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PREDICTION OF THE INFLUENCES OF CONSTRUCTION OF A SEA DYKE ON THE FLOW AND SEDIMENTATION OF ISAHAYA BAY

By

Wataru Nishida

Lecturer, Department of Civil Engineering, Nagasaki University,
1-14 Bunkyo-cho, Nagasaki 852-8521, Japan

Masato Noguchi

Professor, Department of Civil Engineering, Nagasaki University,
1-14 Bunkyo-cho, Nagasaki 852-8521, Japan

and

Satoshi Yanamoto

Urban Water Engineering Department, Nippon Koei Co.,Ltd.
5-4 Kouji-machi, Chiyoda, Tokyo 102-8539, Japan

SYNOPSIS

With the progress of a project to promote a regulation pond as well as areas for agricultural and recreational activities, the innermost area of Isahaya Bay has been enclosed by the construction of a sea dyke, and the water environment around Isahaya Bay will be changed by this project. It is very important to eliminate and minimize the negative impact anticipated by this action around the developed area. In this study, a numerical model was developed to examine the influences of the enclosure of the bay on the flow and sedimentation on the tidal flat. Numerical simulation under several scenarios was carried out regarding the construction stages for the sea dyke. The results show that the shoreline in Isahaya Bay varies as the decrease of water exchange across the sea dyke under construction stage. Suspended particles are deposited owing to the decrease in the current speed, creating a new tidal flat in the bay. Since these areas are also found to be influenced by the outflow from the regulation pond, much attentions must be paid to preserve the tidal flat in Isahaya Bay.

INTRODUCTION

In order to achieve the sustainable development, the prediction and the estimation of environmental quality have to be made before the development action, and several kind of works related to the mitigation are required to eliminate and minimize the negative impacts on environment at and around the developing area.

In Isahaya Bay in Nagasaki, Japan, a reclamation project by the Ministry of Agriculture, Forestry and Fisheries has been started in 1989. As shown in Fig. 1, the innermost area of Isahaya Bay was enclosed by a sea dyke up to an area of $35.5km^2$, of which 18.4 km^2 will be reclaimed for the purpose of promoting a regulation pond for flood control and fields for agriculture and recreational

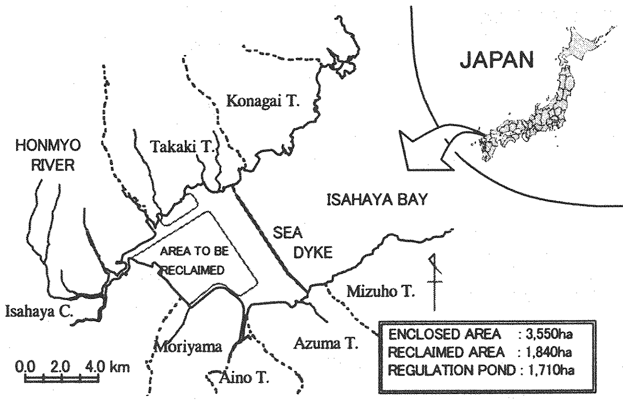


Fig. 1 Schematic view of reclamation project in Isahaya Bay

activities. The sea dyke has enclosed one part of Isahaya Bay, so the inner water area is separated from the outer sea. Thus it is considered that the water environment around this area will be changed significantly in the near future. As mentioned above, influences of the development should be assessed from physical, chemical, and biological viewpoints. The authorities concerned with this project are therefore making continuous monitoring on the environment and taking several measures for prevention of environmental degradation in Isahaya Bay.

Vast areas covered by fine materials such as clay and silt appear as tidal flat during ebb tide in Isahaya Bay, because the tidal range is larger than 4.0m and the bottom slope is very gentle with approximately one thousandth. It is well known that the tidal flat has an important role for achieving the desirable water environment. Then, environmental variation caused by a change of spatial distribution of the tidal flat should be discussed in detail on the basis of the processes of water quality, ecological changes and so on. Several investigations have been on progress to estimate the environmental effects of this project, using both field observations and numerical simulations (1)-(4). Main objectives of this study are to discuss the spatial and temporal variation of tidal flat in Isahaya Bay caused by the construction of the sea dyke. Numerical simulation of currents will be performed in the coastal area including the tidal flat, although there are many difficulties to calculate the temporal variation of flow on tidal flat. Mizudori et al. (5) solved the fundamental equations of flow, assuming that there is no flow when the water depth is minute. Katoh et al. (6) and Kyozuka et al. (7) calculated the flow on the tidal flat using the moving boundary, which shifts at every time step according to the tidal level and topography. Takikawa et al. (8) carried out a numerical simulation assuming the virtual weir at the shoreline. Nakamura et al. (9) applied the weir formula to the flow when the water depth on the tidal flat is very shallow. The tidal change on the open boundary is given from observed results and computational results. In this study, because the calculated current field shows that the enclosure of Isahaya Bay exerts significant influence on the spatial distribution of currents around the mouth of this bay, a numerical model was developed which simulates the currents and the sediment transport for a wide area including the adjoining rivers and sea. The spatial and temporal variation of tidal flat in Isahaya Bay under and after the construction of the sea dyke was estimated by using this model. Furthermore, the influence of control of gates furnished at the sea dyke on currents and tidal flat was discussed.

