On preventive maintenance policy for wave dissipating blocks covering caisson breakwater

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1. Introduction

Background:

Infrastructures … required to keep a certain level of performance during the in-service period

⇔ the performance of the infrastructures including harbor and coastal structures deteriorates due to aging and damage caused by external forces

⇒ it is necessary to perform appropriate and effective maintenance for the purpose of keeping of the performance and control of total cost during the in-service period.

For the wave dissipating blocks covering caisson breakwater… studies on the evaluation of life cycle cost and the optimal design based on Monte Carlo method, and maintenance methods were conducted.

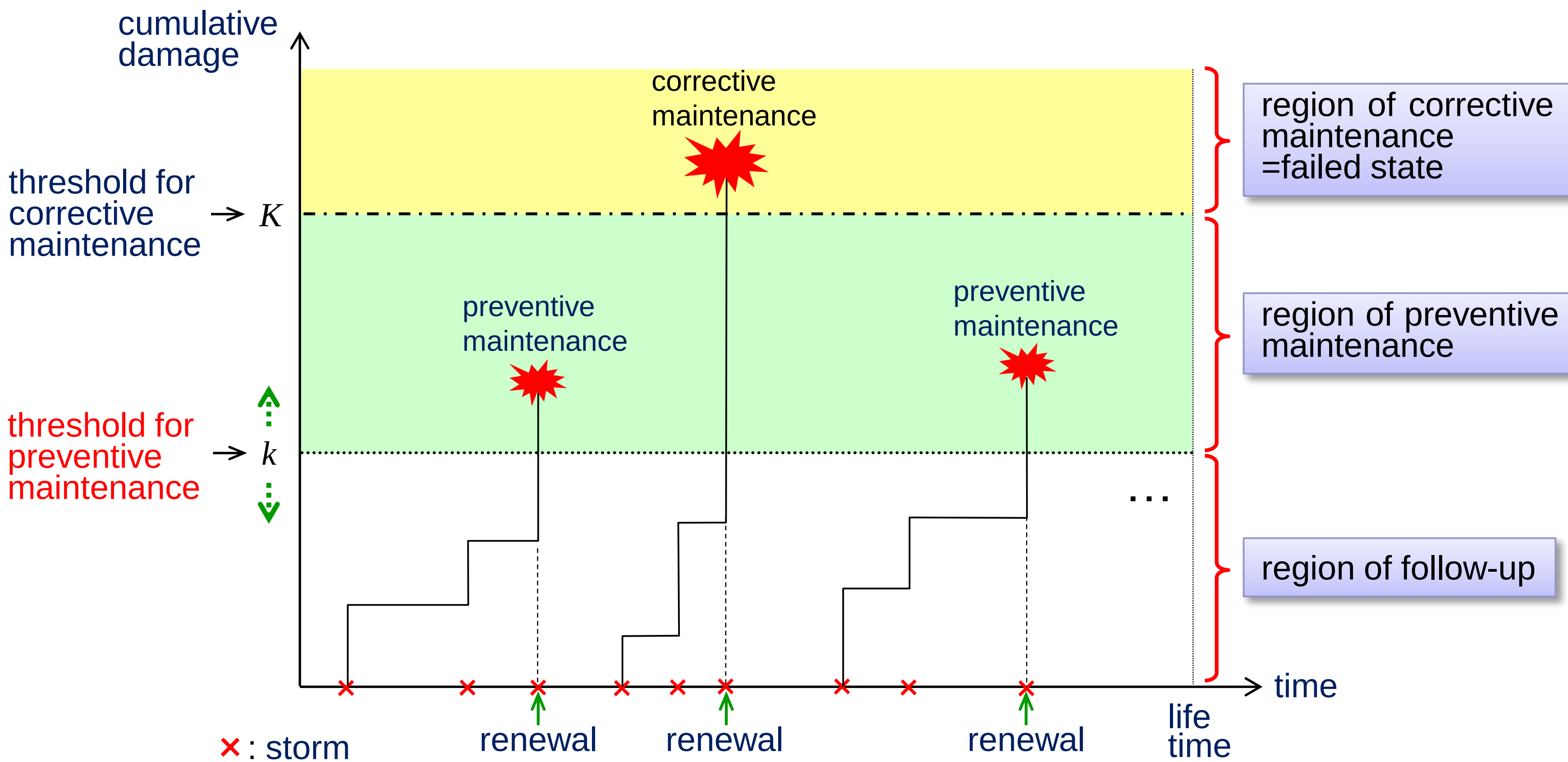
With a goal of establishing an appropriate maintenance method for wave dissipating blocks covering a caisson breakwater ...

