CHAPTER 72

COASTAL ENGINEERING RESEARCHES ON THE WESTERN COAST OF TAIWAN

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SYNOPSIS

Taiwan is an island located at the edge of the continental shelf of the East China Sea. Her eastern coast fronts precipitously on the Pacific Ocean, whereas the major part of the western coast is formed by very flat sandy beaches. Various engineering works such as the planning of newly building or extension of harbors, tidal land development, cooling water intake of steam power plants as well as shore protection works have been performed on this coast.

However, owing to the geomorphological situation of this coast, monsoons of NNE or NE direction originated from high pressure atomosphere overlaying East Asia continent prevail from September to March, and in the summer months, the coast is assailed by typhoons. Waves caused by these meteorological phenomena are mainly being generated in shallow water region, besides, their fetch areas are limitted by the China mainland and Taiwan island. The forecast technics must be reconsidered in stead of utilizing traditional methods. Most coastal engineering structures are subjected to the waves after breaking since the beach slope is exceptionally flat. Many rivers of rapid stream bring tremendous amount of sediment from the high mountains down to the sea. In consequence, sand drift along this coast is so severe that small harbors will be silted up only a few months during monsoon season or after one strong typhoon assailing.

Coastal engineering researches were commenced in Taiwan 8 years ago. Field investigation including wave measurement

and repeated hydrographic sounding have been performed in several sections, in addition, experimental researches are being carried on concurrently. Wave forecasting contrivance especially adapted to the western coast of Taiwan and engineering utilization of experimental result of wave breaking as well as the deformation after breaking are being briefly submitted in this paper in addition to general description of coastal features of western coast of Taiwan.

GENERAL ASPECT OF THE COAST

The total length of the western coast of Taiwan island from its northern point Fukuacho to the south point Oranbi is about 460 km. According to the shoreline alignment, it is to be divided into 4 sections as shown in Fig - 1. Section II and III front China mainland crossing the Taiwan Strait, whereas section I and IV are exposed to the East and South China Sea respectively. The factors affecting the coastal engineering problems are enumerated below.

METEOROLOGICAL ASPECTS

The main meteological phenomena which have influenced on this coast are monsoons in the winter and typhoons in the summer. From September to March of next year, high pressure anticyclones occur contineously in Mongolia and migrate toward south-east. Monsoons of NNE and NE direction from the anticyclones prevail throughout the East China Sea and Taiwan Strait. The duration of winds in excess of 10 m/sec is to be 48 hours in maximum and about 10 hours in average, however, the maximum velocity has hardly exceeding 20 m/sec. In summer months the coast is suffered by typhoon assailing. The main course of typhoons approached Taiwan and their frequency of occurance since 1892 to 1962 are jotted down in Fig - 1. The maximum wind velocity recorded within recent 10 years was 45 m/sec NNE direction in section II of this coast, but the duration of winds over 20 m/sec in the same direction have not been recognized to be longer than 5 hours.

Additionally, in summer days of no typhoon approaching, breezes from S and SW direction beginning to blow around 10 O'clock in the morning and diminishing as the sun set down, but occasionally 10 m/sec wind velocity of 2~3 hour duration are to be recorded in the afternoon.

OCEANOGRAPHICAL ASPECTS

Tidal range in the Taiwan Strait is considerably high in the middle part but decreases gradually as the width of the strait is expanding. Extraordinary high tide can be recorded while the center of typhoon is locating in the strait.

Tributary of Kuroshio flow from south to north almost the whole year, only slight north-to-south flow can be recognized near the coast in the winter.

Waves of monsoon and typhoon seasons were measured in Taichung Harbor in 1959 and 1960. Significant wave period exceeding 10 sec has never been recorded. Owing to the harbor is located on section II of this coast, waves in monsoon season are larger than what have been caused by average typhoons, however in section IV, situation may become inverse.

SEDIMENTS AND COASTAL FEATURES

On account of the geographical location and the disposition of rivers, the sediment and coastal aspect are different in each sections. On section I, the coast is exposed to major waves coming from the north, besides, sediment feeding from the river is not sufficient to maintain coastal stabilization, it is suffered from erosion. Bed material in this section is mainly fine sand whereas cobbles can be found sporadically and rocks exposed in the northern part. Sand drift moves predominantly from north-east to south-west. Shore slope in this section is about 1/50 in average. Seven rivers of rapid stream bring tremendous amount of sediments from the high mountains to the nearshore of section II in typhoon season, soon after, the monsoons begin to blow, the waves raise littoral drift from north to south, quantitative estimation of sand transportation worked out by repeated hydrographical sounding data of Taichung Harbor is arround 1,200,000 m^3 per year. Beaches of this section is still accumulating, nearshore slope of this section is about 1/60 1/80 in the north of Taichung Harbor and becomes flater as going to south, only to be 1/600 1/1000 has been measured in the southern end of this section. Bed material in this section is consisting of fine sand of some 0.2～0.4 mm in diameter, but in the north of Taichung Harbor cobbles can be found in the estuary of rivers. Section III of this coast runs almost exactly from north to south, waves of the monsoon still bring sand down to south, however, the effect of SW direction waves in typhoon season will not be negligible in this section. On the whole, the sand drift migrate toward south except in the area sheltered by a long sand peninsula. Slope of the nearshore is not so flat as the southern part of section II, but still being arround 1/1000 in the water area behind the bars. Bed material in this section is fine sand mixed by silt and clay. Though the bars are suffered by erosion and deformed frequently, but the main coast will said to be stable. The alignment of section IV is entirly different from the others. Consequently waves of monsoon season should not be significant, whereas S and SE direction wind waves and swells predominate over the coast, so that the main direction of sand drift is from south to north. Some positions of this section are severely suffered by erosion for there is a deep sea valley near the coast so that sand transported from the mountain can not deposit in nearshore area. Beach configulation in this section become more complex than the others, bottom slope in the north of river estuary is still as flat as $1/50 \sim 1/80$, and bed materials are also fine, whereas going down to south from the estuary diameters of the sand become more and more coarse and finally only rocks survive, as well as the beach slope is larger than 1/10 in the southern end.

