the detached breakwater body, *i.e.*, the eroded area A_e , can be estimated by calculating the actual number of displaced tetrapods N_{od} . The actual number of displaced tetrapods N_{od} can be related to the damage level S ($= A_e / D_n^2$, A_e : the eroded area of the detached breakwater body in a cross-shore profile). Van der Meer (1994) mentioned that the damage level S for breakwaters covered with concrete armor units was approximately twice as large as the actual number of displaced tetrapods N_{od} . In estimating the damage level S , the porosity of the armor layer is taken into account. On the contrary, in estimating N_{od} , the porosity of the armor layer is not taken into account.

The actual number of displaced tetrapods N_{od} was calculated by the following equation derived from Eq. (1).

$$N_{od} = \frac{N^{0.5}}{3.75^2} \left(\frac{H_{1/3}}{\Delta D_n} s_{om}^{0.2} - 0.85 \right)^2 \quad (2)$$

The damage level S and the eroded area A_e were calculated as follows:

$$S = 2N_{od} \quad (3)$$

$$A_e = S \times D_n^2 \quad (4)$$

Concrete blocks, such as tetrapods, are abraded by wave action and so on. Uchida *et al.* (2004) conducted the exposure test of concrete blocks and showed that the reduction rate in size of the concrete block was 3% for 15 years. From this result, the nominal diameter of tetrapods was assumed to decrease by 0.2% every year in this study.

2.3 Relationship between Deformation of Breakwater and Transmitted Wave Height

The relationship between the deformation of the breakwater body and the transmitted wave height was estimated by experimental results conducted by Araki *et al.* (2008). In the experiment, the detached breakwater had a 1:4/3 slope, the crest width of 0.24m, the crest height above the still water level of 0.05m and the depth at the toe of 0.25m. The detached breakwater was covered with wave dissipating blocks of 0.0145kg. Eq. (1) was proposed for the coastal structures covered with tetrapods with a 1:1.5 slope. However, Eq. (1) was used for estimating the deformation of the detached breakwater because the difference between the stabilities of tetrapods on a 1:4/3 and a 1:1.5 slopes was assumed to be not so large.

2.4 Cost for Repairing Breakwater Body

The detached breakwater was assumed to be repaired when the damage level S for the detached breakwater exceeded the repair criterion. The many researches have reported that the increase in the damage level S

caused the increase in the transmitted wave height behind the breakwater (e.g., Araki *et al.* 2008). Therefore, the increase in the damage level S means the reduction of the hydraulic performance of the detached breakwater.

The cost for repairing the breakwater body per unit length C_r was assumed to be proportional to the eroded area in a cross-section of the detached breakwater. The C_r was estimated by the following equations.

$$C_r = C_{ru} \times A_e \times b + C_{r0} \quad \text{for } S > S_c \quad (5)$$

$$C_r = 0 \quad \text{for } S < S_c \quad (6)$$

where S_c is the non-dimensional allowable deformation of the detached breakwater, *i.e.*, the repair criterion; C_{ru} , the cost for repairing the detached breakwater body per unit volume of the breakwater body; b , the longshore distance of the eroded area ($b=1.0\text{m}$ because of the two-dimensional investigation in this study); C_{r0} , the cost for repairing the detached breakwater body independent of the volume of the eroded area.

2.5 Cost Equivalent to Amount of Damage

The cost equivalent to the amount of damage to the coastal zone behind the detached breakwater C_d was assumed to be simply proportional to the transmitted wave height because it varies depending on the circumstances. The cost C_d was estimated by the following equations.

$$C_d = C_{da} \times (H_t/h_c - H_{tc}/h_c) + C_{db} \quad \text{for } H_t > H_{tdc} \quad (7)$$

$$C_d = 0 \quad \text{for } H_t < H_{tdc} \quad (8)$$

where C_{da} and C_{db} are the constants that depend on the condition of land use in the coastal zone behind the detached breakwater; h_c , the crest height above the still water level; H_{tdc} , the transmitted wave height that represents the threshold of the damage to the coastal zone behind the detached breakwater.

2.6 History of Deformation

The detached breakwater is not repaired if the performance of the detached breakwater is sufficient to maintain tranquility behind the detached breakwater. Therefore, the accumulation of the deformation of the detached breakwater has to be taken into account. The number of the incident wave in the i -th year N' which causes the deformation equivalent to the actual number of displaced tetrapods in the $(i-1)$ -th year $N_{od,i-1}$ was calculated by the following equation derived from Eq. (1).

$$N' = \frac{3.75^4 (N_{od,i-1})^2}{\left(\frac{H_{1/3}}{\Delta D_n} S_{om}^2 - 0.85 \right)^4} \quad (9)$$

Then, the actual number of displaced tetrapods in the i -th year $N_{od,i}$ was estimated by the following equation using the sum of N_i and N' (N_i : the number of the incident wave in the i -th year).

$$N_{od,i} = \frac{(N_i + N')^{0.5}}{3.75^2} \times \left(\frac{H_{1/3}}{\Delta D_n} S_{om}^{0.2} - 0.85 \right)^2 \quad (10)$$

The actual number of displaced tetrapods $N_{od,i}$ in the i -th year estimated by Eq. (10) includes the history of the deformation caused before the i -th year. The eroded area A_e in a cross-shore profile was calculated from Eqs. (3) and (4).