NUMERICAL MODEL

The temporal and spatial variations in currents and tidal levels should be estimated accurately to accomplish the objectives of this study. Moreover, the sediment transport including sedimentation and erosion in the coastal area is also significant concerned with the formation of tidal flat in the long period of time. The coastal area of the Isahaya Bay is widely covered with a thick layer of fine particles. In this study, the particles are assumed to be transported as the suspended form instantly when shear stress at the bottom becomes larger than the critical value, because the particle smaller than $1.5X10^{-4}$m of diameter is transported in a suspended form (10). Continuity and momentum equations for fluid, and the mass balance equations for suspended particles, chlorides and sediments were used as the governing equations of the model. As illustrated in Fig. 2, the movement of particles has been expressed in forms of the resuspension and the deposition of particles and formulated by the following equation:

$$\frac{DC_{SS}}{Dt}=\frac{\partial}{\partial x}\left(K_x\frac{\partial C_{SS}}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial C_{SS}}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial C_{SS}}{\partial z}\right)+\frac{\partial F_d}{\partial z}+\frac{\partial F_c}{\partial z} \tag{1}$$

Where, C_{ss} = the concentration of suspended particles in water; K_x, K_y, and K_z = apparent turbulence diffusivities in the x, y, and z directions, respectively; F_d = the deposition flux of particles; F_c = the resuspension flux of sediment particles. The amount of resuspension is evaluated by the pick-up rate (11). The resuspension rate is varied with the sediment properties such as water content and viscosity (12), and the coefficient, P_I, which is the cohesion of sediment, is introduced into the resuspension flux. This value decreases as the thickness of sediment becomes thin. On the other hand, some equations are applied in order to estimate the deposition flux (13)(14)(15). In this model, the deposition flux is varied with the force balance between the weight of particle and the lifting fluid force. Here, F_c and F_d are estimated by the following equations:

$$\begin{cases}\tau_* \le \tau_{*c} & \cdots\cdots\cdots\cdots\cdots\cdots \quad F_c=0\\ \tau_* \ge \tau_{*c} & \cdots\cdots\cdots\cdots\cdots\cdots \quad F_c=\sigma\cdot v_s\cdot P_s\cdot P_I/a_s\end{cases} \tag{2}$$

$$F_d=C_b\cdot w_0\cdot exp(-V^2/V_c^2) \tag{3}$$

$$P_I=exp\{-\gamma\cdot(1-D/D_{ini})\} \tag{4}$$

in which τ_* = the dimensionless tractive force; τ_{*c} = the dimensionless critical tractive force; σ = the density of particle; P_s = the pick - up rate; v_s = the volume of particle; a_s = the projection area of a particle; w_0 = the settling velocity of particle in fluid; V = the cross sectional mean velocity; V_c = the critical fluid velocity calculated by the force balance between the weight of particle and the lifting fluid force; D = the thickness of the sediment; D_{ini} = the initial thickness of the sediment layer; and γ = a coefficient.

It is advantageous to solve flows in rivers and sea, simultaneously, and one- and two-dimensional analyses are adopted in each domain. Although the representation of depth-averaged form was not ideal at a sea area, this assumption was thought to be reasonable in this study since Isahaya Bay is relatively shallow. Derived equations were solved numerically using the explicit scheme of the finite difference method; which is Leap Flog scheme in time and Donor Cell scheme in space. The time step for the computation is 1.0 second, which satisfies Courant – Friedrichs – Lewy stability condition and the time scale for picking up the particles from the bottom. The treatment of the open boundary conditions and the estimation of initial thickness of sediment layer are the most difficult task for the simulation. For following calculations, Shimabara Sea (Fig. 3(b)) was included in the

