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Optimal Design Conditions for Storm Surge Barriers

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Synopsis

In Japan Isewan Typhoon which caused the severest damages in the recent history of Japan has been employed as a standard typhoon to make a master plan for storm surge protection project and a design for storm surge barriers. The employment has been done without consideration of the return period of the Typhoon. The efficiency of the investment has recently been taken into account even for disaster protection structures. The present paper proposes how to determine design conditions for storm surge barriers from the view point of an economical design because numerous data for storm surges can now be obtained and also numerical simulation tool for storm surges can be utilized. The design condition of the storm surge barriers along Osaka Bay is optimized for an example in the present paper.

Keywords: Storm surges, Optimal design, Storm barriers, Numerical simulation, Osaka Bay

1. Introduction

Storm surges are well known to be abnormal high tides induced by large movable atmospheric depressions like typhoons and hurricanes. Sometimes they have caused great disasters in Japan and also in other foreign countries. The abnormal high tides of the storm surges are caused by two different factors related to the atmospheric depression: One is suctional rise of sea level due to low pressure, and the other is wind-driven rise of the sea level due to shear stress induced by strong wind on sea surface. As Fig.1 shows a typical profile of a storm surge, a small sea level rise, called a fore-runner, first appears and it is followed by a large rapid sea level rise, which is a main storm surge. After the sea rise reaches a peak, the sea level resurges due to the gradual disappearance of the typhoon influence, and shows some small oscillations with a natural period of a bay of interest.

Even if the central atmospheric depression of a typhoon is as large as 940hPa , it sucks up the sea level only by 70cm. Therefore, the storm surge does not become disastrous if the sea level rise due to wind drift is not so much larger than the suctional sea level rise. The effect of wind drift force on the sea level rise becomes significant in a wide sea area of shallow water. Tokyo, Ise, Osaka and Ariake Bays correspond to such wide sea areas in Japan. Large disasters took place in these bays in the past. The bayside area in Tokyo suffered from the large storm surge generated by the typhoon in 1917. In

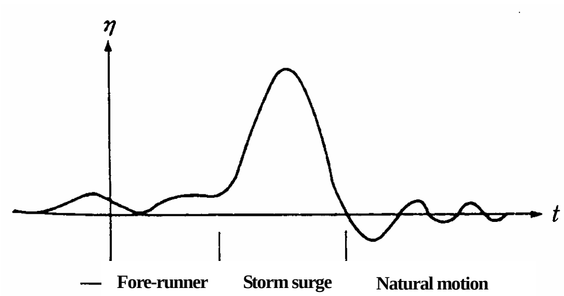

Fig.1 Typical profile of storm surge

Osaka bay the large storm surge generated by the huge typhoon called Muroto Typhoon took several thousand lives in 1934. The largest storm surge generated by Typhoon 5915 called Isewan Typhoon caused a destructive disaster in the seaside region of Ise Bay in 1959. Since then, Isewan Typhoon has been employed as a standard for the design conditions of storm surge prevention works in Japan. The return period of the standard typhoon for design was not evaluated because of insufficient number of observed data, but recently the occurrence probability distribution of storm surges has been tried to estimate by utilizing a numerical simulation techniques. Even if the distribution can be obtained, it is still uncertain the to determine which magnitude of storm surge is appropriate for the design.

The present paper proposes how to determine the design condition for storm surge barriers from the view point of economically optimal design. The optimal design condition is found for storm surge barriers along Osaka Port for an example.

2. Estimation of Expected Damage Cost

As described above in Introduction, Ise-Wan Typhoon caused the historically greatest disaster in Japan. Therefore, it has become the standard typhoon for the design of storm surge prevention works in Japan. The storm surge prevention works have been executed in Tokyo, Ise and Osaka Bays under the design condition estimated from the hypothetical Ise-Wan Typhoon. The return period of the hypothetical Ise-Wan Typhoon depends on the bay of interest, that is, the prevention level against storm surge is not same even if same hypothetical typhoon is employed for design. At present we can gather storm surge data almost enough to analyze their occurrence probabilities. Therefore, an optimal design condition should be proposed instead of the hypothetical typhoon. The present section newly proposes how to determine optimal design condition for storm surge barriers.

