Appendix-E Hindcast of Cyclone Waves

The calculation of cyclone waves were conducted using the model proposed by Horikawa et.al. adopting a grid system.

The program employs Myers' pressure distribution equation as a model for cyclones, and Wilson's equation for a growth of significant waves in the case of prediction of the waves.

The program can calculate the state of winds and waves at every time step at every gridpoint covering the whole sea area.

(1) Calculation of Wind

The pressure distribution P(r) within the cyclone area found by Myers' equation is as follows.

$$P(r) = Pc + \Delta P \cdot EXP(-\frac{r_0}{r}) \quad \ldots\ldots (E.1)$$

Where, P(r) is the pressure at a point located at a distance r from the storm center, Pc is the central pressure, ΔP refers to the difference between the pressure at the outskirts of the storm and Pc and r is the radial distance from the storm center to the region of about maximum wind speed.

The gradient wind velocity $U_1(r)$ can be derived theoretically from equation (E.2)

$$U_1(r) = C_1 \left\{ \frac{\Delta P}{\rho a} \frac{r_0}{r} EXP(-\frac{r_0}{r}) + (\frac{C_r}{2})^2 \right\}^{1/2} - \frac{C_r}{2} \quad \ldots (E.2)$$

Where ρa is the density of air, and C is the Coriolis parameter. C_1 is a constant 0.6 - 0.8.

In the case of a priceeding wind resulting from movement of a cyclone, the absolute velocity appears to be proportional to the velocity of the cyclone V as well as that of the gradiant wind. Thus, the proceeding wind velocity $U_2(r)$ is given by the following equation.

$$U_2(r) = C_2 \frac{U1(r)}{U1(r_o)} V \quad \text{......................(E.3)}$$

Where C_2 is a constant 0.6 ~ 0.8.

The gradient wind is assumed to blow counter-clockwise toward the cyclone center with an angle β (β =15 ~ 30 °) to the isobar, and the proceeding wind is in the direction of tyhoon movement.

Therefore, the composite wind velocity $U(r,\theta)$ and direction θ are obtained by adding $U_1(r)$ to $U_2(r)$ in the vectorial sense as follows.

$$U(r,\theta) = U_1{}^2 + U_2{}^2 - 2U_1U_2 \cos(90° + \alpha - \beta + \theta) \quad \text{...(E.4)}$$

$$\theta = \tan^{-1} \frac{U1\sin(90° + \beta + \theta) + U_2\sin\theta}{U1\cos(90° + \beta + \theta) + U_2\cos\theta} \quad \text{............(E.5)}$$

in which α represents the direction of cyclone movement and (r,θ) indicates the polar coordinates.

(2) Estimasion of Wind Waves

Wilson's formulae are used to estimate the growth of wind waves in cyclone area. They are expressed by equations (E.6) and (E.7).

$$\frac{gH_{1/3}}{U^2} = 0.30 \left[1 - \left\{ 1+0.004\left(\frac{gF}{U_2}\right)^{1/2} \right\}^{-2} \right] \quad \text{.......} \quad (E.6)$$

$$\frac{gT_{1/3}}{2\pi U} = 1.37 \left[1 - \left\{ 1+0.008\left(\frac{gF}{U_2}\right)^{1/3} \right\}^{-5} \right] \quad \text{.......} \quad (E.7)$$

These show the significant wave height $H_{1/3}$ and period $T_{1/3}$ as a function of the fetch F and wind velocity when waves grow and propagate under a constant wind velocity U.

Estimation is now based on the following assumptions.

① The direction of a significant wave growing within the fetch coincides
with the wind direction at any calculation point.

② When a wave of height $H_{1/3}$ changes it's direction by $\Delta\theta$, the waves of $H_{1/3}\cos\theta$ propagate in the new direction.

③ The wave period is kept unchanged in such an occasion.

(3) The Characteristics of the Cyclone

In the calculation, following 5 characteristics of cyclone were used.