2.7 Total Repair Cost

In a year, the sum of the cost for repairing the breakwater body C_r and the cost equivalent to the amount of damage to the coastal zone C_d is the annual total repair cost. The sum of the annual total repair costs over the target period is the total repair cost C_{total} . In summing up the annual total repair costs, the interest was taken into account. The initial construction cost was not included in the total repair cost because the repair cost for the existing detached

breakwaters was investigated in this study.

2.8 Assumptions and Conditions in Estimation

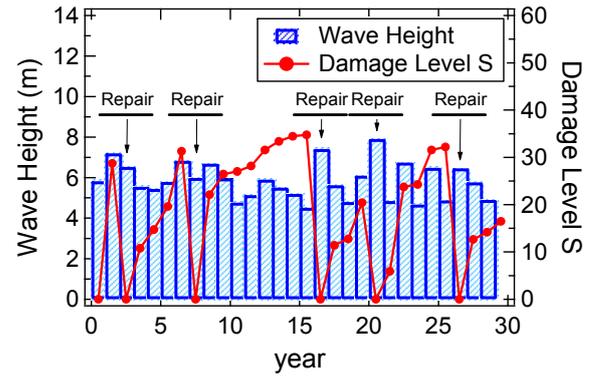
The repair was assumed to be completed by the incidence of the maximum wave in the next year. In the repair, the profile of the detached breakwater was restored to the initial configuration. The hydraulic performances of the repaired detached breakwater were assumed to be the same as that of the detached breakwater just after the initial state.

The number of the iteration in Monte Carlo simulation was 10,000. The interest used in the estimation of the total repair cost was 0.04. The duration of the incident N_i wave was 4,000 waves. The constants for estimating the cost for repairing the breakwater body were $C_{ru} = 14,000$ JPY/m³ (JPY: Japanese Yen) and $C_{r0} = 60,000$ JPY/m³. The constants for estimating the cost equivalent to the amount of damage to the coastal zone behind the detached breakwater were $C_{da} = 8.25 \times 10^7$ JPY//m and $C_{db} = 7.8 \times 10^6$ JPY/m.

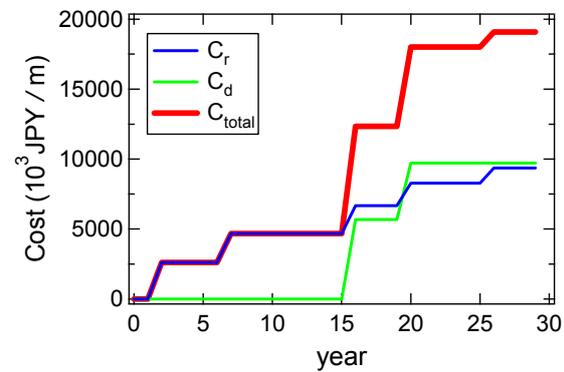
3. RESULTS AND DISCUSSION

3.1 Time Series in a Sample

Figure 2 shows a sample under the condition of $S_c = 32.0$ and $H_{tdc} / h_c = 0.32$ for 30 years in Monte Carlo Simulation. Figure 2(a) shows the relationship between the annual maximum incident wave height and the damage level in the detached breakwater body. The left vertical axis shows the annual maximum incident wave height and the right vertical axis shows the damage level S . Figure 2(b) shows the variations of the cost for repairing the detached breakwater body C_r , the cost equivalent to the amount of damage to the coastal zone behind the detached breakwater C_d and the total repair cost C_{total} which is the sum of C_r and C_d in the same sample as Figure 2(a).



(a) Annual maximum incident wave height and damage level in detached breakwater body



(b) Costs C_r , C_d and C_{total} (JPY: Japanese Yen)

Figure 2. Sample in Monte Carlo Simulation

In this sample, the detached breakwater was gradually deformed almost every year and the cumulative damage level increased. As a result, the detached breakwater was repaired in the 3rd, 7th, 16th, 20th and 26th years because the cumulative damage level was larger than the allowable deformation, *i.e.*, the repair criterion. In the 16th and 20th years, the damage to the coastal zone behind the detached breakwater was caused because the transmitted wave height was larger than the threshold of damage to the coastal zone.