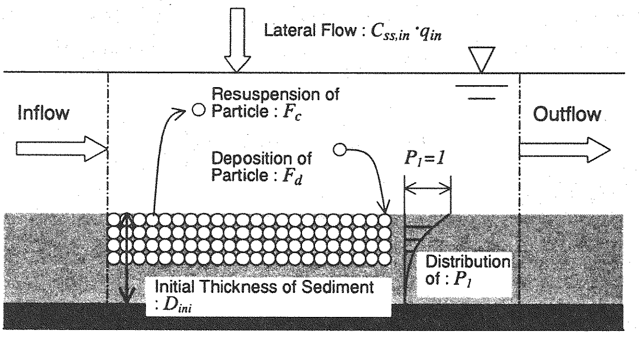


Fig 2. The definition sketch of sediment transport

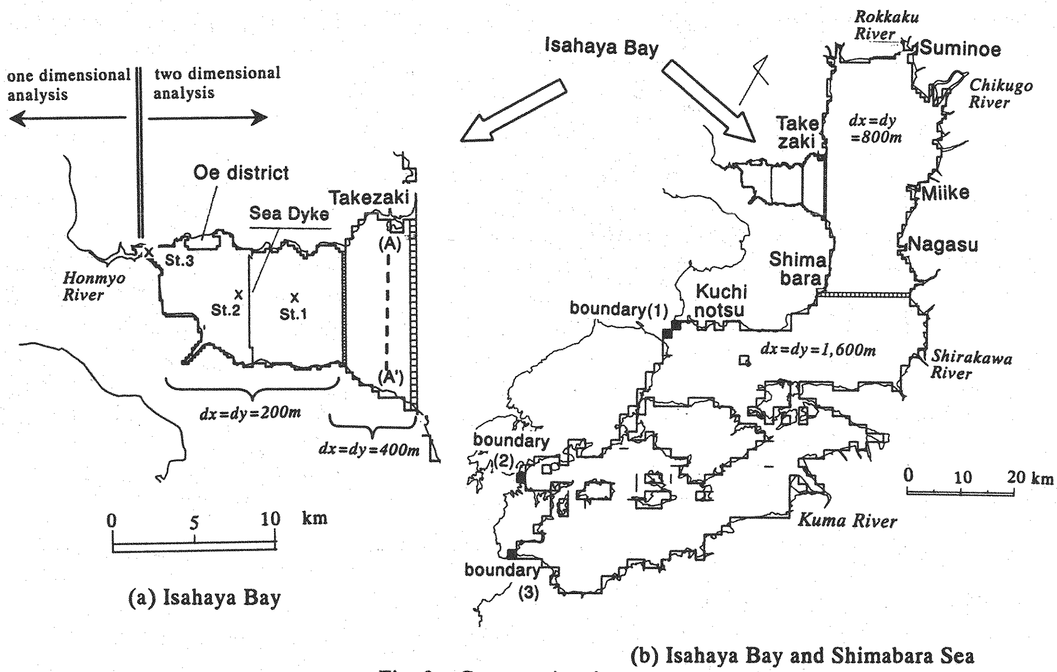


Fig. 3 Computational area

computational domain considering the exchange of water between Isahaya Bay and Shimabara Sea. For one-dimensional analysis, the spatial increments are varied from 52m to 147m in length. On the other hand, as shown in Fig. 3, the region that analyzed in the two-dimensional analysis is divided using four types of grids, with spacing of $dx = dy$ = 200m, 400m, 800m and 1,600m. The Manning roughness coefficients are taken as 0.040~0.021 $s/m^{1/3}$ for the river and 0.028 $s/m^{1/3}$ for the sea. From the observed results, the discharges of Honmyo River and its two tributaries are 0.909m^3/s, 0.474m^3/s and 0.060m^3/s with concentration of suspended particles 8mg/l, 28mg/l and 21mg/l, respectively. The tidal changes of principal lunar semi-diurnal tide (M2) based on the reference (16) are given at the three open boundaries. Each sediment particle is assumed to be a sphere, and the specific weight and the diameter of a particle are 2.60 and 5.0×10^{-5} m, respectively. To determine the spatial distribution of the thickness of sediment layer, the initial thickness of sediment layer was given uniformly in computational area. For equilibrium sediment transport, the numerical simulation was executed for ten tidal cycles, and the calculated spatial distributions of sediment thickness were used as initial values for the next computations. From the comparison between the observed result of suspended sediments at the estuary of Honmyo River and the calculated one, the initial thickness of sediment was given as 0.03m and 0.01m in river and sea areas, respectively.

CALCULATED RESULTS AND DISCUSSION

Model Verification with Field Data

Simulating the variation of currents and tidal flat by the sea dyke, the numerical model was verified using some field data that obtained through references from the Japanese Maritime Safety Agency (16). Fig. 4 shows the calculated results of tidal curve at the six ports in Shimabara Sea. Here, Kuchinotsu and Suminoe ports are situated at the mouth and the innermost areas of Shimabara Sea, respectively. The tidal range at each port gradually increases, as the distances of referring ports

