CHAPTER 176

ADAPTABILITY OF PREDICTION METHOD OF HYDRAULIC MODEL EXPERIMENT FOR THERMAL DIFFUSION

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1. INTRODUCTION

In formation processes of the region of water temperature rise caused by the cooling water discharge from thermal and nuclear power stations located on the site facing the ocean, flow of discharged cooling water itself, current and turbulence existing in the sea region play an important role.

Their motions are predominant in the horizontal direction in the sea region. The horizontal scale of thermal extent is, therefore, extremely larger than the vertical scale of thermal extent.

Therefore, whenever the diffusion experiments of discharged warm water in the far field are conducted by hydraulic model method, the model which has a difference in the geometrical reduced rate between the horizontal and vertical directions, what is called, the distorted model must be used, so that the effects of the viscosity and the surface tension on the experimental model can be avoided.

In such a model, the horizontal scale is determined by the relation between the size of the experimental water basin and the surface area of the sea region to be reproduced.

But, there is no clear method of choosing the vertical scale, though there are some suggestions about it.

For example, the similarity of the 4/3 power law of the diffusion coefficient gives a relation between the vertical scale and the horizontal scale of the hydraulic model.

On the other hand, the similarity of the surface heat exchange coefficient gives another relation between the vertical scale and the horizontal scale of hydraulic model if the surface heat exchange coefficients of hydraulic model and prototype are not same.

Therefore, it is better to give some allowance in the determination of the vertical scale of the hydraulic model within the range where the reproducibility of the diffusion phenomena can be conserved.

To clarify sure the relations between the distortion rate and the reproducibility of the phenomena in the model, experiments on the diffusion of discharged warm water were conducted by using three kinds of tidal hydraulic models having different distortion rates.

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The selected site as prototype is Takasago Point located in the northeastern part of Harima of the Seto Inland Sea in Japan, where the semi-diurnal tidal current is predominant and two thermal power stations in operation are located adjacently.

In this paper the loci of tidal current, the horizontal turbulence of meso-scale and far field temperature distributions obtained in the three hydraulic models having different distortion rates are compared with those of field measurements in prototype.

From these results, same problems of adaptability for the technique of distorted hydraulic model experiment for predicting the diffusion extent of thermal discharge are discussed.

2. RESULTS OF PROTOTYPE INVESTIGATIONS

The selected site as prototype is Takasago Point located in the northeastern part of Harima of the Seto Inland Sea, where are two thermal power stations in operation adjacently.

Figure 1 shows the site map of Takasago Point.

One is Takasago Thermal Power Station of Kansai Electric Power Company (total output 900 MW, maximum volume of cooling water 33.5 m^3/sec.) and the warmed cooling water is discharged into the sea region in front of the power station.

The other is Takasago Thermal Power Station of Electric Source Development Company (total output 500 MW, maximum volume of cooling water 21.8 m^3/sec.) and the warmed cooling water is discharged into the inlet beside the power station.

The temperature rise of the discharged cooling water from both power stations is about 7°C above the ambient sea water temperature.

To examine the characteristics of flow in this sea region, the autocorrelations and the energy spectra of the flow observed for 15 days running at 3 m below the sea surface in the 1 km and 3 km offing of the outlet are calculated.

Figure 2 shows the autocorrelation coefficients of the flow which were observed at station - 2 in Takasago Site.

The autocorrelation of the flow velocity which is parallel to coast oscillates periodically and its period of the oscillation is nearly equal to the period of the semi-diurnal tidal current.

Figure 3 shows the energy spectra of the flow which were observed at station - 2 in Takasago Site.

The energy spectrum of the flow velocity which is parallel to coast has a maximum energy concentration at the frequency equivalent to the period of the semi-diurnal tidal current.

Judging from these figures, it is evident that the semi-diurnal tidal current is predominant in this sea region. It runs north-westward during flood tide and south-eastward during ebb tide.

The amplitude of the semi-diurnal tidal current is about 30 cm/sec. during spring tides.

The actual measurement of the discharged warm water diffusion range in the sea region near Takasago Power Station was carried out by Kansai Electric Power Co., Ltd. from January 22nd to February 3rd, 1972, and also by Water Temperature Survey Corporation from February 15th to 22nd, 1973.