COASTAL ENGINEERING RESEARCHES ON THIS COAST

As described above, the characteristics of this coast is mainly as follows:

1. The offshore region of this coast is shallow water with respect to the wave of larger period.
2. The island is located so near the mainland that the width of fetch area is always limited by China mainland and the northern part of Taiwan. For instance, in average monsoons, the fetch lengths of NNE direction often stretch to the mouth of the Yangtze River, whereas the width of fetch area retains to be some 80 km.
3. The bottom slope is exceptionally flat, as the grain-size of the bed material is very fine for the most part of the coast.

Being associated with these special features of the coast, following problems have been encountered by the coastal engineers in Taiwan.

1. The measured waves always smaller than predicted waves which worked out by traditional forecasting method owing to the limitation of width and shallowness of fetch area
2. Breaking depths and heights of various waves on beaches flater than 1/50 must be worked out for the purpose of engineering design.
3. For the beaches are so flat that coastal structures such as small harbors, dikes of tidal land reclamation, shore protection revetments are located behind the breaking line of

average waves. Behavior of waves after breaking should not be remained in a state of ignorance.

The task of solving abovemetioned problems and furnishing design criteria to field engineers has been assigned to Tainan Hydraulic Laboratory. The results of researches are briefly described below.

WAVE PREDICTION METHOD ADOPTED IN THIS COAST

For the waves caused by typhoon, numerical calculation is adopted, which is to be introduced in another paper in this proceedings, calculation of the waves in monsoons is described here.

The duration of wind in monsoon season often exceeds the limit of fully arisen, and the wind velocity can be recognized remaining constant throughout the fetch area, following contrivances are being made to calculate the waves in monsoon season of this coast.

Supposed that the wave energy at the point of interest A can be considered to be the sum of the energy spreaded from every lateral stripes of the fetch area i.e.

$$E_A = \Delta E_1\,dF + \dots + \Delta E_n\,dF + \dots + \Delta E_F\,dF$$

$\Delta E_n\,dF$ is the energy transmitted from nth stripe to point A, in the case of the width of fetch area is unlimited

$$\Delta E_n = \int_{-\pi/2}^{\pi/2} \Delta E_{n,o} \cos^2\theta\, d\theta = \frac{\pi}{2}\,\Delta E_{n,o}$$

$\Delta E_{n,o}$ is the wave energy per unit area of sea surface obtained from the wind on nth stripe, however, the winds are to be constant throughout the fetch area $\Delta E_{n,o} = \Delta E_o$ everywhere.

In the case of the width of fetch area is limited, being W, as shown in Fig - 2, the wave energy transmitted from the line x to the point A is:

$$\Delta E_n' = \int_{-\tan^{-1}\frac{W}{2(F-x)}}^{\tan^{-1}\frac{W}{2(F-x)}} \Delta E_{n,o} \cos^2\theta\, d\theta$$
$$= \Delta E_o \left[\tan^{-1}\frac{W}{2(F-x)} + \frac{1}{2}\sin\left\{2\tan^{-1}\frac{W}{2(F-x)}\right\}\right]$$

The waves transmitted from this stripe will be equal to the waves from the stripe of the fetch area of width unlimitted, only if dx is enlarged, put

$$\Delta E_n\,dF = \Delta E_n'\,dx$$

then

$$\frac{dF}{dx} = \frac{2}{\pi}\left[\tan^{-1}\frac{W}{2(F-x)} + \frac{1}{2}\sin\left\{2\tan^{-1}\frac{W}{2(F-x)}\right\}\right]$$

From this relation, we can find out the equivalent length Fe which can be used to predict the waves in a width limitted fetch area in stead of natural fetch F using traditional method, Fe can be calculated by

$$\int_0^{Fe} dF = \frac{2}{\pi}\int_0^{F}[\tan^{-1}\frac{W}{2(F-x)} + \frac{1}{2}\sin\left\{2\tan^{-1}\frac{W}{2(F-x)}\right\}]dx$$

However, even in an open sea, the wave energy transmitted to the point of interest would not include that from the infinite point. The wave energy is spreading effectively in an extent, for example,

$$\Delta E_n = \Delta E_0 \int_{-\pi/4}^{\pi/4} \cos^2\theta d\theta = [\frac{\pi}{4} + \frac{1}{2}]$$

and

$$\frac{dF}{dx} = [\frac{\pi}{4} + \frac{1}{2}]^{-1}[\tan\frac{W}{2(F-x)} + \frac{1}{2}\left\{2\tan\frac{W}{2(F-x)}\right\}]dx$$