- To determine the optimal threshold for preventive maintenance to minimize the maintenance cost for the wave dissipating blocks by using a theoretical model.
- To confirm that the stability of breakwater to the horizontal wave force is maintained by the theoretical optimal threshold based on comparison with the experimental results.
- To verify the validity of the theoretical model based on the comparison with the results by Monte Carlo method

2. Cumulative damage model

⇐ based on the method of the reliability engineering

- the damage is caused by storm (high waves) and is accumulated.
- if the amount of damage exceeds K, the wave dissipating works are in the failed state and the corrective maintenance is conducted.



Conceptual diagram of model

Additional assumptions :

- after the corrective or preventive maintenance is conducted, the state of wave dissipating works are recovered.
- the damage caused by each storm is statistically-independent and obeys an identical probability distribution *G*(*x*).
- the storms occur in accordance with a Poisson process.

Theoretical model proposed by Satow et al. (2009) :

↳ preventive maintenance policy based on the cumulative damage

necessary condition to minimize the expected maintenance cost

$$\int_0^k [\,1 + M(x)\,]\, dG(K - x)\, dx = \frac{c_2}{c_1 - c_2} \quad (1)$$

$$M(x) = \sum_{j=1}^{\infty} G^{(j)}(x) \quad (2)$$

c_1 : corrective maintenance cost

c_2 : preventive maintenance cost

$M(x)$: renewal function

$G^{(j)}(x)$: j-fold convolution of $G(x)$

Optimal threshold for preventive maintenance k^* is given so as to satisfy Eq. (1)

3. Investigation of optimal threshold *k**

1) Probability distribution for damage caused by a storm ; *G*(*x*)

It is necessary to determine *G*(*x*)

⟶ estimated on the basis of Monte Carlo method

⟶ using a stability formula for wave dissipating blocks proposed by Hanzawa et al. (1996)

$$N_0 = \left[\frac{H_{1/3}/\{(S_r - 1)D_n\} - b}{a} \right]^5 N^{0.5} \qquad (3)$$

N_0: relative damage level, $H_{1/3}$: significant wave height, D_n: nominal diameter of block
S_r: specific gravity of block, N:number of waves, a, b: constant, a=2.32, b=1.56

Procedures for calculation :

a) To set the specification of the intended wave dissipating block.

b) To calculate the offshore wave height in a storm by using an extremal distribution of offshore waves.

c) The wave height at the location of block is determined by the computation of wave transformation.

d) To calculate the value of N_0 in a storm using the wave height and the number of waves.

e) To repeat the procedure 2) to 4) 250,000 times

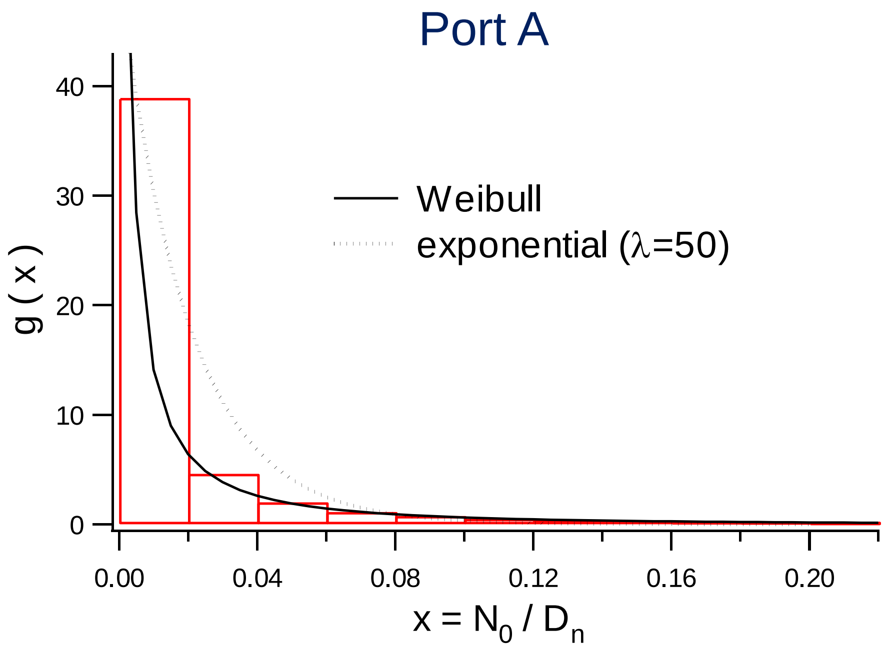
Specification of offshore wave and extremal distribution