The joint occurrence probability $p(\zeta, H)$ of the storm surge ς and the significant wave height H is assumed to be expressed by the following equation:

$$p(\zeta, H) = p_s(\zeta) p_w(H|\zeta) \tag{1}$$

where $p_s(\zeta)$ and $p_w(H|\zeta)$ represent the occurrence probability of storm surge and the conditional occurrence probability of wave height. The conditional probability can be expressed by the following normal distribution:

$$p_w(H|\zeta) = \frac{1}{\sqrt{2\pi}\sigma_H} \exp\left\{-\frac{(H-\overline{H})^2}{2\sigma_H{}^2}\right\} \tag{2}$$

where $\overline{H}$ and σ_H denote the mean value of significant wave height and the standard deviation from $\overline{H}$, respectively. The mean significant wave height can be assumed to be closely related to the magnitude of the storm surge ς as follows:

$$\overline{H} = a\varsigma \tag{3}$$

where a represents a proportional coefficient to the storm surge. The form of $p_s(\zeta)$ is given by the extreme value distribution fittest to the occurrence distribution of actual the storm surges.

If external force over the design condition acts on the storm surge barriers, some of them are possible to damage. The damage probabilities, which is defined as the rate of damaged length to total barrier length, are investigated by Mase as shown in Fig.7. The horizontal axis in Fig.2 is represented by the parameter Z.

$$Z = (H / H_D)(\eta / \eta_D) \tag{4}$$

where η and the subscript D denote the sea level and the value for design, respectively.

The cumulative damage probability curve of the solid line can be expressed as the follows:

$$R_D = \begin{cases} 0 & : \ Z < 1 \\ b(Z-1)^n & : \ Z \geq 1 \\ 1 & : \ b(Z-1)^n \geq 1 \end{cases} \tag{5}$$

where b is constant.

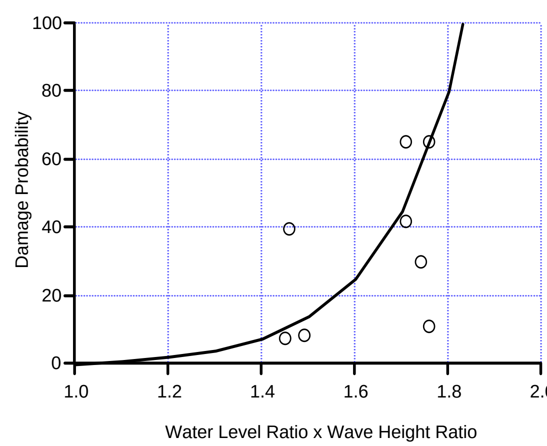

Fig.2 Damage probability of storm surge barriers

The service life time of storm barriers is specified at the design stage. If the life time is given as N_L years, the pairs of storm surge and significant wave height can be selected during N_L years by using Monte Carlo method, as follows:

$$(\eta_1, H_1), (\eta_2, H_2), \cdots\cdots (\eta_{N_L}, H_{N_L}) \qquad (6)$$

where η_i denotes the actual sea water level which is given as a superimposition of astronomical tide and storm surge. The occurrence probability can be approximately expressed as a triangular distribution (Kawai et al., 1997).

The value of Z_i can be calculated if the sea water level and significant wave height are obtained. The damage rate of the storm surge barriers can be estimated as the value corresponding to Z_i in Fig.2. It is assumed that the length of the barriers proportional to the rate lose their function of storm surge protection. If the inundation due to storm surge is simulated under the assumption, the inundated area and flood depth can be obtained. The damage cost due to the flood depends on the flood depth and the inundated area. When the food depth is divided into M_D segments, the damage cost can be estimated as follows:

$$T_{Di} = \sum_{m=1}^{M_D} D_m A_m \qquad (7)$$

where T_{Di} , D_m and A_m represent the damage cost due to i-th storm surge during the life time, the damage cost of m-th flood depth per unit area, and the inundated area, respectively. The total damage cost is given by the summation of T_{Di} for all storm surges during the life time as follows:

$$S_D = \sum_{i=1}^{N_L} T_{Di} \qquad (8)$$

where S_D indicates the total damage cost which is obtained for one set of storm surges during the life time.