As shown in Fig-2(b) a length of W is included in the equivalent fetch

$$Fe = Fe' + \frac{W}{2}$$

$$Fe' = \int_0^{Fe'} dF = \int_0^{(F-\frac{W}{2})}[\frac{\pi}{4} + \frac{1}{2}]^{-1}[\tan^{-1}\frac{W}{2(F-x)} + \frac{1}{2}\sin\left\{2\tan^{-1}\frac{W}{2(F-x)}\right\}]dx$$

$$\frac{Fe}{F} = 0.778[\tan^{-1}\frac{W}{2F} - 0.195(\frac{W}{2F}) + (\frac{W}{2F})\ln\left\{(\frac{2F}{W})^2 + 1\right\}] \quad \dots (1)$$

The hindcast of waves in the winter of 1959 used S.M.B. method only adopting Fe computed by equation (1) in stead of practical fetch length has agreed closely with measured record as shown in Fig 3.

RESEARCHES ON THE BREAKING OF WAVES RUNNING OVER FLAT BEACHES

In order to offer design criteria on the breaking depth and height of waves running over beaches flater than 1/50, numerous experiments have been carried out in the wave channel of Tainan Hydraulic Laboratory. The channel is 75 meter in length, 1 meter and 1.2 meter in width and height. Waves of Ho/Lo = 0.0024~0.08 have been generated on fixed bed beaches of 1/50, 1/65, 1/80, 1/600 slope, in addition, 1/20 slope beach has been also experimented for comparison.

The experimental results are shown in Fig 4 and 5. Apparently, breaking depth indice D_b/H vary inversely propotional to slope s and breaking height indice are propotional to s. The reason of the latter has been explained by Dr. Kishi applying characteristics, whereas on the former, following explanation and semi-theoretical equations are being submitted.

The wave length measured offshore from breaking point will be:

$$Lb = \int_0^T c\,dt \qquad \text{and } c = \int_0^t \alpha\,dt$$

α is the acceleration of wave celerity on slopping beaches $\alpha = c \cdot dc/dx$, in the region $D/L \lessapprox 0.05$ $c \doteqdot \sqrt{gD} = \sqrt{gsx}$, $\alpha = (1/2)gs$ $c = (1/2)gst + k$, while $t = 0$ $c = \sqrt{gDb}$, $k = \sqrt{gDb}$

$$Lb = \sqrt{gDb}\cdot T + (1/4)gsT^2 \quad \text{i.e.}$$

$$Lb = \sqrt{gDb}\cdot T + (1/2)\pi s L_0$$

A large number of wave length have been measured in experiments, the wave length from D/L = 0.20 to the breaking point can be expressed by following equation and Fig-6

$$L = \tanh \frac{2\pi D}{L_A} \cdot L_0 + 1.5\pi s L_0$$

L_A : the wave length at D calculated by Airy's theory

D : depth in the middle of wave length

i. e. $\quad L = L_A + 1.5\pi s L_0 \qquad \ldots.(2)$

According to $H/H_0 = \sqrt{(1/2n)\,C/C_0}$, wave height in breaking point can be expressed as follows

$$\frac{Hb}{Ho} = \frac{m}{2\sqrt{2}}(2\pi\delta_0)^{-1/4}\left(\frac{Db}{Ho}\right)^{-1/4}\left[1 + \frac{1}{6}(2\pi\delta_0)\frac{Db}{Ho}\right] \qquad \ldots (3)$$

$\delta_0 = Ho/Lo$ $\quad$ m: ratio of experimental breaking height and calculated wave height by $H/Ho = \sqrt{(1/2n)\,C/Co}$ at depth Db

Substitute the equations (2) and (3) to the equation of crictial steepness of wave breaking

$$\frac{Hb}{Lb} = k \tanh \frac{2\pi D}{L_A} \doteqdot k\sqrt{2\pi\delta_0 Db/Ho} \qquad \ldots (4)$$

k = 0.143 by Michell and Hamada, however in our experiments 0.143 will be the maximum value and it varys with steepness and slope.

From (4), following equation of breaking depth indice can be found

$$y^5 - 0.0744\, m/k\,\delta_0^{3/4} y^4 + 3.76 s\,\delta_0^{-1/2} y^3 + 1.125 s^2\,\delta_0^{-1} y - 0.0714\, m/k\,\delta_0^{-1/4} = 0 \qquad \ldots(5)$$

$y = (Db/Ho)^{1/4}$

$m = 0.0122\,(\delta_0 - 0.04)^2 + 1.16$ $\quad$ ... experimental result

$k = 0.143\exp(-56s) + 14.1 s\,\delta_0^{0.54}$ $\quad$ ... experimental result

From (5) $\partial y/\partial s < 0$ can be recognized in the region of $\delta_0 < 0.143$ and $y > 1$. In consequence, breaking depth indice are to be proved varying inversely propotional to the slope. In other words, the wave lengths on small beaches are shorter than that of steep beaches, the waves reach critical steepness earlier.