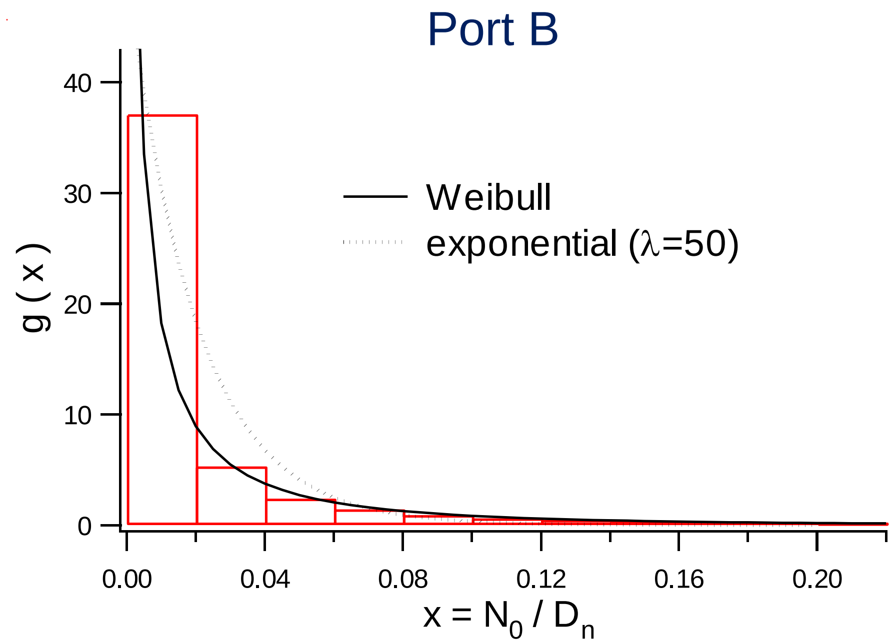
Port	Distribution	Design wave		Wave steepness	Spread param. γ_{50}	Scale param. A	Location param. B	# of occurrences λ
		Height	Period					
A	Weibull(1.4)	10.9 m	12.8 s	0.04	1.13	1.84	3.52	22.3
B	Weibull(1.4)	10.0 m	14.0 s	0.03	1.13	1.68	3.30	20.7

located along the Sea of Japan

Additional conditions of simulation

	Port A	Port B
Sea bottom slope	1/50	1/50
Water depth	19.1 m	15.7 m
Crown height	5.1 m	4.6 m
Nominal diameter D_n	3.26 m	2.96 m





Frequency distribution of relative damage level due to a storm

➡ Weibull distribution can be applied as the probability distribution of damage

↓

$$g(x) = cmx^{m-1}\exp(-cx^m) \quad (4)$$

Port A : m = 0.3888, c = 7.068
Port B : m = 0.4988, c = 8.863

← obtained by the method of least square method

2) Calculation of optimal threshold *k**

By using the Weibull distribution as the probability distribution function *G*(*x*) and probability density function *g*(*x*), the optimal threshold for preventive maintenance *k** is calculated.