The cost of S_D obtained above is for the damage for the flood area. In addition to the food damage, we should take into account the damage cost of barriers, which are sometimes destroyed by huge wave actions. The broken barriers must be reconstructed before coming storm surge. The reconstruction cost can be estimated as follows:

$$T_{Bi} = \sum_{m=1}^{M_B} C_{Bm} l_m R_{Dm} \qquad (9)$$

where T_{Bi} , M_B , C_{Bm} , l_{Bm} and R_{Dm} represents the reconstruction cost, the number of the segmented barriers, the segment length and the damage rate to the segment length, respectively. The total reconstruction cost during the life time is given by

$$S_B = \sum_{i=1}^{N_L} T_{Bi} \qquad (10)$$

3. Optimal Condition for design

The occurrence run of storm surges in the life time depends on a selected seed for random variable which chooses a magnitude of storm surge. Therefore the expected value $\overline{S}_D$ of S_D should be estimated as the mean value for various sets of storm surges in the life time. The expected value $\overline{S}_B$ of the total construction cost should also be estimated.

Thus the flood and destruction damages during the life time of N_L years can be obtained for the barriers which were designed for the storm surge of the return period R_p . The total damage cost is given by the summation expressed as

$$\overline{S} = \overline{S}_D + \overline{S}_B \qquad (11)$$

Probable typhoons during the service life time of the barriers are predicted and the total amount of damage can be obtained. Total cost T_C during the life time of the barriers can be given by the summation of the total amount of damage $\overline{S}$ and the initial construction cost of the barriers. As shown in Fig.3, the total costs are plotted to corresponding design condition, which is indicated by the return period R_p of typhoon. The return period which corresponds to the minimum value of total cost is regarded as the optimal design condition.

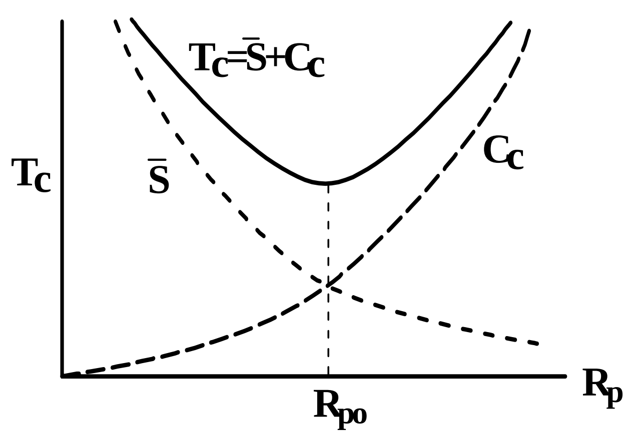

Fig.3 Optimal selection of storm surge return period for design

4. Application to Storm Surge Barriers along Osaka Port for an Example

The optimal design condition for storm surge barriers in Osaka Port is obtained as an example. The storm surge prevention works in Osaka has almost already completed under the design condition of the hypothetical Ise-Wan Typhoon, which is supposed to correspond to the typhoon with the return period of 153 years. The estimation of the optimal design condition assumes that sea level rise in future is predicted as 48cm. Consequently, the return period of the storm surge corresponds to 96 years. The return periods of the present state (96 yrs), 200, 500 and 1000yrs are employed as the design condition. The initial construction cost of storm surge barriers corresponding to the return period are listed on Table 1.

