Effects of Infilling a Sea Caldron on Tidal Currents and Seaweed and Seagrass Bed Habitats

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Abstract: To investigate changes in tidal current arising from infilling a sea caldron and their influence on seaweed and seagrass bed habitats, numerical simulations of tidal current before and after infilling the sea caldron were carried out using a multi-level flow model. Separate simulations were conducted for stages of infilling to clarify stepwise changes in flow field, and changes in horizontal and vertical velocity distributions at the sea caldron were examined. Effects of changes in flow field on the seaweed and seagrass bed habitats around the sea caldron were also investigated. The results indicated that velocity distributions at both ends of the sea caldron changed in the final stage of infilling, while those at the center gradually changed as the filling progressed. The changes in flow field at the seaweed and seagrass beds were found to remain within the inhabitable range for the species present.

Keywords: Sea caldron; Tidal current simulation; Multi-level flow model; Seaweed bed; Seagrass bed

1 Introduction

The Seto Inland Sea is a representative semi-closed sea in Japan and measures about 450 km in the east-west direction and 15–55 km in the north-south direction. It contains many sea caldrons resulting from submarine erosion by tidal currents along the sea bottom (Yashima, 1994). Some of these store a bottom layer of muddy sediment, which often leads to the occurrence of hypoxia when a thermocline is dominant (Tarutani, 2007). The Seto Inland Sea also features tidal flats and seaweed beds, the conservation or regeneration of which was promoted following overdevelopment during the period of rapid economic growth (Ministry of the Environment, 2011).

The infilling of a sea caldron is a conceivable measure to prevent the occurrence of hypoxia while at the same time providing suitable substrate to allow regeneration of seaweed beds. In this regard, it is crucial to assess the influence of topographic changes to the sea bottom on the environment of the surrounding sea area. Previous studies have assessed the possibility of self-forming seaweed beds on filled-in sea caldrons, and investigated the effects on the habitats of aquatic species (Izumi *et al.*, 2014; Izumi *et al.*, 2015; Kanaguchi *et al.*, 2015).

The present study focused on changes in tidal currents. The flow fields at various stages of infilling a sea caldron were simulated by use of a multi-level flow model, and the horizontal and vertical velocity distribution in each stage were investigated. Because there are seaweed (*Sargassum horneri*) and seagrass beds (*Zostera marina*) around the sea

caldron, the influence of the change of flow field on those habitats was also examined.

2 Numerical model

A multi-level flow model (Fujihara *et al.*, 1997) was employed for tidal current simulation. The governing equations are as follows.

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla_h \cdot (\mathbf{u}\mathbf{u}) + \frac{\partial(\mathbf{u}w)}{\partial z} + f\mathbf{k} \times \mathbf{u} = -\frac{1}{\rho} \nabla p + \nabla_h \cdot (\nu_h \nabla_h \mathbf{u}) + \frac{\partial}{\partial z} \left(\nu_v \frac{\partial \mathbf{u}}{\partial z} \right) \quad (1)$$

$$\nabla_h \cdot \mathbf{u} + \frac{\partial w}{\partial z} = 0 \quad (2)$$

$$p = \int_z^\eta \rho g dz \quad (3)$$

$$\frac{\partial \eta}{\partial t} + \nabla_h \cdot \int_{-H}^\eta \mathbf{u} dz = 0 \quad (4)$$

where $\mathbf{u}$ is the horizontally two-dimensional current vector, t is time, ∇_h is the horizontal differential operation, w is vertical current velocity, z is the vertical coordinate (positive upward), f is the Coriolis parameter, $\mathbf{k}$ is the unit vector (positive upward), ρ is water density, p is pressure, ν_h and ν_v are the horizontal and vertical kinematic eddy viscosity coefficients, respectively, g is gravitational acceleration, η is free surface elevation above mean sea level (positive upward), and H is bottom depth below mean sea level. The shear stress at the bottom is expressed as

$$\nu_v \frac{\partial \mathbf{u}}{\partial z} \Big|_{z=-H} = \gamma^2 |\mathbf{u}| \mathbf{u} \quad (5)$$

where γ^2 is the bottom friction coefficient.

These equations are discretized by the finite difference

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method on the staggered grids. In the discretization, the explicit time marching scheme is employed for unsteady terms, the second-order upwind scheme for convection terms, and the central difference for diffusion terms.