The field surveys were conducted at the time of the spring tide both in 1972 and in 1973; and the amplitude of the semi-diurnal current was approximately 30 cm/sec.

The environmental water temperature in the sea region was about between 9°C to 11°C and the marine condition was mild.

According to the results of the actual measurement, the area of 1°C rise above ambient sea water temperature extended about 2 - 2.5 km along the coast on both sides from the outlet and extended about 2 km toward the offing from the outlet.

The area of 2°C rise above ambient sea water temperature extended about 1 - 1.5 km along the coast on both sides from the outlet and extended about 1 km toward the offing from the outlet.

3. SIMILITUDE RULE OF HYDRAULIC MODEL EXPERIMENT

(1) Diffusion Process of Discharged Warm Water in the Coastal Sea Region

Although the diffusion phenomenon of discharged warm water is extremely complicated and the factors which affect the diffusion process are various and numerous, the main process can generally be considered as follows:

In the sea region near the outlet, the main process is the entrained mixing between the discharged warm water and ambient water.

The discharged warm water itself flows toward to offing through the process of mixing, and gradually the flow and turbulence of the discharged warm water become smaller than those in the sea region.

In this sea region, the diffusion process affected by the flow and turbulence of the sea controls the formation process of the water temperature distribution. Accordingly, for the purpose of predicting the diffusion of discharged warm water on the basis of the hydraulic model experiment, it is essential to make actual measurement investigations into the diffusion characteristics in the coastal sea region and to verify each factor which controls the diffusion phenomena in each case, and finally to discover the similitude rules for reproducing these factors on the model.

(2) Near Field

In the hydraulic experiment on the water temperature distribution formed in the sea region near the outlet, the entrained mixing phenomena should be reproduced in the model.

Under the condition that we should correspond the internal Froude number of the model with that of the prototype, this phenomenon can be expected to be reproduced.

This condition gives following equations. m means the model and p means the prototype.

$$Fip = Fim = \frac{U_{op}}{\sqrt{\frac{\rho sp - \rho op}{\rho op} \cdot g \cdot h_{op}}} = \frac{U_{om}}{\sqrt{\frac{\rho sm - \rho om}{\rho om} \cdot g \cdot h_{om}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where

Fi : internal Froude number
Uo : outfall velocity
ρs : density of the environmental water
ρo : density of the discharged water
g : acceleration of gravity
ho : depth at the outlet

In the hydraulic model where the Froude Similitude Rule is applied, the next relation can be obtained.

$$\frac{\rho sp}{\rho op} = \frac{\rho sm}{\rho om} \quad \cdots\cdots\cdots\cdots \quad (2)$$

That is to say, the equation described above shows the condition that we should correspond the environmental water density and the discharged water density of the prototype with those of the model.

However, as it is difficult to grasp the three dimensional phenomena concerning the entrained phenomena near the outlet, more detailed examination of the similitude rule for reproducing the phenomena is considered necessary.

(3) Far Field

In this sea region, the flow and turbulence of the sea play an important role in the formation process of water temperature distribution.

This process is also affected by the heat exchange process between the atmosphere and the sea surface.

The average flow conditions such as the current trace and the topographical current are supposed to be very important factors which play a main role as the advective effects to change the diffusion pattern of the discharged warm water.

After integrating the equation of motion in the vertical direction, neglecting the stress which acts on the water surface and taking into consideration of the stress acting on the sea bed expressed by the help of the friction coefficient, the following relations to reproduce the average flow conditions may be obtained.

$$\frac{Up}{Um} = \frac{Vp}{Vm} = \left(\frac{Zp}{Zm}\right)^{1/2} \quad \cdots\cdots\cdots\cdots \quad (3)$$

$$\frac{t_p}{t_m} = \left(\frac{Xp}{Xm}\right) \left(\frac{Zp}{Zm}\right)^{-1/2} \quad \cdots\cdots\cdots\cdots \quad (4)$$

$$\frac{Cp}{Cm} = \left(\frac{Xp}{Xm}\right)^{-1} \left(\frac{Zp}{Zm}\right) \quad \cdots\cdots\cdots\cdots \quad (5)$$

where,

U, V : vertically averaged velocities in X and Y directions
t : time

C : friction coefficient
X, Z : length scales in horizontal and vertical directions.