Calculation procedure :

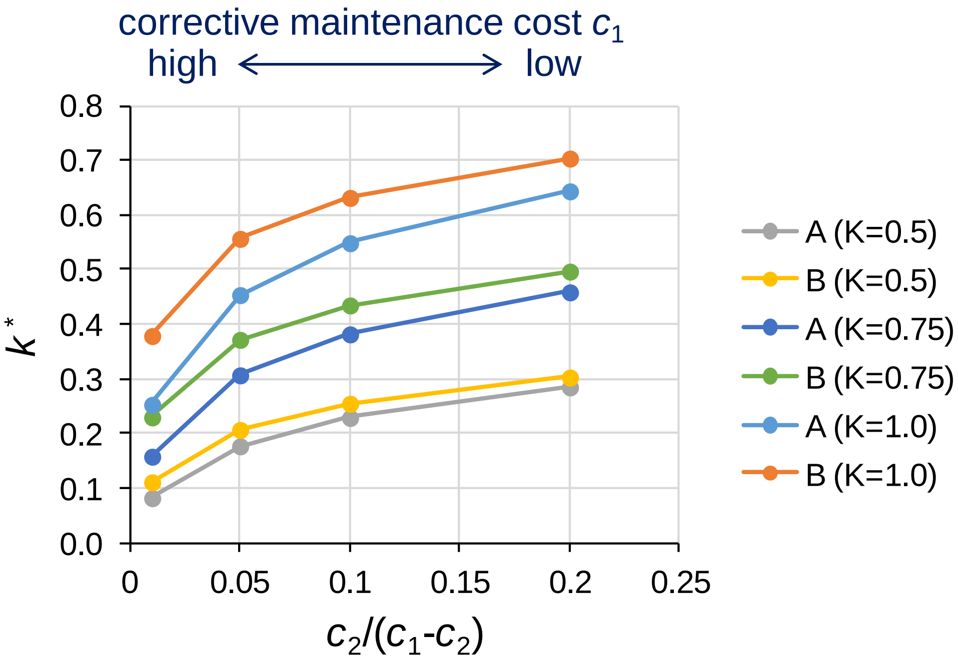
- convolution of *G*(*x*) $$G^{(j)}(x) = \int_0^x G(x-y)\, dG^{(j-1)}(y)$$
- calculation of renewal function (eq. (2)) $$M(x) = \sum_{j=1}^{\infty} G^{(j)}(x)$$
- calculation of *k** (eq. (1)) $$\int_0^k [1 + M(x)]\, dG(K-x)\, dx = \frac{c_2}{c_1 - c_2}$$

  The value of *k** is determined so that the left-side value becomes equal to the given right-side value.

The calculations of convolution and integral are performed numerically.

Calculation results of k*

K	$c_2/(c_1-c_2)$	k* Port A	k* Port B
0.5	0.2	0.285	0.303
	0.1	0.229	0.255
	0.05	0.177	0.207
	0.01	0.082	0.111
0.75	0.2	0.459	0.497
	0.1	0.382	0.435
	0.05	0.307	0.372
	0.01	0.158	0.230
1.0	0.2	0.644	0.704
	0.1	0.549	0.632
	0.05	0.454	0.557
	0.01	0.253	0.379



It is necessary to lower k* as c_1 becomes larger compared to c_2.

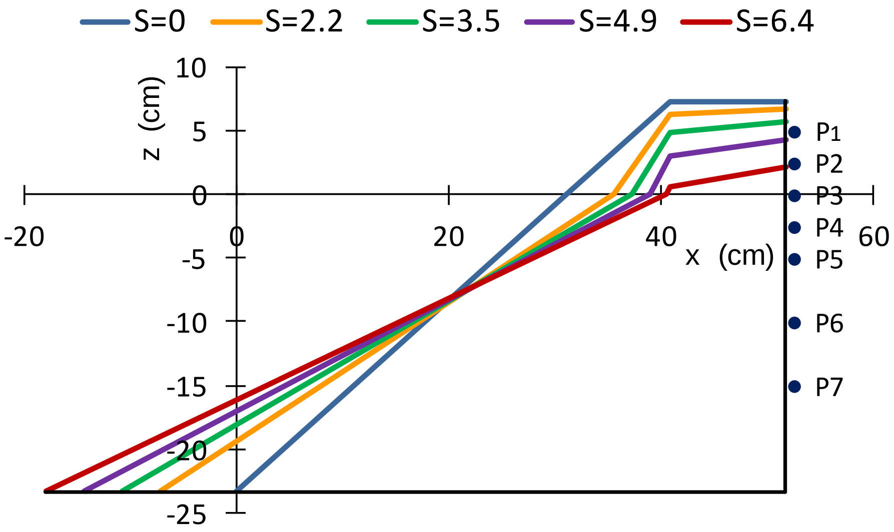
The values of k* at Port A are small by comparison with Port B.

