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Three-dimensional Numerical Modelling of Seawater Circulation of Semi-enclosed Bay with the Flow-control Structures

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ABSTRACT: *The characteristics of tidal circulation with the flow-control structures using the three-dimensional numerical model (POM, Princeton Ocean Model) of Chinhae Bay, Korea were investigated. To confirm the efficiencies of flow-control structures, the training wall and submerged training wall were constructed at the mouth and narrow channel in Chinhae Bay. On the basis of the present investigation, the tidal circulation induced by the construction of flow-control structures could enhance the water exchange improvement appropriately. And, the training wall at the central channel is more dominated than the other structures for the efficient of water exchange. The sites and types of structure and flow patterns seem to be very sensitive in tidal simulation and changes in flow fields.*

1. Introduction

The Chinhae Bay with surface area of 680 km^2 (Figure 1) also has the characteristics of an enclosed basin, which is located in the southern part of Korea peninsula and have problems in water quality and the environmental managements to solve it have been conducted. Observed data reveals that the semi-diurnal tide predominates in the tidal circulation. Tidal transport through the eastern channel, Kaduk channel during the semi-diurnal tidal period is estimated to be 86~90% of total transport at the spring tide, and 61~80% at the neap tide (Chang *et al.*, 1984).

Recently, Kim *et. al.*(2000) are investigated to confirm the efficiencies of flow-control structures using the hydraulic and two-dimensional numerical model of Chinhae Bay. And the tidal circulation induced by the construction of flow-control structures could enhance the water exchange improvement approximately.

The purpose of this study is to present the general features of tidal circulation and to investigate the efficiencies of flow-control structures by the three-dimensional numerical modelling and to compare the results of hydraulic and two-dimensional numerical model experiments by Kim *et al.* (2000) in Chinhae Bay.

2. Three-dimensional Numerical Model Experiments

2.1 Three-dimensional numerical model

The POM (Princeton Ocean Model) used here is a three-dimensional, free surface, primitive equation ocean model which uses the terrain-following sigma coordinate system in the vertical (Blumberg and Mellor, 1987). The numerical scheme used is finite-difference, centered-space in the horizontal, implicit in the vertical, and leapfrog in time. An Asselin filter is used to suppress the numerical noise (Asselin, 1972). The horizontal grid difference scheme is rendered on an Arakawa C-grid and it is split into a two-dimensional external (depth-integrated/barotropic) mode and a three-dimensional internal (baroclinic) mode, for computing the three velocity components, density, surface elevation, and turbulence parameters. The lateral friction and diffusion terms are calculated by the Smagorinsky (1963) parameterization, while the vertical turbulent mixing is parameterized through the use of the eddy viscosities and diffusivities calculated according to the level 2.5 turbulence closure scheme (Mellor and Yamada, 1982). POM has been applied to coastal and estuarine regimes, the Gulf Stream, and many other oceanic regions including simi-enclosed seas, Mediterranean Sea, and South China Sea. Further details concerning the numerics are documented in Blumberg and Mellor (1987), and a description of the model code is given in Mellor (1993).

By assuming an incompressible ocean, the POM solves the following basic equations with two simplifying approximations : hydrostatic and Boussinesq. The continuity equation is

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0 \qquad (2.1)$$

where U, V and W are the horizonal, meridional, and vertical components of the velocity, respectively. The Reynolds-averaged momentum equations are

