Effects of change of density stratification due to Isahaya Sea-Dyke on the fate of anoxic water in the Ariake Sea

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Abstract. In this study, we aim to investigate the possibility that the construction of the Isahaya Sea-Dyke significantly causes anoxic water development in the bottom layer in the Ariake Sea, Japan. We numerically compared the vertical distribution of dissolved oxygen (DO) in the water column between two cases with the dyke and without it. As a result of this research, the followings are clarified: 1) DO totally decreased in Isahaya Bay due to construction of Isahaya Sea-Dyke; 2) The effect is relatively small during neap tide, but is larger in spring tide; and 3) The effect is not shown in the main body of the Ariake Sea.

1. Introduction
After 2000, serious deterioration of the aquatic environment and marine ecosystem has been recognized in the Ariake Sea, which is one of the largest semi-enclosed bays in Japan. Many types of research have been carried out to investigate the principal cause, but it has not been clarified completely yet. It has been recognized that the deterioration is occurred by reduction of velocity of tidal current (barotropic flow) due to shortening longitudinal length of the bay due to construction of the large sea dyke (the Isahaya Sea-Dyke) of 7 km long in the head of Isahaya Bay, which is a branch bay of the Ariake Sea. However, some recent numerical investigations have demonstrated that the sea dyke does not significantly contribute to the decrease of tidal current in the main part of the Ariake Sea, with the exception of Isahaya Bay [1,2]. Meanwhile, in a coastal area off Shimabara Peninsula where the path of the ebb current towards the mouth of the Ariake Sea from Isahaya Bay can be seen, reduction of tidal current has been observed due to the decrease of the volume of Isahaya Bay [3]. Thus, some knowledge of the effect of the dyke on the barotropic flow has been obtained.

On the other hand, baroclinic flow in the bay due to density stratification has not been examined in detail. A few knowledge has been obtained as followings. The research showed the tendency that the average residence time of the bay was shortened, i.e., the long-term tidal exchange between the inner bay and the outer sea area was activated from the long-term field observation of river discharge and salinity [4]. The study also described that the estuarine circulation became stronger in well-mixed season (from autumn to spring) and weaker in stratification season (from spring to autumn), since a ratio of the horizontal circulation and the estuarine circulation depended on the river discharge [5]. The study investigated a relationship between tidal exchange and vertical/horizontal density distribution from the field observation [6]. They also examined a relationship between the stratification and tide in a fortnightly cycle from neap tide to next neap one. The study examined a correlation between the distribution of lower salinity in the northern Ariake Sea and river runoff [7]. They show that riverine freshwater can move counter clockwise in a week and flow into the mouth of Isahaya Bay. However, the effect of the dyke on baroclinic flows has not been clarified.
In a coastal region, riverine freshwater can influence the development of hypoxic water near the sea bottom due to strong density stratification resulting from salinity variation. In addition, the horizontal transport of freshwater can influence the distribution of nutrients, organic matter and phytoplankton. Therefore, the dynamics of freshwater can play an important role that can determine the health of the marine ecosystem. Recently, based on this idea, a concept of Regions of Freshwater Influence (ROFIs) has been proposed. The study indicates the relationship between the marine ecosystem and ROFIs, and point out its importance [8].

It is necessary to examine the detail of the structure of stratification. In other words, baroclinic flows influenced by the sea dyke, in order to clarify the significant reason for the deteriorated aquatic environment in the Ariake Sea. The research has attempted to examine the effect of the dyke on the baroclinic flows in the bay numerically. They show that the sea dyke causes the reduction of the flow velocity in the inner part of Isahaya Bay and coastal areas of the Shimabara Peninsula [9]. The salinity stratification is also enhanced in those areas. The salinity stratification is enhanced by the dyke in the spring tide, but not in the neap tide. The effects of the dyke on the baroclinic flows due to salinity stratification greatly depend on both river discharge and the condition of the tide. However, they focused on only hydrodynamic structure, in other words, density stratification due to salinity distribution. Since an effect of the stratification on DO profile has not been clarified, further investigate on it has been necessary.

In the present paper, we investigate an effect of variation of baroclinic structure (density stratification) due to the construction of the sea-dyke in Isahaya Bay on DO concentration.
(development of anoxic water in the bottom layer) by using 3D hydrodynamic model and vertical 1D turbulent diffusion model for the water column.