Breaking heights can be calculated by equation (3) while Db/Ho are to be calculated by equation (5), however, both equations can not be easily computed, following experimental formulas are submitted for practical use

$$\frac{Db}{Ho} = a\left[\log_{10}\left(\frac{Ho/Lo}{0.04}\right)\right]^2 + b\,\log_{10}\left(\frac{Ho/Lo}{0.04}\right) + C \qquad \ldots (6)$$

$$a = 1.352 - 28.13\,s$$
$$b = 3.2s^2 - 2.4s \qquad \text{(only in the region}$$
$$c = 1.516 - 5.\dot{3}s \qquad s < 1/50)$$

$$\frac{Hb}{Ho} = d\left(\log\frac{0.08}{Ho/Lo}\right)^e + 0.92 \qquad \ldots\ldots (7)$$

$$d = 4.642 \times 10^5 S^3 - 2.99 \times 10^4 S^2 + 350.4S$$
$$e = 1.263 \times 10^6 S^3 - 8.096 \times 10^4 S^2 + 921.9S$$
(only in the region $s < 1/20$)

RESEARCHES ON THE WAVES AFTER BREAKING OVER FLAT BEACHES

Experiments on waves after breaking were being performing concurrently with the breaking experiments, the main conclusion obtained from the results are:

1. Wave height decreases rapidly within 2~3 wave length from breaking point and is attenuated slowly only by the effect of bottom friction thereafter.
2. Wave period varies slightly but equals the period before breaking in average.
3. Secondary wave crests can sometime be recognized between two main crests
4. The index of wave enfeeblement H/Hb varies with the ratio of distance exponentially as Fig-7.
5. H/Hb varies propotionally to the beach slope s.
6. Within the range $0.04 < Ho/Lo < 0.08$, H/Hb is decreasing with the steepness, however, the tendency is seemed to be not very clear especially in the region $Ho/Lo < 0.04$.

For the purpose of finding out the formula for calculation, following discussion has been made.

The enfeeblement ratio of wave energy with respect to the distance from the shore line is

$$\frac{dP}{dx} = \epsilon_t + \epsilon_f$$

$P = ncE$

c: wave celerity $\qquad n = \frac{1}{2}\left(1 + \frac{4\pi D/L}{\sinh 4\pi D/L}\right)$

$E = \frac{1}{8}\rho g H^2$:total energy of waves per unit area

x: the distance from shoreline

ϵ_t = dissipation rate of energy by turbulence and other effects during breaking

ϵ_f = dissipation rate of energy by bottom friction.

However ϵ_t is so complex that cannot be expressed by equation exactly, in this case, supposing that the dissipation of energy by turbulence is occuring suddenly in the breaking point and the remained wave height is Hs = nHb. n will be evaluated from experiments. Under this hypothesis,

$$\frac{dP}{dx} = \epsilon_f$$

and while $x = xb$ $\quad H = Hs = nHb$

xb: distance from shore to breaking point.

Water depth after breaking is so shoal that long wave theory can be applied, therefore

$$P = \sqrt{gD}\cdot E = \frac{1}{8}\rho g^{1.5} s^{0.5} x^{0.5} H^2$$

$$\epsilon_f = f\rho g^{1.5} H^3 / 6\pi s^{1.5} x^{1.5}$$

ρ : density of water

f: friction coefficient

and let $\eta = H/Hb$ $\quad \xi = x/xb$ $\quad$ the equation becomes

$$\frac{d\eta}{d\xi} = k\frac{\eta^2}{\xi^2} - \frac{1}{4}\frac{\eta}{\xi}$$

$$k = \left(\frac{2f}{2\pi s^2}\ \frac{Hb}{xb}\right) = \left(\frac{2f}{2\pi s}\ \frac{Hb}{Db}\right)$$

while $\xi = 1$ $\quad \eta = Hs/Hb = n.$

The solution of this equation is

$$\eta = \frac{\alpha\,\xi}{1-(1-\alpha/n)\xi^{1.25}}$$

$$= \frac{1.25}{k} = 1.25\left(\frac{3\pi s}{2f}\ \frac{Db}{Hb}\right)$$

From experimental results, the curves can be represented by

$$\frac{H}{Hb} = \frac{\alpha(x/xb)}{1-(1-\alpha/n)(x/xb)^{1.25}} + (1-n)\left(\frac{x}{xb}\right)^{\beta} \quad \ldots\ldots (7)$$

$$n = 0.749 \qquad \alpha = 24\pi s \qquad \beta = 960s - 35840s$$

$$(1/600 < s < 1/50)$$

RESEARCHES ON THE WAVE RUN UP AFTER BREAKING

Waves after having broken also run up on shore structures. The experiments on this phenomenon have been also carried out by the Tainan Hydraulic Laboratory on dike slopes 1/2, 1/3, 1/4, 1/5, 1/6. A semitheoretical formula derived from energy transmission point of view is as follows:

$$\frac{R}{Hb} \quad \frac{k_2 - k_3 n}{k_4 \operatorname{cosec}\theta + 1}\ \frac{CT}{Hb} + \frac{k_1}{k_4 \operatorname{cosec}\theta + 1} \quad \ldots\ldots (8)$$

R: run up height

Hb: breaking height

$C = \sqrt{gDb}$ $\qquad$ Db: breaking depth

T: wave period
θ: angle between dike surface to the sea bottom.
$n = x/CT$
x: distance from dike toe to the breaking point
$k_1 = f(CT/Hb)$ as shown in Fig-8
$k_2 = f(\cot\theta)$ as shown in Fig-9
$k_3 = 0.005\sqrt{Db/Dt + 1}$
Dt: water depth at dike toe
k_4: 0.26 on smooth surface and 0.35 on rubble mound surface.