The equations (3) and (4) can be transferred to the following equation.

$$\frac{Up}{\sqrt{g\ Zp}} = \frac{Um}{\sqrt{g\ Zm}} = Fr \quad \text{.................................} \quad (6)$$

where,

Fr : Froude number.

The equation (6) shows the similitude rule of Froude.

It is considered that the average flow condition such as the tidal current trace or the topographical flow can be reproduced by corresponding the Froude number of the model with that of the prototype.

On the other hand, the mechanism and characteristics of the turbulence which play a very important role in the diffusion process in the sea region can be obtained by statistically analizing the results of long term continuous observation on the flow velocity fluctuations. They can be clearly expressed in the autocorrelation functions and the energy spectrum functions.

According to the results that were obtained using the distored model on the reproducibility of the horizontal turbulence which exists in the tidal current,[1] it is shown that the statistical characteristics and mechanism of the horizontal turbulence which are expressed in the autocorrelation and the energy spectrum can almost be reproduced in the model by applying the similitude rule of Froude. However, as far as the reproducibility of horizontal turbulence is concerned, it seems that some restrictions are given by the Reynolds number and topographical features at the site to be investigated for the experiment.

Accordingly, in order to reproduce the diffusion process in the sea region far from the outlet on the model, it is necessary to adopt the similitude rule of Froude, and it is also important to check the reproducibility of the average flow condition and the horizontal turbulence by comparing the results of the model with those of the actual measurements in prototype.

The heat balance between the atmosphere and the sea surface is determined by the short wave radiant energy coming from the sun and the sky, the long wave radiant energy from the atmosphere and the water surface, the transfer of the sensible heat energy and the latent heat energy, and by the additional heat energy caused by the discharge of warm water.

The factors which affect the surface heat exchange are the wind velocity, the water temperature, the atmospheric temperature, the humidity, the cloudiness and so on.

The rate of the surface heat exchange is usually expressed by introducing the surface heat exchange coefficient.

The relation of the surface heat exchange coefficient ratio can be obtained from the equation of thermal diffusion which is integrated in the vertical direction and from the similitude rule of Froude, as follows.

$$\frac{K_{Tp}}{K_{Tm}} = \left(\frac{Xp}{Xm}\right)^{-1} \left(\frac{Zp}{Zm}\right)^{3/2} \qquad (7)$$

where, K_T : surface heat exchange coefficient

This relation shows that the model must be given distortion if the surface heat exchange coefficient of the model is the same as that of the prototype. Actually however, the former is different from the latter and the coefficient heat exchange in the model is generally presumed to be smaller than that in the prototype because no consideration is given to the effects of the wind.

If a correct coefficient of the heat exchange in the model as well as in the prototype is obtained, the equation (7) provides a means of determining the distortion ratio. However, it is very difficult at the present stage to apply the similitude condition regarding the effect of heat balance in the hydraulic experiment because of difficulty in obtaining the coefficient of surface heat exchange.

4. EXPERIMENTAL METHOD AND MODELING RATIO

The diffusion basin used for the hydraulic model experiment is 20 m x 10 m x 1 m, and the tide production equipment is installed at the end of the basin. This air pressure system can produce the change of the water level and the flow in the model basin by alternating the air pressure in the airtight chamber. (See Figure 4)

Water temperature, current speed and their variations in the basin were measured by using thermistors and a supersonic currentmeter connected to a data-logger.

The average flow conditions such as the loci of tidal current were measured by photographing the movements of float in the basin from the upper part.

The horizontal length ratio was chosen as 1/1,000 to reproduce the prototpye area of 15 km along the coast by 6 km offshore in the experimental basin.

The vertical length ratio was chosen as 1/50, 1/100 and 1/200, so three models having different distortion rates were constructed.

The relations between the values of the prototype (P) and the values of three models (m) are shown in the following table.

Table 1. Summary of Modeling Ratios for the Experiment

		Case I	Case II	Case III
Horizontal length	$Xp/Xm = Yp/Ym$	1000	1000	1000
Vertical length	Zp/Zm	200	100	50
Distortion rate	$(Xp/Xm)/(Zp/Zm)$	5	10	20
Horizontal velocity	$Up/Um = Vp/Vm$	14.14	10	7.07
Flow rate	$Qp/Qm=(Xp/Xm)(Zp/Zm)^{3/2}$	2.83×10^6	10^6	3.54×10^6
Time	$t_p/t_m = (Xp/Xm)(Zp/Zm)^{-1/2}$	70.71	100	141.42

5. EXPERIMENTAL RESULTS

(1) Reproducibilities of Average Flow Conditions and Horizontal Turbulence

Before the experiment of the thermal diffusion, the reproducibility of the average flow conditions such as the loci of tidal current and the reproducibility of the horizontal turbulence of meso-scale which play an important role in the diffusion phenomena in the sea were examined.