① X : Cyclone Location

② Y :

③ $\Delta P = P_\infty - Pc$: where P_∞ is the nomal atmospheric pressure and Pc is the central atmospheric pressure of the cyclone

④ r_0 : The radical distance from the storm center to the region of maximum wind speed

⑤ V : Velocity fo the cyclone

ΔP and r_0 of the cyclone which occurred in November 1978 were not obtained. Where, these characteristics were estimated by maximum wind speed in cyclone area using equation (E.1).

Appendix - F Details of 2-D Model Tests

1 Tests for Sand Overtopping

1.1 Instruments

The instruments used in these tests are as follows.

i)	*Wave Gauge*	*: 4 capacitance wave gauges were used. These* locations are indicated in Fig. F.1.1.
ii)	Data Analysis	: A wave analyzer was used to calculate the wave dimensions and spectra.
iii)	Measurement of Wave Overtopping	: Overtopping water was collected by the steel box and measured by a graduated cylinder.
iv)	Measurement of Sand Profile	: A sand profile follower was used.

1.2 Arrangement of Model

The sea bed profile and the general arrangement of the model are shown in Fig. F.1.1. A movable bed is indicated by the hatched portion.

1.3 Wave Spectrum

Fig. F.1.2 shows the typical swell wave spectrum in Kirinda used for the model tests.

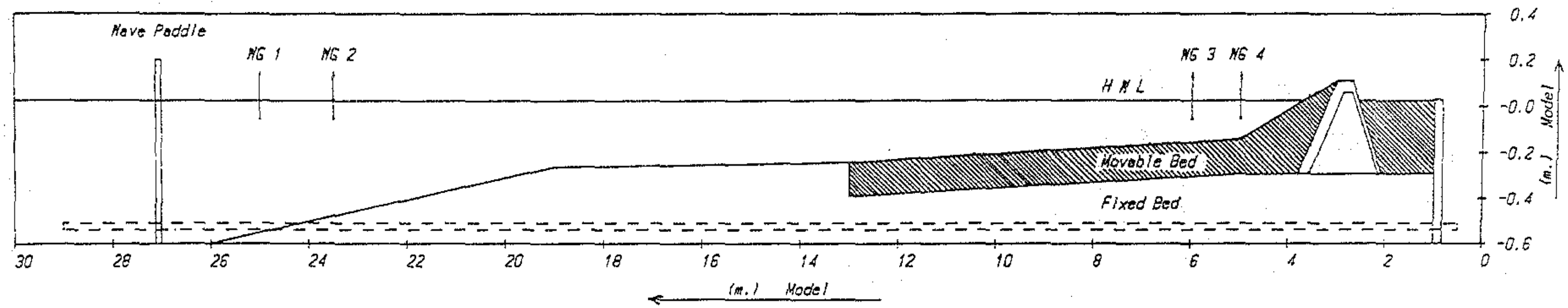

Fig. F.1.1 Seabed Profile and General Arrangement of the Model

```
Serial Number =  91

Time =  88  7 23 21:00
HMO  (m)  ,  TO2  (s)    :      1.80    8.16
1,2,3,5,10,50 th highest wave ht(m) :  2.78 2.66 2.62 2.19 1.92 1.02
Hrms(m), Hs(m), Tz(s) nWaves :     1.12    1.57    8.72    131
Havg(m), H10%(m), Tzj :     0.97    2.17   13.21

period (s) % energy

     25.60       3.33 *****
     21.33       8.39 ************
     18.29      29.02 ****************************************
     16.00      15.58 *********************
     14.22       4.45 ******
     12.80       4.68 *******
     11.64       2.23 ***
     10.67       2.68 ****
      9.85       5.08 *******
      9.14       3.35 *****
      8.53       2.25 ***
      8.00       1.15 *
      7.53       1.76 **
      7.11       0.57
      6.74       1.12 *
      6.40       1.30 **
      6.10       1.24 *
      5.82       0.57
      5.57       0.78 *
      5.33       0.47
      5.12       0.55
      4.92       0.84 *
      4.74       0.42
      4.57       0.33
      4.41       0.30
      4.27       0.44
      4.13       0.36
      4.00       0.29
      3.88       0.31
      3.76       0.43
      3.66       0.36
      3.56       0.18
      3.46       0.41
      3.37       0.17
      3.28       0.25
      3.20       0.18
      3.12       0.11
      3.05       0.12
      2.98       0.15
      2.91       0.15
      2.84       0.25
      2.78       0.08
      2.72       0.10
      2.67       0.09
      2.61       0.19
      2.56       0.10
      2.51       0.10
      2.46       0.13
      2.42       0.10
      2.37       0.06
      2.33       0.08
Energy Presented =  98 %
```