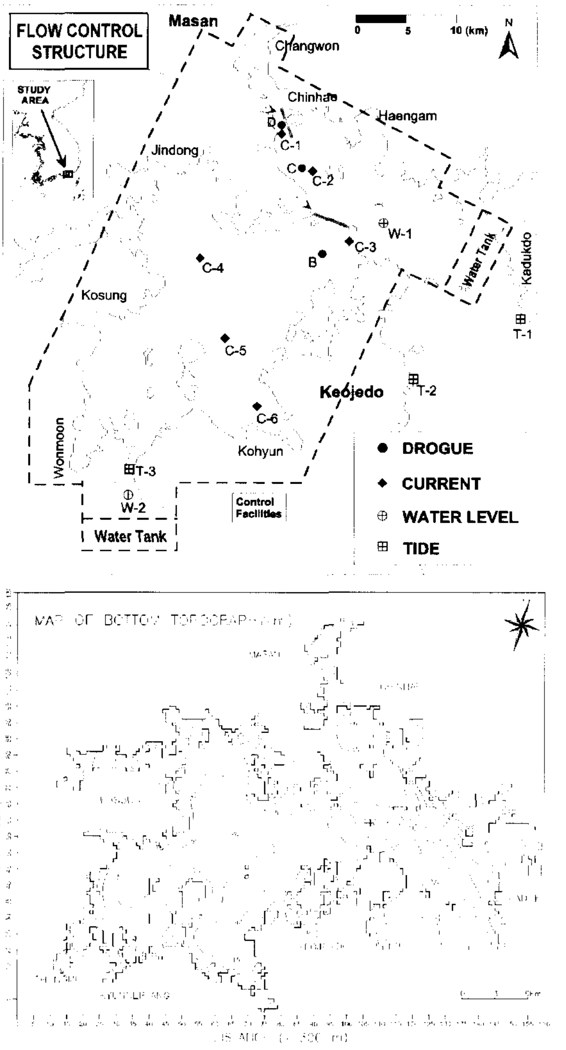


Fig. 1 Modelling domain (upper) and bottom topography and computational grid system (lower) in Chinhae Bay

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + W\frac{\partial U}{\partial z} - fV = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}\left(K_M\frac{\partial U}{\partial z}\right) + F_x \qquad (2.2)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + W\frac{\partial V}{\partial z} + fU = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + \frac{\partial}{\partial z}\left(K_M\frac{\partial V}{\partial z}\right) + F_y \qquad (2.3)$$

$$\rho g = -\frac{\partial P}{\partial z} \qquad (2.4)$$

where ρ_0 and ρ are the reference density and in situ density, respectively; g is the gravitational acceleration, P is the pressure, K_M is the vertical eddy viscosity, and f is the Coriolis parameter on the β-plane and F_x and F_y are the horizontal components of friction.

Table 1 Scale of prototype and model in the flow-control structures

Structures	Distance Scale (Water depth)	Prototype	Model
Training wall (Jetty)	1/2,000 (1/159)	300m×4km (25m)	0.15m×2m (0.16m)
Submerged Training wall	1/2,000 (1/159)	300m×4km (15m)	0.15m×2m (0.09m)
Floating Training wall	1/2,000 (1/159)	300m×1.2km (5m)	0.15m×0.6m (0.03m)

Table 2 Cases of the numerical model experiment

Case	Structure type	Remark
CASE 0	Present state	
CASE 1	Submerged Training Wall at CS	
CASE 2	Training Wall at CS	Table 1 & Table 3 CS : Central Channel MB : Masan Bay
CASE 3	Training Wall at CS, MB	
CASE 4	Training Wall at MB	
CASE 5	Submerged Training Wall at CS, Training Wall at MB	

2.2. Numerical model experiments

On the basis of Kang (1999), the variations of the tidal currents due to the flow-control structures were simulated using the three-dimensional numerical model (POM, Princeton Ocean Model) in Chinhae Bay. Physical scales of parameters are deduced in accordance with the Froude's similarity law, and are listed in Table 1 (Kim *et al.*, 2000). To confirm the effectiveness of flow control structures, the training wall (Jetty) and submerged training wall were constructed at the mouth and narrow channel of Masan bay, inner bay in Chinhae Bay (Figure 1; Table 2).

This model consist of 160×130 horizontal cells and 5 vertical levels (Table 3). The horizontal grid is fixed to 300 m in both x and y directions and the vertical division on the sigma coordinate is divided to 0.2 (Kang, 1999). It can be considered to the tidal elevation boundary condition of the main 4 tidal harmonic constituents (M2, S2, K1 and O1) on the open boundary. The computation conditions in numerical model experiments are shown in Table 3 (Kang, 1999).

3. Results and Discussion

The flood current water which flows into Chinhae Bay through Kaduk channel separated into two branches. One flows in the

Table 3 Computation conditions in numerical model experiment

Item	Computation condition
Study area	Chinhae Bay (included Masan Bay) (Figure 1)
Grid size	160 × 130 ($\Delta x=\Delta y=300$ m)
Vertical division	5 levels ($\Delta\sigma=0.2$)
Depth (h)	Nautical Chart No. 206 (D.L. - m)
Time step	DTE=2 sec, DTI=30 sec
Coriolis coeffcient (f)	$f=2\omega\sin\varphi$, $\omega=\frac{2\pi}{24\times60\times60}$, φ N
Bottom roughness coefficient (C)	$C=19.4\ln(0.9\overline{h})$
Initial values (t=0)	$u=v=w=\eta=0$
Initial horizontal diffusivity	10 m^2/sec
Initial vertical diffusivity	0.001 m^2/sec
Initial salinity & temperature	35‰ and 20℃

central Chinhae Bay turning westwards and the other in Chinhae Harbor and Masan Inlet. The maximum current speed of faster than two knots is observed along the deepest depressions in the central channel between Jangmok of Keojedo Islands (Chang et al., 1984). Observed data reveals that the semi-diurnal tide predominates in the tidal circulation. Tidal residual currents in the Kaduk and Kyunnaeryang channel and upper part of Chilchundo during the spring tide has strong eddies. Tidal residual currents in the western and northern part of the Chinhae Bay during the spring tide are very weak. Tidal residual currents rotating clockwise and anti-clockwise in the central part of the bay occur, and the currents rotating clockwise around Budo are generated.