2. Methodology

2.1. Hydrodynamic model

In this study, we use the numerical model that was developed by applying the DELFT3D-FLOW, which is a generalized three-dimensional hydrodynamic numerical model in a coastal area or an estuary [10,11]. As shown in figure 1, the computational domain is an area combining the Ariake Sea and the Yatsushiro Sea, which is also one of the largest semi-enclosed bays in Japan. We apply the linear orthogonal coordinate system of 10" interval resolution ($\Delta x=250m$) horizontally and the 10 uniform layers $\sigma$-coordinate system vertically. The open boundary is set as a line connecting Akune in Kagoshima Prefecture to Kabashima in Nagasaki Prefecture. 40 tide components are given as an open boundary condition, based on the known harmonic constant by Japan Coast Guard of both edges (Akune and Kabashima). The harmonic constants (amplitude and lag) only for the four major tidal components (M2, S2, K1, and O1 tides) were adjusted to the measurement result of tide at several tide gauges [10]. Further, the moving wall boundary model (dry-wet model) for a flat tidal area is adapted [11]. Horizontal eddy viscosity/diffusivity is estimated from Sub-Grid Scale model (Smagorinsky model). While vertical eddy viscosity/diffusivity is calculated by $k-\varepsilon$ turbulent model, including the buoyancy effect. We omit a description in detail for the validation of the present model here, because it has been fully confirmed by our previous studies on stratification, the tide and tidal currents [10].

We use measured hourly river discharge from eight A-class rivers (the Chikugo R., the Yabe R., the Kase R., the Rokkaku R., the Kikuchi R., the Shira R., the Midori R., and the Kuma R.) by Ministry of Land, Infrastructure, Transport and Tourism, Japan and estimated hourly ones from nine B-class rivers (the Shiota R., the Kajima R., the Seki R., the Tsuboi R., the Hikawa R., the Ohtsubo R., the Sashiki R., the Yunoura R., and the Minamata R.) as same specific discharge as neighbouring A-class river for simulation of the baroclinic flows due to riverine freshwater inflow. The present numerical study does not take into account of freshwater inflows from the Honmyo River, which flows into the regulation pond generated by the sea dyke at the head of Isahaya Bay in a case without the sea dyke, and one from two drainage gates of the sea dyke in a case with the dyke to focus on only the physical effect of the dyke as a fixed large wall on the baroclinic flows. In the Ariake Sea, the salinity stratification is subsequently predominant in a rainy season from June to September, and thermal stratification due to heat flux from the atmosphere can generally develop from August to September before the vertically well-mixed season starting from October. In this research, we focus on only salinity stratification, and the effect of water temperature stratification is not taken into account. Furthermore, influences of wind, i.e., wind waves and drift current due to winds, are not taken into account in order to investigate the only significance of the sea dyke.

2.2. One-dimensional DO model

Using the result of vertical eddy viscosity/diffusivity profile at a given station from the hydrodynamic simulation 1D simulation for the vertical profile of dissolved oxygen (DO) concentration is conducted for a water column. The basic equation is a vertical 1D turbulent diffusion equation (equation (1)):

$$ \frac{\partial C}{\partial t} = \frac{\partial}{\partial z} \left( K_z \frac{\partial C}{\partial z} \right) \tag{1} $$

Where, $C$: concentration of DO, $K_z$: vertical eddy diffusivity, $t$: time, and $z$: vertical coordinate. On the sea surface oxygen flux $D$ from the atmosphere to seawater by aeration is estimated from equation (2):

$$ D = K_d (C_s - C) \tag{2} $$
where, \( C_s = C_s(T, S) \): saturated DO concentration decided by water temperature \( T \) and salinity \( S \), and \( K_a \): aeration coefficient (=0.6 day\(^{-1}\)). On the sea, bottom DO consumption is taken into account. The rate is given as 0.98 gO\(_2\)/m\(^2\)/day from the observed value in the bay [12].

3. Results and discussions

3.1. Numerical simulation results

In this paper, two cases are considered in numerical simulation. The first case is before construction of the sea dyke at the head of Isahaya Bay. The second one is after the construction, that is, the present geographic condition. The period of calculation is from the 1st January, 2006 to the end of September, 2006. The year 2006 was known as a typical year that showed anoxic water in the bottom layer in the bay. Figure 2 shows the position of three stations for comparison between two cases of computation. Sta. A is located in the center of Isahaya Bay. Sta. B is set in the coastal area of Shimabara Peninsula and Sta. C is in the northern area of the main body of the Ariake Sea.

