Impacts of sea-level rise on port facilities

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Abstract

From the viewpoint of coastal hydrodynamics, one of the most important effects of global warming is a sea-level rise in coastal areas. In the present study, impacts on port facilities against sea-level rise were investigated.

The sea-level rise causes the increase of the water depth, and it generates variations on the wave height, buoyancy, tidal system and nearshore current system and so on. The increase of water depth gives rise to the decrease of crown height of the structure and it causes increase of wave overtopping quantity. It may flood the port zone and its facilities, and may decrease harbor tranquility. It also leads to difficulties on navigation, mooring and loading/unloading at the port. Increase in water depth also causes increase of wave height in surf zone. This high wave makes structures unstable and may cause them to collapse during storm. In addition, increase in buoyant force due to sea-level rise also makes the gravity type structures unstable. Consequently, theses variations due to sea-level rise will cause functional deterioration of port facilities. In order to protect port facilities from the functional deterioration, reinforcement plan is required such as raising the crown height and increase in block weight and so on.

Hence proper estimation method for the protection cost is necessary in order to protect port facilities efficiently. Moreover response strategies and integrated coastal zone management plan is required to maintain the function of port facilities. A simple estimation of cost for breakwaters in Korea was performed in the present study.

Keywords: sea-level rise, port facilities, impact, protection cost

1. Introduction

Recently, global warming due to greenhouse effect has brought worldwide attention. It affects almost everything on the earth and causes various environmental variations such as global climate system, biological system and human society. From the viewpoint of coastal and harbor hydrodynamics, one of the most important effects of global warming is a sea-level rise in coastal zone.

Many researchers have tried to predict a range of future sea-level rise. The IPCC (Intergovernmental Panel on Climate Change)[1)] predicted 9～88cm sea-level rise during 1990~2100. Wigley and Raper[2)] also predicted sea-level rise which was close to that of IPCC. These predicted values can be used as an input data for estimation of impacts against sea-level rise.

In this study, we will focus on port facilities such as breakwater, seawall and quay. The change of the water depth caused by sea-level rise varies the wave force, buoyant force and flow system of sea water. Since wave force is proportional to the cube of wave height, higher waves caused by sea-level rise will be more powerful against rocks and concrete blocks of breakwaters and may damage breakwaters as they cause rock slippage and scouring of foundations. The increase in buoyancy due to sea-level rise makes the gravity type structures unstable and may cause them to collapse during storm. Consequently, theses variations will cause functional deterioration of port facilities. Therefore the study about functional deterioration and its countermeasure is required.

Although sea-level rise is a problem that is being faced, its impacts are not considered in the design of port facilities or coastal protection facilities. It may be caused by the ignorance of the importance about sea-level rise and its impacts. Moreover evaluation of impacts is very complicated. Because the change of the water depth causes various environmental changes such as wave height distribution, current patterns and buoyancy of structures. And estimation of its impacts is not sufficient yet..

In the present study, we will investigate the impact of sea-level rise on the port facilities and then evaluate the protection costs of port facilities against sea-level rise.

2. Functional Variation of port facilities to sea-level rise

Figure 1 represents outline of relationship between global warming and its environmental impacts. As shown in this figure, sea-level rise causes not only changes of coastal nature systems such as coastal morphology, natural ecosystems and water resources, but also changes of human society such as human settlement, industries and coastal infrastructures.

In this study, impacts of sea-level rise to port facilities are investigated and its outline is shown in Figure 2. As shown in this figure, increase in water depth due to sea-level rise causes increase in wave force and buoyancy. And they make the port facilities such as breakwater, seawall and quay unstable. Also, they may cause rock and concrete block slippage and scouring of foundations of structures.

The increase in water depth gives rise to insufficiency of crown height of structures and it causes increase in wave overtopping quantity. In case of seawall or quay, wave overtopping gives rise to the inundation. On the other hand, in case of breakwater, it gives rise to decrease in harbor tranquility. Therefore it may cause difficulties on navigation, mooring and loading/unloading at the harbor.

The following explains functional deterioration of port facilities such as breakwater, seawall and quay.