3 Study area

3.1 Outline of study area

The bathymetric map of the study area is shown in Figure 1. In the center of the map, there is a sea caldron of 27 m maximum water depth below mean sea level, with a bottom formed by muddy sediment. In the south-west, seaweed beds consisting of *Sargassum horneri* and seagrass beds consisting of *Zostera marina* are found on the shores of the island.

3.2 Field observations

Field observations were carried out at flood tide (8:00–9:00) and falling tide (13:00–14:00) on 16 and 17 May 2011. Since the horizontal current dominated relative to the vertical current in the study area, flow direction and velocity in the horizontal direction were measured at stations denoted St.1, St.2, and St.3, using electromagnetic velocity meters (ACM-210D; JFE Advantech Co., Ltd.). The observation results, shown in Figure 2, were used for the validation of the tidal current simulation.

3.3 Computational conditions

In the present study, the construction of an artificial seaweed bed on the infilled sea caldron was assumed. The sea caldron is infilled up to 5 m below mean sea level. Figure 3 shows the bathymetric of the study area after infilling the sea caldron.

The computational domain measured 10 km in the east-west direction and 6 km in the north-south direction and included the 3×2 km study area (dashed frame) (Figure 4). The whole domain was discretized into 50×50 m square meshes in the plane (in the following, “horizontal”) and 10 levels in depth (in the following, “vertical”) (2 m intervals at 0–10 m, 4 m intervals at 10–26 m, and a single interval below 26 m).

As open boundary conditions, the tidal current velocities (driven by a periodic function of period 12 h and amplitude 0.39 cm/s) were given at the west boundary, and a free out-flow condition was applied along the east boundary. Along the imaginary north boundary and the land boundary, a non-slip condition was applied. The coefficients of horizontal kinematic eddy viscosity were determined according to Richardson’s 4/3 law based on the computational grid ($1.0 \text{ m}^2/\text{s}$). The coefficients of vertical kinematic eddy viscosity ($0.2 \text{ m}^2/\text{s}$) and bottom friction (0.0026) were set such as to reproduce tidal current observations.

To investigate stepwise changes in the flow field, the tidal current simulation was carried out for each state of infilling the sea caldron. Simulation cases were as follows: (1) the present state, (2) 5 m of infilling from present state (5m-up), (3) 10m-up, (4) 15m-up, (5) 22m-up. The horizontal velocity distribution of the flow field was investigated at lines A-A’, B-B’, and C-C’, and the vertical velocity distribution of flow field at points a, b, c, as shown in Figure 3.

Figure 1: Bathymetric map of study area

(a) Flood tide (b) Falling tide
Figure 2: Observation results

Figure 3: Bathymetric map after infilling the sea caldron

Figure 4: Computational domain

Table 2: Error of flow velocity in simulation

Flood tide		St. 1		St. 2		St. 3	
		AE (cm/s)	RE (%)	AE (cm/s)	RE (%)	AE (cm/s)	RE (%)
4 m	5/16	5.9	20.4	11.2	35.5	7.9	34.0
	5/17	2.8	7.3	14.2	41.0	1.5	4.7
8 m	5/16	5.2	18.5	12.0	37.6	12.8	70.3
	5/17	4.8	12.4	16.6	45.4	0.8	2.5
12 m	5/16	6.8	27.3	13.2	41.0	13.9	91.2
	5/17	5.9	15.8	12.7	40.1	1.7* ¹	6.1* ¹
16 m	5/16			15.5	46.5		
	5/17			13.3	42.7		
20 m	5/16			12.6	43.0		
	5/17			11.4	40.6		
24 m	5/16			13.6	46.8		
	5/17			6.7	30.3		
Average		5.2	17.0	12.8	40.9	6.4	34.8
Falling tide		St. 1		St. 2		St. 3	
		AE (cm/s)	RE (%)	AE (cm/s)	RE (%)	AE (cm/s)	RE (%)
4 m	5/16	6.4	16.0	9.7	31.2	9.0	39.1
	5/17	1.9	5.3	9.5	30.7	3.4	11.9
8 m	5/16	7.3	18.0	1.0	4.4	14.1	78.9
	5/17	2.4	8.0	5.4	20.4	10.3	47.6
12 m	5/16	4.3	11.8	4.0	16.8	14.7* ²	91.6* ²
	5/17	4.3	15.2	5.8	22.6	17.7* ¹	135.9* ¹
16 m	5/16			10.6	35.9		
	5/17			4.7	19.8		
20 m	5/16			8.9	33.6		
	5/17			6.9	28.2		
24 m	5/16			13.9	46.0		
	5/17			3.6	18.0		
Average		4.4	12.4	7.0	25.6	11.5	67.5

