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Countermeasures for Preserving Riverine Tidal Flats in a Ship-Bottom Shaped Channel of the Lower Ota River Floodway

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ABSTRACT: In the lower Ota River floodway, the cross-sectional profiles have gradually changed to ship-bottom shaped cross-sectional bed profiles from compound cross-sectional profiles by bed scouring and erosions due to flood flows. In the deformation processes of the river bed profiles, the tidal flats are gradually reducing in size due to bed scouring and erosions induced by alternate bar movements. The tidal flats in the lower floodway have grown abundant intertidal creatures. It is necessary to preserve the tidal flats against bed scouring and erosions. Therefore, first, we evaluated topographic changes in the ship-bottom shaped channels on the lower floodway in the past about 30 years by developing numerical model for flood flows and bed variations. Second, we elucidated the deformation processes of the tidal flats by the numerical model developed for flood flows and bed variations. Finally, our numerical model provided locations and elevations of ripraps for preserving the tidal flats against bed scouring and erosions by simulating bed variation and tidal flats deformations within the next about 60 years.

Keywords: Ship-bottom shaped channel, Tidal flat, Bed variation, Flood flow, Alternate bar, Riprap, BVC method, Estuary

1 INTRODUCTION

River bed excavations have been considered as one of important techniques for increases in flood discharge. However, excessive excavations of river beds cause channel degradations, which result in channel incisions and narrowing. The channel incisions and narrowing have made a negative impact on river structures in alluvial rivers (Darby et al. (1999)). Therefore, many researchers and engineers have investigated river bed shapes in stable rivers and proposed a lot of regime equations on alluvial stable rivers and irrigation channels (e.g. Chow (1964)). However, the equations derived from regime theories were empirical and generally inapplicable. Ikeda et al. (1986) provided a relationship between properties of channel shapes and channel-forming discharge on stable alluvial rivers and their experiments of channel widening, however the derived relations could not account for the properties of various stable rivers where channel shapes are formed and adjusted by dynamically change in river beds and banks due to flood flows.

Fukuoka (2012a) indicated dynamic relation equations (Fukuoka's equations) between a river's dimensionless width, dimensionless depth and dimensionless channel-forming discharge based on properties of channel shapes in stable alluvial rivers. Moreover, he proposed design method for improvements of incised and narrowed rivers by coupling the Fukuoka's equations and numerical simulations of the flood flows and bed variations on gravel bed rivers in the Satsunai River where the channel degradation and incision results from a series of spur dikes and vegetation growing on the flood plains (Fukuoka (2012b)). The stable cross-sectional bed profiles provided by his study were almost similar to ship-bottom shaped cross-sectional profiles (see Figure 6) which have a continuous bed boundary seen in natural rivers. The ship-bottom shaped cross-sectional bed profiles are formed and adjusted by bed variations and bank erosions under the channel-forming discharge. Thus the ship-bottom shaped channels in natural alluvial rivers are almost stable under the channel-forming discharge. Sasaki & Fukuoka et al. (2014) investigated the effects of the ship-bottom shaped cross-sectional bed profiles in the Onga River where the ship-

