

## CHAPTER 124

### RESEARCH ON THE MODEL SHELTERING

### INVESTIGATION OF A HARBOR

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#### ABSTRACT

The Model Sheltering Experiment deals with the planning arrangement of the proposed harbor and is done by the worst wave condition (with respect to wave direction, wave height, and wave period) which probably occurred on the proposed harbor. The objectives of this experiment are to get the wave pattern of the harbor basin and to understand the various phenomena of the wave refraction, diffraction, and reflection caused by model test due to different harbor arrangement, and to comprehend the sheltering effect of the outer breakwaters. From the analysis of these test results, harbor planning of the most effective arrangement - the most economic length of breakwaters and the most ideal width of harbor entrance could be selected. For the purpose of analyzing results of model tests; comparison of theoretical wave diffraction calculation is proposed.

#### INTRODUCTION

Here is research of the outer breakwater arrangement of a big harbour. Taichung Harbor is pending to be constructed as an international commercial harbor on the mid-western coast of Taiwan. It is a pure artificial harbor.

The wave sheltering effect is most important of all. For obtaining safe navigation, especially easy maneuverability of the ship and calm harbor basin for normal operation. The optimal arrangement was required. For getting the optimum result, a large-scale model experiment was necessary to check and compare all proposed arrangements.

The author was in charge of the model investigation of Taichung Harbor. However, he wished to appreciate the direction of Ito (Head of Hydraulic Engr. Division, Port and Harbour Research Institute, Japan) and Tang (Professor and Chairman of Hydraulic Engr. Dept., National Cheng Kung University, Taiwan, R.O.C.). Hence, he could get the better achievement of harbor planning.

## 1. ELEMENTS OF THE SHELTERING MODEL EXPERIMENT

### 1.1 The Model Construction and The Test Method

On the test basin, at first, the mortar model of the whole harbor area including the harbor basin, inner harbor arrangement, outer breakwater arrangement, and topography of seaward up to 50 M deep was made. The navigation chart is 1970. The undistorted model was constructed by the scale of 1/150. The model was referred to fixed bed model. For the convenience of measurement, contours were painted white to determine depth of the head of breakwaters. Fresh water was pumped into the test basin from outer reservoir. The required water level is measured by point gauge.

Before model test pr-ocessed, the rating curve of wave period vs. wave height was calibrated by neon tube wavemeter and step resistance wavemeter, separately. Incident wave height were checked by wave meter. Since the plunger type wave generator is autocontrollable by the motor and the gear, therefore different wave directions of the test were got done. From wave

height measurement in the wide area harbor region, the diffraction coefficients (ratio of wave height in the harbor region to incident wave height) were got. Then, from all equal wave height ratio lines, the wave pattern of the harbor region was obtained. The figure is called wave diffraction diagram. From this diagram, different sheltering effect of each arrangement of the outer breakwaters against the intruding waves was realized. Such an experiment is known as the Sheltering Model Experiment.

In this Sheltering Model Experiment the phenomena of wave shoaling and refraction due to water depth change could be got further informations. Simultaneously, those of wave overtopping and wave reflection through the breakwater when waves attached, were perceptible from the model test and could be noted down for the references of the structure design and section stability test.

#### 1.2 Purpose of Sheltering Model Experiment

The purpose of this test was to compare wave sheltering effects of harbor basin of eight proposed outer breakwater arrangements, and decide the optimal arrangement of the wave sheltering effect.

#### 1.3 Model Scale

The scale of this undistorted model was determined by the harbor area and the size of the test basin. Whence, the horizontal plane and vertical scale was chosen as  $n_H = n_V = 1/150$ .

#### 1.4 Test Conditions

##### A. Wave conditions

Wave conditions were based on recent 10 year records of wind (including typhoon and monsoon) and waves and selected by the largest typhoon and the strongest monsoon.

According to the analysis of typhoon data, the largest two typhoons were Elsie typhoon and Pamela typhoon. From the calculations of Wilson

moving fetch method, the largest waves which could occur around the coast of Taichung harbor shown as Table 1.

Table 1. Wave Conditions of Taichung Harbor

Wave Direction	Wave Height $H_{1/3}$ (m)	Wave Period $T_{1/3}$ (sec)	Remarks
NNE	4.9	10	Elsie (at depth -15 m)
N	5.8	12.4	Pamela (at depth -10 m)
NNW	5.4	10.2	Pamela (at depth -10 m)
NW	5.0	11.2	Pamela (at depth -10 m)
NNW	3.9	8.6	Elsie (at depth -15 m)
W	4.2	9	Elsie (at depth -15 m)
WSW	3.3	12.2	Elsie (at depth -15 m)
SW	3.1	11.2	Pamela (at depth -10 m)

During the monsoon of the winter, the wave which occurred frequently was in deep water       $H_0 = 2.78$  m,       $T_0 = 7.9$  sec

Wave direction: NNE

From above data, therefore the selected waves for model test were showed below:

- (1) N direction:  $H = 6$  m,  $T = 12$  sec was the largest significant wave of N direction caused by typhoon or strong monsoon of the winter season.
- (2) N direction:  $H = 3$  m,  $T = 8$  sec was the wave of monsoon of

the winter season during storm time.

(3) WNW direction:  $H = 4.5 \text{ m}$ ,  $T = 9 \text{ sec}$  was the largest incident wave due to typhoon intruded from WNW direction, just opposite to the direction of the harbor entrance.

(4) WSW direction:  $H = 3.5 \text{ m}$ ,  $T = 9 \text{ sec}$  was the largest significant wave caused by typhoon intruded from WSW direction.

#### B. Tide

The tide of Taichung Harbor is semi-diurnal, but after 5 or 15 days there is a high tide or a low tide only, the tidal difference of each day is very obvious.

Because Taichung Harbor is located in the middle of the Taiwan Strait, therefore, its tidal range is particularly large. The maximum tidal range is 5.5 meters or so. According to tide statistical analysis of recent ten years the tide of Taichung Harbor is shown as follows:

Mean Tide Level (M.T.L.): +2.90 m

High Water of Spring Tide (H.W.O.S.T.): +5.00 m

Low Water of Spring Tide (L.W.O.S.T.): +0.40 m.

For the Sheltering Model investigation, H.W.O.S.T. is used, therefore tide level was selected as +5.00 m, as model water level: +3.33 cm.