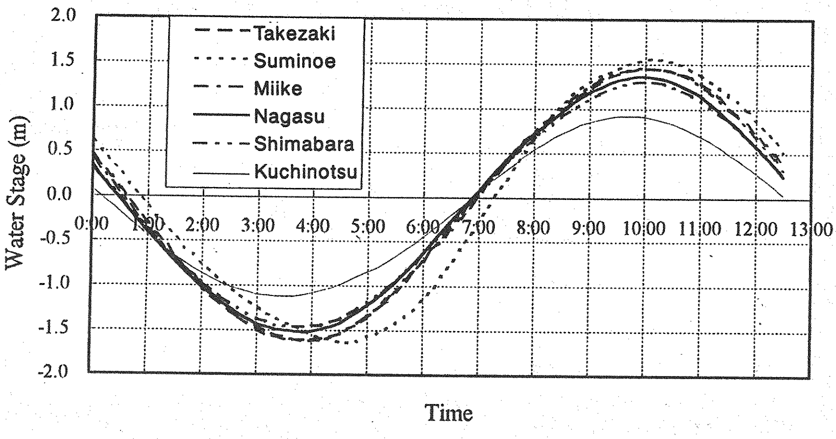


Fig. 4 Temporal variation of tidal level in Shimabara Sea (calculated)

Table. 1 Comparisons between calculated results and observed field data at five ports

		Shimabara	Miike	Nagasu	Takezaki	Suminoe
Tidal range	Calculated	1.38	1.53	1.44	1.53	1.60
(*m*)	Observed	1.47	1.53	1.43	1.53	1.72
Difference in time	Calculated	20	20	15	25	30
(*min.*)	Observed	13	16	16	18	34

The value of time difference is between each reference port and Kuchinotsu port.

become farther from the Kuchinotsu port. Its range at Suminoe port is 1.5 times larger than that of Kuchinotsu. Furthermore, the time delay of ebb and flood tides is approximately 30 minutes. At the coastal area where sea bed dried out according to the tidal change, there is the fairway extended from a river mouth to the sea. The calculated results show that the water flows along fairway, and the rise of tidal level is temporally fast during the flood tide. The tidal level gently decreases compared to other water area. Because the water depth becomes very shallow even at fairway during the ebb tide, and the current velocity is strongly affected by the shear stress at bottom. Comparisons of measured and calculated values for both the tidal range and the time difference between each reference ports and Kuchinotsu port are summarized in Table. 1. Although there are small discrepancies between the calculated results and the observed values, it can be considered that the tidal change at Shimabara Sea is predicted well by this model.

Variation of Currents and Tidal Flat in Isahaya Bay

In order to estimate the impact of sea dyke on the tidal flat in Isahaya Bay, simulations were

Table. 2 The calculation conditions for each case

	Condition of sea dyke	Initial thickness of sediment
Case - A	Before the construction of sea dyke	Thickness of sediment is given 0.01m in sea area.
Case - B	Oe district (1.48 km^2) is reclaimed. Sea dyke is constructed 5,800m in length.	Predicted result under Case-A is given.
Case - C	Construction of sea dyke is completed. Water stage in the regulation pond is controlled at T.P.-1.0m by two gate stations.	Predicted result under Case-B is given.
Case - D	Gates always are opened	Predicted result under Case-C is given.
Each numerical simulation is executed for 10 tidal cycles.		

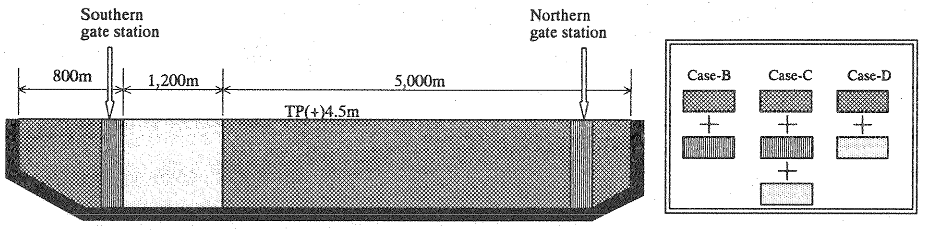
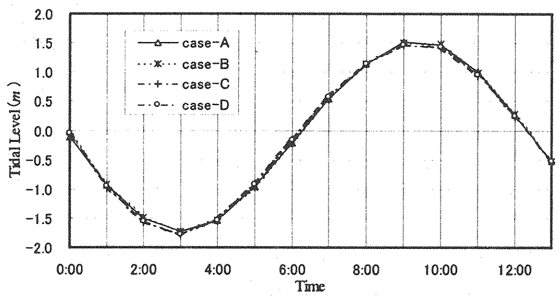