Fig. F.1.2 Typical Wave Energy Spectrum in Kirinda
(Used for Model Test)

1.4 Test Method

(1) Test Duration

The duration of the wave acting was 2 hours in total in each of cases. The wave action was divided into 3 periods; 30 minutes, 30 minutes and 60 minuets, i.e. a total of 2 hours.

(2) Measurement

The sand surface measurement and the wave overtopping measurement were conducted by following time schedule.

```
                                                                  (min.)
                                  0        30        60        90       120
Wave Acting                       ¦----¦----¦----¦----¦----¦----¦----¦----¦

Sand surface measurement          x         x         x                  x

Overtopping Measurement           <-------><--------><-------------------->
                                     1st       2nd            3rd
```

1.5 Results of Preliminary Tests

The preliminary tests were conducted to determine the wave condition in the main tests.

(1) Test Cases

The preliminary test cases are shown in Table F.1.1.

(2) Wave Overtopping Rate

Table F.1.2 and Fig. F.1.3 show the results of the wave overtopping rates.

Table F.1.1 Preliminary Test Cases

CASE	Tp*(sec)		H1/3(m)	
	PROTO.	MODEL	PROTO.	MODEL
P15610	15.6	3.12	1.0	4.0
P18205	18.2	3.64	0.5	2.0
P18210	〃	〃	1.0	4.0
P18215	〃	〃	1.5	6.0
P21910	21.9	4.38	1.0	4.0

* Corresponding to the peak energy

Table F.1.2 Results of Wave Overtopping Rates

Case	Tp	H1/3	Wave Overtopping Rate ($m^3/m/s$)		
			0 ~0.5h*	0.5 ~1h*	1 ~2h*
P15610	15.6	1.0	5.67×10^{-3}	6.25×10^{-3}	3.01×10^{-3}
P18205	18.2	0.5	2.82×10^{-4}	—	—
P18210	18.2	1.0	6.13×10^{-3}	7.29×10^{-3}	7.47×10^{-3}
P18215	18.2	1.5	3.21×10^{-2}	1.13×10^{-2}	4.76×10^{-3}
P21910	21.9	1.0	5.09×10^{-3}	7.06×10^{-3}	8.04×10^{-3}