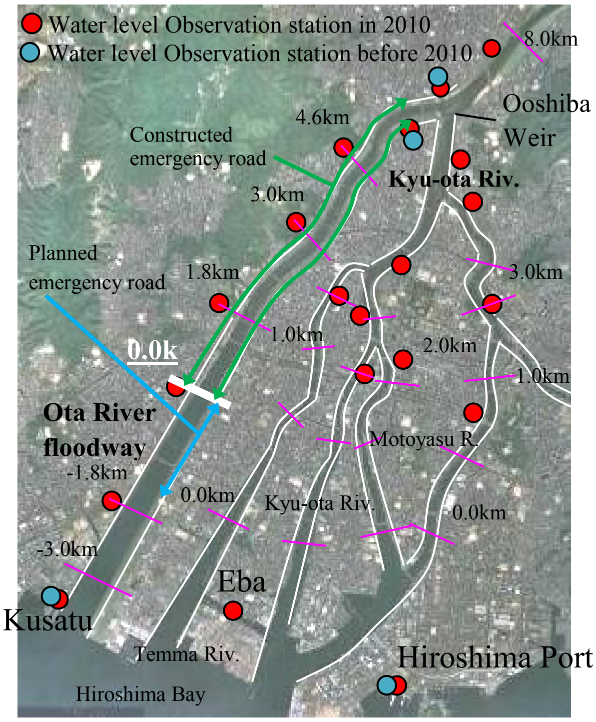


Figure 1. Air photograph of the Ota River delta in 2007 and July 2010's flood observation system

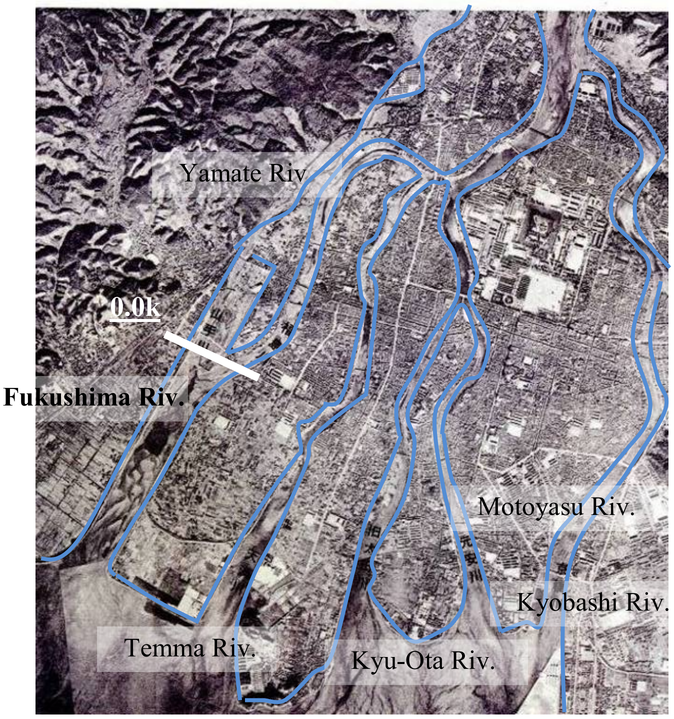


Figure 2. Air photograph of the Ota River delta in 1939

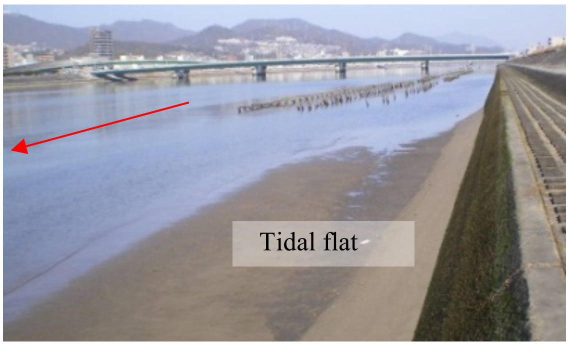


Figure 3. Tidal flats along the riverside in the lower Ota River floodway

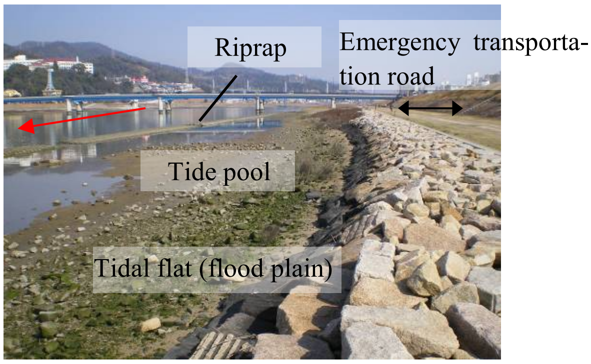


Figure 4. Tidal flats along the riverside at the middle section of the Ota River floodway

bottom shaped cross-sectional profiles had been already applied for river improvements. Their study indicated that the ship-bottom shaped channels were effective for improvements of incised and narrowed rivers. However, they couldn't clarify how to protect river banks in the ship-bottom shaped channels. For adopting the ship-bottom shaped channels for river improvement works under various river conditions, we need to consider the river bank protection measures which can also maintain self-adjustments functions of river widths and water depth of alluvial rivers.

