Chapter 33

THE ECONOMICAL HEIGHTS OF SEA WALLS FOR COAST PROTECTION IN JAPAN

Senri Tsuruta, Dr. Eng.
Head, Hydraurics Division
Port and Harbour Technical Research Institute
Ministry of Transportation, Yokosuka, Japan

Yoshimi Nagao, Dr. Eng.
Chief of Engineer with Special Responsibilities
for Planning and Disaster Prevention
Port and Harbour Bureau, Ministry of Transportation
Tokyo, Japan

Takeshi Ijima, Dr. Eng.
Head, Design Standard Division
Port and Harbour Technical Research Institute
Ministry of Transportation, Yokosuka, Japan

INTRODUCTION

The purpose to construct coast protection works is to protect properties and human lives from the disasters of storm tides, cruel waves, beach erosions, and others. We may expect that the stronger the works are built, the more the disasters will be prevented, but it cost more to strengthen them.

From a view point of national economy, both the construction cost and the amount of damages are regarded as the losses. In general, the amount of damages will be enormous if no protection work is constructed, but the construction cost of protection works to reduce the damages infinitely small will also be enormous. The loss in national economy, or the sum of the damages and the construction cost, will be minimized on some suitable magnitudes of protection works. We deviced a concrete calculation method to decide economical magnitudes of coast protection works, and have applied the method to practical plannings. The paper discusses the fundamental idea of the method and the results of the application.

NATURAL CONDITIONS OF JAPANESE COASTS AND COAST PROTECTION POLICIES

Japan is a country of small islands located at the north-western end of the Pacific Ocean with a very little land being flat and level. She is also a prominent country of industry. Her industry, however, imports most of raw materials from abroad, processes them into manufactured products, and exports them abroad to get raw materials in return. For these reasons, most of her population and industry are gathered along the coastal areas of low level land. Especialy, the main industrial areas are concentrated on the low land along coasts where good ports and harbors are available.

Since Japan is so frequentry attacked by typhoon, her coasts, especially in low land, often suffer enormous damages by storm tides and waves. The strong waves which are produced by typhoons or winter seasonal-winds cause coastal erosions too. In addition, earthquaks occur so often and the disasters of tsunamis follow the earthquakes in many cases.

Viewed from a point of national economy and stabilization of people's livelihood, the protection of coastal districts from the attack of sea is very important. The measures adopted in Japan in order to protect the coast districts are firstly to prevent the disasters which are caused by storm tides and waves, and secondly to issue a typhoon warning to evacuate and to carry out anti-flood measures in case being attacked by a typhoon. These policies are to be planned and practiced from the view point of national economy.

FUNDAMENTAL IDEAS TO DECIDE ECONOMICAL CROWN HEIGHTS

FUNDAMENTAL IDEA

The damage in the properties along coastal districts are decreased with the enlargement of coast protection works, but the construction cost of the protection works increases at the same time. We have to choose a certain magnitude of structures for the protection works. The most reasonable way of the determination will be to choose such the magnitude that will make the sum of the expected damages and the construction costs at the minimum, because both the damages in properties and the construction costs are the losses in national economy.

In order to find out such the most economical magnitude of structures, the following five informations are necessary:
1) Occurrence frequency curves of storm tide, waves and others.
2) Rates of inundation of inland area under various combinations of the magnitudes of protection works and storm tides.
3) Kinds, amount and distribution of properties in the inland region to be protected.
4) Damage-rate of properties under a certain inundation.
5) Construction cost of protection works estimated for various magnitudes of structures.

The first four informations are required to calculate the expected damages.

PRINCIPLES OF CALCULATION

As a model of calculation the following district is considered here; the tops of natural banks and/or coastal embankments which surround the entire periphery of the district to be protected are higher than the ordinary high water level, and the natural banks and/or coastal embankments are not destroyed by a storm tide and waves.