Figure 5 shows the loci of tidal current during ebb tide obtained in three models having different distortion rates.
In this figure, the experimental results are indicated as the values of the prototype values, and they are compared with the loci of tidal current obtained in the field surveys.

From this figure, it is considered that the average flow conditions such as the tidal current trace obtained in three models having different distortion rates are not influenced so remarkably by the variation in distortion rate, and it is also confirmed that the results of the field surveys are reproduced in these models.
The average flow conditions at the time of flood tide are also reproduced in the models.

S. Hayami et al2) proposed the similitude to give the distortion rate for the model of tidal current, considering the bottom friction in the laminar flow regime, as follows.

$$\frac{Cp\ (Rep)^{1/2}}{1.328} \cdot \left(\frac{Xp}{Xm}\right)^{1/2} = \left(\frac{Zp}{Zm}\right)^{5/4} \quad \cdots\cdots\cdots\cdots \quad (8)$$

They conducted the hydraulic model experiments by the use of three models of horizontal length ratio 1/500, distortion rates of 2, 4 and 8.
From the experimental results, they concluded that the flow patterns of the field surveys were reproduced better in the model having distortion rate of 2, which satisfied the relation of equation (8).

But it is considered to be difficult to determine the distortion rate using the relation of equation (8), owing to the fact that the value of the Reynolds number varies with space and time.

Judging from the results of author's experiments and the previous works done by others, it may be concluded that the average flow conditions, such as the loci of tidal current, can be reproduced in the distorted Froude model not influenced so remarkably by the variation in distortion rate.

But carefull attention must be paid to the fact that large distortion rate makes the flow in the model basin three dimensional.

The characteristics and mechanism of the horizontal turbulence are represented remarkably by the energy spectrum which can be obtained by statistic analysis of the results of long term continuous observation of fluctuations in flow velocity.

For the purpose of examing the reproducibility of the horizontal turbulence, long term continuous measurements of fluctuations in flow velocity were conducted at the same point as the field survey spot.

The energy spectrum of fluctuations in flow velocity obtained by the experiments performed in the tidal hydraulic models having three different kinds of distortion rates is shown in Fig. 6. The point of measurement is St. 2 shown in Fig. 1.

The energy spectrum shown in this figure is obtained by excluding the oscillating current component in the model which corresponds to the semidiurnal current component. And in the case of the prototype, the spectrum is obtained by excluding the semidiurnal current and the diurnal current. The values of the model are indicated as the values of the prototype according to the similitude rule of Froude.

The energy spectra of the flow parallel to coast show the same energy level as the level of the prototype in both high and low frequency ranges.

But the energy spectrum obtained in the model of distortion rate of 20 shows a larger peak at the frequency equivalent to the period of 6 hours in comparison with those of other two models and prototype.

On the other hand, the energy spectra of the flow normal to coast obtained in three models having different distortion rate are about the same as those of prototype in the high frequency range, but in the low frequency range the energy levels of spectra obtained in two models of distortion rate of 5 and 20 are lower than that of prototype.

Due to the results mentioned above, it has been recognized that the horizontal turbulence having a fluctuation period of less than several hours can be reproduced in the model without being remarkably influenced by the difference in distortion rate. But as far as the horizontal turbulence having a long fluctuation period is concerned, the energy level of the flow normal to coast is lower than the level of the prototype, and the isotropy in the horizontal direction is lost by the effects of the distortion rate of the model, the topographical characteristics of the investigated site, the scale of the experiment and so forth.

(2) Reproducibilities of Diffusion Phenomena of Discharged Warm Water

After examing the reproducibilities of the average flow conditions like the tidal current trace and the horizontal turbulence, experiments on the diffusion of discharged warm water were conducted.

From the experimental results, the reproducibility of diffusion phenomena and the effect of distortion on the reproducibility were examined.

