CHAPTER 87

HYDRAULIC MODEL EXPERIMENT ON THE DIFFUSION DUE TO THE COASTAL CURRENT

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ABSTRACT

The diffusion phenomena due to the tidal current and the longshore current inside and outside a harbor are studied in a hydraulic model experiment, for which the Kashima Harbor area is used as the prototype. The tidal current, the longshore current and the effect of density are taken into account, but the direct effects of wind and waves are not considered.

A model of Kashima Harbor, with horizontal and vertical scales of 1/500 and 1/63 respectively, was constructed, and a semidiurnal tide generated by an automatically controlled pneumatic tide generator and longshore current by a water circulating system were provided for it. The water level at 4 stations and current pattern were measured. The diffusion of dyed water from instantaneous point sources and a continuous point source was investigated by the photographic method and dye concentration analysis.

INTRODUCTION

After the completion of new coastal industrial zones, which are now under construction or in the planning stage, it is expected that various kinds of industrial waste water will be discharged into the sea so that water pollution may become an important problem. In order to execute such a plan rationally it is essential to forecast its probable after-effects and the hydraulic model experiment is one of the most useful means of doing so[1].

Generally there are many factors controlling the diffusion phenomena in the sea, for example the ocean current, the tidal current, the longshore current, density stratification, waves, the wind and so on. In this study, however, the tidal current, the longshore current, and the effect of density are taken into account.

Kashima Harbor, which faces directly to the Pacific Ocean, was used as the prototype.

PROTOTYPE

The Kashima Nada Coast is a monotonously straight coast 70 km long as shown in Fig. 1. The bottom slope in this area is about 1/150 to a depth of 20 m and less than 1/500 from 20 to 40 m as shown in Fig. 2. The contour lines are almost parallel to the coastal line. Kashima Harbor, an artificial harbor for 100,000 ton ships, is now under construction in this area. The water depth in the harbor is 16 m at the entrance and 10 m in the inner part of the harbor. The southern breakwater is 2.8 km long and the northern one 1.4 km. The bottom material in this area is fine sand with a median diameter of 0.13 to 0.17 mm as shown in Fig. 2[2].

There are three major ocean currents in this area as shown in Fig. 3, that is, the Kuroshio, Tsushima Current, and Oyashio. The former two are warm currents and the latter is a cold current. The current pattern in this area is very complex and the relation between such ocean currents and the longshore current in front of Kashima Harbor is not so clear. The longshore current often flows northwards in summer and southwards in winter, which corresponds with the main direction of the winds.

The tidal constants in this area are shown in Table 1. The spring tidal range is about 94 cm and the neap range 35 cm at Choshi, 25 km away from Kashima Harbor. The monthly mean sea level is highest in October and lowest in April as shown in Table 2. The difference between them is about 25 cm.

Table 1 Tidal constant in the prototype

Constituent / Station	M_2		S_2		K_1		O_1	
	H(cm)	κ(°)	H(cm)	κ(°)	H(cm)	κ(°)	H(cm)	κ(°)
Onahama	30.2	127.2	13.9	161.2	22.4	172.6	17.3	159.3
Choshi	32.2	130.7	14.6	163.4	23.0	175.8	18.6	159.6
Mera	35.6	141.3	16.3	171.9	21.6	175.3	16.7	158.5

The current ellipses obtained at a point 16 m deep are shown in Fig. 4. In this figure the length written on the right of the figure shows the value above the bottom. The diurnal tidal current flows almost parallel to the coastline (NNW-SSE) and the semidiurnal rather normal to that (NE-SW).