* Wave acting time(hours) in the model

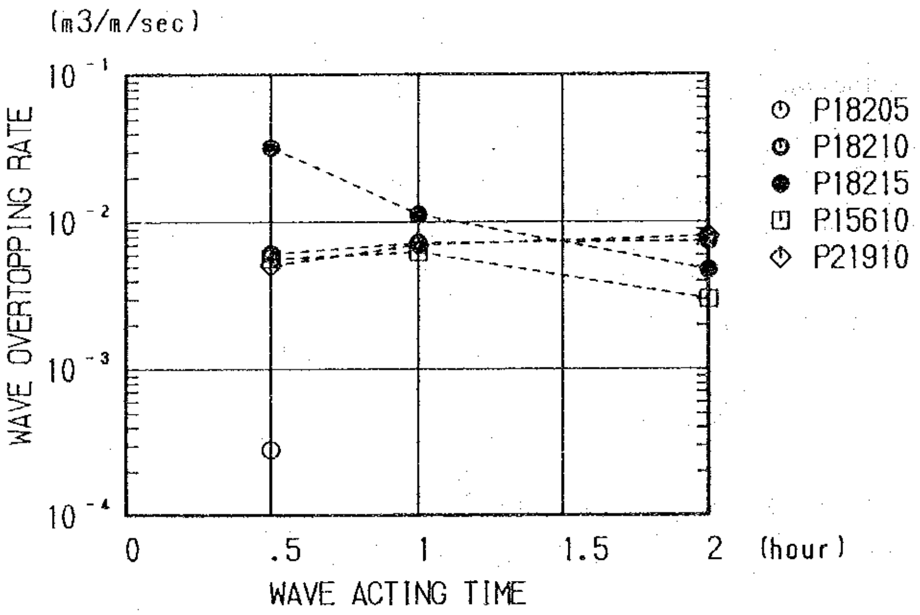

Fig. F.1.3 Results of Wave Overtopping Rates

In Case P18205, T=18.2sec and H=0.5m, the wave overtopping accord little. On the contrary, in Case P18215, T=18.2sec and H=1.5m, too heavy wave overtopping occurred in the beginning of wave acting, as time it was getting less by the deformation of the sand profile in front of the breakwater. Further more, the wave overtopping rates for the cases with the wave height of 1.0m were nearly $10^{-2}m^3/m/sec$.

(3) Transformation of Sand Profile

Fig. F.1.4 shows the transformations of the sand profiles in the preliminary tests.

The sand profile in Case P18205 was scarcely changed, while, in the other cases the sand on the sea side of the breakwater were eroded and flowed into the backside of the breakwater over the breakwater.

(4) Selection of Wave Condition for Main Tests

The sand overtopping appeared in the preliminary tests except Case P18205. The depth of the wave breaking zone, which is considered to be 3 or 4m in the site for the ordinal waves, reappeared well in the case with the wave height of 1.0m. Further more, considering the difference of the sand profile deformation for the tested wave period, the case with the wave period of 18.2sec resulted in the largest deformation of all.

From these results, the following wave condition was adopted in the main tests.