On the Ota River delta, the construction project of the Ota River floodway had been conducted for about 40 years in order to protect Hiroshima City which is largest city in Chugoku region, Japan. The construction project finished in 1972. Although the lower Ota River floodway was constructed by excavations and expansions of the Fukushima River (see Figure 1 and Figure 2) which had flowed before the floodway constructions, the river bed profiles of the lower floodway is almost stable after the completion of the constructions. However, since the riverside-main channel transition zones have been scoured and eroded by a series of floods in past years, the cross-sectional bed profiles in the lower floodway have gradually changed to ship-bottom shaped channels (see Figure 6) from compound channels. On the riversides of the lower floodway, tidal flats have developed and grown abundant creatures in the estuaries (see Figure 3). Thus, it is necessary to preserve the tidal flats in the ship-bottom shaped channel of the lower floodway along the riverside against bed variations and erosions.

In this study, we attempt to understand topographic changes in the ship-bottom shaped channel with tidal flats after the completion of the floodway constructions. In the middle sections of the Ota River floodway, the floodplains which become tidal flats by being located within intertidal zone are already preserved by ripraps in front of them as shown Figure 4. Therefore, we evaluate effects of ripraps on the topographic changes in the tidal flats and determine appropriate locations and elevations of the ripraps for preserving the tidal flats by numerical simulations for flood flows and bed variations. This issue is closely related with the design method of river bank protections in the stable ship-bottom shaped channels.