AE: Absolute error, RE: Relative error

*¹ Errors at the depth of 11 m*² Errors at the depth of 10 m

Table 3: Error of flow direction in simulation

Flood tide		St. 1		St. 2		St. 3	
		AE (°)	RE (%)	AE (°)	RE (%)	AE (°)	RE (%)
4 m	5/16	9.4	5.2	10.3	5.7	7.5	4.2
	5/17	0.4	0.2	4.7	2.6	2.5	1.4
8 m	5/16	9.2	5.1	0.8	0.5	5.8	3.2
	5/17	10.2	5.7	10.2	5.6	2.2	1.2
12 m	5/16	14.9	8.3	2.5	1.4	12.7	7.1
	5/17	21.9	12.2	13.5	7.5	0.3* ¹	0.2* ¹
16 m	5/16			0.2	0.1		
	5/17			16.8	9.3		
20 m	5/16			1.5	0.9		
	5/17			19.5	10.8		
24 m	5/16			5.2	2.9		
	5/17			18.8	10.4		
Average		11.0	6.1	8.7	4.8	5.2	2.9
Falling tide		St. 1		St. 2		St. 3	
		AE (°)	RE (%)	AE (°)	RE (%)	AE (°)	RE (%)
4 m	5/16	10.1	5.6	22.1	12.3	1.9	1.0
	5/17	4.1	2.3	20.1	11.2	11.1	6.2
8 m	5/16	6.5	3.6	8.4	4.7	5.5	3.1
	5/17	5.5	3.1	20.4	11.3	12.5	7.0
12 m	5/16	3.6	2.0	20.2	11.2	30.2* ²	16.8* ²
	5/17	9.4	5.2	10.2	5.6	22.2* ¹	12.3* ¹
16 m	5/16			2.8	1.5		
	5/17			18.8	10.4		
20 m	5/16			1.8	1.0		
	5/17			24.8	13.8		
24 m	5/16			0.8	0.4		
	5/17			4.2	2.4		
Average		6.5	3.6	12.9	7.2	13.9	7.7

AE: Absolute error, RE: Relative error

*¹ Errors at the depth of 11 m*² Errors at the depth of 10 m

4 Results and discussion

4.1 Validation of simulation accuracy

The accuracy of the simulation was validated in terms of the reproducibility of the observation results. Tables 2 and 3 show the errors in respectively flow velocity and direction between observations and simulation. In Table 2, the gray-colored box means that the simulation overestimates the observation result.

The simulation performed well in reproducing flow direction. On the other hand, the errors in flow velocity are not necessarily negligible. Errors at St. 1 (where errors were smallest) reached maxima of average absolute and relative errors of 5.2 cm/s and 17.0%, respectively. Average absolute and relative errors at St. 2 were below 12.8 cm/s and 40.9%, respectively, and the reproducibility of falling tide was higher than that of flood tide at this station. Reproducibility

of falling tide at St. 3 was the lowest of all observation points, with average absolute and relative errors of respectively 11.5 cm/s and 67.5%. Achieving high reproducibility at all observation points proved difficult. Although simulations using a fine computational grid (25 × 25 m mesh) were carried out to improve reproducibility, little improvement in reproducibility and much computation time were obtained. There was also the potential for introducing errors into the observation results themselves through the field method of dropping velocimeters into the sea from the survey boat. In summary, the reproducibility of the simulated flow velocity would have benefited from improvements but was judged sufficient for the study's purposes.

4.2 Changes in flow fields

Flow fields in the surface layer at flood and falling tide as computed for the four simulation cases are shown in Figures

(1) Present state

(2) 5m-up

(3) 10m-up

(4) 15m-up

(5) 22m-up

Figure 5: Flow field in the surface layer at flood tide

(1) Present state

(2) 5m-up

(3) 10m-up

(4) 15m-up

(5) 22m-up

Figure 6: Flow field in the surface layer at falling tide

(1) A-A' line

(2) B-B' line

(3) C-C' line

Figure 7: Horizontal distribution in the flood tide

(1) A-A' line

(2) B-B' line

(3) C-C' line

Figure 8: Horizontal distribution in the falling tide

5 and 6, respectively.