#### 1.5 Element of Waves of Model Experiment

Table 2. Model Waves vs Actual Waves

Items	Scale	Prototype	Model
Wave Period	$\frac{1}{\sqrt{150}}$	12 sec	0.98 sec.
$T_{1/3}$	$= \frac{1}{12.2}$	10 sec	0.84 sec.
		9 sec	0.75 sec.
		8 sec.	0.65 sec.
Wave Height	$\frac{1}{150}$	6 m	4.00 cm
$H_{1/3}$		4.5 m	3.00 cm
		3.5 m	2.33 cm
		3 m	2.00 cm

## 2. SIMILARITY OF MODEL EXPERIMENT

## 2.1 Similarity of Wave Motion

Now if the factors of bottom friction and wave transformation of the model are neglected and Cartesian Coordinate is used, then the equation of motion could be written as:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = - \frac{1}{\rho} \frac{\partial p}{\partial x} \quad (2.1)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = - \frac{1}{\rho} \frac{\partial p}{\partial y} \quad (2.2)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = - g - \frac{1}{\rho} \frac{\partial p}{\partial z} \quad (2.3)$$

where

$U$ ,  $V$  and  $W$  are velocity components of  $x$ ,  $y$  and  $z$  respectively.  $p$  is pressure.

Here, in order to make kinematic similarity between model and prototype, therefore from the ratio of each term of equation of motion of prototype with respect to each term of equation of motion of model, correspondingly, the term of prototype is marked subscript "p". Likewise, the term of model is marked "m" on the subscript , too. From equation (2.1) the following equivalent equation is got

$$\frac{u_p/t_p}{u_m/t_m} = \frac{u_p^2/x_p}{u_m^2/x_m} = \frac{v_p u_p/y_p}{v_m u_m/y_m} = \frac{w_p u_p/z_p}{w_m u_m/z_m} = \frac{\rho_p / \rho_p x_p}{\rho_m / \rho_m x_m} \quad (2.4)$$

In the test basin, fresh water is used, but in the prototype, the fluid is sea water. Here  $\rho_p \approx \rho_m$  is assumed. Therefore, from the first term and the second term of eq. (2.4). The following equation is obtained.

$$\frac{u_p/t_p}{u_m/t_m} = \frac{u_p^2/x_p}{u_m^2/x_m} \therefore \frac{t_m}{t_p} = \frac{u_p}{u_m} \frac{x_m}{x_p}, \therefore \frac{u_p}{u_m} = \frac{x_p/x_m}{t_p/t_m} \quad (2.5)$$

Simultaneously from the first term and the third term, and from the first and the fourth term, the following two equations are obtained.

$$\frac{V_p}{V_m} = \frac{g_p/g_m}{t_p/t_m} \quad (2.6)$$

$$\frac{W_p}{W_m} = \frac{\beta_p/\beta_m}{t_p/t_m} \quad (2.7)$$

From the second and the fifth term, the following equation is got, too.

$$\frac{P_p}{P_m} = \frac{U_p^2}{U_m^2} \quad (2.8)$$

Similarly from the third term and the fifth term of equation (2.2) yields

$$\frac{P_p}{P_m} = \frac{V_p^2}{V_m^2} \quad (2.9)$$

Then, from the fourth term and the sixth term of equation (2.3) yields

$$\frac{P_p}{P_m} = \frac{W_p^2}{W_m^2} \quad (2.10)$$

Furthermore, from the second term of the left hand side and the first term of the right hand side of equation (2.3) yields

$$\frac{U_p W_p / X_p}{U_m W_m / X_m} = \frac{g_p}{g_m}$$

because  $g_p = g_m \quad \therefore \quad \frac{U_p W_p}{X_p} = \frac{U_m W_m}{X_m} \quad (2.11)$

Likewise, from the third term and the fourth term of equation (2.3) with respect to the first term of the right hand side of equation (2.3) the following two equations are obtained

$$\frac{V_p W_p}{g_p} = \frac{V_m W_m}{g_m} \quad (2.12)$$

$$\frac{W_p^2}{Z_p} = \frac{W_m^2}{Z_m} \quad (2.13)$$

The above equations are concluded that from equations of (2.8), (2.9) and (2.10)

$$\frac{U_p}{U_m} = \frac{V_p}{V_m} = \frac{W_p}{W_m} = \frac{V_p}{V_m} \quad (2.14)$$

From equations of (2.11), (2.12) and (2.13)

$$\frac{U_p W_p}{U_m W_m} = \frac{x_p}{x_m}, \quad \frac{V_p W_p}{V_m W_m} = \frac{y_p}{y_m}, \quad \frac{W_p^2}{W_m^2} = \frac{z_p}{z_m} \quad (2.15)$$

The relationship between eq. (2.14) and eq. (2.15) yields

$$\frac{x_p}{x_m} = \frac{y_p}{y_m} = \frac{z_p}{z_m} = \frac{l_p}{l_m} \quad (2.16)$$

Thus, from the relationship of equation (2.14) and equation (2.16), then

equation (2.15) can be expressed as

$$\frac{V_p}{V_m} = \left( \frac{l_p}{l_m} \right)^{\frac{1}{2}} \quad (2.17)$$

Above form can be reduced as

$$\left( \frac{l_p}{l_m} \right)^{\frac{1}{2}} = \frac{l_p/l_m}{t_p/t_m}$$

or

$$\frac{t_p}{t_m} = \left( \frac{l_p}{l_m} \right)^{\frac{1}{2}} \quad (2.18)$$

Therefore, the scales of wave (short period) motion of model experiment are determined as follows.

- (1) From equation (2.16), the horizontal scale and the vertical scale must be equal to each other.
- (2) From equation (2.14) and equation (2.17), velocity scale is the root of length scale.
- (3) From equation (2.18), time scale is the root of length scale.
- (4) From equation (2.8), (2.9) and (2.17), the scale of the pressure force per unit area is equal to length scale.

## 2.2 Similarity of Wave Refraction and Wave Diffraction

- A. Similarity of the variation of wave height due to refraction effect  
Wave refraction phenomena is caused by wave propagates into different

water depth and celerity is changed, then wave is transformed.

From the finite amplitude wave theory.

$$C = \sqrt{\frac{gL}{2\pi} \tanh \frac{2\pi h}{L}} \quad (2.19)$$

Where  $g$ ,  $L$ ,  $h$  are gravity acceleration, wave length and water depth.

If the celerity of prototype is similar to that of model, then wave refraction phenomena is kept the same with each other.