Kim *et al.* (2000) pointed out that the hydraulic and two-dimensional numerical model experiments are able to reproduce the semi-diurnal tidal current and give an idea on the general feature of the flow pattern of water motions in Chinhae Bay. Figure 2 show the comparisons of drogue tracking between the prototype and the hydraulic model during the spring and neap tide (Kim *et al.*, 2000). And, the training wall at the central channel is more dominated than the other structures for the efficient of water exchange. They can not, however, simulate satisfactory the maximum speed of the water motion appeared at the central channel probably because they do not simulate the effects of wind, the freshwater run-off and another tidal constituents.

To investigate the efficiency of water exchange due to the flow-control structures, the six cases of three-dimensional numerical model (POM, Princeton Ocean Model) experiments including the present state during the spring tide are simulated (Table 2).

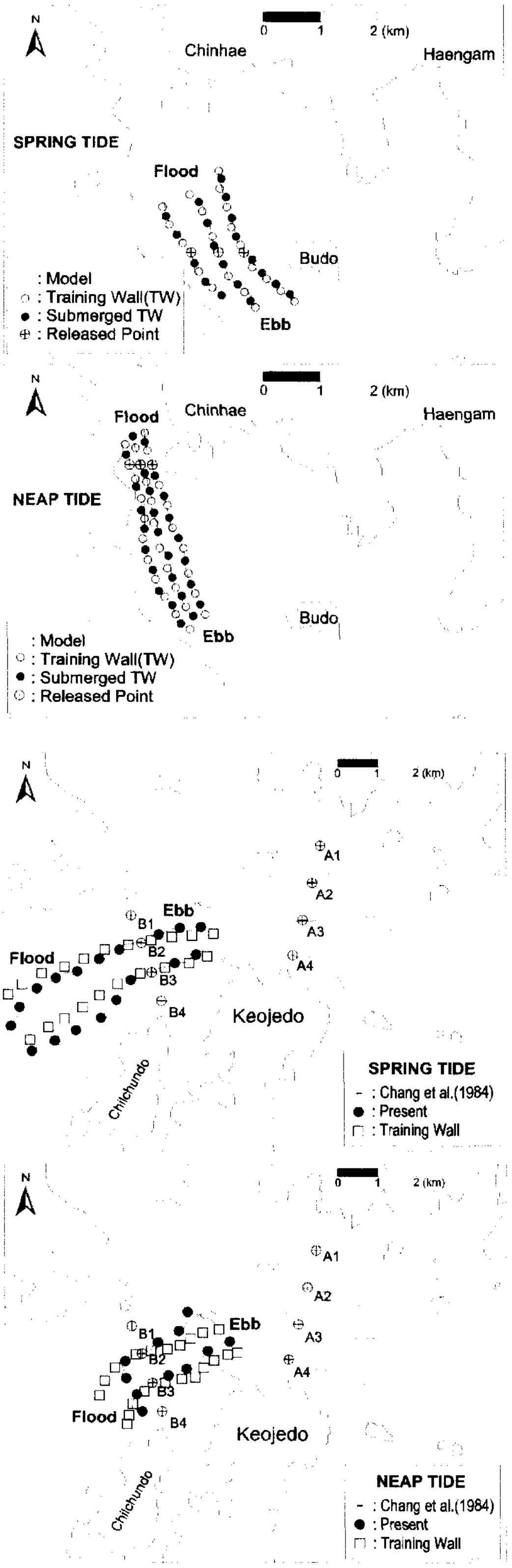


Fig. 2 Comparisons of drogue tracking between the prototype and the hydraulic model during the spring and neap tide (Kim *et al.*, 2000)

Figure 3 show the flow diagram of maximum current of flood (left) and ebb (right) flow during the spring tide in the case of the present state (CASE 0). In case of the present state, this model has represented well the three-dimensional flow patterns through the tidal phase such as the tidal phase lag, bottom frictional effects between surface layer and bottom in prognostic mode. Maximum surface current of flood and ebb flow during the spring tide is about 100~110 cm/s at the entrance of Kaduk channel and about 70 cm/s at the Kyunnaeryang channel (Figure 3).