→ the probability distribution $G(x)$ at Port A has wider skirt and the occurrence probability of damage of blocks caused by large wave is high.

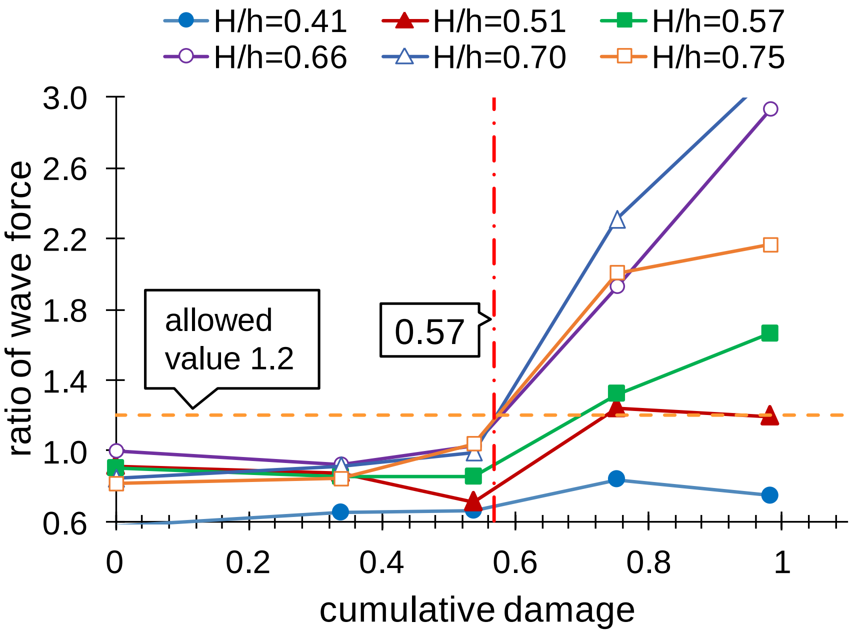
3) Validation of *k** from mechanical viewpoint

It is confirmed that the stability of breakwater is kept at *k**.

⟶ Laboratory experiments (model scale 1/70) to measure horizontal wave force utilizing model profiles of damaged block layer. (Kawamura et al., 2017)



Model profiles of damaged block layer (Port A)



Change of horizontal wave force with progression of damage (Port A)

3) Validation of *k** from mechanical viewpoint

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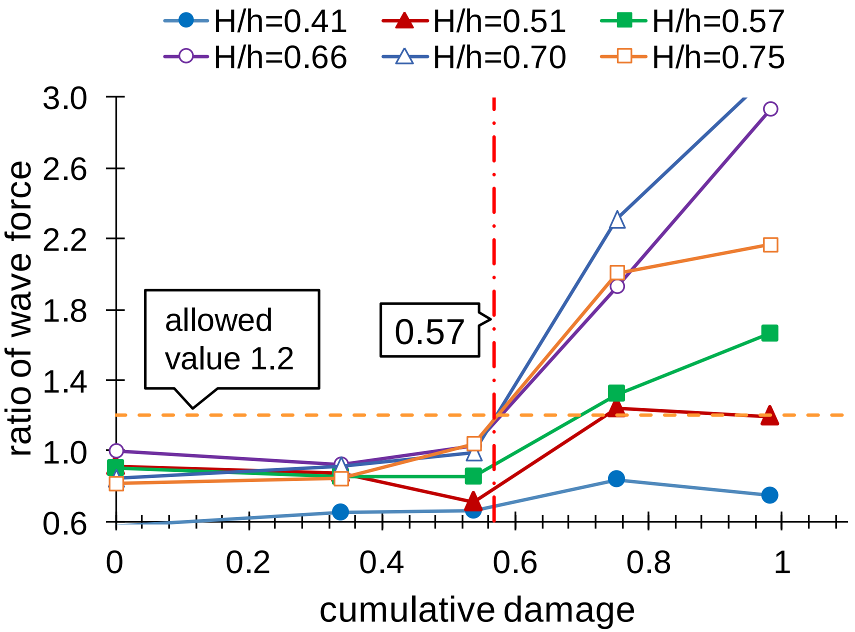
ratio of wave force to that of initial profile