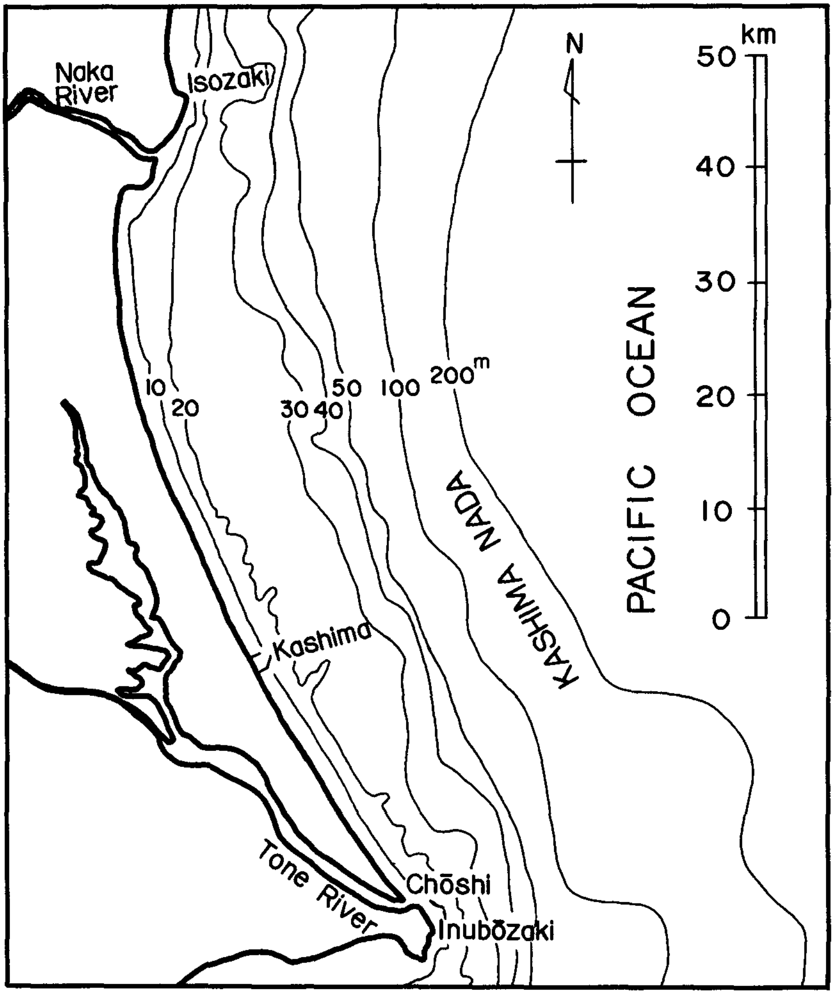

Fig. 1 Bathymetric chart of the Kashima Nada

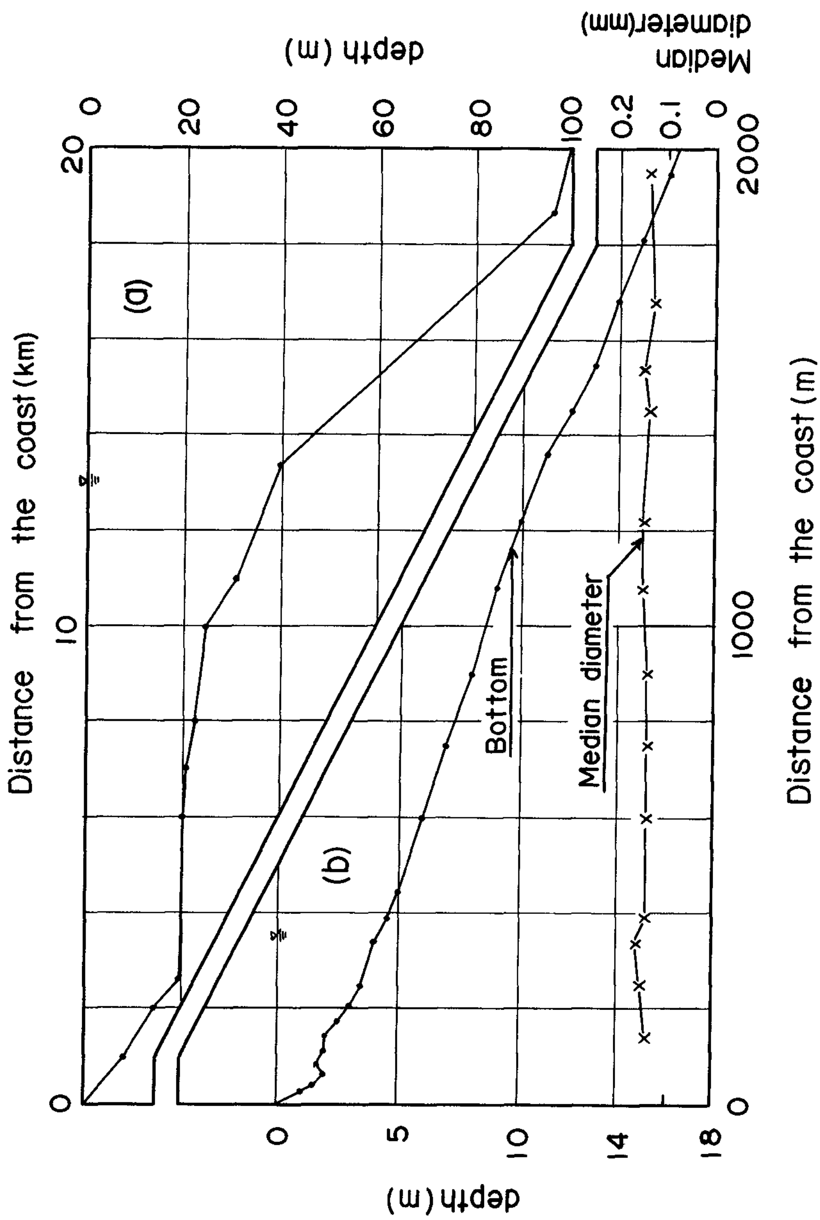

Fig. 2 Bottom profile near the coast (a) and median diameter of bottom material (b)