Figure 4 show the variation of the tidal ellipses (left) and tidal residual currents (right) during the spring tide in case of the present state (CASE 0). The tidal residual currents is weak at the inner bay except the central channel of Chinhae Bay and Kaduk channel. There are many complicated eddies which have the magnitude of up to 20 cm/s and radius 3 km at the central channel of Chinhae Bay and Kaduk channel (Figure 4). Based on the results, the water exchanges of the Chinhae Bay almost take place through Kaduk channel. Therefore the water exchanges through Kyunnaeryang channel are weak.

Figure 5 show the variation of the tidal ellipses (left) and tidal residual currents (right) during the spring tide after the construction of flow-control structures in case from 1 to 5, respectively (Table 2).

The submerged training wall (CASE 1) to be increased the water exchanges was installed at the central channel of Chinhae Bay. Constructional depth is under the 5 m below the datum level. The variation of the tidal ellipses and the tidal residual currents didn't appear visually as compared with the present (Figure 4). Another is the case of the training wall (CASE 2) constructed. Based on the results, the maximum tidal currents of flood and ebb flow during the spring tide is increased up to 160 cm/s on the surface level. The tidal residual currents extended the radius to more than 5 km and the magnitude to about 30 cm/s. The sites and types of structure and flow patterns seem to be very sensitive in tidal simulation and changes in flow fields (Figure 5).