![Figure 2. Location of the Ariake Sea and computational domain.](image)

Figure 3 shows the calculation results of salinity at Sta. A in two cases in June. Figure 4 shows the difference of salinity between two calculation results. This salinity difference isopleth means the result in case without the sea dyke subtracted from the result in case with the sea dyke. Thus, a positive value (blue) means salinity increases due to the sea dyke, while the negative one (red) means salinity decreases. So, if we see red colour in the surface layer and blue in the bottom layer, then it means the sea dyke has intensified the stratification. We can confirm that stratification is intensified in spring tide (25th June to 1st July), but stratification does not change significantly in the neap tide.

Figure 5 shows the calculation results of DO concentration at Sta. A in two cases. Figure 6 shows the difference of DO between two calculation results in the same manner as figure 4. Thus, positive
value (blue) means DO increase due to the sea dyke, vice versa. So, if we see a red color near the sea bottom, then it means the sea dyke can accelerate the development of anoxic water.

![Figure 4](image-url)

**Figure 4.** Isopleth of the difference of salinity between two cases.

![Figure 5(a)](image-url)

**Figure 5(a).** Isopleth of DO at Sta. A (Isahaya Bay). [Case with the sea dyke (present)].

![Figure 5(b)](image-url)

**Figure 5(b).** Isopleth of DO at Sta. A (Isahaya Bay). [Case with the sea dyke (present)].

![Figure 6](image-url)

**Figure 6.** Isopleth of the difference of DO between two cases.

3.2. **Discussions**

From the comparison between figure 4 (salinity difference) and figure 6 (DO difference), the relationship of them can be seen. The construction of sea dyke in the head of Isahaya Bay may influence salinity stratification (density stratification). It can intensify the stratification and development of anoxic water. Acceleration of reduction of DO due to the sea dyke can be seen in the period of spring tide, while it cannot be shown in the neap tide. Tidal current can be weakened in neap tide generally. On the other hand, it can be dissolved in spring tide because of the strong tidal current. Therefore, this result of numerical experiments shows that the sea dyke is impervious to anoxic water development in the bay. This can give important information to consider the significant reason for the deterioration. To redefine the problem structure may be necessary.

In addition, these results at Sta. B and Sta. C, which was not shown in this paper, were also compared. But, there was no significant effect of the sea dyke on DO concentration. Thus, the sea dyke can affect DO profile in only inner Isahaya Bay but cannot in the main body of the Ariake Sea.
4. Conclusions
We compared vertical DO profiles at a few points for one month in the rainy season from 1st June, 2006 to the end of June. We found a difference between two cases in Isahaya Bay, while significant differences cannot be seen in the main body of the Ariake Sea. As a result of this research, the followings are clarified:

- DO is totally decreased in Isahaya Bay due to construction of Isahaya Sea-Dyke;
- The effect is relatively small during the neap tide, but is larger in spring tide; and
- The effect is not shown in the main body of the Ariake Sea.

In further research, we need to conduct the same numerical experiments using 3D model and ecosystem model. Also, other aspects of the sea dyke construction, for example, a loss of tidal flat, tempo-spatial change of freshwater inflow, change of sediment quality and grain size, etc. should be focused on.

References
[1] Manda A and Matsuoka K 2006 Estuaries and Coasts 29 645-652
[2] Tai A, Hatta M P, Yano S, Saita T and Komatsu T 2006 Annual J. Coastal Engineering, JSCE 53 331-335
[3] Nishinokubi H, Komatsu T, Yano S and Saita T 2004 Annual J. Coastal Engineering, JSCE 51 336-340
[4] Yanagi T and Abe R 2003 Oceanography in Japan 12 269-275
[5] Yanagi T and Shimomura M 2006 Continental Shelf Res. 26 2598-2606
[6] Yano S, Saita T, Hashimoto Y, Koyama Y, Fujita K and Komatsu T 2004 Annual J. Coastal Engineering, JSCE 51 331-335
[7] Yamaguchi S and Hayami Y 2009 Bulletin on Coastal Oceanography 46 161-173
[8] Simpson J H and Sharples J 2012 Introduction to the Physical and Biological Oceanography of Shelf Seas (Cambridge: Cambridge University Press) p 424
[9] Yano S and Nishimura K 2014 Proc. the 19th IAHR-APD Cong. 2014 (Hanoi)
[10] Yano S, Winterwerp J C, Tai A and Saita T 2010 J. JSCE B2 (Coastal Engineering) 66 341-345
[11] Deltares 2012 DELFT3D-FLOW user manual ver.3.15 (Delft: Deltares) p 674
[12] Abe J, Matsunaga N, Kodama M, Tokunaga T and Yasuda S 2003 Annual J. Coastal Engineering, JSCE 50 996-970