From

$$\frac{C_p}{C_m} = \frac{\sqrt{\frac{g_p L_p}{2\pi} \tanh \frac{2\pi h_p}{L_p}}}{\sqrt{\frac{g_m L_m}{2\pi} \tanh \frac{2\pi h_m}{L_m}}} \quad (2.20)$$

$L = L_0 \tanh \frac{2\pi h}{L} = \frac{gT^2}{2\pi} \tanh \frac{2\pi h}{L}$  & let  $\frac{g_p}{g_m} \approx 1$ , be substituted into above equation yield

$$\frac{C_p}{C_m} = \frac{T_p \tanh \frac{2\pi h_p}{L_p}}{T_m \tanh \frac{2\pi h_m}{L_m}}$$

or

$$\frac{C_p}{C_m} \times \frac{T_m}{T_p} = \frac{\tanh \frac{2\pi h_p}{L_p}}{\tanh \frac{2\pi h_m}{L_m}}$$

Because for "Shallowwater" condition,  $\tanh \frac{2\pi h}{L} \approx \frac{2\pi h}{L}$

$$\therefore \frac{C_p}{C_m} \times \frac{T_m}{T_p} = \frac{h_p L_m}{h_m L_p}$$

hence

$$\frac{C_p}{C_m} \times \frac{T_m}{T_p} \times \frac{L_p}{L_m} = \frac{h_p}{h_m} \quad (2.20 a.)$$

Otherwise, from

$$\frac{L_p}{L_m} = \frac{L_{op}}{L_{om}} = \frac{T_p^2}{T_m^2} \quad (2.20 b.i)$$

and

$$\frac{C_p}{C_m} = \frac{L_p/T_p}{L_m/T_m} = \frac{T_m}{T_p} \times \frac{L_p}{L_m} \quad (2.20.b-ii)$$

$$\therefore \frac{C_p}{C_m} = \frac{T_m}{T_p} \times \frac{T_p^2}{T_m^2} = \frac{T_p}{T_m} \quad (2.20.b-iii)$$

Equations (2.20b) be substituted into equation (2.20a) yields

$$\frac{T_p}{T_m} \times \frac{T_m}{T_p} \times \frac{T_p^2}{T_m^2} = \frac{h_p}{h_m}$$

$$\therefore \frac{T_p}{T_m} = \sqrt{\frac{h_p}{h_m}} \quad (2.21)$$

For "deep water"  $h/L > \frac{1}{2}$ ;  $\tanh \frac{2\pi h}{L} = 1$ .  $\therefore C^2 = \frac{gL}{2\pi}$ , thus

$$\frac{C_p}{C_m} = \sqrt{\frac{L_p}{L_m}} ; \text{ at the stage, no required on } L_p/L_m.$$

Therefore, the scale of wave period be selected as the root of the scale of water depth, then the similarity of wave refraction is obtained.

#### B. Similarity of the variation of wave height due to diffraction effect

Wave diffraction means diffusion of wave energy along the parallel direction of wave crest. Therefore, in order to get the similarity of wave length must be met. Thus, the scale of wave period must be chosen as the root of the scale of wave length. Shown as following:

$$\frac{L_p}{L_m} = \frac{\frac{g T_p^2}{2\pi} \tanh \frac{2\pi h_p}{L_p}}{\frac{g T_m^2}{2\pi} \tanh \frac{2\pi h_m}{L_m}} \quad (2.22)$$

(i) If distorted model is used. Let  $(L_H)_r = \frac{(L_H)_m}{(L_V)_m}$ ;  $(L_V)_r = \frac{(L_V)_p}{(L_V)_m}$   
thus,  $(L_H)_r \neq (L_V)_r$ . Now  $L_r = (L_H)_r$ , where  $L_r = L_p/L_m$

For "Shallow Water"  $C = \sqrt{g h} \therefore C_r = (h_r)^{1/2} = (L_V)_r^{1/2}$

$$C = \frac{\Delta x}{\Delta t} = \frac{L}{T} ; \therefore L_r/T_r = (L_V)_r^{1/2} \therefore T_r = (L_H)_r/(L_V)_r^{1/2}$$

For "Intermediate Water"  $L_r = T_r^2 \frac{\tanh 2\pi h_p/L_p}{\tanh 2\pi h_m/L_m \cdot \frac{(L_H)_r}{(L_V)_r}}$

$$\therefore L_r = (L_H)_r = T_r^2 \frac{\tanh \frac{2\pi h_p}{L_p}}{\tanh \frac{2\pi h_p}{L_p} \cdot \frac{(L_H)_r}{(L_V)_r}}$$

For "Deep Water"  $T_r = L_r^{1/2} = (L_H)_r^{1/2}$ .

(ii). If undistorted model is used, then  $(L_H)_r = (L_V)_r$ . From Eqn (2.22)

$$\text{Thus, } \frac{T_p}{T_m} = \sqrt{\frac{L_p}{L_m}} \quad (2.23)$$

### 3. SCOPE OF MODEL AND FACILITIES

#### 3.1 Scope of Model

The Sheltering Model Experiment of Taichung Harbor was accomplished in the Large Test Basin of the Taichung Harbor Hydraulic Laboratory. The size of the Large Test Basin is 60 meters long, 43 meters wide and 1 meter high.

The scope of model was based on the harbor area of Taichung Harbor 10 year development main plan and was constructed with the topography of the harbor entrance area, water depth reached to -50 m. According to this range, the undistorted model scale 1/150 was used and the fixed-bed model was made of mortar in order to match Geometric Similarity between the model and the prototype.

#### 3.2 Experimental Facilities

The main equipment of the Sheltering Model Experiment are listed as below:

##### 3.2.1 Wave Generator

The plunger type wave generator was used in the Sheltering Model Experiment. Its plunger is 30 meters long, therefore, it could produce regular waves within 30 meter wide area. The wave generator was composed of motor, accelerator, eccentric roller, gear box and wave-making plunger. Its power is 30 horsepower. When the power switch is turned on, its motor makes the accelerator and eccentric roller operating, and causes the shaft to bring the plunger move upward and downward periodically. Then the waves are produced. Wave height is determined by the eccentric distance of the eccentric roller, its maximum range is 150 mm. Wave period is adjusted by the accelerated ratio of the accelerator, its period range is from 0.55 sec/cycle to 2.2 sec/cycle.

The wave generator was installed on the semi-circular gear rail and regular rails, therefore it could be moved along the semi-circular trail and changed its position, then the waves from different direction were produced. The wave producing situation is shown as Fig. 3.1.

### 3.2.2 Wavemeter

Two kinds of wavemeter were used in the experiment. One was Neon-tube type wavemeter, the other was Step-resistance type wave meter. The former was used to determine the wave height of the position of wave generator, the latter was used to measure incident wave heights and wave heights of the harbor basin.

#### A. Neon-tube type Wavemeter

The Neon-tube Wavemeter is composed of pick-up and neon-tube indicator. Shown as Fig. 3.2. During the experiment, the pick-up was put on the measured point of the test basin, it was connected to the neon-tube indicator, then the indicator was connected with AC power. Therefore, the pick-up neon-tube indicator and water of the test basin composed a close circuit. Each neon-tube circuit of the indicator with respect to each circuit of the pick-up was formed as a parallel series. Therefore, when water waves reached the pick-up, electric current passed through the circuits of the underwater part of the pick-up. Then the lights of the neon-tube indicator are shown. Due to oscillation of wave crest and wave trough, the number of the lights showing would be increased and decreased correspondingly. By the difference of the number of the lights showing, wave height was calculated.