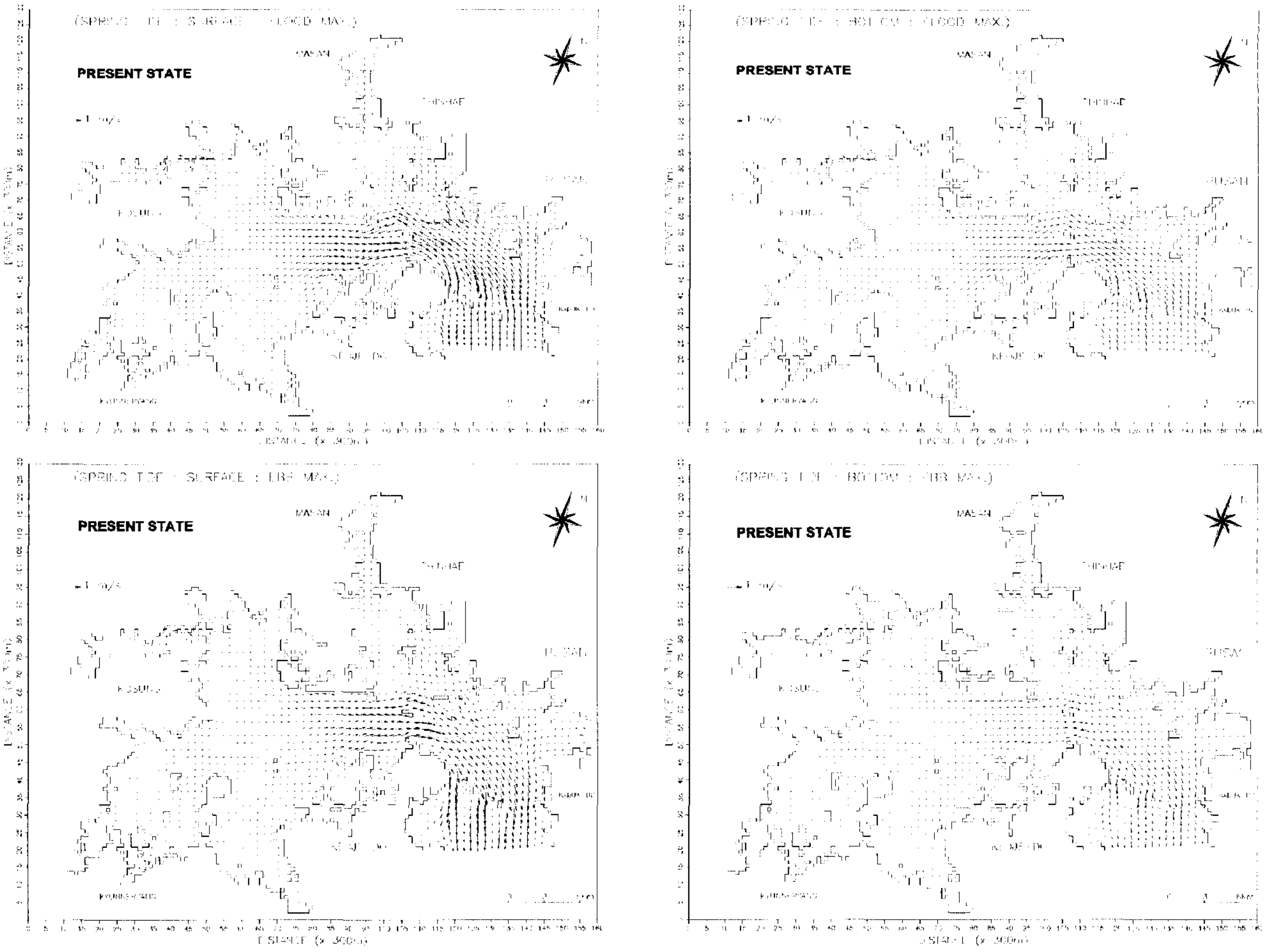


Figure 3 Show the flow diagram of maximum current of flood (left) and ebb (right) flow during the