In order to calculate the economical magnitude of the coastal embankments and other fascilities to protect the above model district, three fundamental diagrams are to be drawn in the beginning. The first diagram is the estimated damage which the model district with the protection work of a certain crown height will suffer from a storm tide of a given height, such as shown in Fig.1(a). The estimation of the damage can be made from the calculation of overflowing discharge into the district for the given conditions of protection works, storm tide, and wave heights (being assumed as a function of the storm tide only) and the calculation of the inundated depth in the district. The second diagram is the occurrence frequency of the storm tide level shown in Fig.1(b). The third diagram is the construction cost of the protection works as a function of the crown height as illustrated in Fig.1(c).

Then, the variation of expected damages with the possible height of sea level for a certain height h_l of the protection works such as shown in Fig.1(d) is obtained by multiplying the estimated amount of the damages for one sea level of storm tide in Fig.1(a) with the occurrence frequency of that sea level in Fig.1(b). The left-hand side area surrounded with two curves of no protection work and of h_l in Fig.1(d) indicates the expected amount of property protection by the protection works with crown height of h_l. The right-hand side area surrounded with the two curves represents the amount of expected damages yet to occur.

These expected amount of property protection and the amount of expected damages are plotted in Fig.1(e) against the crown height. The construction cost of coast protection works in Fig.1(c) is also re-plotted in Fig.1(e). The expected amount of property protection means the averted amount of expected damage by the construction of the protection works encircling the district entirely with crown height of h_l in comparison with the primary condition of protection work. The amount of expected damage means unprotective amount of damage to be expected even with the protection works of crown height h_l. The sum of the construction cost and the amount of expected damage gives the curve of total loss as shown in Fig.1(e).

The point A in Fig.1(e) is the most right hand side intersection point of the curve of the expected amount of property protection and the curve of construction cost. The value of the abscissa of the intersection point A indicates the highest limit of crown height for the economical construction. In Fig.1-(e), the curve of total loss has a minimum value at the point B (there may be more than two points for the minimum values).