CONCLUSION OF RESEARCHES

Owing to the special features of the western coast of Taiwan, following result are to be suggested to estimate the waves from the sea to the shore

1. In monsoon season, traditional wave forecasting method can be used to calculate the waves only change the practical fetch length F to equivalent fetch length Fe by equation (1)
2. Waves caused by typhoons should be calculated by numerical calculation method of shallow water
3. Breaking wave height and depth of various waves can be calculated by equation (3), (5) or (6) (7) on beaches flater than 1/50
4. wave heights in surf zone can be estimated from equation (8)
5. Run up on the dike located in surf zone can be worked out from equation 9.

REFERENCE

Kenneth S. T. Chang: Shore Process of South Taiwan. Report of Land Developement Planning Commission of Taiwan, 1966 (in Chinese)

Frederick L. W. Tang et al: Planning Report of Taichung Harbor. Keelung Harbor Bureau, 1962. (in Chinese)

L. Hsie: On the Application of P.N.J.Method to Western Coast of Taiwan. Master Thesis of Cheng Kung Univ. 1965 (in Chinese)

H. W. Iverson: Waves and Breakers in Shoaling Sea. Proceedings of 3rd Conference on Coastal Engineering 1952.

T. Kishi: Transformation, Breaking and Run up of a Long Wave of Finite Height, Proceedings of 8th Conference on Coastal Engineering. 1963.

T. Hamada: Breakers and Beach Erosion. Report of Transportation Research Institute No. 1, 1956.

C. T. Kuo: Experimental Study of Breaking Waves in Shoaling Water. Research Report No.7 of Civil Engineering Cheng Kung Univ. 1962. (in Chinese)

T. Ijima et al. Wave Characteristics in the Surf Zone Observed by Stereophotography. Report of Transpotation Technical Research Instiute No. 31. 1958.

C. L. Bretchneider: Field Investigation of Wave Energy Loss of Shallow Water Ocean Waves. Tech. Memo No.46 B.E.B. 1954.

C. Kao: Experimental Study of Waves after breaking. Master Thesis of Cheng Kung Univ. 1964 (in Chinese)

Frederick L. W. Tang: Wave Run up after Breaking. Proceedings of 10th Conference on Coastal Engineering of Japan Japanese Civil Engineers Society 1963. (in Japanese)