The diffusion patterns of discharged warm water obtained in the tidal hydraulic models alternate in accordance with change of the tidal current.

The range of water temperature rise spreads toward the northwestern sea region during flood tide and it spreads toward the southeastern sea region during ebb tide.

As regards the diffusion patterns of discharged warm water at each tidal time obtained both in the hydraulic model and prototype, some similar diffusion patterns are recognized, but many different kinds of diffusion patterns are also recognized.

This is due to the fact that the natural phenomena are extremely complicated and have lots of random characteristics. On the other hand, the model keeps the so-called regularity comparatively well as it is simplified in order to reproduce the main factors in the diffusion process of the prototype.

Also it is due to the fact that there is no simultaneity between the data of the field survey because it takes a long time to measure one diffusion pattern.

Accordingly, in examining the reproducibility of diffusion phenomena by comparing the experimental results with the field survey results, it is more reasonable to compare the diffusion range as the envelope of all the patterns than to compare the each individual diffusion patterns.

Figure 7 shows the comparison between the actual measurement results of 1°C and 2°C rise in the surface layer and the enveloped range of 1°C and 2°C in the surface layer obtained in the hydraulic experiments conducted under the conditions corresponding to the conditions at the time of the actual measurement.

From the experimental results on diffusion area of the discharged warm water obtained in the two models with distortion rate of 5 and 10, there was no remarkable difference between them. The diffusion areas of the actual measurements in prototype were reproduced in each experimental result.

On the other hand, as far as the diffusion area of the discharged warm water obtained in the model with distortion rate of 20 is concerned, it was found that the variation in the distortion rate gives greater effects on the reproducibility of diffusion phenomena as compared with the results obtained in other two models and in the field surveys.

It is considered that these results are attribute to the fact that the flow volume of the discharged warm water in the model experiment increases as the distortion rate in the model becomes larger.

In order to determine the flow volume of the discharged warm water in the model having a large distortion rate, therefore, it is not enough to apply Froude similarity rule only.

H. Higuchi et al 3) proposed the similitude to give the distortion rate for the model of turbulent diffusion considering the 4/3 power law of the horizontal diffusion coefficient, as follows.

$$\frac{Zp}{Zm} = (\frac{Xp}{Xm})^{2/3} \quad \text{......................................(9)}$$

This relation requires a distorted model having distortion rate of 10 if the horizontal length ratio is chosen as 1/1000.

But as far as the results of author's experiments are concerned, the diffusion phenomena of discharged warm water are reproduced even in the model having distortion rate of 5 which does not satisfy the relation of equation (9).

6. CONCLUSIONS

Judging from above mentioned results, in order to conduct the diffusion experiment of discharged warm water by using the distorted hydraulic model applying Froude similarity rule, the distortion rate of model should be smaller than 10 within the range where the effects of the viscosity and the surface tension can be neglected.

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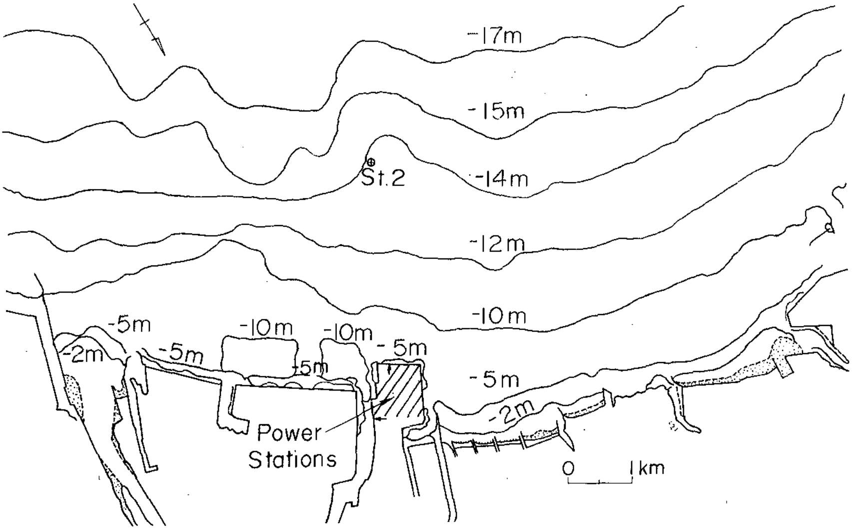