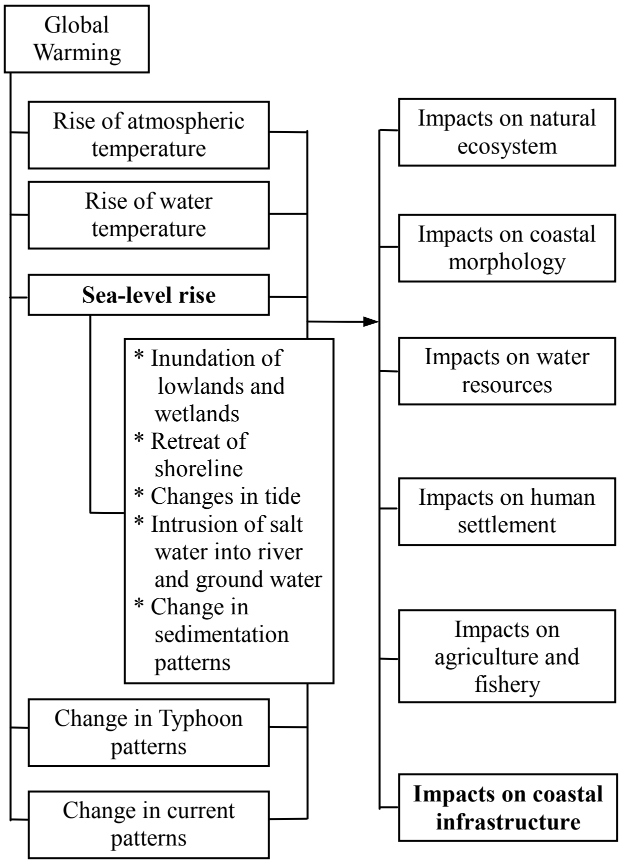

Figure 1. Impacts of global warming.

2.1 Breakwater

The main function of breakwater is maintenance of the harbor tranquility for the efficient navigation, mooring, and loading/unloading. And it also has a role of protecting the port facilities from the wave.

Increases in water depth, wave height and strength of typhoon due to global warming causes increases in buoyant force and wave force. And it makes the breakwater unstable. Since wave force is proportional to the cube of wave height, rocks and concrete blocks, which are installed on the rubble mound breakwater or the composite type breakwater, may be collapsed by large waves. In addition wave overtopping and wave diffraction decrease the harbor tranquility.

Figure 3 and figure 4 represent safety factor of the composite type breakwaters located in various harbors in Japan with different environmental conditions such as water depth and wave height.[3] This safety factor is estimated on the assumption of 0.6m and 1.0m rise in sea-level. The horizontal axis represents the degree of sea-level rise and the vertical axis represents relative safety factors against sliding or overturning, and it represents the ratio between present safety factor and that after sea-level rise. Plotted marks such as square, triangle and diamond in these figures represent the ratio of the water depth to the deepwater wave height in each harbor.

Although difference due to ratio of the water depth to the wave height exists, all cases show the decrease in safety by sea-level rise.

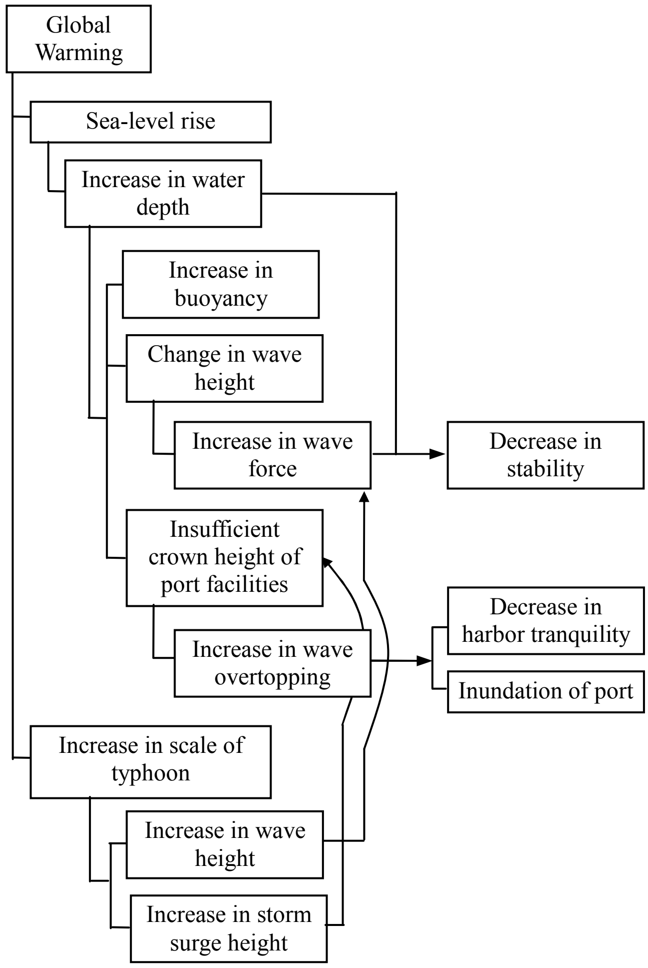

Figure 2. Impacts of sea-level rise to the port facilities.