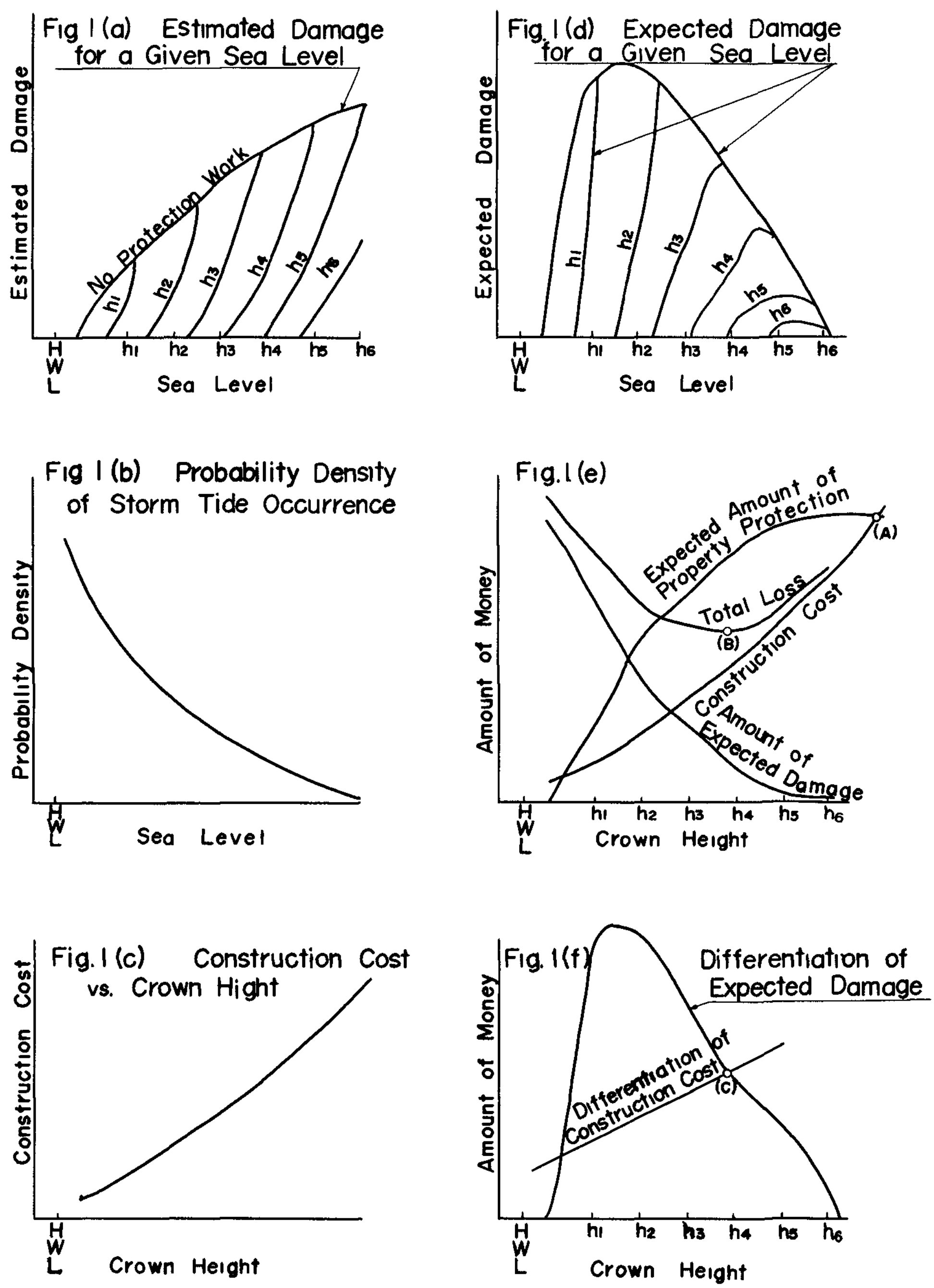


Fig. I Explanation Diagrams for the Calculation of Economical Crown Height

This most economical crown height is determined more accurately as the abscissa of the point C in Fig.1(f); the point C is the intersection of the differentions of the construction cost curve and the expected damage curve.

TIME EFFECTS

The reconstruction period of coast protection works should be decided most economicaly, considering various factors such as construotion cost, primary strength, structural weakening, chemical weakening, external forces to attack the protection works and so on. But such a determination is a difficult task. For this reason the reconstruction period of 50 years has been adopted for all protection works according to the previous practioe. Thus the construction cost and the primary strength are so designed for the protection works as to endure the attack of external forces for 50 years.

In practice, there is a time lag between the investment (construction of coast protection works) and the benefit yielding, and the benefit is expeoted to be yielding during the reconstruction period. Hence the amount of investment and the amount of damages averted should be summed up respeotively from the beginning of the investment to the end of the reconstruction period. But in this case the investment interest and the profits which are produced from the amount of damages averted should be taken into consideration. We have evaluated these investment interest and the profits at the end of the term with the compound interest rates of 7% and 8% a year, respectively.

Since the variation in the properties of the protective region during the reconstruction period must be considerd too, we have assumed that the property will increase with the rate shown in Table 1, every year. In order to simplify the method of calculation for economical magnitude, only one coefficient (I') has been introduoed for the combined effect of interest rate, profit rate and property variation. (This coefficient is also shown in Table 1.) In actual calculations, the construotion costs were multiplied with this over-all coefficient (I') so as to adjust the time effect. With this over-all coefficient (I'), the benefit-cost ratio can be calculated with the following equation.

$$\frac{P_n}{C_n} = \frac{P_n'}{C_o} = \frac{50 P_o}{I'} \Big/ C_o$$

where P_n : Amount of expected property protection in the whole period, which is evaluated at the end of reconstruction period with consideration of all time effects.

P_n' : Amount of expected property protection in the whole period, which is evaluated at the beginning point of reconstruction period with consideration of all time effects.

c_n: Construction cost evaluated at the end of reconstruction period.

c_0 : Construction cost.

50: Years of reconstruction period.

p_0 : Expected amount of property protection in one year by having coast protection works.