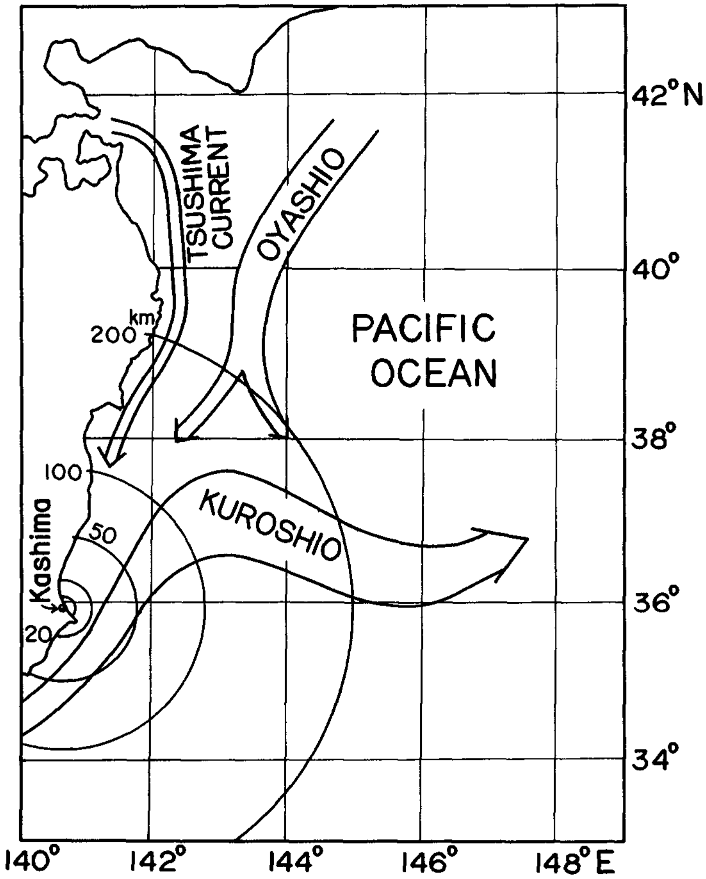

Fig. 3 Ocean currents near the Kashima Nada

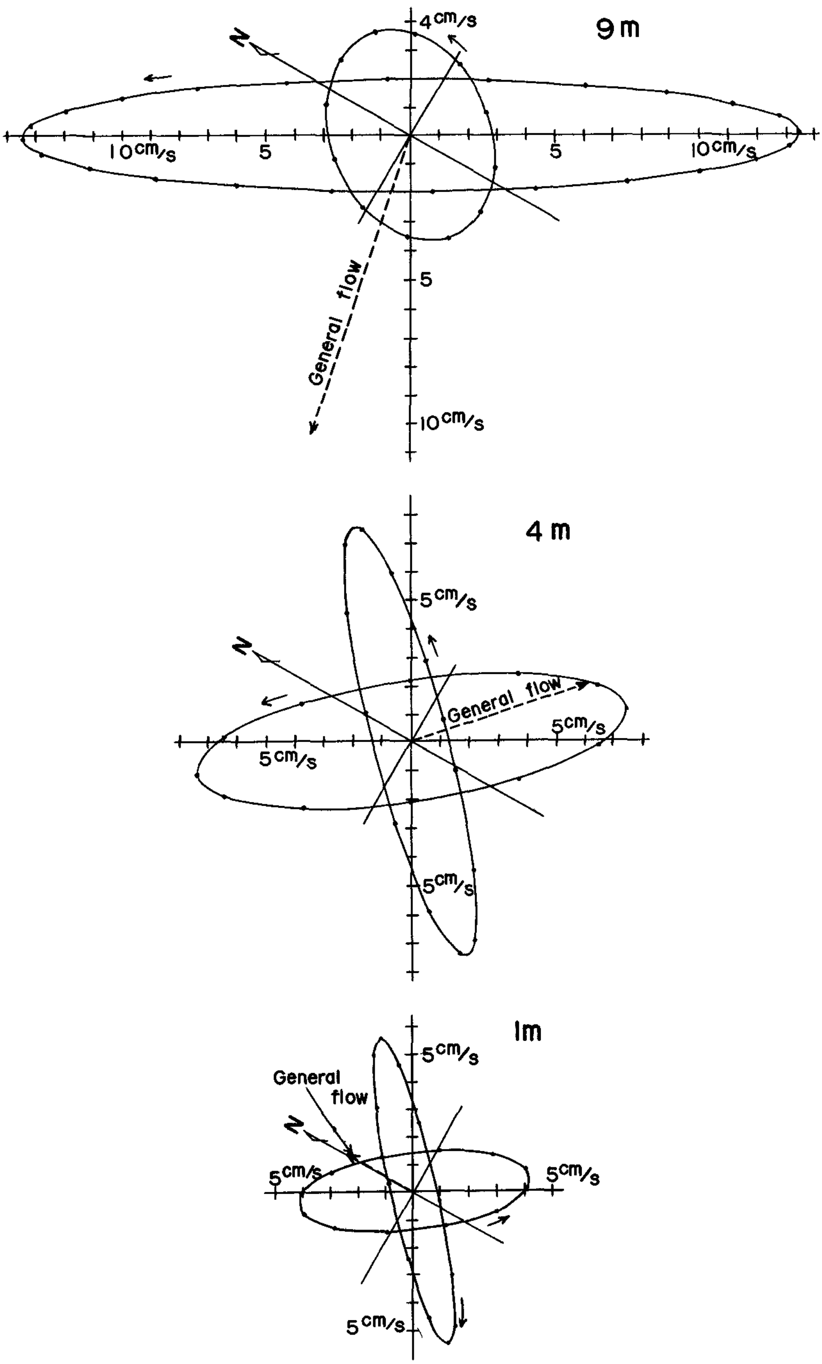

Fig. 4 Tidal ellipse at Kashima at 1, 4, and 9 m above the bottom

Table 2 Monthly mean sea level at Choshi (1955 ~ 1965)

Month	1	2	3	4	5	6	
Sea level (cm)	107.9	98.5	94.3	90.0	91.8	101.6	
	7	8	9	10	11	12	Mean
	106.8	111.4	114.6	115.1	107.2	107.6	103.9

When industrial waste water is discharged into the sea, it is supposed that the diffusing area consists of two regions[3] ; the first region, in which vertical mixing mainly occurs due to the upwards intrusion of sea water into the waste water, and the second region, in which horizontal mixing mainly occurs due to the horizontal eddy diffusion. As to Kashima Harbor, it is to be expected that the inner part of the harbor will belong to the first region and the outer part to the second region. Since the harbor has not yet been constructed, a field observation for the diffusivity was carried out only in the outer part of the harbor. This was made by taking aerophotographs of dye patches. A sketch of the movement of the dye patches is shown in Fig. 5. The time change of the area of the dye patches is shown in Fig. 6. In this figure the letters A,B, etc. show the locations in Fig. 5.