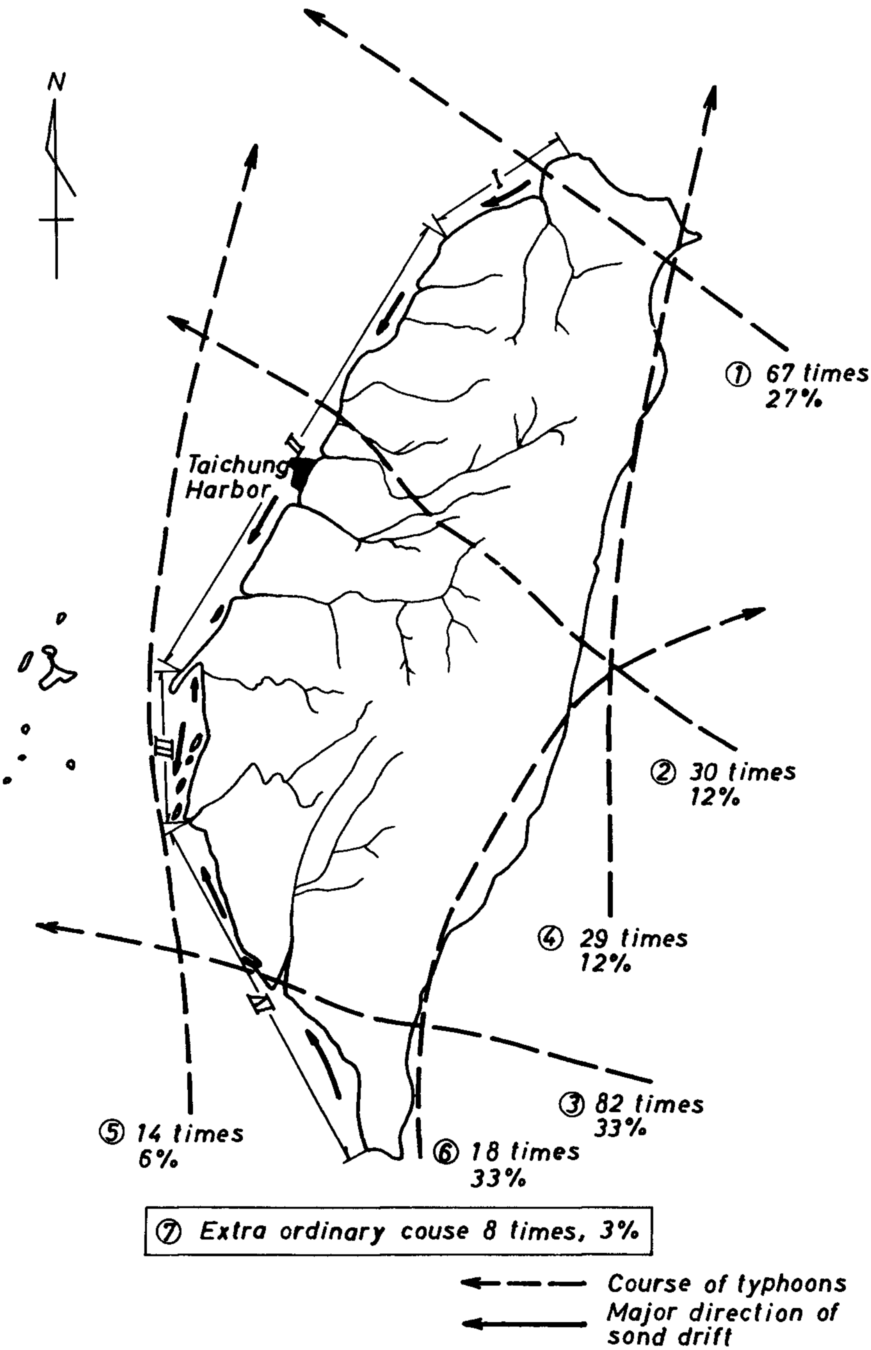

Fig. 1. Map of Taiwan.

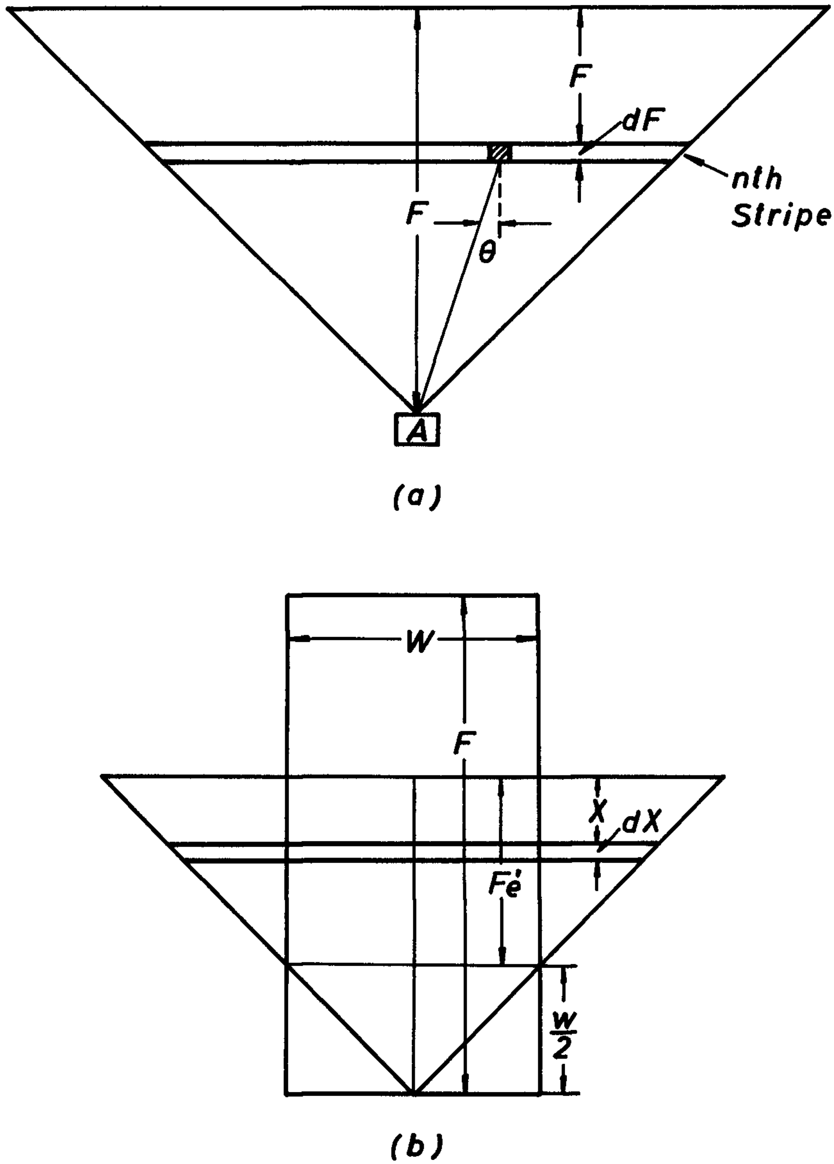

Fig. 2. Illustration of equivalent fetch.