Class of District	Increasing Rate of Property/One Year	(I′)
Established Industrial Districts	5.9 %	1.00
Newly Developing Districts	7.3 %	0.74
Districts with Promising Development Plans	6.1 %	0.96
Other Districts	5.0 %	1.19
Mean of Whole Nation	6.3 %	

Table 1. Increasing Rate of Property Protection and Over-all Coefficient for Time Effect Adjustment, (I′).

The maintenance and administrative expence are not considered explicitly, but they are included in the term of interest rate for the construction cost which is far larger than the formers.

DETAILS OF CALCULATION

OCCURRENCE FREQUENCY OF STORM TIDE LEVEL

The occurrence frequency distributions which have been used for the estimation of high water discharge of river, amount of rainfall and others are the logarithmic normal distribution, the Gumbel's distribution, exponential distribution and others.

As for the storm tide level there are little differences among these distributions in an extent to which observation data are available, but for an extraordinary high tide levels which will occur once in several hundreds to one thousand years, there are considerable differences among these distributions. It is difficult to decide which distribution is the most suitable one for such extraordinary high tide level in Japanese observation data. We have employed the exponential distribution, because it gives a middle value between the values of the logarithmic normal distribution and the Gumbel's distribution and the calculation method of storm tide level by the exponential distribution is simple and easy to be instructed.

Occurrence frequency of storm tide in the exponential distribution - When we found observation data in fairly long term at the planning site or a near-by location which is nearly equal in natural features, we calculated the exceeding occurrence frequency of storm tide level in the one year basis. When we could not find observation data of long period, we estimated the exceeding occurrence frequency in one year by calculating the deviations of sea level with meteorological data (atmospheric pressure, wind velocity and wind direction) and by adding suitable height of astronomical tide to the above deviations with the proper consideration of co-occurrence probability.

We presumed that the exceeding occurrence frequency of storm tide level in one year is expressed by the following exponential equation after Wemelsfelder (1960):

$$m = 10^{\frac{h-h_1}{s}} = e^{\frac{\alpha(h-h_1)}{s}}$$

where m : Exceeding occurrence frequency per one year.
h : Storm tide level.
$\alpha = \log_e 10 = 2.3026$
$s < 0$, $h_1 > 0$: Both are constant, h_1 is such the sea level that its exceeding occurrence frequency per one year is unity.

We calculated the constants, s and h_1, from the observation data or calculated values of storm tide levels by means of the least square s method.

CALCULATION METHOD OF SUBMERSION LEVEL

Modelling of storm tide level variation - We devided the storm tide elevation into astronomical tide and meteorological tide, classifying them according to their regional characteristics The astronomical tides at all obserbation points are classified with diurnal inequality and four major partial-tides. In regards to the meteorological tide, we made a nation-wide investigation of the actual observation data of tidal records for the continuation times of various heights of storm tides at various locations. Both the astronomical and meteorological tides were modeled to isosceles triangles in their time-variations. The continuation times of the astronomical tide were classified regionally and those of the meteorological tides were classified both regionally and by step of tide level (see Table 2). By superposing two models of Table 2 as illustrate in Fig. 2, we can obtain the models of storm tides; the tide model with longer continuation time is taken as the base for the storm tide model. It should be mentioned that these models are applicable only when the crown height or ground height is higher than the astronomical tide level.