Wave Period : 18.2 sec

Wave Height : 1.0 m

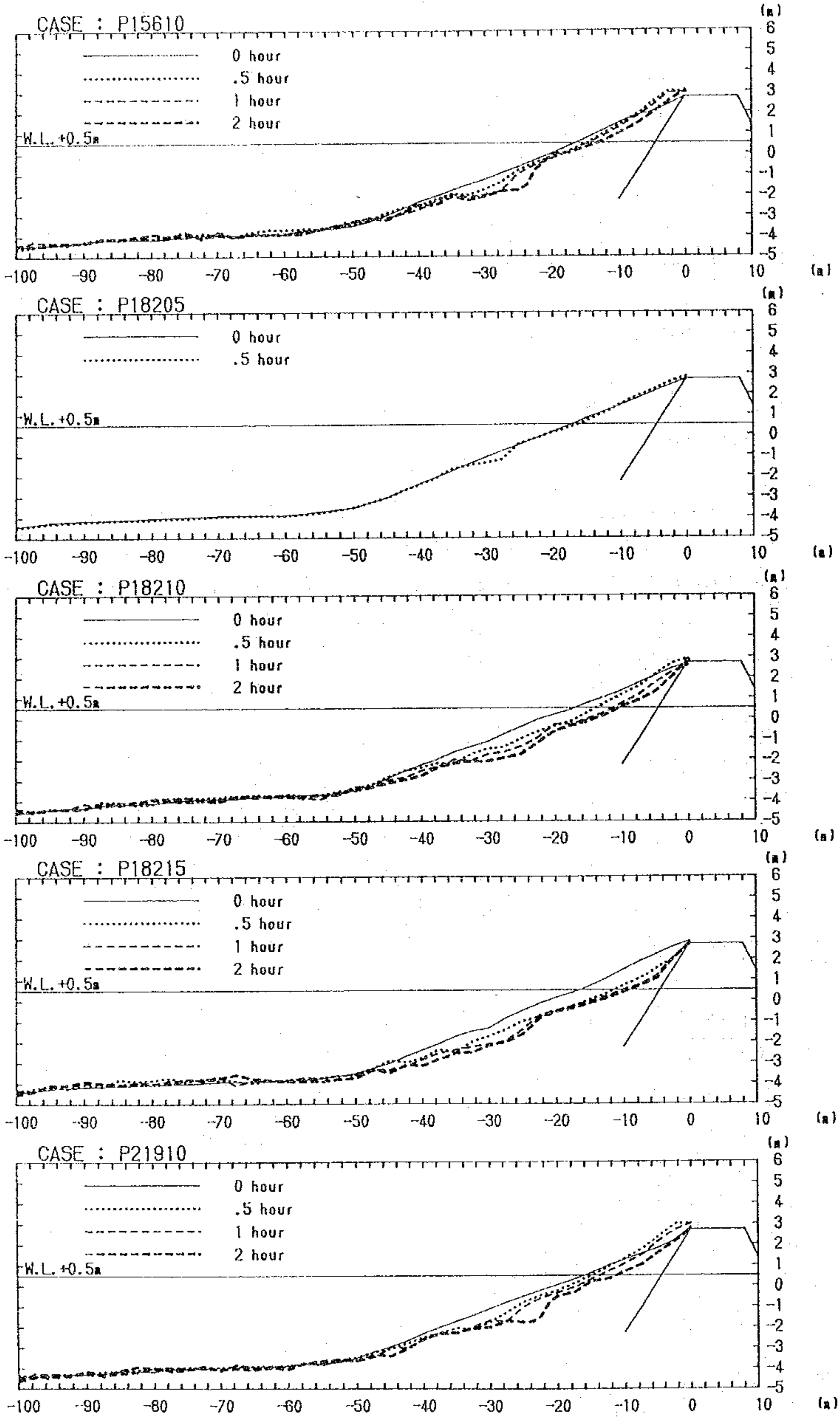

Fig. F.1.4 Transformations of Sand Profiles

1.6 Similitude in Movable Tests

In general, the similitude regarding the sand movement characteristics is considered to be acceptable in a case where the following equation satisfies.

$$(Wo)m/(Wo)p = (U_*)m/(U_*)p \qquad (F.1.1)$$

where Wo : Settling Velocity
U_* : Friction Velocity

The settling velocity ratios between the model and the prototype calculated using the Rubey's equation and the Yalin's equation are as follows.

Rubey : 0.24
Yalin : 0.20

On the other hand, by applying Froude's Model Law to the friction velocity, the right term of the equation (F.1.1) is calculated as follow.

$$(U_*)m/(U_*)p = \sqrt{(1/25)} = 0.2$$

where the model scale is 1/25.

From these examinations, the similitude of the sand movement in these tests is considered to be acceptable.

2 Stability Tests

2.1 Instruments

The instruments used in these tests are as follows.

i)	Wave Gauge	: 4 capacitance probe type wave gauges were used.
ii)	Data Analysis	: A personal computer was used to calculate the wave dimensions and spectra.
iii)	Measurement of Sand Profile	: 3 sand profile followers were used.
iv)	Measurement of Stability	: Observation

2.2 Arrangement of Model

The sea bed profile and the general arrangement of the model are shown in Fig. F.2.1. A movable bed is indicated by the shadowed portion.

2.3 Test Method

(1) Main Breakwater

1) Test Duration

The duration of the wave acting was 5 hours in total in each of cases. The wave action was divided into 3 periods; 1 hour, 2 hours and 2 hours, i.e. a total of 5 hours.