Table１ Construction costs of storm surge prevention structures

(units: billion yen)

Return period	Watergates	Storm barriers	River embankment	total
96yrs	0	1.98(64.1)	1.11(35.9)	3.09(100)
200yrs	0.24(0.7)	33.64(96.1)	1.11(3.2)	34.99(100)
500yrs	0.79(2.1)	35.89(94.1)	1.43(3.8)	38.11(100)
1000yrs	1.95(4.7)	37.82(90.7)	1.89(4.6)	41.66(100)

Figures in（ ）:（%）

Existing storm surge barriers in Osaka Port were constructed under the design condition of the return period 153yrs without future sea level rise. It is assumed that the storm surges of the return periods of 96, 200, 500 and 1000 years attack Osaka Port. The flooded area expands as the magnitude of storm surge becomes large. The expansion of the flooded area is shown in Fig.4. Though some parts are flooded even at the attack of 96yrs storm surge, these flooded parts belong to the area unprotected by the barriers. The amount of damage is estimated from the flooded area and depth. The amounts of damage are obtained in same manner for other protection levels of 200, 500 and 1000yrs return period. Assuming that the service life time of the barriers is 100 years, the expected amounts of damage during the life time are calculated and listed on Table 2.

The initial construction costs of barriers and the expected amounts of damage are plotted by the dotted line and the chain one in Fig.5. The total costs indicated as the summation of the initial construction costs and corresponding expected amounts of damage are also plotted by the solid line in Fig.5. The horizontal axis of Fig.10 indicates the return period for barrier design conditions. The optimal return period corresponding to the minimum total cost can be obtained as about 1000 years from Fig.5. Thus, the design condition for storm surge prevention barriers can be estimated as the storm surge of the return period 1000years because urban precious estates are concentrated in Osaka portside area. If the effect of the barrier damage is taken into account, the return period would become longer.

5. Concluding Remarks

The present paper has described the reliability of the existing prediction model for storm surges by checking the accuracy of the numerical computation through the comparison between the computed and observed data. It has also proposed the optimal design method for storm surge barriers. In the optimal design the return period of design storm surge is selected as the point corresponding to the minimum expected total cost.

The existing model can predict storm surge with sufficient accuracy from the practical view point, if the central part of typhoon is excluded. Super-gradient wind, which is difficult to reproduce, exists in the central part. Though some methods are proposed to improve super-gradient wind, they are applicable only to hindcasting and useless for forecasting. Therefore, a new prediction model of super-gradient wind is expected to be developed. Though the optimal design condition is obtained for storm surge barriers in Osaka portside, the effect of barrier damage is ignored and only 4 storm surges are employed to estimate the amount of damage due to flooding. More detailed computation is necessary to get more accurate design condition through the optimal method.