3.2 Estimated Expected Repair Cost

Figure 3 shows the variations of the cost for repairing the detached breakwater body C_r , the cost equivalent to the amount of damage to the coastal

zone behind the detached breakwater C_d and the expected total repair cost C_{total} under the condition of the non-dimensional transmitted wave height that represents the threshold of damage to the coastal zone $H_{tdc} / h_c = 0.32$ for 30 years. The horizontal axis shows the allowable damage level S_c in the detached breakwater body, *i.e.*, the allowable deformation.

In the range of $S_c < 11$, the cost for repairing the detached breakwater body C_r is high because any deformation in the detached breakwater body is repaired immediately. On the contrary, the cost equivalent to the amount of damage to the coastal zone C_d is low because the transmitted wave height does not become large. In the range of $S_c > 11$, the cost for repairing the detached breakwater body C_r decreases because a small deformation which is less than the allowable deformation is not repaired. On the contrary, the cost equivalent to the amount of damage to the coastal zone C_d increases with the increase in the allowable deformation. From these characteristics, the lowest total cost can be founded around $S_c = 24$ in this condition.

3.3 Influence of Reduction Rate in Size

Figure 4 shows the influence of the reduction rate in size of tetrapods due to abrasion on the expected total repair cost. The horizontal axis shows the allowable damage level S_c in the detached breakwater body. The reduction rate in size was set to be 0.2% in this study. However, the reduction rate in size ranged from 0% to 2.0% here. The rate of 2.0% is much larger than that reported by Uchida *et al.* (2004). However, wave-dissipating blocks sometimes chip or break by wave attack. If the effect of chips and breakage of wave-dissipating blocks is also included, the reduction rate in size will be larger. The expected total repair cost C_{total} were estimated under the condition of $H_{tdc} / h_c = 0.32$ for 30 years.

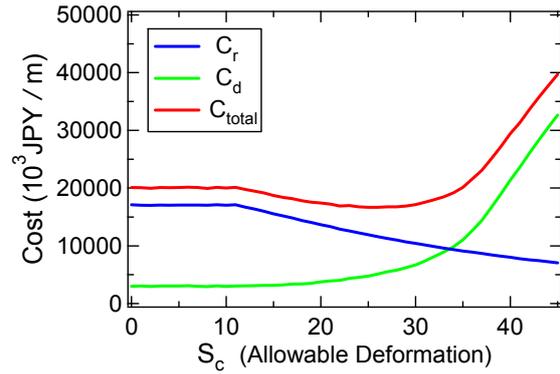


Figure 3. Variation in estimated cost

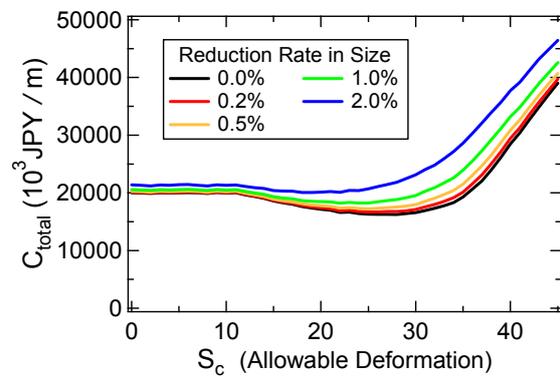


Figure 4. Influence of reduction rate in size

The reduction rate in size affected the expected total repair cost in the range of larger S_c more than that in the range of smaller S_c . In other words, the differences between the expected total repair costs C_{total} for the reduction rates in size 0.0% and 2.0% in the range of larger S_c is larger than that in the range of smaller S_c . In the expected total repair cost C_{total} for the reduction rate in size 2.0%, the cost equivalent to the amount of damage to the coastal zone behind the detached breakwater C_d increases at the smaller allowable deformation S_c . As a result, the allowable deformation at which the expected total repair cost C_{total} is the lowest for the reduction rate in size 2.0% is smaller than that for the reduction rate in size 0.0%. In addition, the difference between the expected total repair cost at $S_c = 0.0$ and the lowest expected total repair cost around $S_c = 18$ is small for the reduction rate in size 2.0%. Therefore, an earlier

repair after deformation in the detached breakwater body was relatively important for the reduction rate in size 2.0%.

4. CONCLUDING REMARKS

The expected total repair cost for the detached breakwater covered with wave-dissipating blocks was estimated using Monte Carlo simulation. The total repair cost was assumed to be composed of the cost for repairing the detached breakwater body and the cost equivalent to the amount of damage to the coastal zone behind the detached breakwater. In estimating the expected total repair cost, the influence of the reduction rate in size of the wave-dissipating block due to abrasion and so on was included. In the high reduction rate in size, *i.e.*, 2.0%, an earlier repair after deformation in the detached breakwater body was relatively important because the difference between the expected total repair cost at the allowable deformation $S_c = 0.0$ and the lowest expected total repair cost was small.

The values of the parameters used in this study were based on the assumptions. The values of the parameters vary depending on the circumstances. If the different values of the parameters are used in the estimation, the characteristics of the estimated costs will be changed.

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