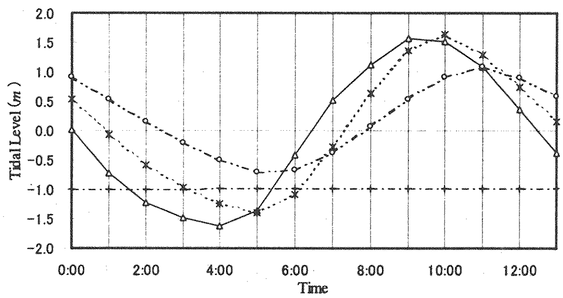
Fig. 5 Conditions of the sea dyke in each calculation

conducted for three cases, as shown in Table 2 and Fig.5, which are before the construction of sea dyke, during the construction and after the completion of the dyke. During the construction of sea dyke, the reclamation of about 1.48 km^2 land in Oe district was assumed to be completed and the constructed sea dyke length and height were 5,800m and 4.5m, respectively. After the construction, the water level in the regulation pond is controlled at T.P. -1.0m by northern and southern gate stations. Furthermore, another calculation was done to predict the spatial variations in currents and tidal flat, for the condition that the northern and southern gates were always opened. These conditions are named as the case-A, B, C and D, respectively. The initial thickness of the sediment layer has to be estimated to predict the spatial variation of sediment caused by the sea dyke. Here, the initial thickness of sediment layer in sea area is given as a constant for the case-A, and calculations for the four cases are executed in the order of case-A, B, C and D, in which results obtained by the previous computation were used for the following one.

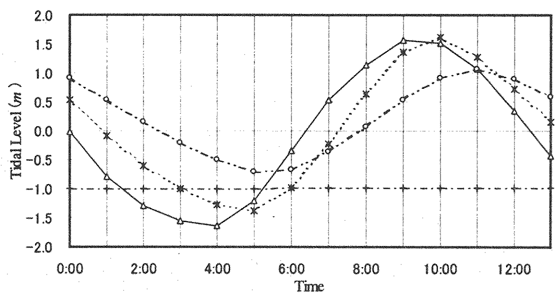
Fig. 6 shows the temporal variations of sea levels at three points in Isahaya Bay. Before the construction of the sea dyke, in case-A, though the tidal level becomes maximum approximately at the same time in everywhere of Isahaya Bay, there are obvious differences in the time of minimum water level between the innermost area and the bay mouth area. And the tidal level of high water in the innermost area is higher than that of at mouth of the bay. As



(a) St.1: outside the sea dyke (4.0km)

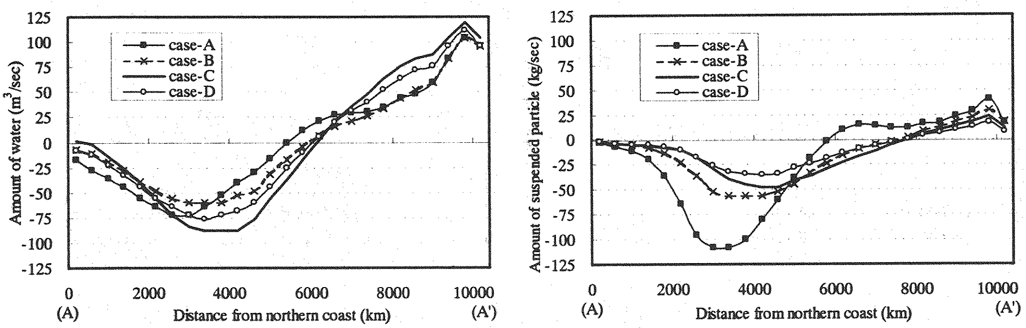


(b) St.2: inside the sea dyke (0.2km)



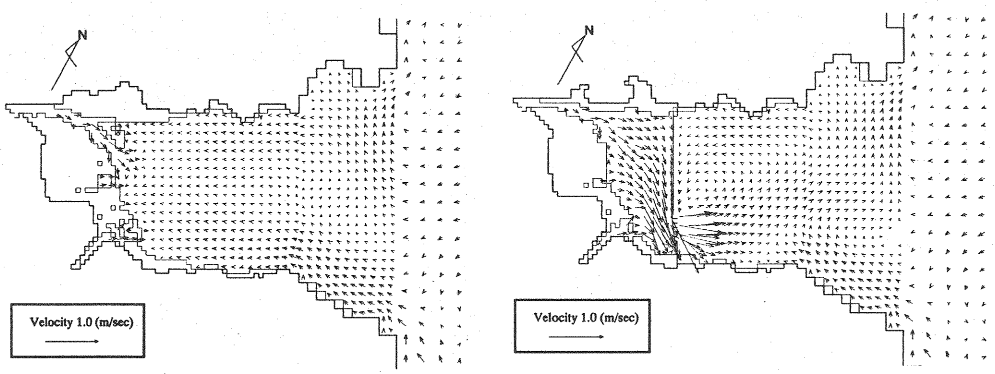
(c) St.3: inside the sea dyke (6.4km)