#### B. Step-resistance type Wavemeter

The Step-resistance type wavemeter is composed of pick-up with electric resistance box (See Fig. 3.3), electric power control box, and pen-oscillograph

(1) Pick-up: Its section has knife-like shape and is made of acrylic material. A lot of metallic points which were used to connected circuits, were attached to the acrylic material. The clearance of the metallic point is 2 mm. The upper part of the pick-up was electric resistance box. Each circuit of the resistance box, was connected with the circuit of the pick-up and formed as parallel series, respectively. Pick-up was connected into electric power control Box by cable.

(2) Pen-Oscillograph: By using electric power control Box as a center part, then Pen-Oscillograph was connected into the control Box by cable. When a series of waves caused water particles move up and down then electric resistances of the whole circuit of the pick-up decreased and increased respectively. Therefore, electric current occurred opposite to the effect of resistance. The effect of electric current is conducted by cable to electric power control box, then be strengthened and amplified by control box, later conducted to Pen-Oscillograph which writes the wave fluctuation pattern on the record paper.

### 3.2.3 Point Gauge

For determining and fixing water level of model test, point gauge is usually used. When the wall of the test basin connects with water surface, due to surface tension, the connecting point is higher than real water level. The purpose to use point gauge is to avoid the error. A point gauge is fixed by the wall of the basin and kept a little distance with the wall. When it is operated, at first horizontal level is adjusted by turning the triangular screws, then the measuring pole is moved up or down to make sure the expected water level. Outer side of the measuring pole, a rectangluar-type of timber is installed a little lower than the water surface. The rectangular timber box can prevent oscillation of water waves, therefore the point gauge can determine and

fix the expected water level accurately.

#### 4. WAVE DIFFRACTION THEORY

Penny and Price (1944; 1952) showed that the Sommerfield solution of the diffraction of light is also a solution of the water wave diffraction phenomenon.

When incident waves are moving toward the coastal structure, they will be reflected, or break, or both, whereas the portion propagating past the tip of the structure will be the source of a flow of energy in the direction essentially along the wave crest and into the region in the lee of the structure. The "end" of the wave will act somewhat as a potential source and the wave in the lee of the breakwater will spread out in approximately a circular arc with the amplitude decreasing exponentially along this arc. The same phenomenon will also occur in the reflected portion of the wave.

This complicates the physical picture considerably, as part of the wave energy associated with the "radial" wave being generated from the end of the reflected wave will travel into the harbor region. The two sets of waves, cylindrical and radial, reinforce and cancel each other in such a manner as to cause an irregular wave height in this region. This physical phenomenon is known as diffraction.

##### 4.1 Definition of the Diffraction Coefficient

The surface elevation of the linear water wave theory can be expressed as

$$y_s = \frac{Aikc}{g} e^{ikct} \cosh kd \cdot F(x, z) \quad (4.1.1)$$

where the real part of the expression on the right is used.

For the case of progressive waves travelling in the direction of the x axis with no structure present,  $F(x, z) = e^{-ikx}$ , therefore

$$\begin{aligned} y_s &= \frac{Aikc}{g} e^{ik(ct-x)} \cosh kd \\ &= a \sin k(ct-x) \end{aligned} \quad (4.1.2)$$

The diffraction coefficient,  $K'$ , is defined as the ratio of the wave height in the area affected by diffraction to the wave height in the area unaffected by diffraction; it is the ratio of the amplitude of Eq. (4.1) to (4.2). Therefore,  $K'$  is expressed by the modulus of  $F(x,z)$  for the diffracted wave as

$$K' = |F(x,z)| \quad (4.1.3)$$

#### 4.2 Diffraction Calculation of Arrangement of Breakwaters

Diffraction situation of waves intruding into the harbor region, and sheltering effect of breakwaters, can be calculated by mathematical model solutions for the case of water areas of the navigational channel and the harbor entrance of same depth.

Now, the head of the breakwater is considered as the origin of the polar coordinate and the line of the breakwater is referred to the polar axis. Shown as Fig. 4.1.

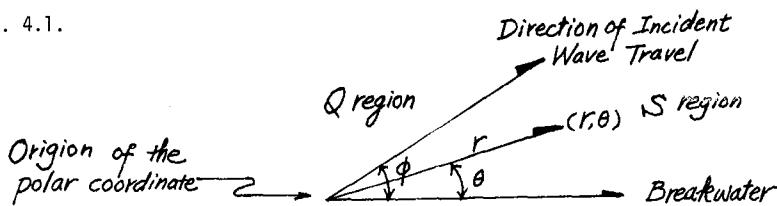


Fig. 4.1 Nomenclature for Wave Diffraction Calculation at the Breakwater Head.

Therefore, the diffraction coefficient  $K'$  of any point  $(r,\theta)$  of the harbor basin, can be calculated by the following equation

$$K' = |A + iB| = \sqrt{A^2 + B^2} \quad (4.2.1)$$

Here,  $K'$  indicates the ratio of the wave height  $H$  of any point (affected by diffraction) of the harbor basin to the incident wave height  $H_0$  (Unaffected by diffraction) of the harbor entrance.

In the shelter area, i.e. in the lee of the breakwater, region S as Fig. 4.1

shown.

$$A = U_1 \cos [Krcos(\theta - \phi)] + U_2 \cos [Krcos(\theta + \phi)] \\ + W_1 \sin [Krcos(\theta - \phi)] + W_2 \sin [Krcos(\theta + \phi)] \quad (4.2.2)$$

$$B = W_1 \cos [Krcos(\theta - \phi)] + W_2 \cos [Krcos(\theta + \phi)] \\ - U_1 \sin [Krcos(\theta - \phi)] - U_2 \sin [Krcos(\theta + \phi)] \quad (4.2.3)$$

If the point  $(r, \theta)$  in the area of the wave intruding direction, i.e. in region Q as Fig. 4.1 shown.

$$A = \cos [Krcos(\theta - \phi)] - U_1 \cos [Krcos(\theta - \phi)] + U_2 \cos [Krcos(\theta + \phi)] \\ - W_1 \sin [Krcos(\theta - \phi)] + W_2 \sin [Krcos(\theta + \phi)] \quad (4.2.4)$$

$$B = -\sin [Krcos(\theta - \phi)] - W_1 \cos [Krcos(\theta - \phi)] + W_2 \cos [Krcos(\theta + \phi)] \\ + U_1 \sin [Krcos(\theta - \phi)] - U_2 \sin [Krcos(\theta + \phi)] \quad (4.2.5)$$

where  $K = 2\pi/L$ , L: Wave Length

$\phi$ : the angle of the breakwater line with the direction of incident wave travel.