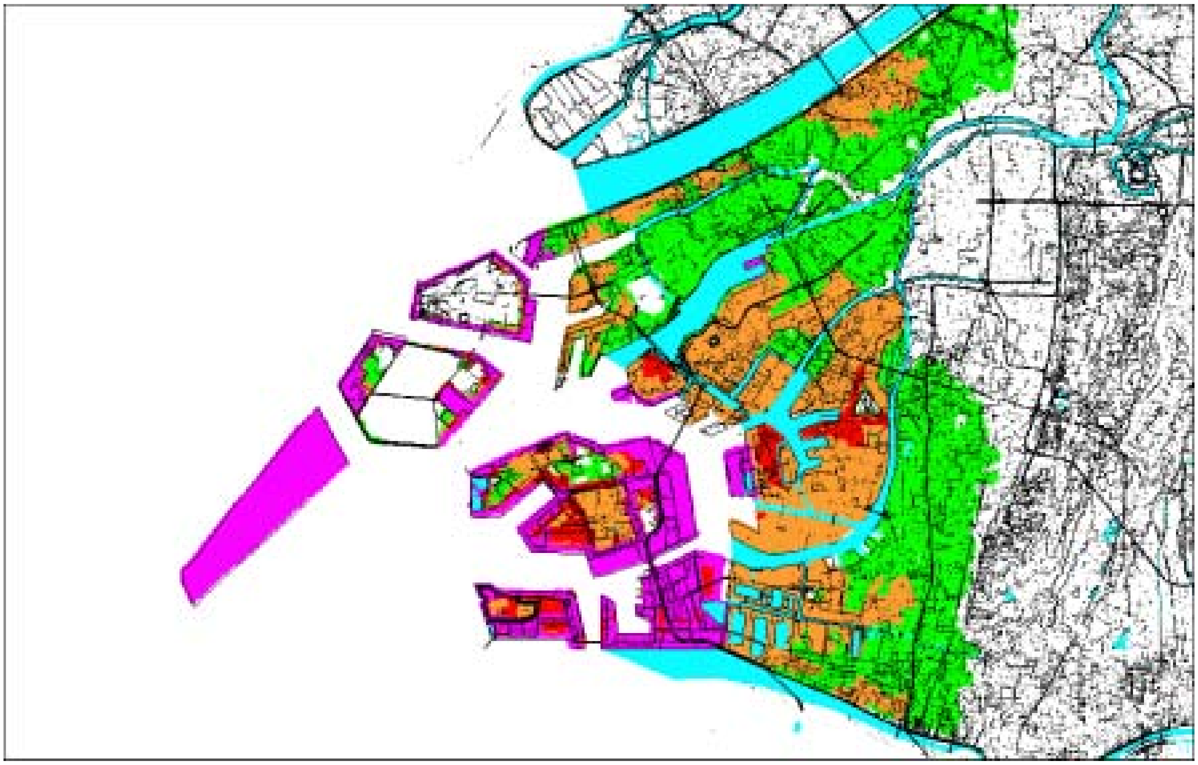

Fig.4 Inundation areas due to storm surges of 96, 200, 500 and 1000yrs

Table 2 Expected damage costs of extreme storm surges during life time of 100yrs

(units: billions yen)

Storm surge for design	Storm surges of attack			
	96yrs	200yrs	500yrs	1000yrs
96yrs	31.72	66.00	464.40	1458.70
200yrs	0	4.30	202.90	669.10
500yrs	0	0	14.50	371.00
1000yrs	0	0	0	125.00

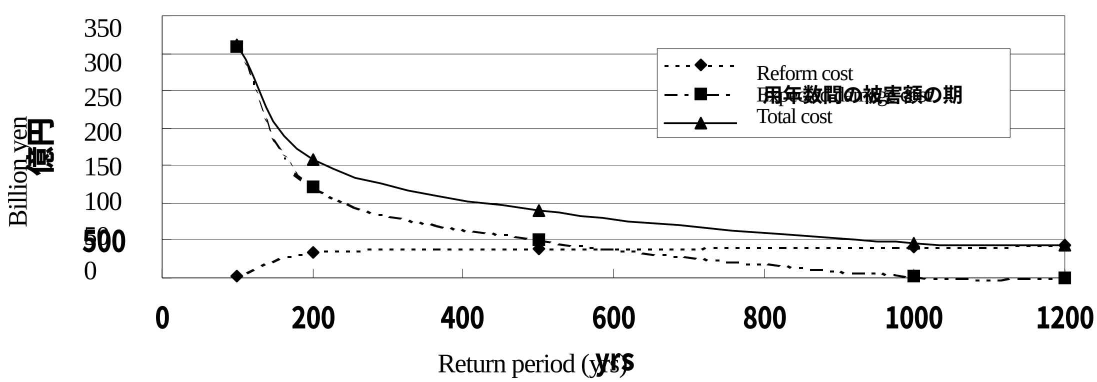

Fig. 5 Optimal return period of design storm surge

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高潮防潮堤の最適設計

高山知司・間瀬　肇

要　旨

わが国における高潮対策事業では，防潮堤の設計に用いる高潮や高波の条件として，伊勢湾台風を標準台風として推算された値が一般に用いられている．伊勢湾台風は，昭和 34 年に名古屋地方を襲って，わが国において未曾有の高潮災害を起こした台風である．伊勢湾台風が既往の最大級の台風であるところからこれが東京湾や大阪湾等における高潮対策事業に用いられているが，この台風の再現期間については必ずしも明確に調べられていない．近年，防災事業であっても事業の投資効果が問われるようになってきている．そこで，本論文は，投資効果を考慮して，防潮堤の最適設計を行う手法を提案したものである．投資効果の判定としては，防潮堤の建設費と維持管理費に加え，防潮堤の耐用年数間における期待被害額の総和を最小にする最適条件である．そして，この最適条件における再現期間の台風で設計すればよいことになる．例として，この方法を大阪港の防潮堤に適用して結果について報告する．

キーワード：高潮，最適設計，防潮堤，数値計算，大阪湾