spring tide in the case of the present state (CASE 0)

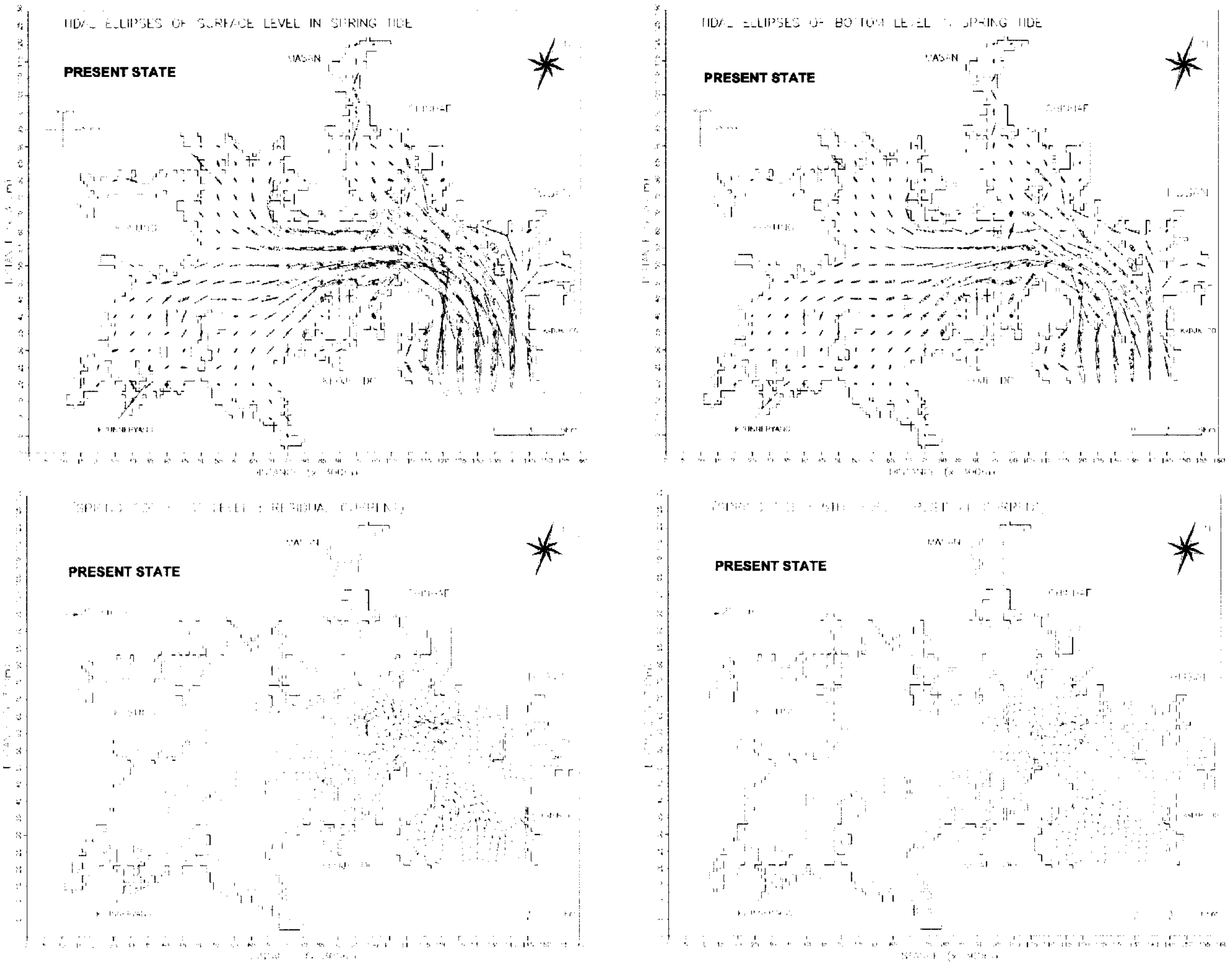
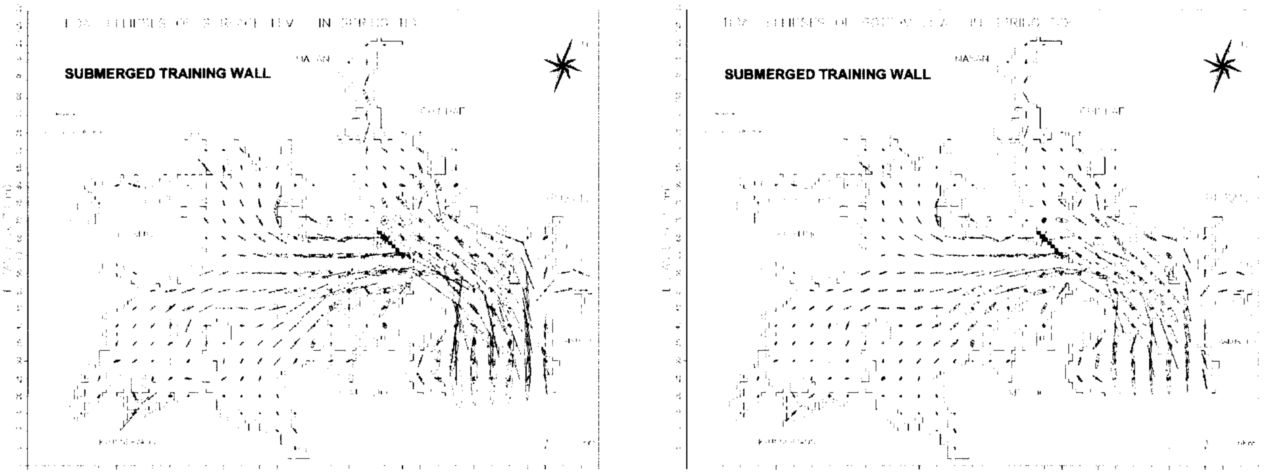