⟶ allowed value is considered as 1.2

minimum value of the cumulative damage at the intersection of allowed value and graph = 0.57

most of calculated value of *k** is smaller than 0.57

⟶ optimal thresholds are in the range that satisfy the stability of breakwater



Change of horizontal wave force with progression of damage (Port A)

4. **Validation** of *k** based on Monte Carlo method

The method of Takayama et al.(2006) based on the Monte Carlo method by Hanzawa et al.(1996)

↳ calculation of expected repair cost and standard deviation of repair cost

Definition of life cycle cost (LCC)

$$LCC = C_{\mathrm{I}} + \overline{C_{\mathrm{R}}}$$

C_{I} : initial construction cost, $\overline{C_{\mathrm{R}}}$: expected repair cost (defined as the average of total repair cost during the in-service period)

Initial and repair cost include direct and indirect construction costs. For repair cost … change of cost by scale and number of times of repair is considered.

When the cumulative damage exceeds the threshold *k* or *K*, the preventive or corrective maintenance cost is allocated.

Procedures for calculation of expected repair cost

a) To calculate offshore wave height in a storm by using an extremal distribution. The annual number of occurrence of high waves is assumed as one.

b) The wave height at the location of wave dissipating work is determined by the computation of wave transformation.

c) To calculate damage of wave dissipating block layer in a storm and to cumulate the damage. If the cumulative damage exceeds the threshold value, the repair cost is estimated.

d) To estimate the total repair cost during the in-service period (50 years).

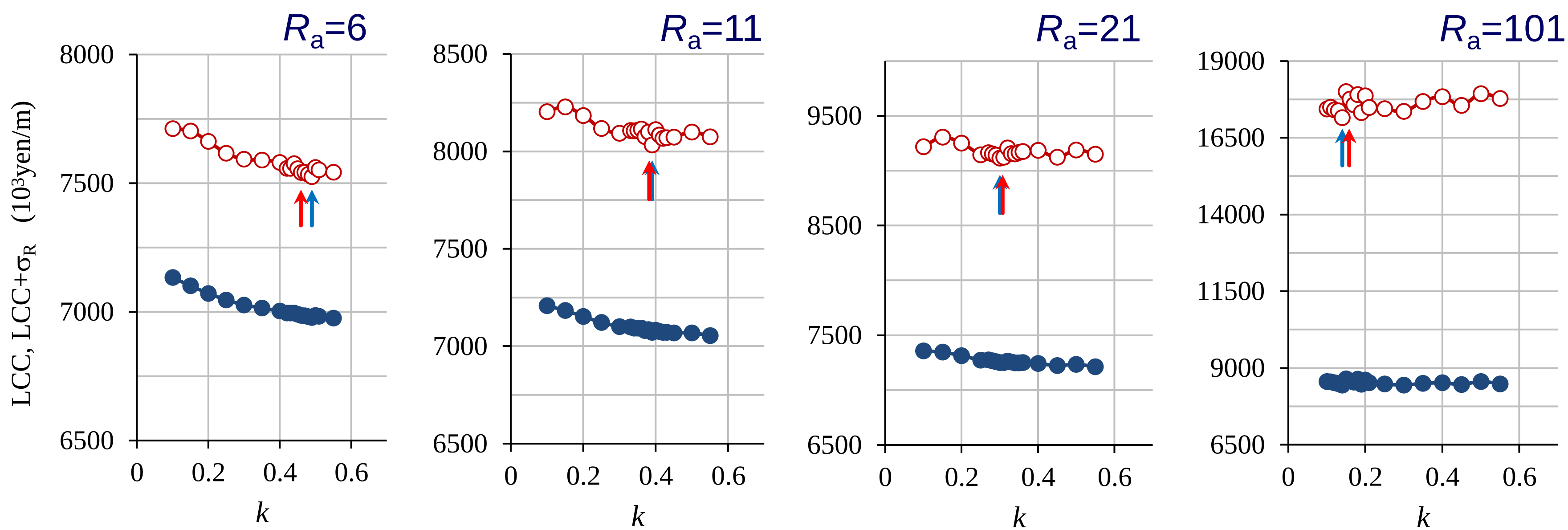
e) By repeating the procedure a) to d) 5000 times, the expected repair cost is obtained as the average of total repair cost. The standard deviation of total repair cost σ_R is also obtained.