Table 2a

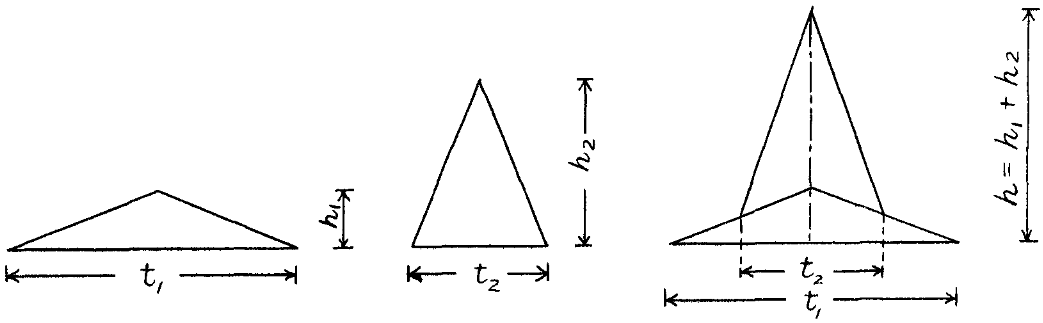
Sea Level (Above Datum Level, Meter) / Tipe of Astronomical Tide (Hour) / Classification of Coast Districts		Tipe of Meteorological Tide (Hour) 1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5
the Japan Sea	18	18	12										
South Coast of Hokkaido	18	-	-	24									
East Coast of the Pacific Ocean	18	-	-	-	18								
South Coast of the Pacific Ocean													
(on the East of Cape Irozaki)	18	-	-	24	18								
(on the West of Cape Irozaki)	15	-	-	-	24	18	12						
the Kii Channel	15	-	-	-	24	18	12						
the Bungo Channel	15	-	-	-	-	18	12						
West Coast of Kyushu (Coasts of Open Sea)	12	-	-	-	-	18	18	18					
the Kagoshima Bay	12	-	-	-	-	24							
the Tokyo Bay	15	-	-	-	-	24	18	12	(9)	(9)			
the Ise Bay the Kinuura Bay	12	-	-	-	-	18	12	12	12	(9)	(9)	9	9
the Atsumi Bay	12	-	-	-	-	-	18	12	12	6	(6)	(6)	
the Osaka Bay	18	-	-	-	18	12	12	9	(6)	(6)	(6)		
East Part of the Seto Inland Sea													
(the Harimanada Bay)	15	-	-	-	18	18	12						
(the Hiuchinada Bay and the Western Bays)	12	-	-	-	-	-	-	-	18	18	12	12	

Table 2b

Meteorological Tide / Tipe of Astronomical Tide (Hour) / Classification of Coast Districts		Tipe of Meteorological Tide 0.5	1.0	1.5	2.0	2.5
the Ariake Bay	12	18	18	12	12	12
the Yatsushiro Bay	12	18	18			

Example: Type of 18 hours means a type of storm tide which continuous 18 hours with tidal variation of an isosceles triangle.
( ); Calculated by digital computer

Table 2. Models of Storm Tide



Note: 1. The "sea level" on the Table 2 means h (= $h_1 + h_2$) in Fig.2.
2. In practical calculation, spring rise (HWL - DL) is used as range of astronomical tide.
3. Range of meteorological tide in Table 2a is (h-range of astronomical tide) in Fig.3.
4. Elevation of sea level (above datum level) = elevation of astronomical tide + range of meteorological tide.

Fig.2. Superposing Method of Storm Tide Models.

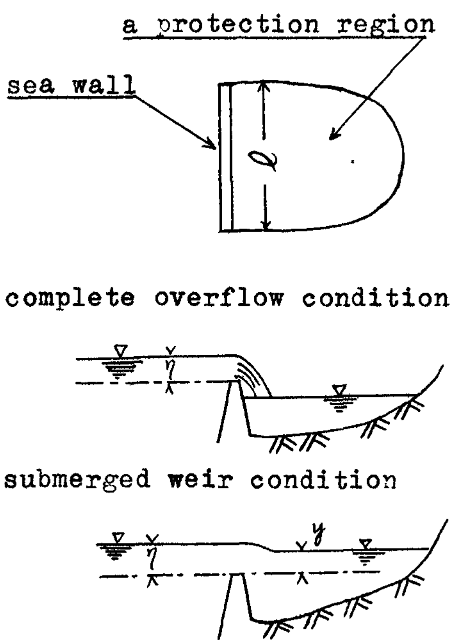


Fig.3. Definition Sketch of Overflow Conditions.