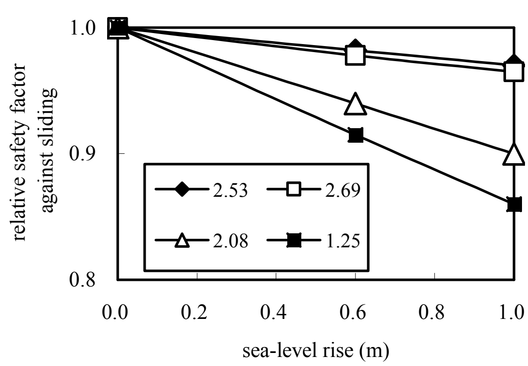

Figure 3. Relative safety factors against sliding after sea-level rise (revised from reference 3).

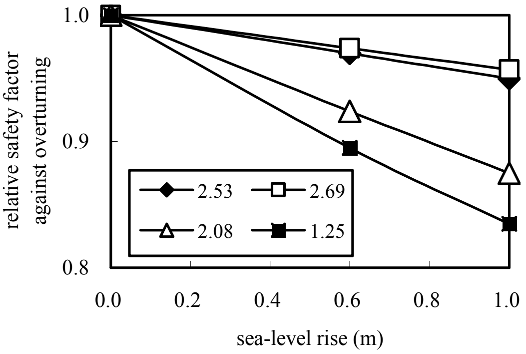

Figure 4. Relative safety factors against overturning after sea-level rise (revised from reference 3).

Takayama[4] investigated stability of breakwater against sea-level rise by using the reliability theory. They reported that the more water depth is shallow, the more stability is decreased.

2.2 Seawall

The seawall is constructed in order to protect wave overtopping and shoreline retreat from the high waves. Recently, mild slope seawall is frequently used.

Seawall also has almost the same mechanism as the breakwater against sea-level rise.

Inoue et al.[5] carried out experiments about wave overtopping on the seawall. They reported that as for protection efficiency for the overtopping, mild slope seawall is superior to general rubble mound seawall on the condition of present sea-level. However if sea-level increases, protection efficiency of mild slope seawall is rapidly decreases. As for 0.9m rise in sea-level, wave overtopping quantity of mild slope seawall reached about 4 times of general rubble mound seawall. Specially, this tendency is clear for small wave steepness.

Yamamoto et al.[6] reported that wave overtopping quantity is very sensitive to water level and it is rapidly increases in the shallow coast.

2.3 Quay (Wharf)

The main function of quay is safe berthing and loading/unloading. It also takes a role of protecting the overtopping. Increase in wave height and buoyancy makes quay unstable and it leads to collapse of structures. In addition it affects ship disturbance and may cause destructions of ship itself, quay and mooring line and neighboring other structures. Therefore proper increase in crown height and reinforcement is necessary.

2.4 Coastal protection facilities

Increase ratio of design factors for costal protection facilities after sea-level rise is shown in Table 1~Table 4.[7] These tables include change ratios of wave height, crown height, block weight and overtopping quantity. Costal protection facilities located in about 50 coasts in Japan are used for analysis. The range of water depth and equivalent deepwater wave height are 0m~8m and 2m~11m respectively. The values in tables are average of all facilities. The analysis is performed following assumptions. Storm effect is not considered. Increase in sea-level is 0.30m and 0.65m. Changes of design factors due to sea-level rise are calculated by the basis on present design wave height of each harbor. Weight of block is calculated by Hudson’s formula.

Values in tables were evaluated on dividing needed values after sea-level rise by those used initial design.

These tables show that raising the crown height or using the more massive block is required to maintain structures stably after the rise in sea-level. As for mild slope seawall shown in Table 4, required block weight after 0.65m sea-level rise reaches 1.91 times of the present block weight. This shows the vulnerability of mild slope seawall against sea-level rise.

Because of the freeboard fixed on the initial design, evaluated crown heights in these tables were considered only increase in wave height. Therefore it is thought that additional raising the crown height is needed, since it should include height of sea-level rise and reflect the acceleration in sea level rise as a result of human-induced climate change.

From the viewpoint of functional aspects, costal protection facilities are somewhat different from port facilities, but both facilities have almost same structural formation. Hence it is though that this result is applicable to port facilities.

Table 1. Increase ratio of design factors for detached breakwater after sea-level.

Design factor	Sea-level rise	
	0.30 m	0.65 m
Design wave height	1.05	1.12
Crown height	1.06	1.16
Weight of block	1.16	1.37

Table 2. Increase ratio of design factors for groin after sea-level rise.

Design factor	Sea-level rise	
	0.30 m	0.65 m
Design wave height	1.07	1.14
Crown height	1.12	1.27
Weight of block	1.21	1.49

Table 3. Increase ratio of design factors for seawall after sea-level rise.