The conditions about wave and breakwater are same as those of previous simulation mentioned in Chapter 3.

Other conditions :

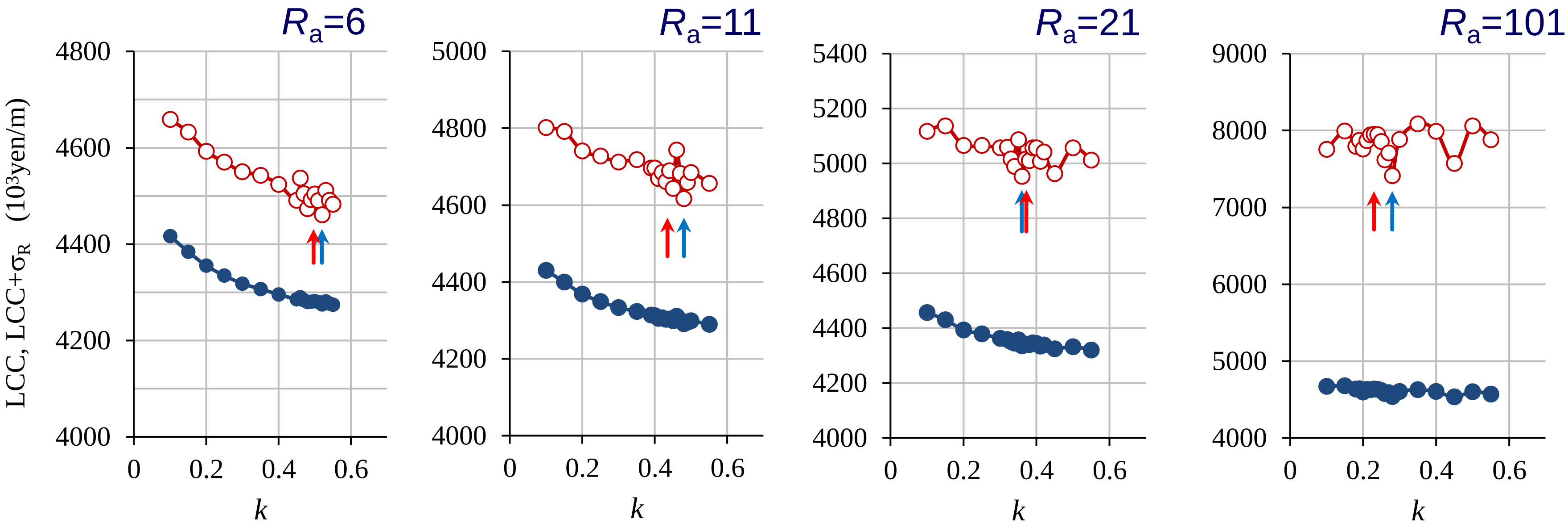
- K=0.5, 0.75, 1.0
- $c_1 = R_a \times c_2$, R_a=6, 11, 21, 101 ← same as $c_2/(c_1-c_2)$=0.2, 0.1, 0.05, 0.01
  c_2 ; assumed as the same preventive maintenance cost when k=0.5
- the range of k in the simulation ; $0.01 \leq k < K$

Results of calculation (Port A, K=0.75)



● : LCC, ○ : LCC+σ_R , ↑ (blue) : minimum value of (LCC+σ_R) , ↑ (pink) : k^*

Results of calculation (Port B, K=0.75)