The concentration of the dye at time t in the dye patch, which had the symmetrical distribution $C = Co \exp(-r^2/a^2)$ initially, was obtained as follows.

$$C = \frac{C_o}{1 + 4Kt/a^2} \exp\left\{\frac{-r^2}{a^2\,(1 + 4Kt/a^2)}\right\} \tag{1}$$

from

$$\frac{\partial C}{\partial t} = K\left(\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\,\frac{\partial C}{\partial r}\right) \tag{2}$$

Supposing the same concentration at the rim of the patch the concentrations at t_{i-1} and t_i are written as follows,

$$\frac{C_o}{1+4Kt_i/a^2} \exp\left\{\frac{-r_i^2}{a^2(1+4Kt_i/a^2)}\right\} = \frac{C_o}{1+4Kt_{i-1}/a^2} \exp\left\{\frac{-r^2_{i-1}}{a^2(1+4Kt_{i-1}/a^2)}\right\}$$

Assuming

$$\frac{1}{1 + 4Kt_i/a^2} \sim \frac{1}{1 + 4Kt_{i-1}/a^2}$$

and

$$\exp\left\{\frac{-r^2}{a^2(1 + 4Kt/a^2)}\right\} \sim 1 - \frac{r^2}{a^2(1 + 4Kt/a^2)}$$

the diffusivity is written as follows,

$$K \sim \frac{r_i^2 - r^2_{i-1}}{4(t_i - t_{i-1})} \tag{3}$$

or

$$K \sim \frac{\Delta S_i}{4\pi \Delta t_i} \tag{4}$$

where $S = \pi r^2$, $S_i - S_{i-1} = \Delta S_i$ and $t_i - t_{i-1} = \Delta t_i$. The relation between the diffusivity K_p evaluated by this equation and the equivalent radius of the patch r is shown in Fig. 7. The slope of the straight line in the figure is 4/3.

SIMILITUDE

In the hydraulic model experiment for the coastal current it is necessary for the following equations to be valid in order to hold a dynamic similitude between the prototype and the model

$$t_r = x_r h_r^{-1/2} \tag{5}$$

and

$$n_r = x_r^{-1/2} h_r^{2/3} \tag{6}$$

where x is the horizontal length, h the vertical length, t the time, n Manning's roughness coefficient, and the suffix r shows the ratio of the quantity in the prototype to that in the model.

When the flow in the model belongs to the turbulent regime the 4/3 power law, $K = \epsilon^{1/3} L^{4/3}$, must be valid, where ϵ is the rate of energy dissipation. On the other hand, the ratio of the diffusivity K_r is expressed by $K_r = x_r^2 t_r^{-1}$ from the consideration of the dimension. Equating both diffusivities under the condition $L_r = x_r$, we get

$$u_r = \epsilon^{1/3} x_r^{1/3} \tag{7}$$

Assuming $\epsilon_r = 1$, the following equations are obtained from equations (5), (6), and (7).

$$h_r = t_r = x_r^{2/3} \tag{8}$$

$$n_r = x_r^{-1/18} \tag{9}$$

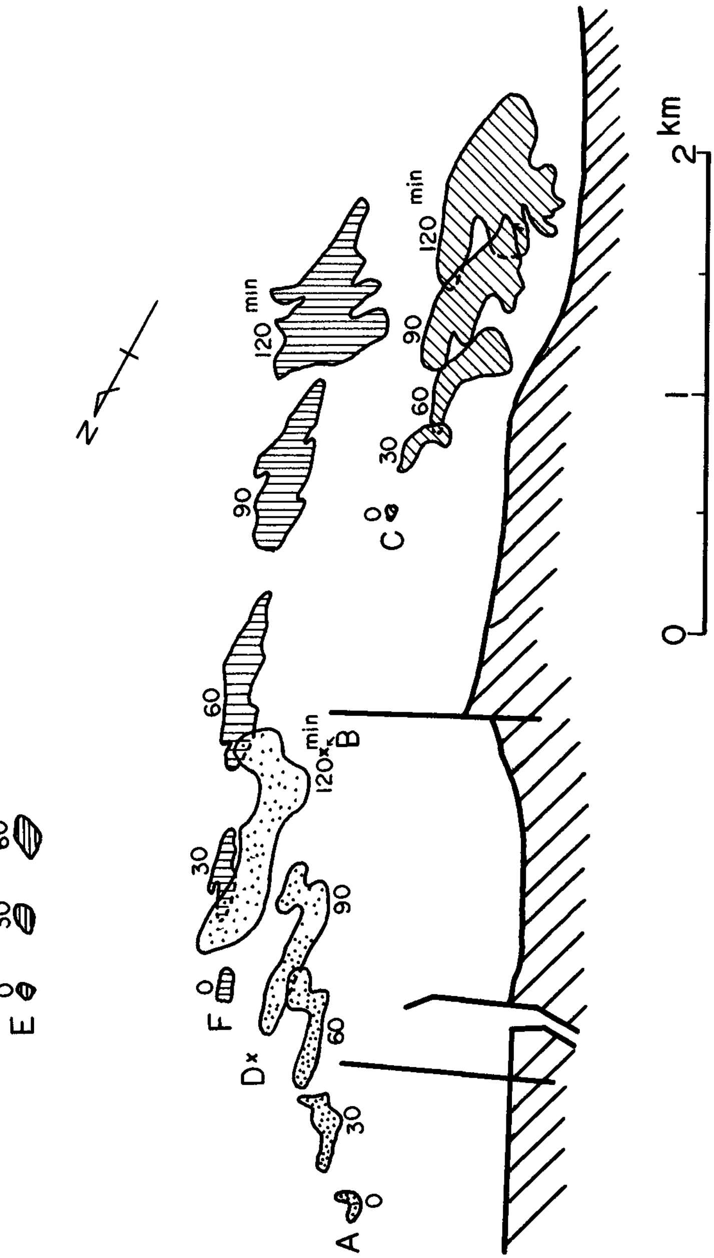

Fig. 5 Sketch of change in the area of dye patches from instantaneous point sources (prototype)