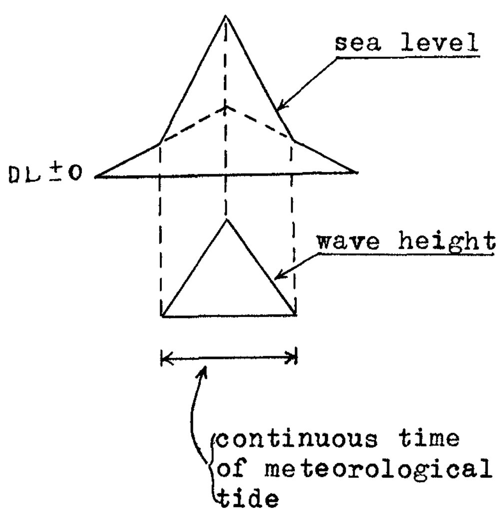


Fig.4. Time Variation of Wave Height.

Calculation method of submersion level - Submersion levels were calculated with the assumption that the submersion quantity of water is calmly stored in the region behind coastal embankments. The submersion quantity was considered to be composed with overflowing discharge which was calculated with the model storm tide level described in the previous paragraph and the overtopping discharge of waves which are accompanied with storm tide.

Quantity of overflow was calculated with the next equations.

(1) Complete overflow condition ($y \leq \frac{2}{3}\eta$)

$$Q = m\sqrt{2g}\,\eta^{\frac{3}{2}}\ell$$

(2) Submerged weir condition ($y \geq \frac{2}{3}\eta$)

$$Q = m'\sqrt{2g(\eta - y)}\,y\,\ell$$

where η: Sea level above crown height (see Fig.3)
y: Inundation level measured upward from crown height.
Q: Quantity of overflow for length per unit time.
ℓ: Length of embankment.
m: Coefficient of overflow for broad weir (theoretical value of $m = 0.385$ is used).
m': Coefficient of overflow for submerged weir $m' = 2.6\,m = 2.6 \times 0.385 = 1.0$

Since quantity of overtopping is influenced by many elements such as wave steepness, crown height, site of embankment, type of embankment and others, it is not easy to calculate the quantity in general. But the overtopping quantity can not be neglected in comparison with quantity of overflow. Thus the following method has been adopted to calculate the quantity of overtopping.

1) The wave height varies with respect to time as shown in Fig.4.

2) The quantity of over topping is considered to be stored in the region only when the condition of $H \geq 1.0$ m and $+H \geq R \geq -H$ are satisfied and further the sea level is higher than the ground level of the region behind embankments. R=(crown height - sea level)

3) Quantity of overtopping is calculated by the following equation:

$$q_w = 57.6 \cdot K \cdot H^{\frac{3}{2}} \cdot \ell$$

where q_w : Quantity of overtopping (m^3/min.)
H : Wave height in front of sea wall (m); equal to the equivalent offsea significant height, H_o' for water depth larger than H_o', and equal to water depth for depth smaller than H_o').
K : Coefficient of which value decreases linearly from K=0.25 for R=0 to K=0 for R=±H.

CALCULATION OF DAMAGE AMOUNT

Property in the region to be protected - The calculation has been made for each unit protection region which is a unit of the coast protection plannings. As a rule the protection works of every unit area is independent of each other and complete in its area. Amount of properties in the protective regions were investigated for every step of ground level along storm tide coasts. Unit cost of property was investigated by sample surveys along each coast, then unit cost was applyed to other unit regions along the same coast. Included in the investigations were building, household property, assets of industry, goods in stock, land, outputs of agriculture and industry, public facilities etc.

The data to be used for the investigation were the statistical data prepared by the national government and local self-governing bodys; these data were specified beforhand.

Depth of Submersion (cm) / Kind		0 ~ 49	50 ~ 99	100 ~ 149	150 ~ 199	200 ~ 299	300 ~
House		3	13	28	39	54	67%
House Hold Property		0	27	43	55	69	77
Farm-House, Fishmans House	Properties for Depreciation	0	25	36	45	53	57
	Goods in Stock	0	29	47	61	73	76
Firm, Office and Work	Properties for Depreciation	0	38	44	51	61	74
	Goods in Stock	0	21	40	55	69	74

Note: 1. Submersion depth is measured from ground level.
2. Height of floor above ground level is presumed to be 50 cm.
3. Japanese houses are made of wood in most cases.

Table 3. Damage Ratio of Properties.