Fig.1 Site mop of TAKAGO POINT

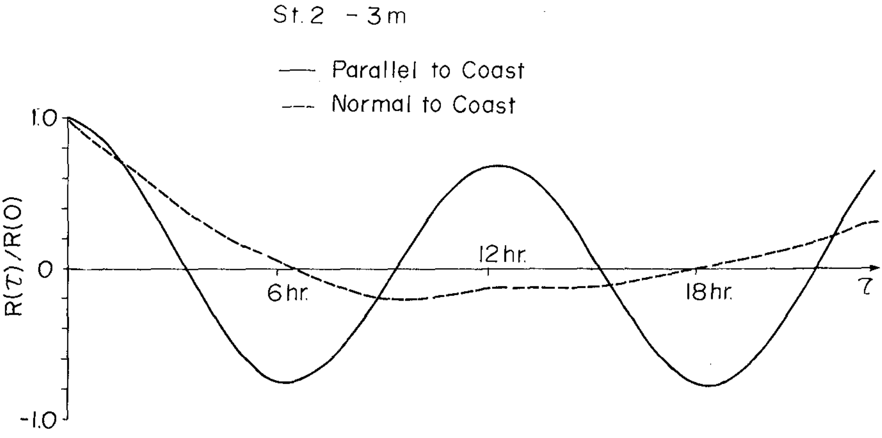

Fig.2 Autocorrelations of flow velocity (Prototype)

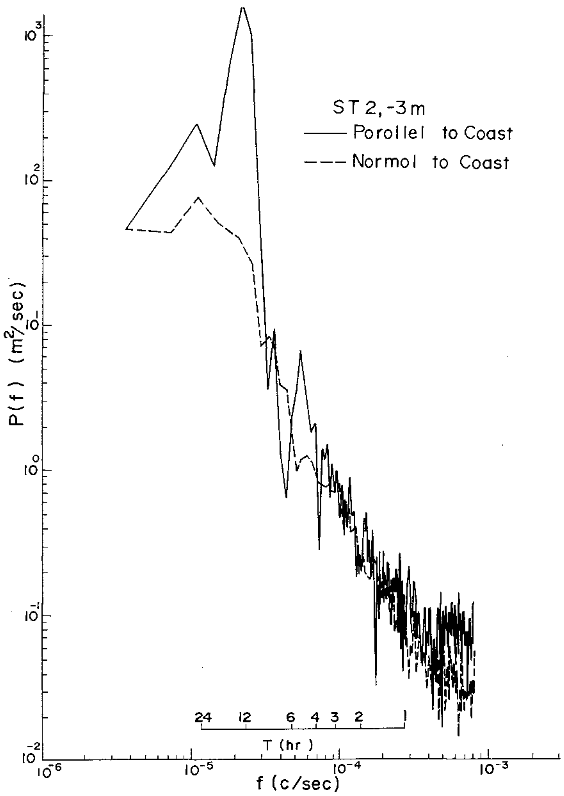

Fig. 3 Energy spectra of flow velocity (Prototype)