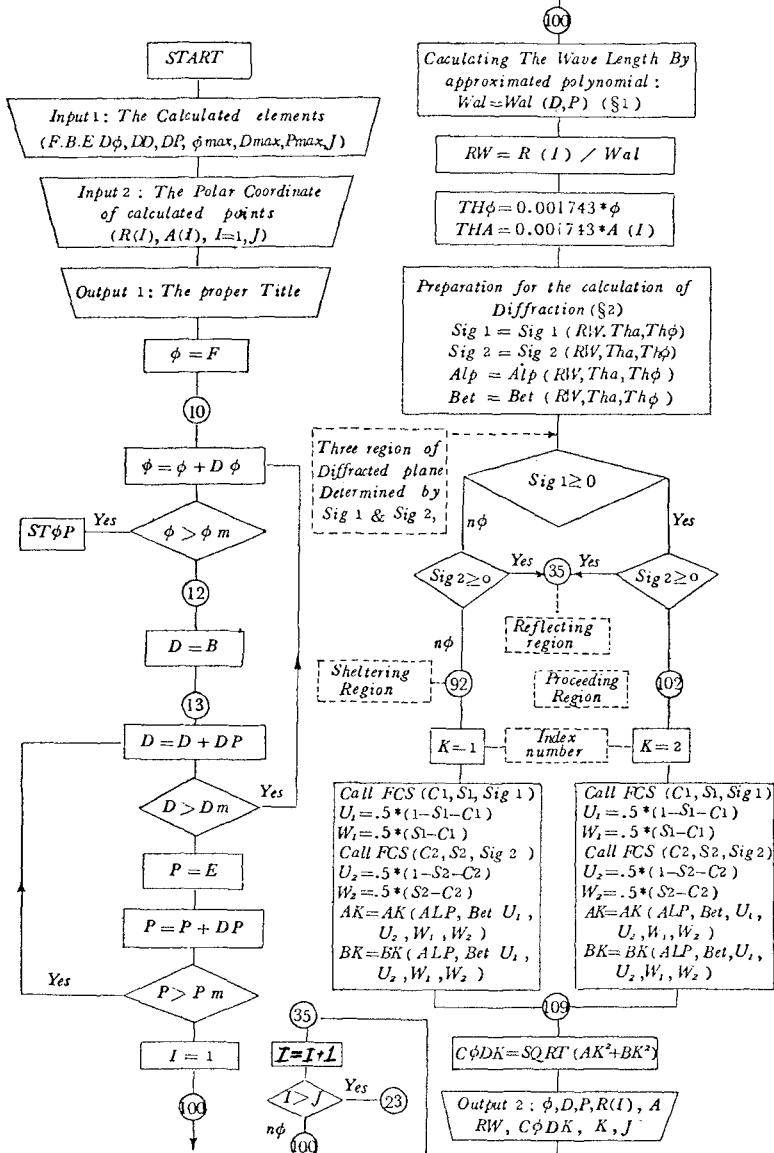
$$U_{1,2} = \frac{1}{2} \left[ \int_0^{\tilde{\theta}_{1,2}} \cos \left( \frac{\pi}{2} \tilde{\theta}^2 \right) d\tilde{\theta} + \int_0^{\tilde{\theta}_{1,2}} \sin \left( \frac{\pi}{2} \tilde{\theta}^2 \right) d\tilde{\theta} \right] \quad (4.2.6)$$

$$W_{1,2} = \frac{1}{2} \left[ \int_0^{\tilde{\theta}_{1,2}} \cos \left( \frac{\pi}{2} \tilde{\theta}^2 \right) d\tilde{\theta} - \int_0^{\tilde{\theta}_{1,2}} \sin \left( \frac{\pi}{2} \tilde{\theta}^2 \right) d\tilde{\theta} \right] \quad (4.2.7)$$

$$\tilde{\theta}_1 = 2\sqrt{\frac{kr}{\pi}} \sin \left[ \frac{1}{2}(\theta - \phi) \right] \quad (4.2.8)$$

$$\tilde{\theta}_2 = -2\sqrt{\frac{kr}{\pi}} \sin \left[ \frac{1}{2}(\theta + \phi) \right] \quad (4.2.9)$$

Diffract procedure of waves intruding into the harbor region, from Eq. (4.2.1) to (4.2.9), could be rewritten as Flow Chart shown in the following.



## 5. THE PROPOSED EIGHT ARRANGEMENTS OF OUTER BREAKWATERS AND TEST RESULTS:

### 5.1 Experiments of N wave direction

For the test condition of N direction: Wave height was 6 M, wave period was 12 sec. The arrangements and test results were shown from Fig. 5-1, **5-2**, Fig. 5-1-1 to 5-1-8.

Case 1: The pier head of north breakwater reached up to -12 M water depth.

Test result: The waves of the harbor mouth were very confused, the wave height of outer harbor basin was above one meter. Since the distance which north breakwater overlapped south breakwater was not long enough, waves easily intruded into harbor basin. Waves diffracted from the north pier head, travelled to the south pier head and reflected. Due to these effects, the harbor entrance was disturbed. Therefore, wave sheltering effect was bad.

Case 2: The pier head of north breakwater of Case 1 was prolonged along its original direction up to -20 M water depth. South breakwater was kept the same as Case 1.

Test result: Wave sheltering effect was quite good. Harbor basin was almost calm. The effective width of harbor entrance became a little smaller. Ship navigation should be changed to a curved course.

Case 3: Based on the arrangement of Case 2, the north pier head part of water depth from -15 M to -20 M, its total length was 150 meters to be shifted northward, and this part was made to be parallel to WNW direction.

Test result: Wave sheltering effect was not so good as that of Case 2. Waves passed through the north pier head, then intruded along south breakwater obviously. However, navigational course was suitable for ship being maneuvered.

Case 4: The oblique parts of outer breakwaters was parallel shifted landward, the north pier head reached to water depth -10 M, and the south pier head

reached to water depth ~7 M. The distance between the north pier head and the south pier head is 220 meters.

Test result: Wave sheltering effect was not good because water depths of the pier heads were not deep enough.

Case 5: The direction and width of harbor entrance was kept the same as that of Case 1 and the oblique part of north breakwater was turned northward, and let the angle between the straight part and the inclined part be  $20^{\circ}30'$ , the north pier head was prolonged to water depth -20 M.

Test result: Wave heights of the harbour mouth showed a little small, comparing to Case 4, but outer harbor basin existed oscillation of stationary waves. Its wave sheltering effect was not really good.