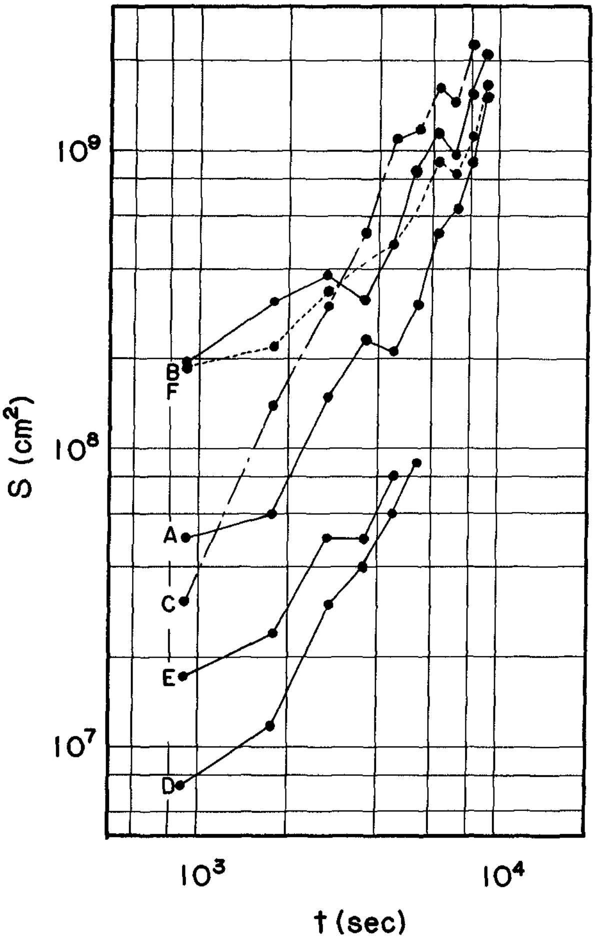

Fig. 6 Change of area with time of dye patches from instantaneous point sources (prototype)

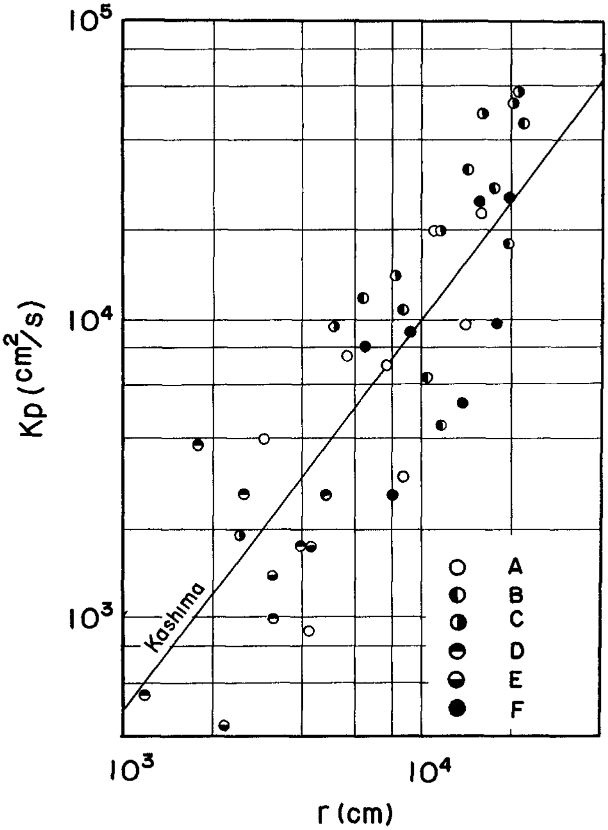

Fig. 7 Diffusivity K_p and equivalent radius r (prototype)

As to the horizontal diffusivity, we get

$$K_r = x_r^{4/3} \tag{10}$$

When $x_r = 500$, other scale ratios become as follows; $h_r = 63$, $t_r = 63$, and $n_r = 0.7$.

The Reynolds number in the area changes according to the tidal phase and the strength of the longshore current. The maximum value in the model is expected to be 3200 at the entrance of the harbor assuming the current velocity to be 10 cm/sec in the prototype. Therefore it can be regarded as an experiment in the turbulent regime.

The hydraulic factors in the model are shown in Table 3.

Table 3 Hydraulic factors in the prototype and the model

Factors	Scale	Prototype	Model
Distance	1/500	4 km	8 m
Water depth	1/63	16 m	25 cm
Tidal range	1/63	126 cm	2 cm
Tidal period	1/63	12 hr 25 m	11 m 50 s
Current velocity	1/8	10 cm/s	1.3 cm/s
Discharge	$1/2.5 \times 10^5$	$9 \times 10^5 m^3/day$	$42 cm^3/s$
Diffusivity	$1/4 \times 10^3$	$4 \times 10^3 cm^2/s$	$1 cm^2/s$

EXPERIMENT

The experiment was carried out at Ujigawa Hydraulic Laboratory, Disaster Prevention Research Institute, Kyoto University.

A model of Kashima Harbor, as shown in Fig. 8 with horizontal and vertical scales of 1/500 and 1/63 respectively, was made of concrete. The bottom roughness in the model was fixed at n = 0.015 by use of sand of 3 mm in median diameter. In this study the model of the harbor in the temporary stage was used, that is, the harbor was closed along the broken lines in Fig. 8. The semidiurnal tide and the longshore current were provided by an automatically controlled pneumatic tide generator and by a water circulating system, respectively. The water level at 4 stations is measured by wave meters of the electric resistance type. The flow pattern was obtained by intermittently photographing many floats scattered on the water surface with 35 mm cameras. The vertical distribution of the current velocity was measured by photographing the colored line drawn by a dye particle in the water. The diffusion from instantaneous point sources and a continuous point source was investigated mainly by the photographic method and dye concentration analysis. Warm water colored by 'methylen blue' dye was used in place of waste water. The difference of the density between sea water and waste water in the model is usually controlled so as to be 1.4×10^{-3}.