Fig. 6 Temporal variation of tidal level in Isahaya Bay

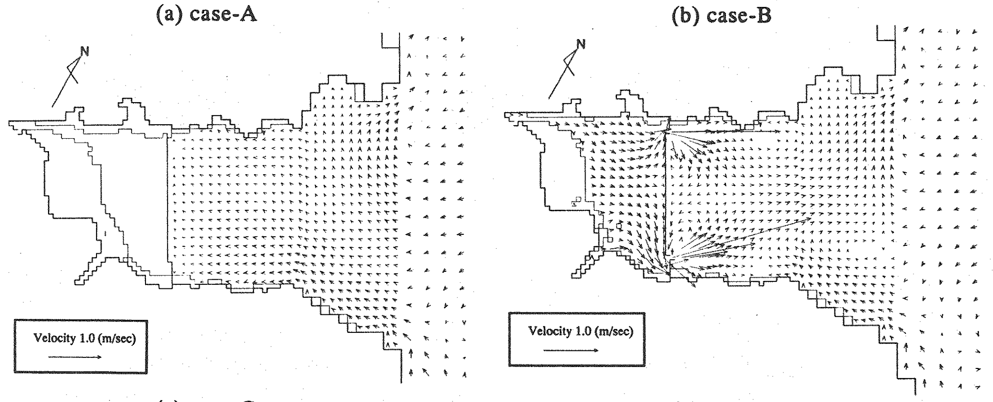


(a) amount of water (b) amount of suspended particle

Fig. 7 Spatial distribution of inflow and out flow of water and suspended particles at (A)-(A') section



(a) case-A (b) case-B



(c) case-C (d) case-D

Fig. 8 Calculated shoreline and velocity in Isahaya Bay during ebb tide

discussed previously, the temporal change of water level around the tidal flat is strongly affected by the seabed topography. A comparison of the results of the case-A with the other cases gives indication of the variations in the tidal changes. The tidal range outside the sea dyke decreases due to the fall of flood sea level, as the construction of sea dyke. For the case-B, it is found that the time difference of tidal change between outside and inside the dyke becomes remarkable, and the low water tide level inside the dyke rises 0.23m than before. After the completion of the sea dyke, in case-C, the water area inside the sea dyke is utilized for flood regulation pond, in which the temporal variation of water level can hardly be recognized even if all the gates are controlled. Otherwise, when all the gates are always opened, the water inside and outside the dyke is exchanged through gates according to tidal

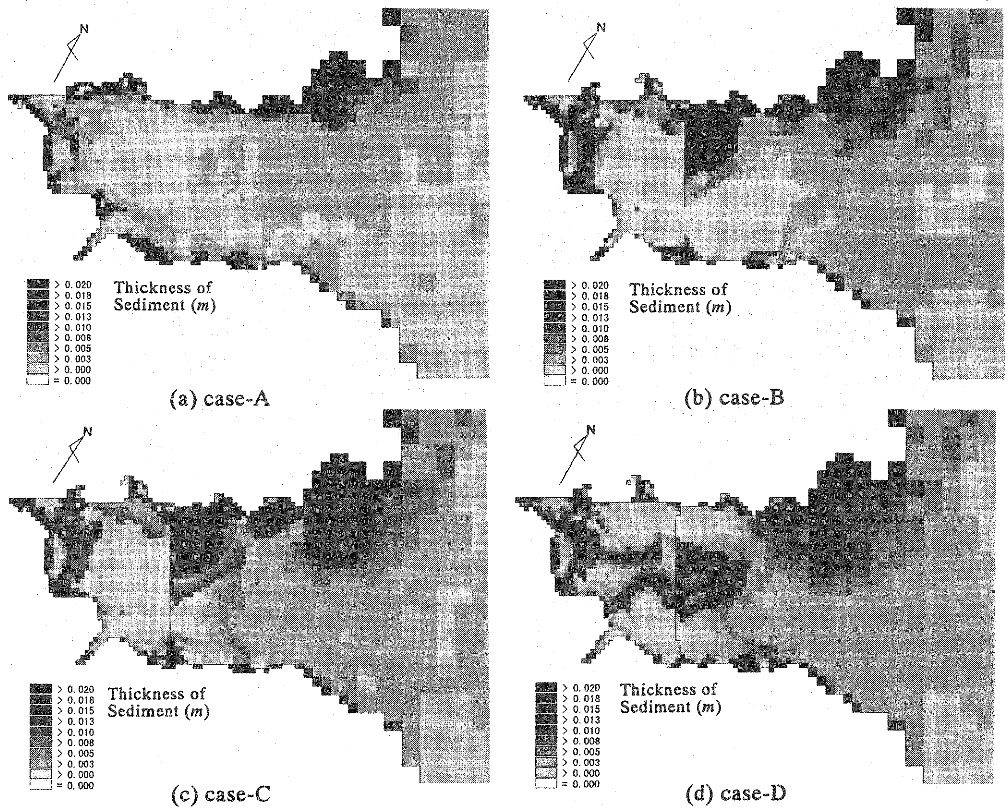


Fig. 9 Spatial distribution of sediment thickness in Isahaya Bay

change in Isahaya Bay. This result shows the rise and fall of water levels inside the dyke at ebb and flood tides, and the differences of sea levels between the outside and the inside of the dyke strongly influence the spatial distribution of velocity in Isahaya Bay.