Damage ratio of property - The standard damage ratio of property by inundation were determined as shown in Table-3 based on the census-taking data at times of the typhoon Ise Bay and Chilean earthquake tsunami. Damage ratio of property by wave force were also determined from the inspection data at times of various typhoon. In order to evaluate the indirect damages, the number of days on which plants or stores suspend the operation was estimated as shown in Table 4.

Depth of Submersion (cm) / Kind	0 ~ 49	50 ~ 99	100 ~ 149	150 ~
Light Industry	0	16.4	29.3	34.0 days
Heavy Industry	0	22.3	24.0	29.0
Petro-Chemical Industry	0	19.4	26.7	31.5
Store	0	16.0	39.0	44.0

Note: 1. Submersion depth is measured from the ground level.
2. Period of inundation is presumed to be less than 10 days.

Table 4. Number of days on which plants or stores suspend the operations.

Damage amount of protective region - Damage amount of protective region was the sum of direct and indirect damages. The amount of direct damage was calculated by summing up the number of properties multiplied by the unit costs and damage ratios all over a unit protective region. The amount of indirect damages was calculated by summing up the daily added values of plants and stores multiplyed by the number of days of business suspention.

CONSTRUCTION COST OF COAST PROTECTION WORKS

Standard curves of unit construction cost related to the heights of sea walls were first established for various types of structures after investigating recent designs of coast protection works all over the nation. Then the cost estimate of a particular design section was made at each unit region, and the cost curve drawn parallel to a standard cost curve passing through the point of the construction cost of the particular section was utilized to estimate construction costs of coast protection works with various crown heights.

RESULTS OF INVESTIGATION

With the method described in the preceding sections a nation - wide investigation has been made to calculate the economical crown heights of coast protection works for 81 harbors with 226 unit regions for storm tide protection. The investigation showed that the investment ratio is greater than unity at 192 unit regions. By constructing the protection works with the economical magnitudes at 192 unit regions, the expected damages in 50 years are estimated to be reduced to the amount of 74 millions dollars from the amount of 44 billions dollars for the case of no protection work. The total construction cost of these magnitudes of protection works is only 400 million dollars. Therefore the overall benefit-cost ratio is nearly 110.

It has been proved that the method presented in this paper is very efficient to decide the magnitude of investment for coast protection works, that the coast protection project in Japan is very productive object of the investment, and that the investment by the government is a very profitable one from a stand point of national economy.

CONCLUDING REMARKS

On the above, we have introduced the fundamental ideas of the concrete calculation method, which was already put into use in Japan, to decide the economical magnitudes of coast protection works, with a few results of the investigations. We have found that the method is effective and appropriate to the practice, and also proved that the coast protection works in Japan is a very benefitial project.

But in this method, the protective effect of the structures against astronomical tide is omitted for the areas where the ground level is lower than the ordinary high water level. We must continue our research to find the calculation method of such the protective effect for astronomical tide (in general, the protective effect for astronomical tide has little influence on the determination of the economical crown height). For the improvement in the accuracy of the present method, it is also necessary to enrich observation data of natural conditions, to make research further on the damage rate of protective property and reconstruction period of coast protection works. It is also necessary to simplify the investigation of the properties in the region behind the protection works in order to apply the present method to a great number of districts.

ACKNOWLEDGEMENTS

The application of the present method to practical plannings were undertaken by the Port and Harbour Bureau of Ministry of Transportation, with the co-operations of Regional Bureaus of Port and Harbour Construction, the Port and Harbour Technical Research Institute, the Meteorological Agency, local self-government bodys and administrators of the ports and harbours concerned. The researches for this method and its development were made possible through the efforts of Messrs. Yoshihisa Kawakami and Hisashi Aono. The authors wish to express their appreciations for the all members assisted the investigation.

REFERENCES

Gumbell, E. J. "Statistics of Extremes", Columbia University Press, New York, 1958, 375 pp.

Wemelsfelder, P. J. "On the Use of Frequency Curves of Stormfloods", Proceedings, 7th Conference on Coastal Engineering, 1960, pp. 617～632.