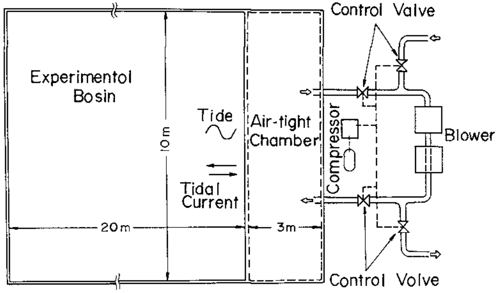

Fig. 4 Tide generation system

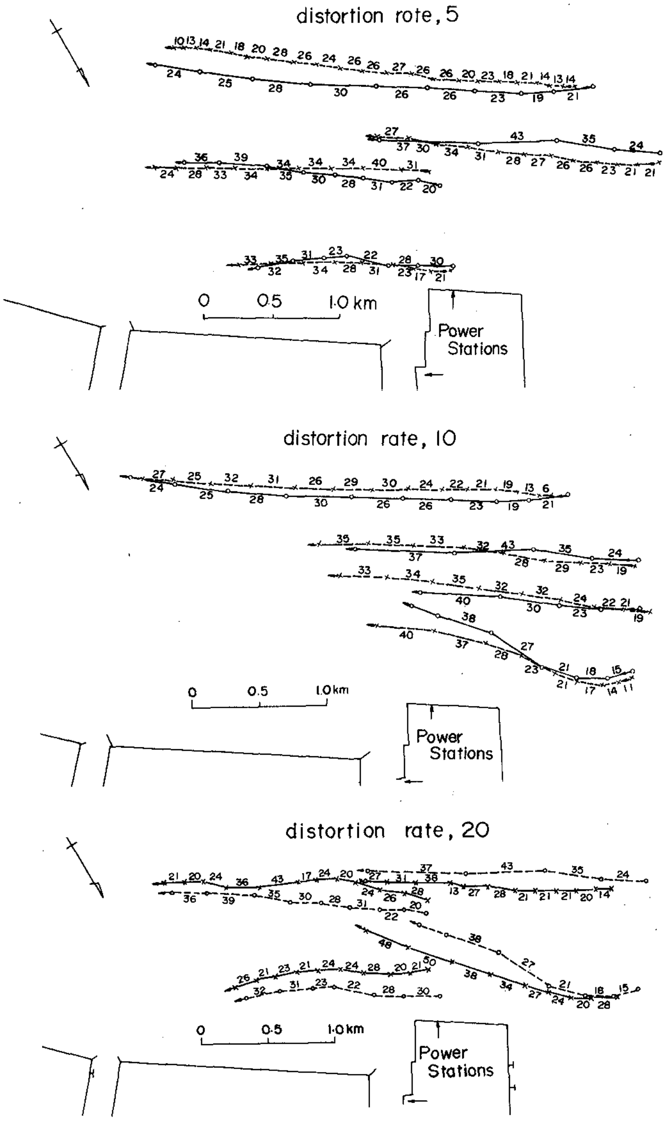

Fig. 5 Comparison between model and prototype loci of tidal current. (Ebb tide)