The spatial distributions of water and suspended particles transported in section A-A' (Fig. 3 (a)) are illustrated in Fig. 7. Each result represents the mean value throughout the one tidal cycle. Positive values indicate the outflow from Isahaya Bay and vice versa. Although the tidal currents spatially varies according to tidal condition, the water is flowing into and out from Isahaya Bay near northern and southern coastal area in a tidal cycle. This flow pattern becomes remarkable for the results obtained from the case-C, since the construction of sea dyke decreases the inflow from Shimabara Sea into Isahaya Bay. Calculated results show that suspended particles are distributed with water motion, and particles are transported along the northern coast and accumulated in Isahaya Bay. Results also show that the inflow of suspended particles into the bay decreases.

Fig. 8 shows the shoreline and spatial distribution of velocity in Isahaya Bay at the time when the tidal level becomes low. As mentioned in the above, the variation of tidal currents due to the sea dyke can be seen around the mouth of bay. During ebb tide, the tidal flat appears around the coastal area where the ground level is higher than –1.0m. Area of tidal flat was about 25.44km^2 before the construction of sea dyke. The area of tidal flat for the case-B, C and D, decreases about 6.84km^2, 22.32km^2 and 14.20km^2, respectively. Although the tide level inside the sea dyke varies with tide in Isahaya Bay for the case-B and C, the area of tidal flat becomes smaller due to the decrease of tidal range. Regarding the progress of reclamation, it is predicted that the tidal flat inside the sea dyke will appear only around the northern and southern coastal area in case-D.

The calculated results of sediment thickness are shown in Fig. 9. As illustrated in Fig.8, the water flows from and into Isahaya Bay during ebb and flood tide. Before constructing the sea dyke, the current velocity was up to 0.7m/sec around the southern area at the bay mouth, and the thickness of sediment layer decreased due to resuspension of sediment. The thickness of sediment layer increases around the coastal area where tidal flat develops during an ebb tide, because current velocity at tidal flat during flood tide is larger than that of during ebb tide. The picked up particles are deposited at tidal flat except for the fairway around the mouth of Honmyo River, and the other particles remain in the water as suspended form. For case-B, under construction state, the current velocity increases at the southern part of Isahaya Bay and inside of the sea dyke. Accordingly, the amount of resuspension also increases in these areas. On the other hand, at the northern coastal area, especially outside the sea dyke, the thickness of sediment layer thickens up because the deposition of suspended particles is occurred due to the recession of current velocity. After the completion of the sea dyke, the water stage inside the sea dyke is maintained by control of gates, and the excessive inflow of particles caused by flood is not considered. Consequently, compared to the previous result, the spatial variation of sediment inside the dyke is negligible. Otherwise, the current velocity becomes slower outside the sea dyke, and suspended particles are deposited to the seabed. Regarding the spatial distribution of velocity in Isahaya Bay, the particles contained in the outflow from the regulation pond are deposited near the northern and southern gates. Comparing the calculated result of sediment thickness in case-C with the others, it is predicted that the thickness of sediment increases around the northern coastal area at the mouth of Isahaya Bay. In case-D, the current velocity is very large around the northern and southern gates, since the difference between the sea levels inside and outside the sea dyke is large. Thus, the sediment erosion is occurred at the northern and southern coastal area, and suspended particles are deposited at other places, where the flow is moderate, such as at areas in front of the sea dyke.

CONCLUSIONS

In order to estimate the influences of the construction of a sea dyke on the flow and sedimentation on the tidal flat in Isahaya Bay, numerical simulations are carried out for the four computational conditions with regard to the construction stages of the sea dyke and the control of gates.

It was found from these calculations that the tidal range at the innermost area of bay becomes small, and the area of tidal flat decreases with the progress of construction. The variation of tidal currents exerts significant influences on spatial distribution of sediment. Since 1997, all the gates of sea dyke have been controlled similar to the simulation condition case-C, to prevent the flood disaster and reclaim the land. Numerical simulation suggested the appearance of a new tidal flat at northern coastal area and near the sea dyke owing to the supply of sediment. On the other hand, another results show that the extent of area with remarkable deposition is strongly affected by the condition of gates. Thus, the attention should sufficiently be paid for the control of gates to preserve the tidal flat in Isahaya Bay in future. Monitoring and sufficient maintenance works should be undertaken around this bay to attain a sound and desirable water environment. Since these predicted results are obtained with consideration of only resuspension and deposition of particles, the model should be refined including a production and dissipation of sediment from chemical and ecological aspect, in order to improve the accuracy in estimating water environment.