Case 6: The position of the head point of north breakwater was fixed as Case 5. The straight part of north breakwater was kept the same as Case 5. The middle part of north breakwater was turned  $10^{\circ}15'$  southward with the straight part. The pier-head part, 240 meters long, was turned southward, and the head was matched with water depth of -20 M. The direction, position and length of south breakwater was kept the same as those of Case 1.

Test result: Its wave sheltering effect seemed a little better, wave heights of outer harbor basin were below one meter. It looked good.

Case 7: The straight part of north breakwater was based on Case 1 and prolonged 210 meters seaward, then turned southward. The oblique part of north breakwater was kept parallel with that of Case 1, but the pier head part, which was deeper than -20 M, was 46 meters. South breakwater was the same as Case 1.

Test result: Its wave sheltering effect was better than that of Case 6, even not so good as that of Case 2. However, wave heights of harbor basin except those of harbor mouth, were below one meter. It met the requirement of operation.

Case 8: The arrangement of this case was almost the same as Case 7. The only difference is, the pier head part of north breakwater was cut down 46 meters, so that the pier head reached to water depth -20 M.

Test result: Its wave sheltering effect was not so good, compared with that of Case 7, and its width of harbour mouth showed a little large.

## 5.2 Theoretical calculation of N wave direction for the selected five arrangements

Based on flow chart of wave diffraction coefficients for Case 1, 2, 5, 6 and 7 were calculated by Digital-Computer. From calculating results showed that wave sheltering effects of Case 2 and Case 7 were quite good, the same trend as that of model experiment. Shown from Fig. 5-2-1 to Fig. 5-2-5.

When test results being compared with theoretical calculations, it could be found out that the wave heights in the outer harbor entrance measured from model test were larger than the calculated figures, and that the wave heights in the inner harbor entrance were smaller than the calculated values. The difference is due to the following reasons: (1) There were boundaries such as reinforced concrete walls of the test basin, timber plates for the wave guiders etc. in the model test; these often produced reflection of waves. The basin of the outer harbor entrance was easily influenced by these reflections. Therefore, the wave heights in this area of the model test were larger than those of the theoretical results. (2) The theoretical wave heights were based on waves in irrotational, inviscid flow, whereas there was a viscosity effect in the model, as well as bottom friction; viscosity and bottom friction in the model were relatively much larger than in the prototype for the shallow harbor basin areas, but for those deep basin areas such as navigational channel, etc. Their viscosity and bottom friction could not be in scale by model law.

For above reasons, the theoretical wave heights in the outer harbor entrance and navigational channel may be considered to be more accurate than those of the

model. Wave heights in the inner side of the breakwater and waves in the shallower water depths of the harbor basin were selected from the results of the model test, because the effects near to real phenomena were considered. The wave heights of the inner harbor entrance and its surrounding basin area were between the model and the theoretical values.

### 5.3 Experiment of Waves from WNW and WSW directions

The objective of the experiments of WNW and WSW directions was to check whether the ship could be safely anchored in the dock and controllably maneuvered in the navigational channel or not during the worst weather of hurricane intruding.

Therefore, except the experiment of N direction, the experiments of WNW and WSW were required to test and investigate. Here the most ideal case among those arrangements were selected to process these experiments. How much of waves intruding the harbor mouth and harbor basin during waves from WNW and WSW directions were measured. Test results were shown from Fig. 5-3-1 to Fig. 5-3-4.

From test results, they showed waves from WSW direction, the wave heights of the inner harbor basin occurred below one meter, and did not affect the operation of navigation. But waves from WNW direction, the wave heights of the inner harbor basin were high above one meter, they could not meet the requirements of operation. In order to reduce wave heights of inner harbor basin, the quay wall against the harbor entrance direction should be designed for wave-energy absorbent function, and the width of inner harbor entrance should be reduced some quantity. Of course, the width of inner harbor entrance could not diminish too much. For the concept of "harbor paradox", the condition of small mouth and large basin easily caused harbor resonance, since that the inner harbor entrance need to be reduced suitably so that it could prevent waves intruding from outer basin, and it can also release the waves of inner basin out of inner entrance.

## 6. CONCLUSION

1. From above results of wave sheltering model investigation, we could select the optimal sheltering effect of harbor arrangement. As above mentioned arrangements, Case 2 was the best; however Case 3, Case 6, and Case 7 could also meet the requirements. It should however be noted that although Case 2 appears to offer the optimal solution of sheltering effect of the harbor arrangement, but because of other effects such as those related to sand prevention and maneuverability of navigation, the final arrangement selected was that close to Case 7.
2. For the selected arrangement the inner side of outer breakwaters, and north quay which opposed against harbor mouth should be designed for wave energy absorption function to prevent waves from WNW direction caused by hurricane.
3. Because experimental results and theoretical calculations showed the same trend, therefore we could obtain the better achievement of harbor planning.

## Acknowledgement

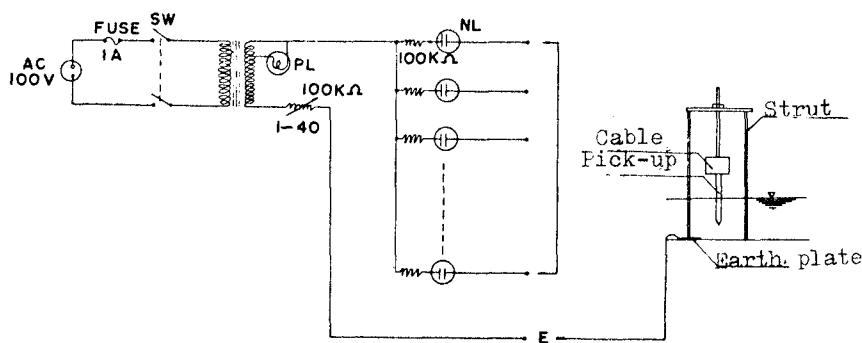
I wish to express my appreciation to the Leaders of Taichung Harbor Construction Bureau, Taiwan, R.O.C., they are Director, General M. C. Chen, Deputy Director, C. L. Wang and Vice Chief Engineer, C. C. Chang, through their recommendation and direction. I got fellowship of National Science Council to take my Ph.D. courses in University of Florida and obtained this chance to present my paper in the 14th Conference. Then, I want to thank Mr. J. T. Juang and Mr. S. C. Liang who assisted me to carry out laboratory work successfully.