Fig. 4 show the variation of the tidal ellipses (left) and residual currents (right) during the spring tide in case of the present state (CASE 0)



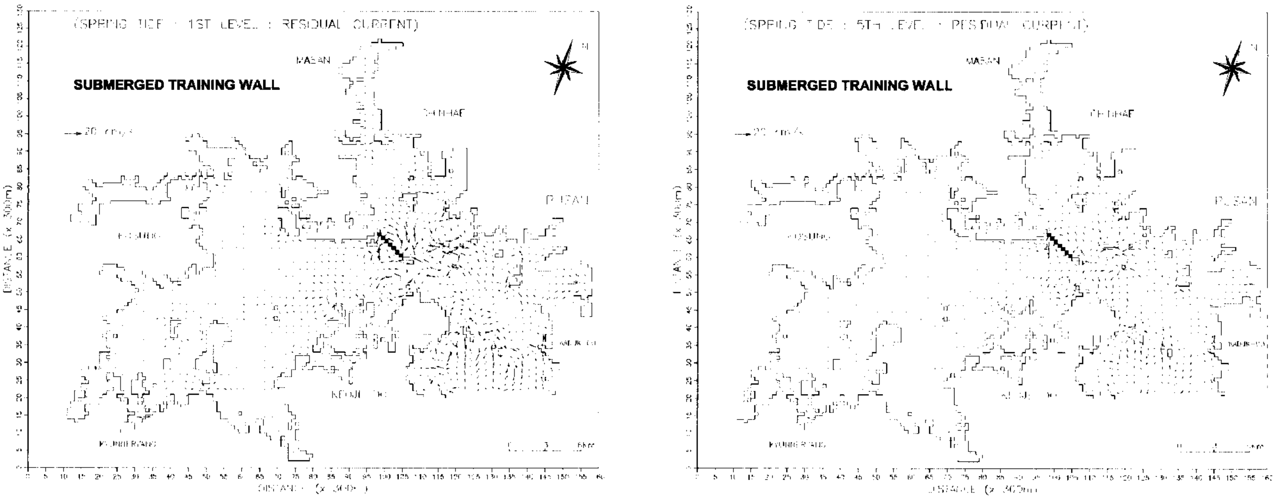


Fig. 5 show the variation of the tidal ellipses (left) and residual currents (right) after the construction of flow-control structures during the spring tide in CASE 1