The time change of the visual area of dye patches was

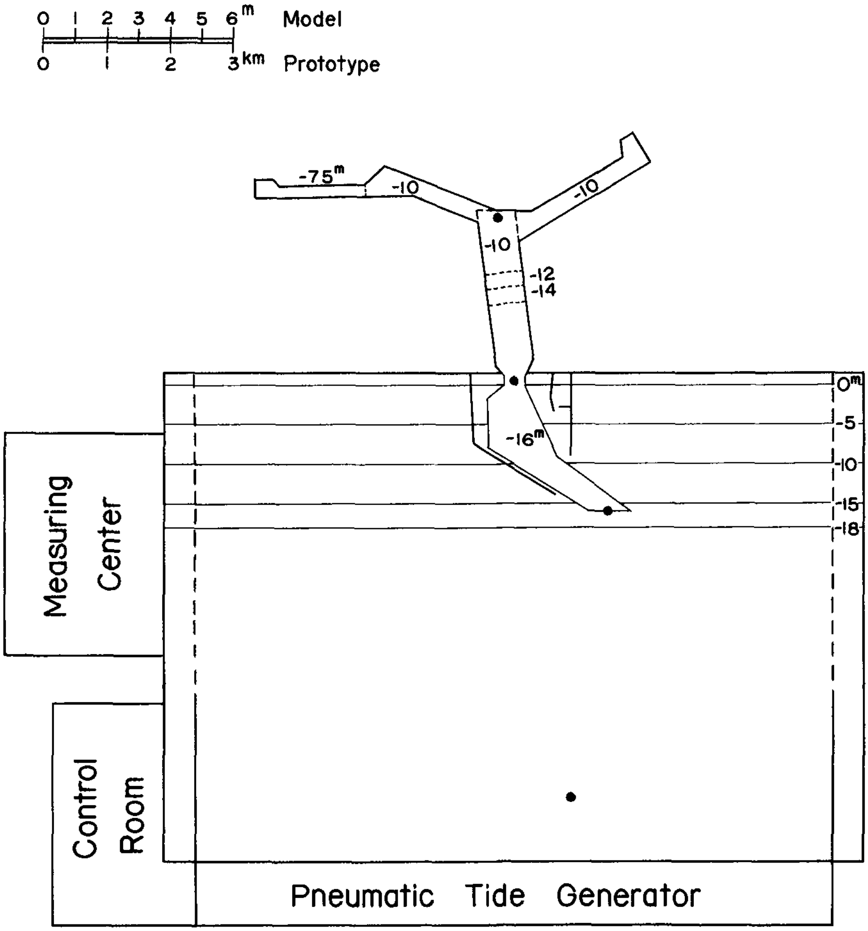

Fig. 8 Model of Kashima Harbor

observed in the same way as in the prototype. When only the semidiurnal tide is provided the diffusivity in and out of the harbor in the model reduced by $K = \Delta S/4\Delta t$, by using warm colored water, is shown in Fig. 9 against the equivalent radius of the patch r. The straight line indicates the value obtained in front of the harbor in the prototype (Fig. 7). The diffusivity in the model is smaller than that in the prototype. This may be caused by the different conditions in the prototype and in the model, that is, there was a southerly longshore current of 20 to 30 cm/sec in the prototype but only the semidiurnal tide was provided in the model.

The diffusivity in the harbor is shown in Fig. 10 when both the semidiurnal tide and the discharge of fresh water of $4.5 \times 10^5 m^3$/day from the innermost part of the harbor were provided. The diffusivity is about twice that of the preceding result (Fig. 9). It is considered that the discharged water stimulates the turbulence in the harbor. This figure shows that the diffusivity is about $10^4 cm^2$/sec for the dye patch of 100 m in equivalent radius.

As to the diffusion out of the harbor in presence of both the semidiurnal tide and the longshore current of about 25 cm/sec, the diffusivity has been reduced by $K = \Delta W^2/32\Delta t$ for the plume discharged from a continuous point source, where W is the width of the plume. The result is shown in Fig. 11. In this figure N means the result for northerly current and S for southerly current. Although the methods of analysis are different from each other, the experimental value agrees well with the one observed (Fig. 7).

The front of the dyed water continuously discharged from the innermost part of the harbor is shown in Fig. 12. The full line indicates that in the case without tide and the broken line that with tide. When a discharge of $9 \times 10^5 m^3$/day is provided the front comes to the harbor entrance after 2 days, and it goes out to the open sea as a potential flow. The presence of the tide accelerates the diffusion. When the front passes through the harbor entrance in presence of the tide it is pushed into the harbor at high tide and pulled out of it at low tide.

The concentration of the dye near the surface and the sketch of the vertical section along the center line of the harbor is shown in Fig. 13. Entry mixing occurs in the region of the first 1 to 1.5 km and then mixing is weak until a little outside the narrow part (st. 7) and it becomes strong again in the sea area. The length of the region where entry mixing occurs depends on the rate of discharge, that is, the larger the discharge provided is, the longer the length of the region appears.

When both the tide and the longshore current are provided the dyed water pulled out of the harbor at low tide flows discontinuously like a mass of cloud downstream with the longshore current and diffuses horizontally in the early stage. In the later stage, that is, after a few days, the dyed water flows continuously out of the harbor like smoke from a chimney.

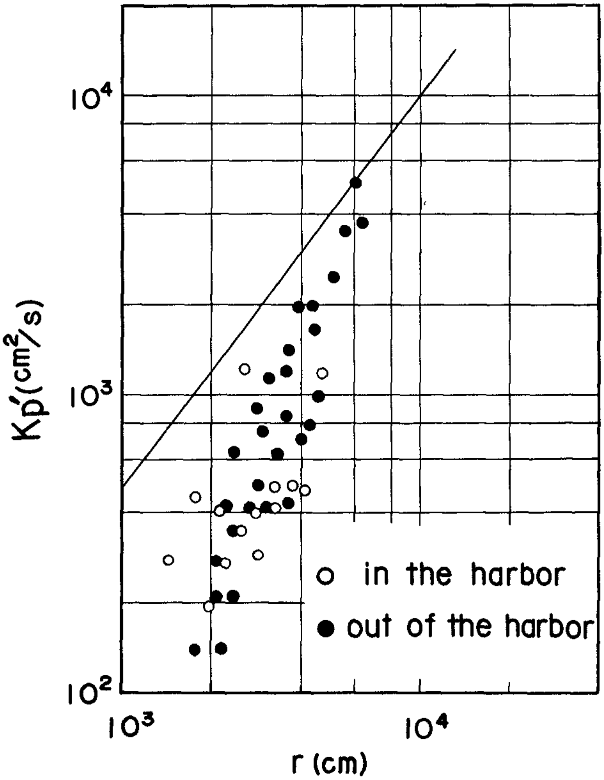

Fig. 9 Diffusivity K_p' and equivalent radius r in presence of the tide (model)