## References

1. Hou, H. S. "Research of Model Experiment on Outer-Breakwater Arrangement of Taichung Harbor", Research Report of National Science Council, Taipei, Rep. of China; June, 1973
2. Hou, H. S. "A Study of the Wave, Alongshore Current, and Littoral Drift in South-eastern Taiwan", Journal of Civil Engineering, Vol. 14, No. 1 p. 1 - p. 28, Taipei, R. O. C., Aug, 1971.
3. Johnson, J. W. "Generalized wave diffraction diagrams", Proceeding of First Conference on Coastal Engineering, 1951.
4. Johnson, J. W. "Engineering aspects of diffraction and refraction", Proc. A.S.C.E. Vol. 118, 1953.
5. Penny-Price: "Diffraction of Sea Waves by breakwaters", Artificial Harbours, Dire. Misc. Weapon Develop. Tech. His. No. 26, 1944.
6. Wiegel, R. L.: "Diffraction of waves by semi-infinite breakwater", Proc. A.S.C.E. Vol. 88, No. HY1, part, 1962.



Fig. 3.1. The Plunger-Type Wave Generator



Neon NL 52 AC 60V

Fig. 3.2. The Principle of Connected Diagram  
of Neon-Tube Wavemeter.

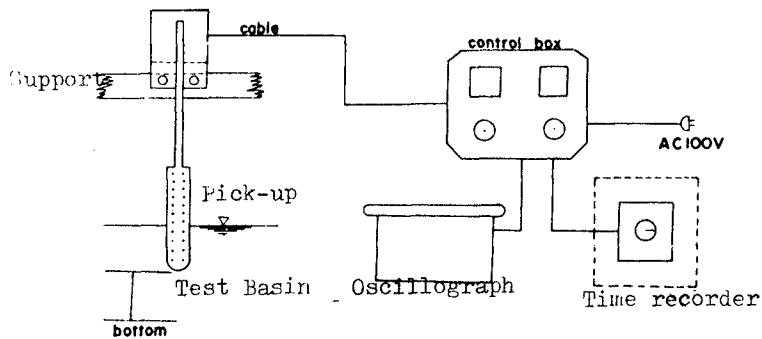


Fig. 3.3. The Principle of Connected Diagram  
of Step-Resistance Wavemeter.