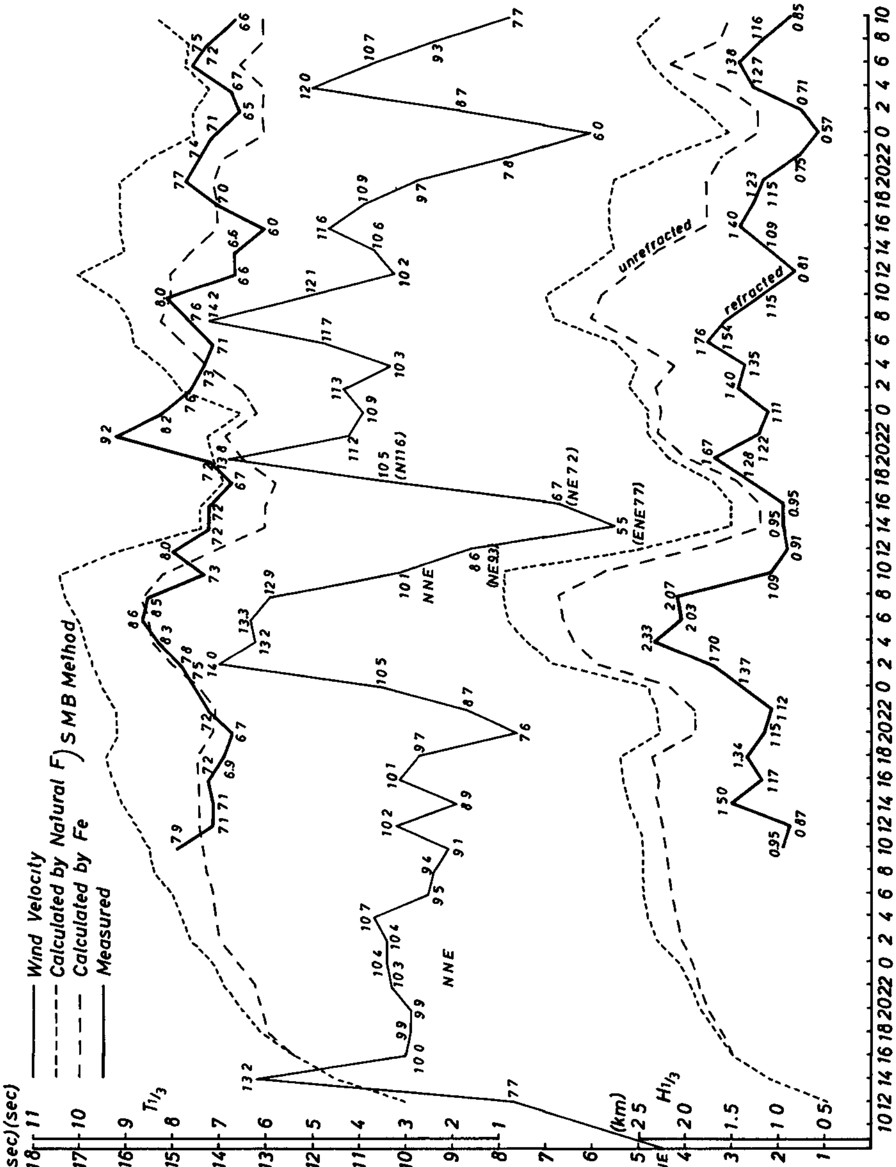

Fig. 3. Comparison of measured and calculated wave features.

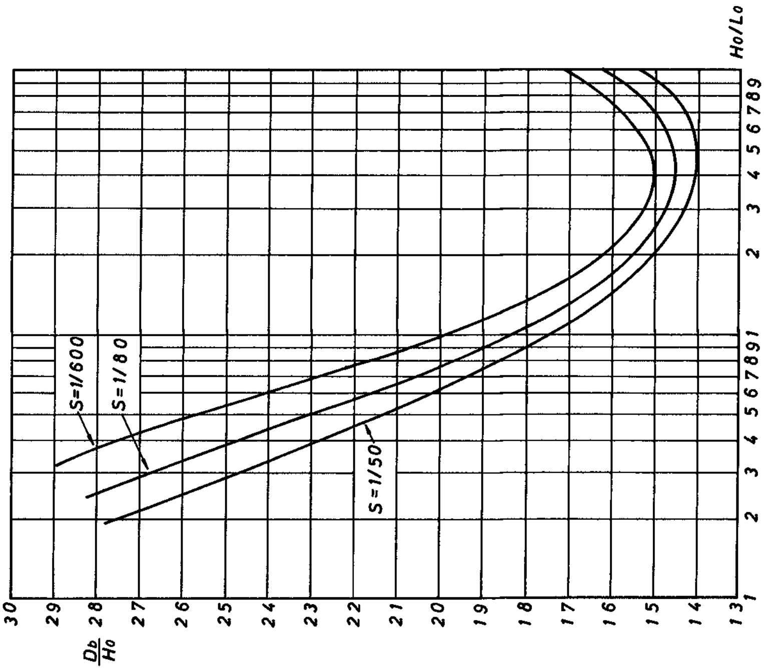

Fig. 5. Breaking depth indice.

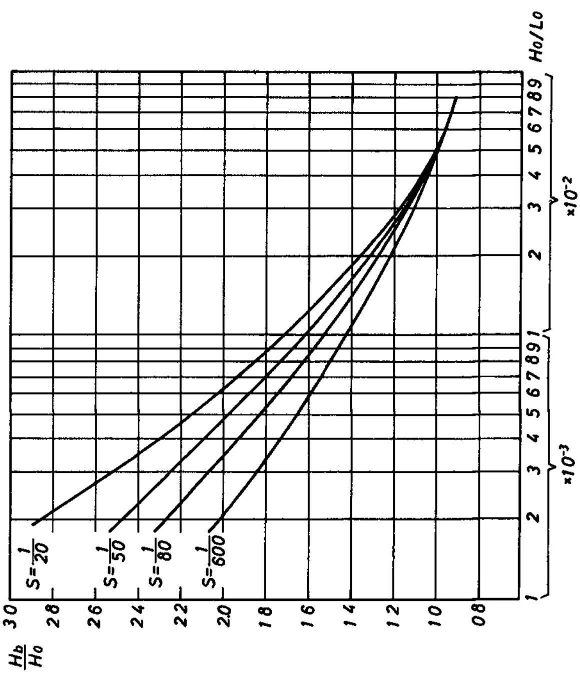

Fig. 4. Breaking height indice.