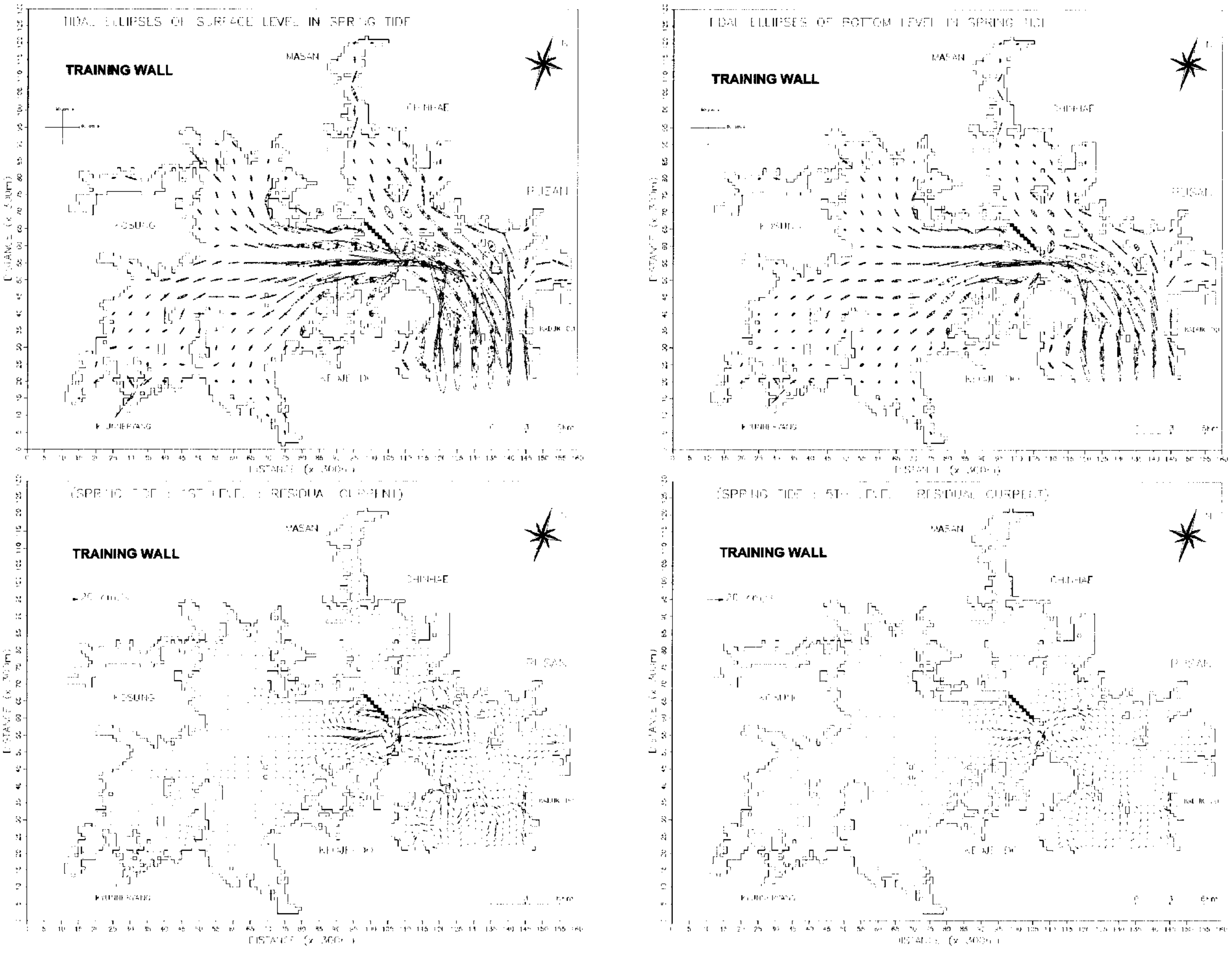


Fig. 5 (Continued) in CASE 2

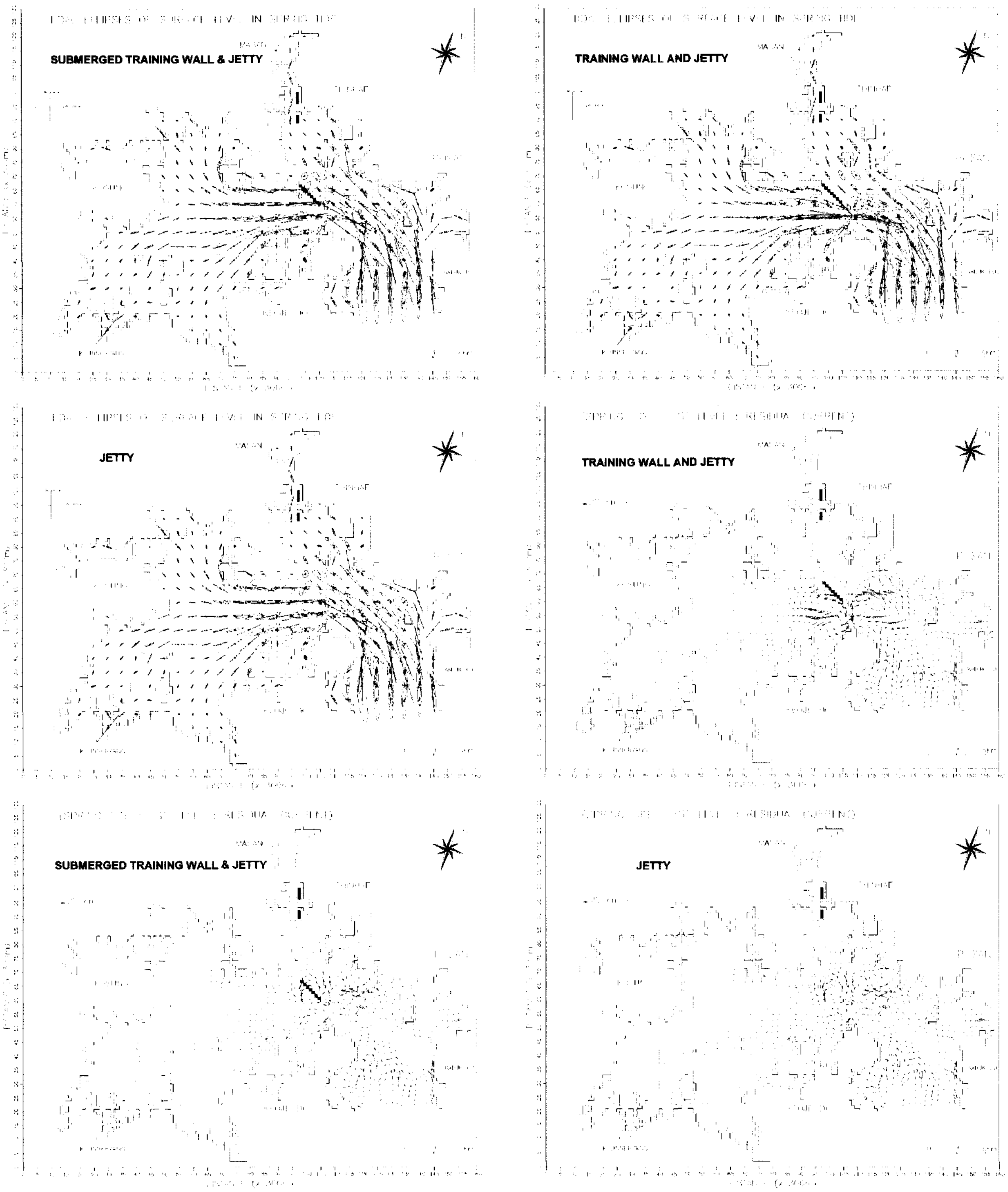


Fig. 5 (Continued) in CASE from 3 to 5

For the reasons mentioned above, the training wall at the central channel is more dominated than the submerged training wall for the efficiency of water exchange. The flow features of the three-dimensional numerical model (POM) and hydraulic model experiments (Kim *et al.*, 2000) were identified in Chinhae Bay.

4. Conclusion and Perspectives

The three-dimensional numerical model (POM, Princeton Ocean Model) experiments of tidal circulation were carried out to clarify the efficiencies of tidal exchange by the flow-control structures in Chinhae Bay. The characteristics of tidal circulation in association with each construction of flow-control structures are as follows.

The flow patterns of three-dimensional numerical experiment has represented well, and the tidal circulation induced by the construction of flow-control structures could enhance the water exchange improvement appropriately. The training wall at the central channel is more dominated than the submerged training wall for the efficiency of water exchange. The sites and types of structure and flow patterns seem to be very sensitive in tidal simulation and changes in flow fields

In the future, we can look forward to update the model results with use of observational data and data assimilation strategy. The results of this study can be used as the long-term and integrated environmental impact assessment model in the inner bay.

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