Design factor	Sea-level rise	
	0.30 m	0.65 m
Overtopping quantity	1.60	2.54
Crown height	1.06	1.14

Table 4. Increase ratio of design factors for mild slope seawall after sea-level rise.

Design factor	Sea-level rise	
	0.30 m	0.65 m
Design wave height	1.12	1.25
Crown height	1.06	1.13
Weight of block	1.35	1.91

3. Cost for protection of port facilities

It is necessary to estimate the cost for maintain port facilities stable against sea-level rise. The cost of building or reinforcement such facility is quite expensive. Also the cost of maintenance and periodic replacement is required because they are destroyed by high waves during storm. Hence proper estimation method of the cost is requared in order to protect port facilities efficiently.

Kitajima et al.[8] estimated the cost of protecting port facilities and coastal structures in Japan against 1m rise in sea level. This estimate assumed no change for the natural environment other than the sea-level rise, no further development for port and neighboring urban areas, no consideration of time-dependent process, the cost estimation based on the monetary value in 1992. A ratio of increase of construction cost for structure was calculated by comparing the two costs, and the ratio was multiplied by the present construction cost on all the existing structure in order to estimate total protection cost.

Total costs for protection were estimated at 115 billion US $. About 78 billion US $ are necessary for raising the port facilities, another 36 billion US $ are for the costal protection facilities.

Composite type breakwater is most widely used as an outer structure of port, and it is applicable to deep areas. Equation (1) is a cost estimation formula of composite type breakwater per unit length.[9]

$$C = t\,b\,(d - x) + S\,x\,\frac{2B + \alpha\,x + \beta\,x}{2} \qquad (1)$$

Where C is a construction cost for unit length, t is a construction cost of upper gravity type structure for unit volume, S is a construction cost of lower rubble mound type structure for unit volume, α and β represent slopes of lower rubble mound structure. And the other values are shown in Figure 5.

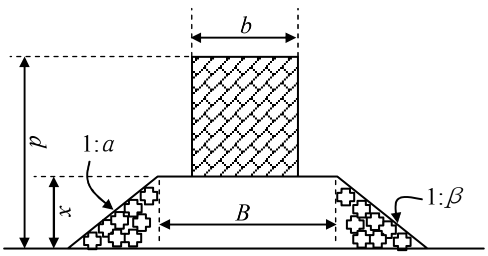

Figure 5. Profile of composite type breakwater

If we consider only crown height for estimation of cost against sea-level rise, equation (1) shows that the protection cost is depends on only the construction cost of upper gravity type structure for unit volume. It represents that if increase of block weight is not required, the composite type breakwater requires relatively low cost for reinforcement.

On the other hand, rubble mound breakwater may require relatively high cost for reinforcement. Since blocks composed of rubble mound breakwater are exposed near the sea surface where the wave force is the strongest.

As explained in previous chapter, increase of block weight, crown height and facility's own weight is required to maintain stable condition for the raised sea-level. Therefore it is very difficult to estimate protection cost of various kinds of structures considering above mentioned factors.

We tried to estimate the protection cost of breakwater in Korea. This estimation is performed under the following assumptions. For simplicity, protection cost is 10%~30% of latest average construction costs of breakwaters. Kind of breakwater is ignored.

Table 5 represents latest construction costs of breakwaters in Korea.[10]

Estimated cost of protecting breakwaters is calculated about 9170 US$/m ~27510 US$/m.

On the other hand, total length of breakwaters of main harbors in Korea which include 28 commercial harbors and 23 coastal harbors are 63,540m.[11] Therefore cost of protecting breakwaters in 51 main harbors reaches 0.53 billion US$~1.75 billion US$. This is the result based on breakwaters of main harbors only. There are about 418 fishery harbors and other structures in Korea. Inclusion of protection costs for these harbors and its facilities may increase in total costs of protection.

Table 5. Latest construction costs of breakwaters in Korea. (1US$=961.4 Korean Won)

Location	Length (m)	Construction period (year)	Cost per unit length ($/m)
Busan New Port	1490	97~02	86100
Young-il bay	3100	97~05	100700
Kunsan Port	3000	97~04	79600
Cheju Port	1425	01~06	100300

4. Conclusion

In the present study, impacts on port facilities against sea-level rise were investigated.

In order to protect port facilities efficiently against sea-level rise, the following may be required.

1. The study about wave distribution, tidal system and nearshore current pattern due to increase in sea-level
2. The study about evaluation of values such as crown height and block weight in order to maintain stability of structures after sea-level rise
3. The study about cost estimation method with consideration of above factors.

Finally, we propose that a reduction of cost may be produced by introducing crown height and block weight needed for raised sea-level to the initial design of coastal infrastructure.

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