—o—30—o— Prototype } Numerals mean prototype
—x—28—x— Model } velocity in cm/sec

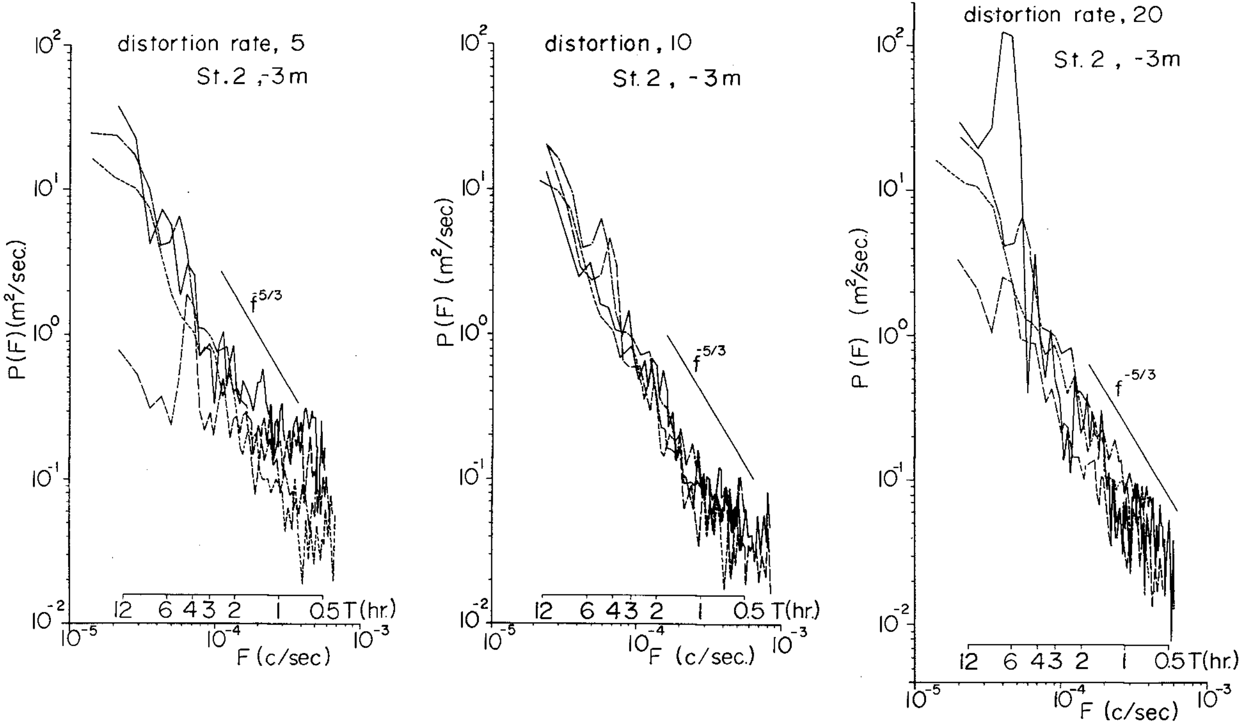

Fig. 6 Comparison between model and prototype energy spectra of turbulent velocity. (Periodic components of tidal current are removed.)

——— Model } Parallel to coast
—·— Prototype }

— — — Model } Normal to coast
------ Prototype }

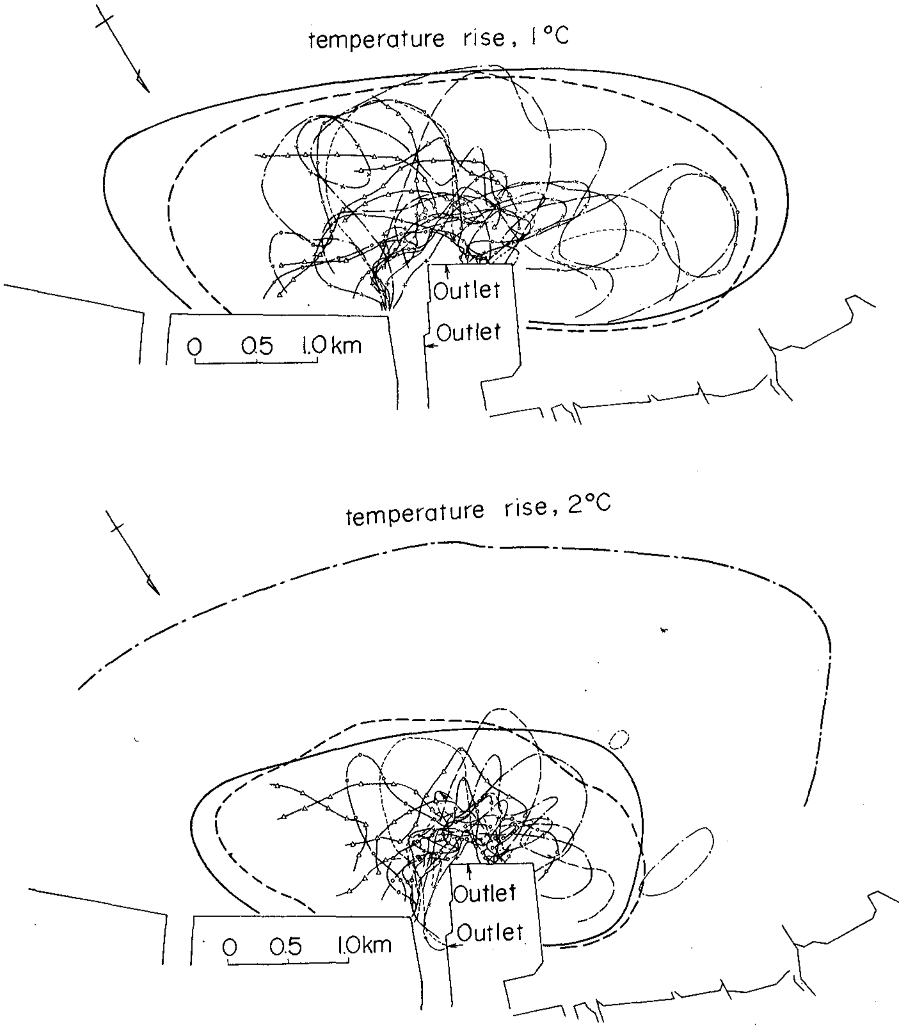

Fig. 7 Camparisan between madel and pratotype diffusian areas.
(Diffusion areas af madel show the areas in which the thermal extents at varians tidal phases are envelaped.

– – – distortian rote, 5
—— distortion rate, 10 } model results
—·— distortion rote, 20

other line : Actual meosurments in prototype