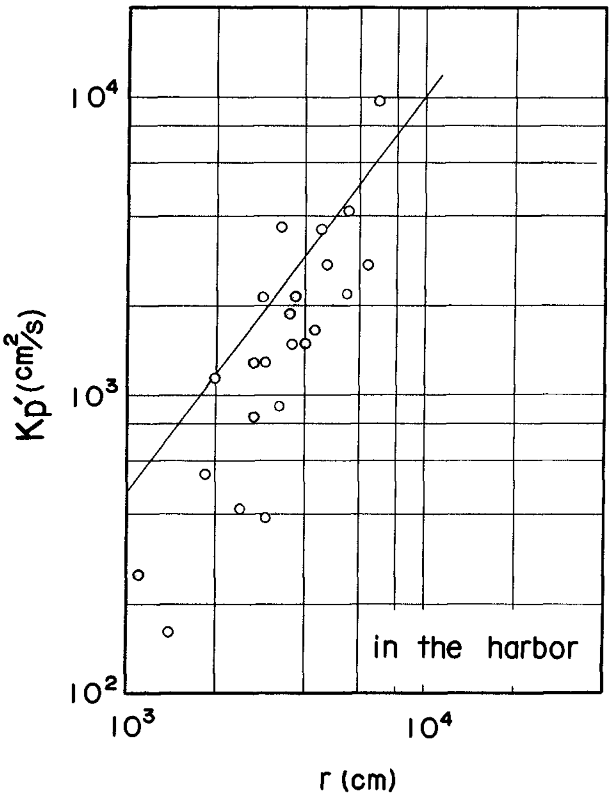

Fig. 10 Diffusivity K_p' and equivalent radius r in presence of both tide and discharge (4.5×10^5 m^3/day) (model)

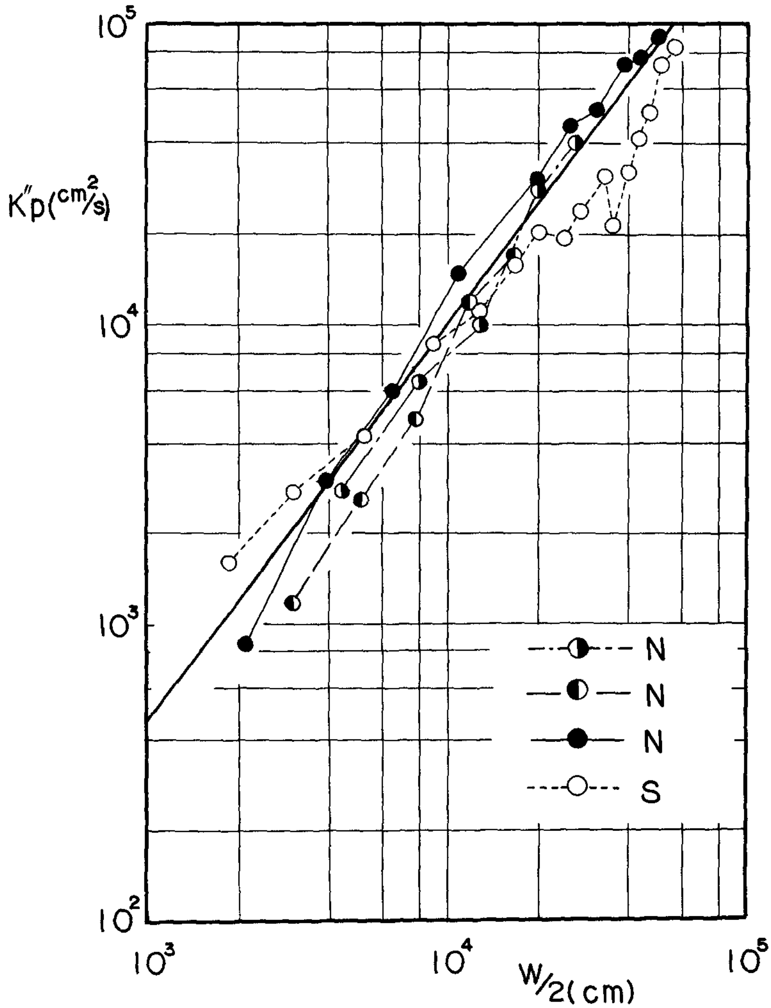

Fig. 11 Diffusivity K''_p and a half of the width of the plume W/2 in presence of both tide and longshore current (model)