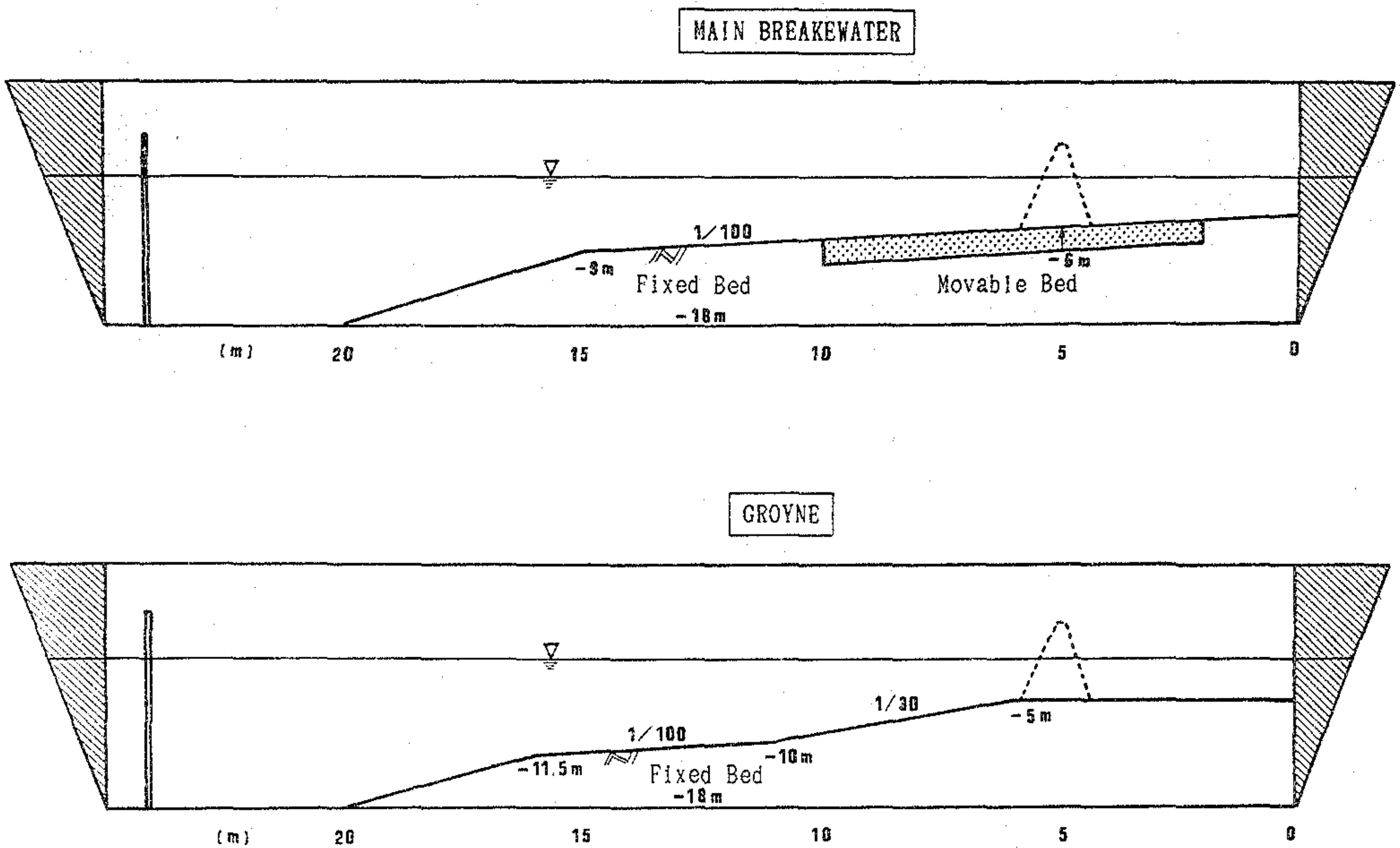

Fig. F.2.1 Seabed Profile and General Arrangement of the Model

2) Measurement

The sand surface measurement and the wave overtopping measurement were conducted by following time schedule.

	0	1	2	3	4	5(hour)
Wave Acting	¦----¦----¦----¦----¦----¦					
Sand Surface Measurement	x	x		x		x
Observation of Stability	<------------------------>					
Measurement of Transmitted Wave		x		x		x

(2) Groyne

The stability was examined for about 1000 waves in each case. The transmitted waves were measured for about 100 waves in each case.

2.4 Similitude in Movable Tests

In the same way as the sand overtopping tests, with consideration of the relation indicated by the equation (F.1.1), the settling velocity ratios between the model and the prototype by using the Rubey's equation and the Yalin's equation are obtained as follows.

Rubey : 0.20
Yalin : 0.15

Meanwhile the friction velocity ratio is calculated as follow.

$$(U_*)m/(U_*)p = \sqrt{(1/30)} = 0.18$$

where the model scale is 1/30.

Hence the similitude of the sand movement in these tests is considered to be acceptable.

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