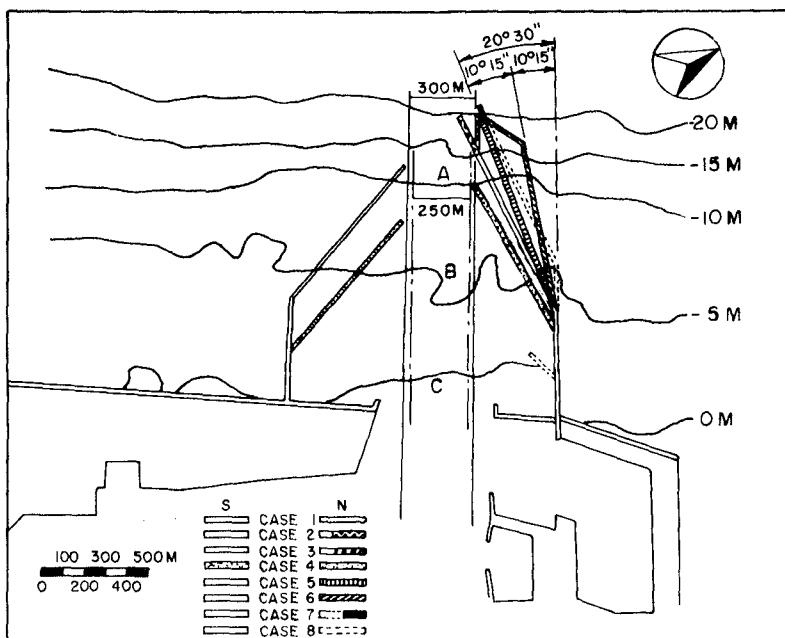


FIG. 5.1. THE OUTER-BREAKWATER ARRANGEMENTS OF 8 DIFFERENT CASES

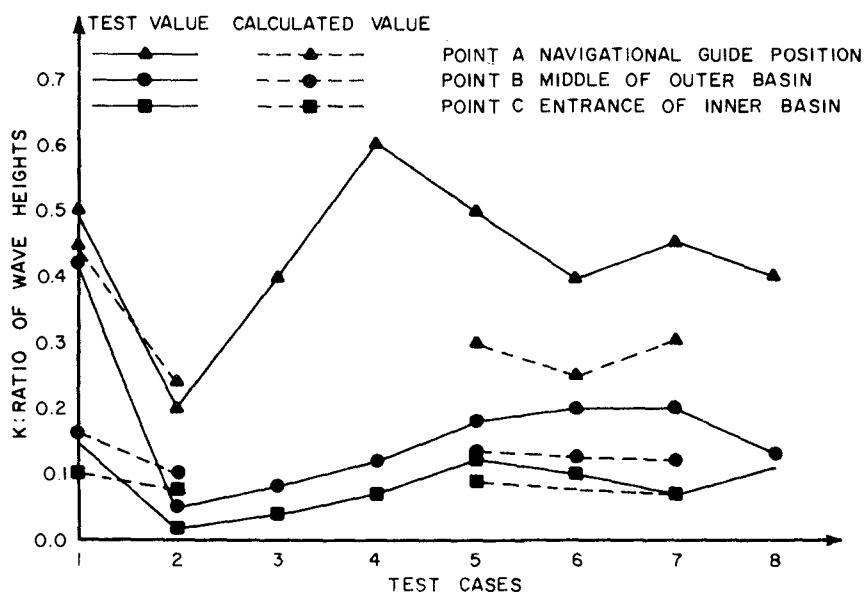


FIG. 5.2. COMPARISON ON RATIO OF WAVE AGAINST INCIDENT WAVE AMONG DIFFERENT CASES

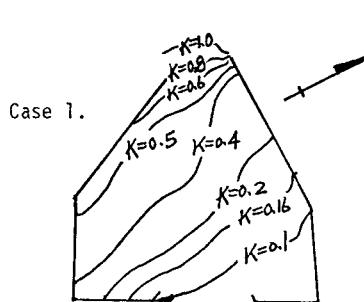


Fig.5-1-1

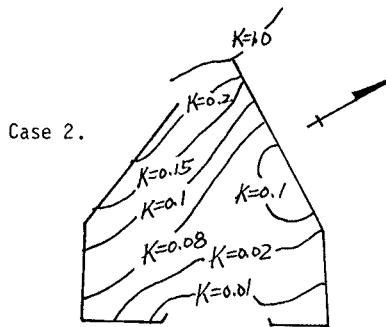


Fig.5-1-2

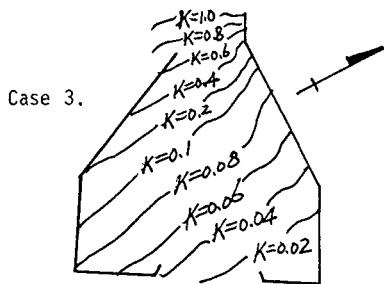


Fig.5-1-3

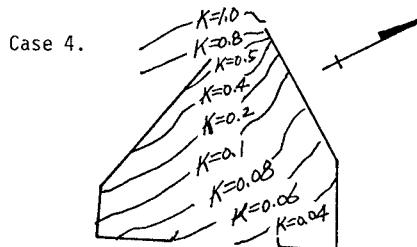


Fig.5-1-4

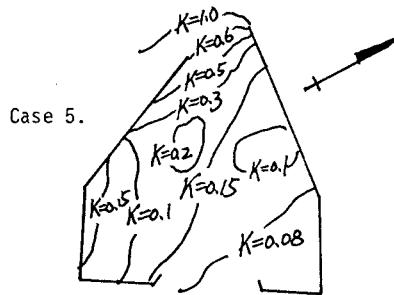


Fig.5-1-5

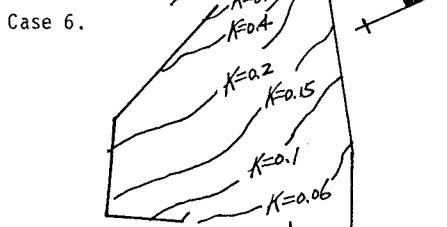


Fig.5-1-6

Wave Patterns of Test Results of N Dir.

Fig.5-1-7 Wave Pattern

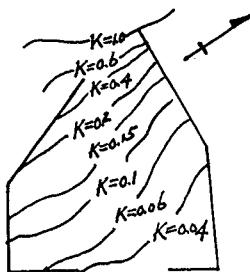


Fig.5-1-8 Wave Pattern

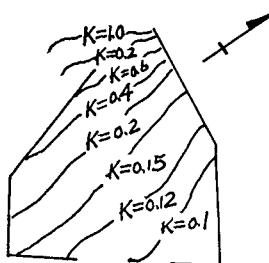
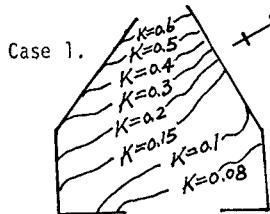
Fig.5-1-1 to Fig.5-1-8 Test Results of N Wave Direction.

Fig.5-2-1

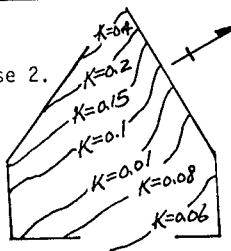


Fig.5-2-2

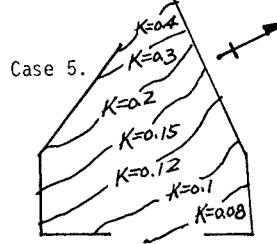


Fig.5-2-3

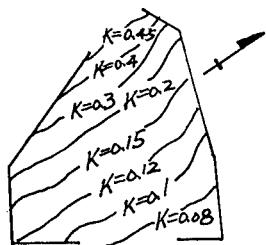


Fig.5-2-4

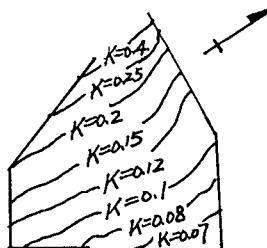


Fig.5-2-5

Fig.5-2-1 to Fig.5-2-5 Calculated Diffraction Diagram.

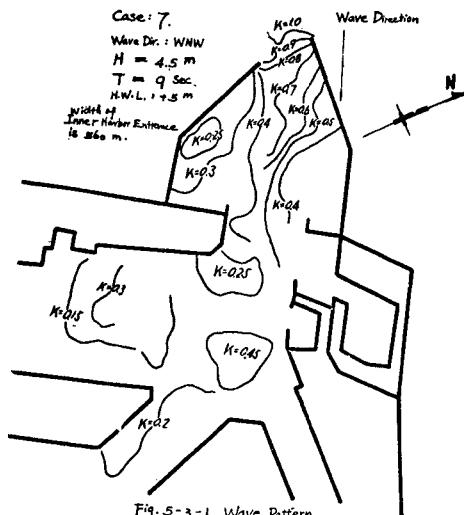


Fig. 5-3-1 Wave Pattern

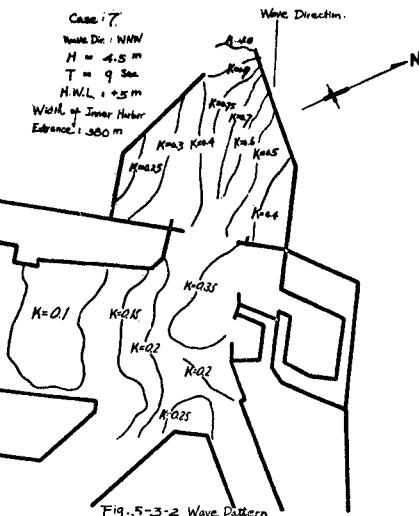


Fig. 5-3-2 Wave Pattern

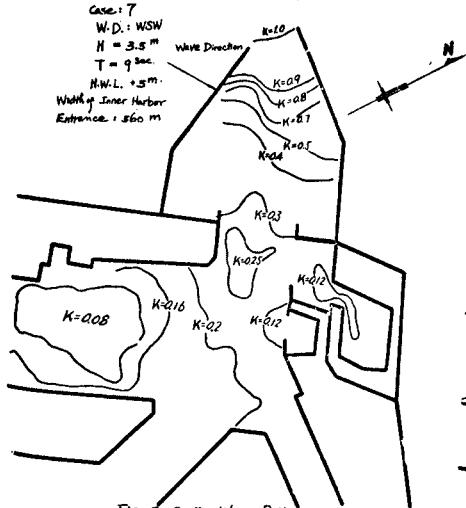


Fig. 5-3-3 Wave Pattern

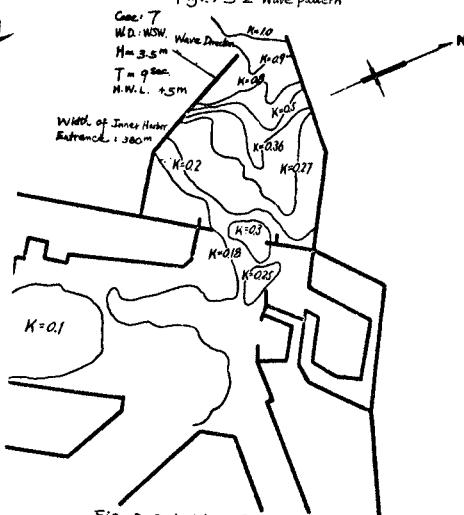


Fig. 5-3-4 Wave Pattern