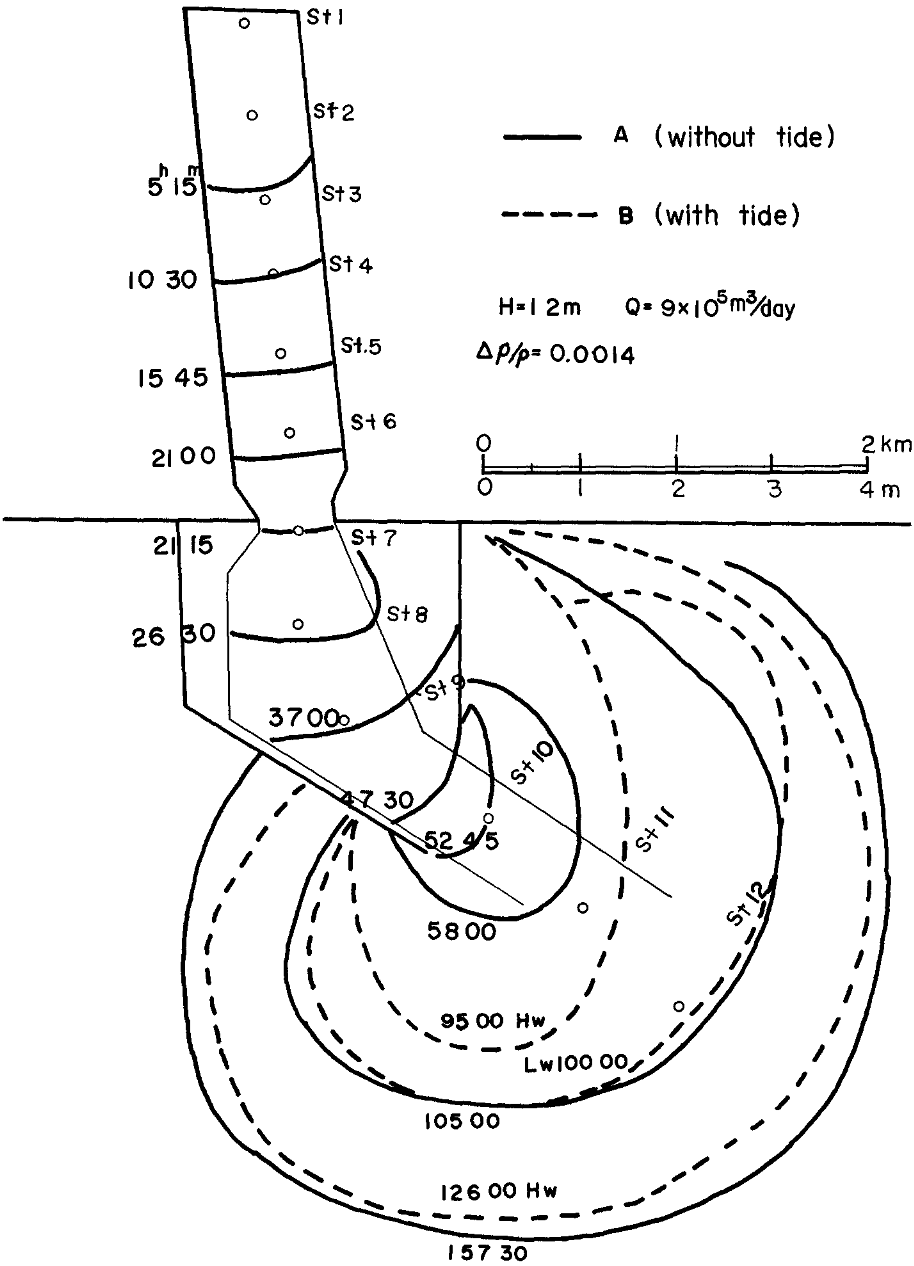

Fig. 12 Change of area with time of dyed water from a continuous point source (model)

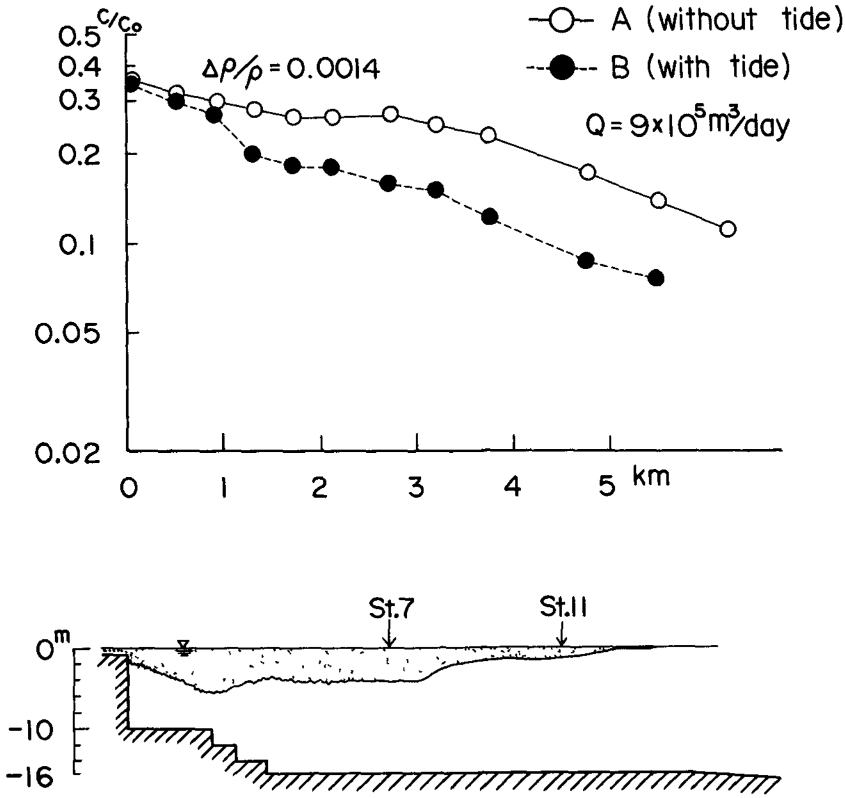

Fig. 13 Horizontal distribution of the relative concentration near the surface (upper)and a sketch of the vertical section (lower) (model)

CONCLUSION

By the present hydraulic model experiment, where the model used to represent the semidiurnal tide and the longshore current had a horizontal scale of 1/500 and a vertical scale of 1/63 and where the direct effect of wind and waves were disregarded, it is established that the diffusion phenomena out of the harbor are almost reproduced in the model. Since the tidal current and also the diffusion are considered to be reproduced in the harbor, the diffusion of waste water in the prototype is expected to be almost the same as in the model.

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