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REFERENCES

1. Nishida, W., M. Noguchi, and K. Mitsuhara : Influence analysis of a sea dyke on water environment, Proceedings of International Conference on Water Resource and Environment Research, Vol.II, pp.399-406, 1996.
2. Nishida, W., M. Noguchi, and S. Yanamoto : Prediction of water quality change under a construction of sea dyke, Annual Journal of Hydraulic Engineering, JSCE, Vol.41, pp.457-462, 1997 (in Japanese).
3. Noguchi, M. and W. Nishida : Impacts of a construction of sea-dyke and reclamation project on water quality at Isahaya Bay, Proceedings XXVIII th International Congress of IAHR, p.344, 1999.
4. Noguchi, M., W. Nishida, and W.B. Park : Pollutant runoff and its effect on the newly constructed regulatory pond in a bay, Proceedings of 8th International Conference of Urban Storm Drainage, Vol.4, pp.1631-1638, 1999.
5. Mizudori, M., M. Kadoyu, S. Soga, M. Katoh, and W. Wada : Water temperature variation and heat transport in tidal flat area, Proceeding of the 30th Japan Conference on Coastal Engineering, JSCE, pp.541-545, (1983) (in Japanese).
6. Katoh, K., T. Tanaka, and K. Nadaoka : Tidal simulation on tidal marsh and numerical forecasting of its topographic deformation, Report of the Port and Harbour Research Institute, Vol.18, No.4, P.72, 1979 (in Japanese).
7. Kyozuka, Y. and K. Yokoyama : Ocean environment changes due to an offshore airport in Ariake bay, Proc. of West-Japan Society of Naval Architects, No.88, pp.83-94, (1994) (in Japanese).
8. Takikawa, K., F. Yamada, H. Harada, Y. Kitazono, and K. Nakajima : Denitrification of tidal flat and tidal current in the coast of Ariake Sea, Proceedings of Coastal Engineering, JSCE, Vol.45, pp.991-995, (1998) (in Japanese).
9. Nakamura, T. and S. Shiotani : Numerical simulation of tidal current in Shimabara bay, Report of Influence of Volcanic Action of Mt. Fugen on Fishery, pp.66-95, (1996) (in Japanese).
10. Ashida, K. and M. Fujita : Mechanism of particle suspension in an open channel, No.375,II-6, pp.79-88, 1986 (in Japanese).
11. Murakami, S., T. Tsujimoto, and H. Nakagawa : Pick-up rate of sand and gravels, Proceedings of JSCE, No.443, II-18, pp.9-16, 1992 (in Japanese).
12. Otsubo, K. and K. Muraoka : Estimation of resuspension rate of cohesive sediments by currents, No.375, II-6, 43-52, 1986 (in Japanese).
13. Onishi, Y. : Sediment-contaminant transport model, Journal of the Hydraulics Division, ASCE, Vol.107, No.HY9, pp.1089-1106,1981.
14. Tsujimoto, G. , G.H. Stefan, and S. Kusakabe : Simulation of sediment resuspension transport by wind driven current in a shallow lake, Annual Journal of Hydraulic Engineering, JSCE, Vol.39, pp.799-804, 1995 (in Japanese).
15. Zhou, S. and J.A. McCorquodale : Modeling of rectangular settling tanks, Journal of the Hydraulics Division, ASCE, Vol.117, No.10, pp.1391-1405,1991.
16. Japanese Maritime Safety Agency : Tide Table in 1996, Vol.1, No.781, 1996 (in Japanese).

APPENDIX - NOTATION

The following symbols are used in this paper:

a_s	= the sectional area of a particle;
C_{SS}	= the concentration of suspended particles;
D	= the thickness of the sediment;
D_{ini}	= the initial thickness of the sediment;
dx, dy	= the spatial increments in the two- dimensional analysis;
F_c	= the resuspension flux of sediment particles;
F_d	= the deposition flux of suspended particles;
K_x, K_y, K_z	= apparent turbulence mass diffusivities in the x, y and z directions, respectively;
P_l	= expresses the cohesion of sediment and this value decreases when a sediment layer becomes thin;
P_s	= the pick - up rate;
t	= time;
V	= the cross section mean velocity;
V_c	= the critical fluid velocity calculated by the force balance between the weight of particle and the lifting fluid force;
v_s	= the volume of particle;
w_0	= the terminal velocity of particle in fluid;
x, y	= co-ordinate directions in horizontal plane;
z	= co-ordinate in vertical directions;
γ	= the coefficient;
σ	= the density of particle;
τ_*	= the dimensionless tractive force; and
τ_{*c}	= the dimensionless critical tractive force.

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