At flood tide, the main flow direction was southeast (Figure 5). Changes in the flow field are centered on the sea caldron. The maximum flow velocity was 20 cm/s in the present state and eventually reached 45 cm/s, gradually increasing as infilling progressed. At falling tide, the main flow direction was northwest, with flow field changes again centered on the caldron (Figure 6). Details of the horizontal and vertical distribution of flow fields are discussed in the following subsection.

4.2.1 Horizontal distribution of flow fields

Figures 7 and 8 show the horizontal velocity distribution in the surface (top) layer at flood and falling tide, respectively. The control lines were A-A', B-B' and C-C' as shown in Figure 3, with A-A' and C-C' located at the ends of and B-B' located at the center of the sea caldron. Note that the flow velocities plotted are the values in the element of computational grid.

Horizontal flow velocity was fastest in the center (Figure 7). Distributions at A-A' and C-C' were almost identical prior to 15m-up. In 22m-up, the distribution shifted to the right or

(1) Point a

(2) Point b

(3) Point c

Figure 9: Vertical distribution in the flood tide

(1) Point a

(2) Point b

(3) Point c

Figure 10: Vertical distribution at falling tide

sharpened, and maximum flow velocity changed from 40 cm/s to 45 cm/s and from 30 cm/s to 45 cm/s at A-A' and C-C', respectively. For B-B', the distribution gradually sharpened, with maximum flow velocity changing from 20 cm/s to 45 cm/s. At falling tide (Figure 8), the tendencies in distribution changes were very similar to those of the flood tide.

4.2.2 Vertical distribution of flow velocity

Figures 9 and 10 show the vertical distribution of flow velocity at flood and falling tide, respectively, at points a, b and

c as shown in Figure 3. The flow velocity in each layer is depicted at each point.

The distribution at point a remained almost unchanged prior to 15m-up, shifting to the right at 22m-up (Figure 9); the change in velocity at the surface is equal to the change in maximum velocity (Figure 7). Point c showed similar dynamics with the exception of the distribution at 15m-up. Distributions at point b gradually shifted to the right as the infilling progressed. Distribution tendencies at falling tide were very similar to flood tide (Figure 10).

4.3 Influence on seaweed and seagrass beds

Seaweed (*Sargassum horneri*) and seagrass (*Zostera marina*) beds are present around the sea caldron. Their presence and growth can be assumed to be limited by environmental factors such as bottom flow velocity (e.g., Okabe *et al.*, 2004; Hasegawa, *et al.*, 2007). The effects of changes in flow field on the seaweed and seagrass beds were thus of interest.

Figures 11 and 12 show the change in flow fields at flood and falling tide, respectively. Double-lined squares (S1–S5) represent seaweed beds in the computational domain, while single-lined squares (Z1–Z13) represent seagrass beds.

In *Sargassum horneri* habitat, the largest changes in flow velocity were found at S3 and S4 at flood tide, when flow velocity increased from 10.8 cm/s to 20.6 cm/s and from 3.7 cm/s to 8.4 cm/s, respectively. However, *Sargassum* spp. beds have been reported to form at flow speeds of up to 100 cm/s or more (Hasegawa *et al.*, 2007). A large change in flow direction was also found at S5 at flood tide, but at very slow velocities. In *Zostera marina* habitat, large changes in flow velocity were found at Z3 and Z4 at falling tide when flow velocity increased from 3.6 cm/s to 9.2 cm/s and from 2.7 cm/s to 14.0 cm/s, respectively. The flow velocity range suitable for *Zostera marina* growth includes flows of up to 60 cm/s (Morita and Takeshita, 2003). In addition, changes in flow direction appear minimal. The results thus indicate that any changes in flow field in seaweed and seagrass habitats would be well within the inhabitable range.

5 Conclusions

Changes in tidal current arising from infilling a sea caldron and their effect on seaweed and seagrass bed habitats were investigated using numerical stepwise simulations of infilling stages.

The results demonstrate that velocity distributions at both ends of the sea caldron changed in the final stage of infilling, that velocity distributions at the center of the sea caldron gradually changed as the infilling progressed, and that the changes in flow field remained within the inhabitable range for the species present at the seaweed and seagrass beds.

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Figure 11: Changes in flow field at seaweed and seagrass beds at flood tide

Figure 12: Changes in flow field at seaweed and seagrass beds at falling tide

Discussion open until December 31, 2017