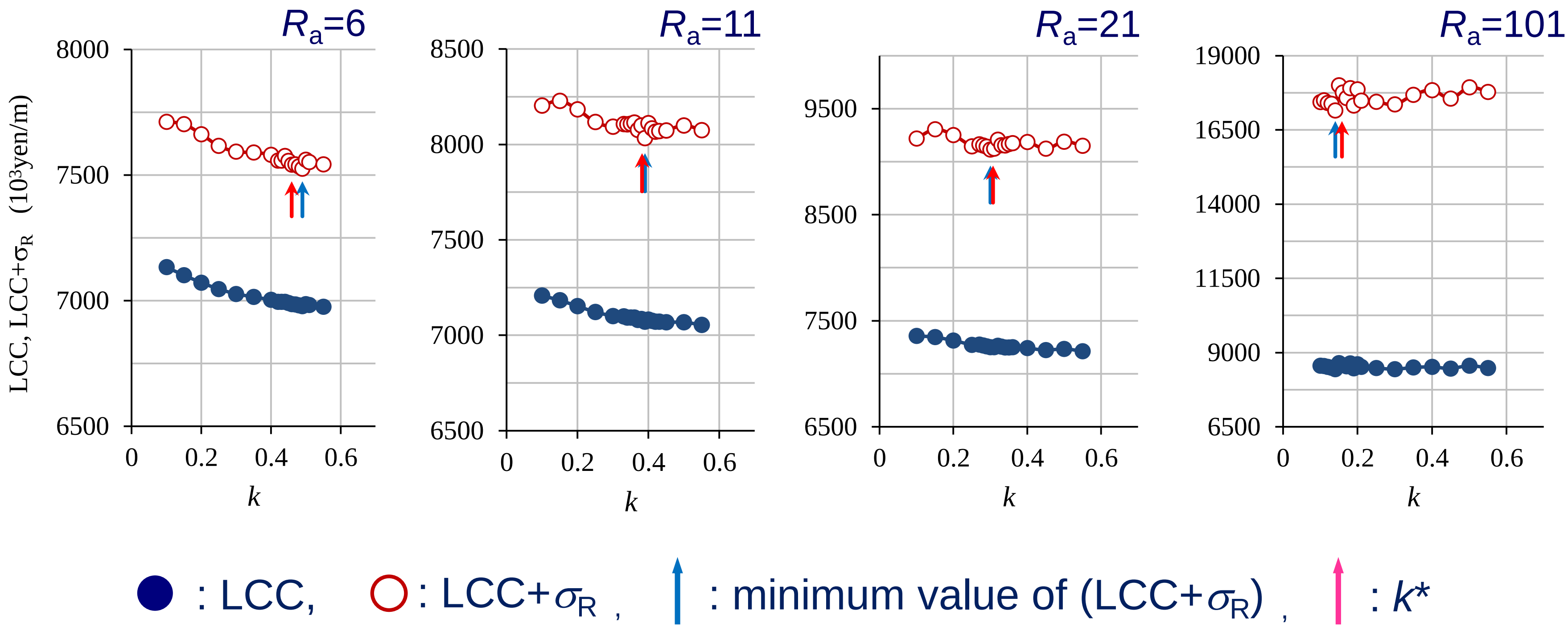
● : LCC, ○ : LCC+σ_R , ↑ (blue) : minimum value of (LCC+σ_R) , ↑ (pink) : k^*

About the results of LCC ;

in the cases of R_a=6-21, the variations with k are small and the values decrease as k becomes larger.

→ in the part of large k, it is considered that the reduction of preventive maintenance cost is canceled by the increase of corrective maintenance cost and the variation of expected repair cost becomes small.

Results of calculation (Port A, K=0.75)



Miyata et al. (2009) ; a criterion for repair of block layer to minimize sum of expected repair cost and standard deviation of repair cost to evaluate the risk of large-scale damage (corrective maintenance).

The values of k^* almost agree with the minimum values of (LCC+σ_R).

➡ This shows the validity of the theoretical model.

5. Conclusions

1. The optimal threshold for preventive maintenance to minimize the life cycle cost is determined for the wave dissipating blocks covering caisson breakwater by a theoretical model.

2. The Weibull distribution can be used as the probability distribution of the damage of block layer caused by a storm on the basis of result of Monte Carlo simulation utilizing a stability formula for wave dissipating block.

3. It is confirmed that the stability of breakwater to the horizontal wave force is maintained by the theoretical optimal threshold for preventive maintenance based on comparison with the experimental results.

4. The theoretical optimal thresholds almost agree with the simulated results that is obtained from Monte Carlo method considering the variation of repair cost and the validity of the theoretical model is verified.

Future subject … how to determine the actual value of threshold for corrective maintenance K and the cost of corrective maintenance c_1