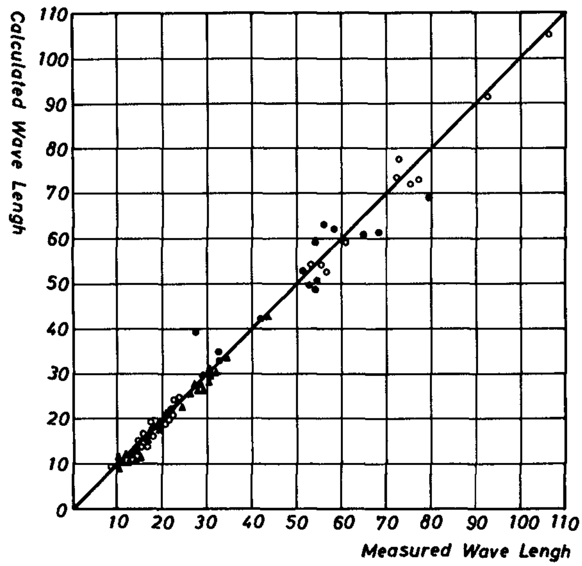

Fig. 6. Comparison of measured and calculated wave length.

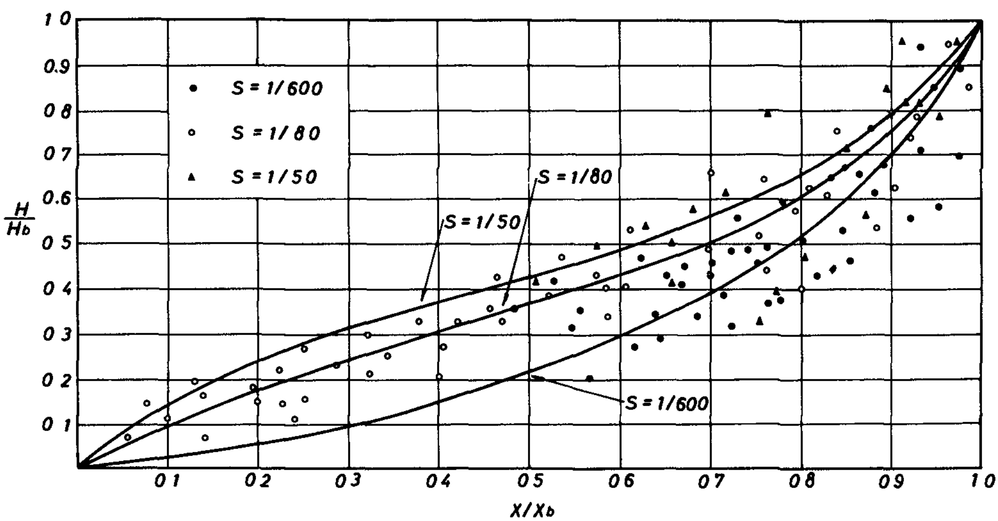

Fig. 7. Wave height after breakıng.

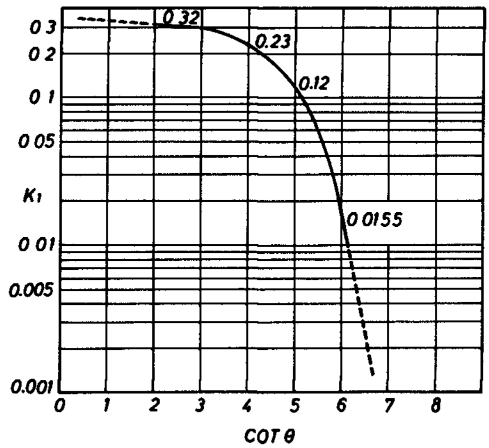

Fig. 8. Coefficient k.

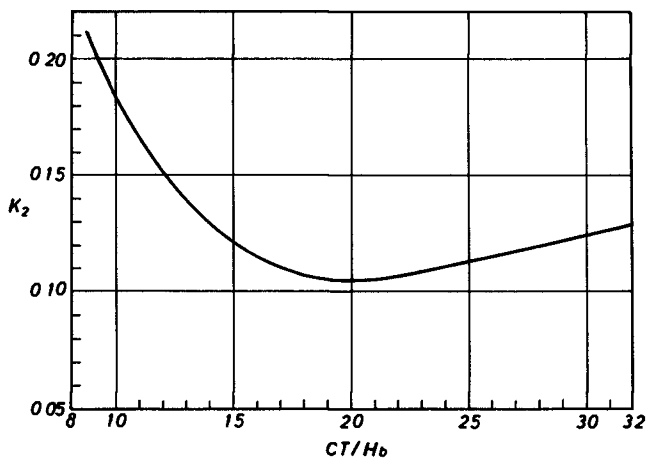

Fig. 9. Coefficient k.