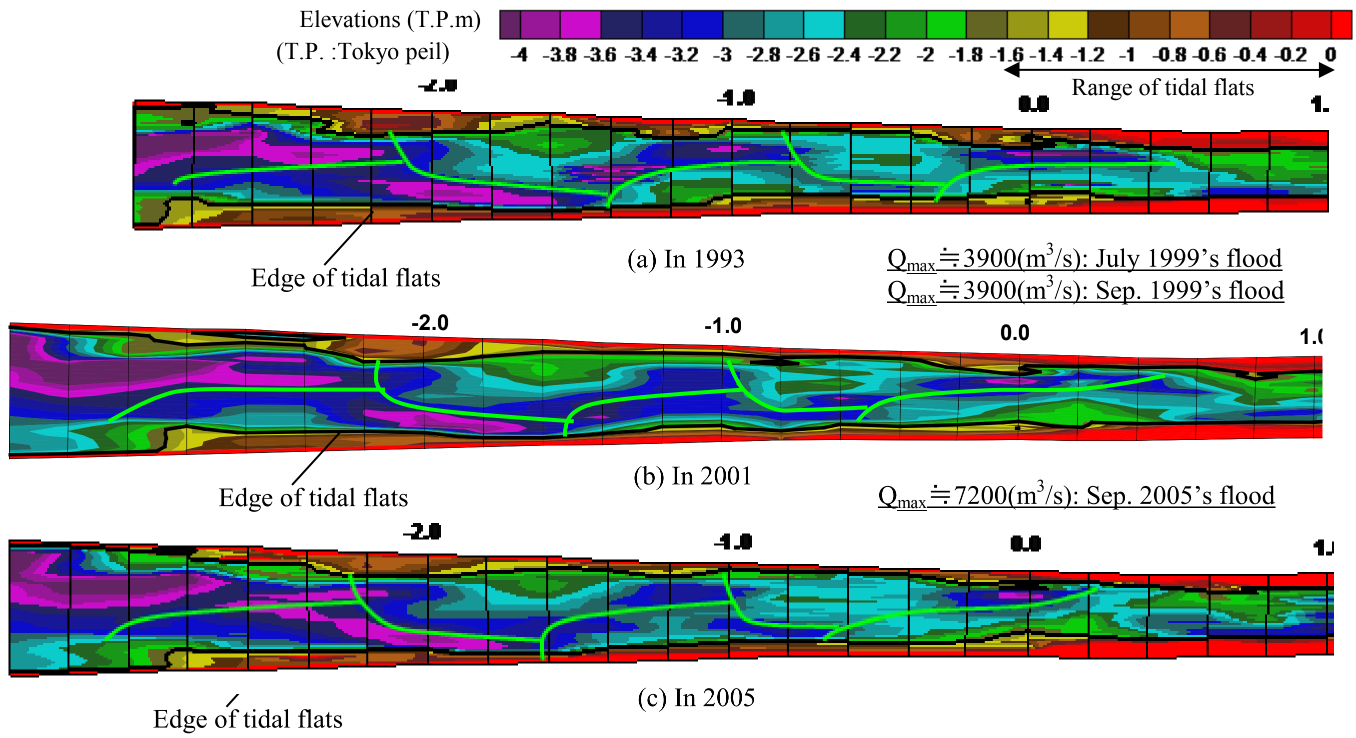


Figure 5. Contour of the observed bed profiles in the lower Ota River floodway

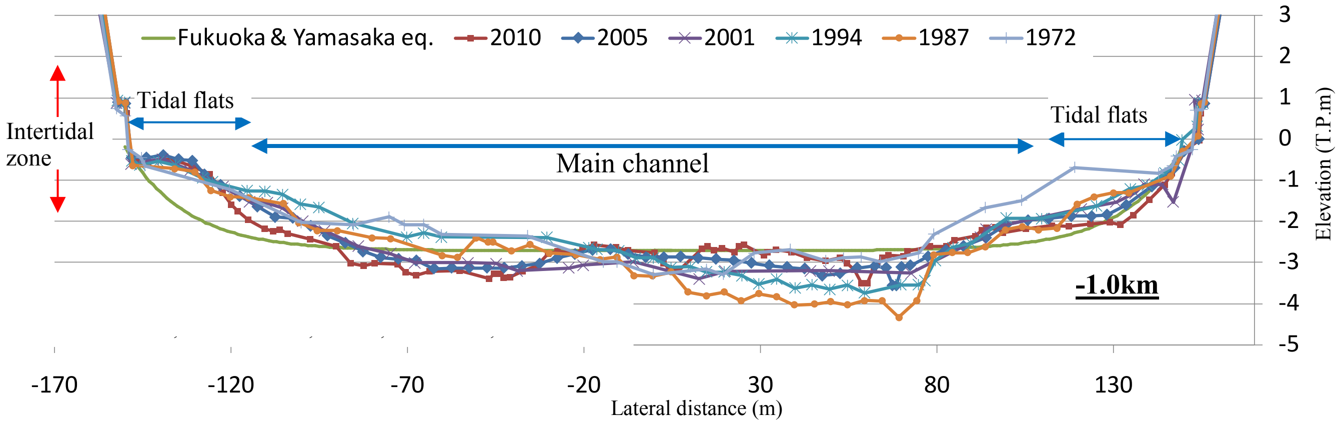


Figure 6. Cross-sectional observed bed profiles in ship-bottom shaped channels with tidal flats in the Ota River floodway

2 OBSERVED TEMPORAL CHANGES IN BED PROFILES OF THE TIDAL FLATS IN THE LOWER OTA RIVER FLOODWAY

Figure 1 shows the air photograph of the Ota River delta in 2007 and observation system in July 2010's flood. The Ota River delta is composed of the Ota River floodway and other five branched rivers. Cross-sectional shapes of the Ota River floodway are compound cross-sectional channels from 5.8km to 0.2km and simple cross-sectional channels from 0.2km to -3.4km. The channel widths of the floodway are about 300-400m. Figure 2 shows the air photograph of the Ota River delta in 1939 when the floodway was under constructions. Although there were extensive tidal flats around the river mouth at that time, the tidal flats have been lost by land reclamations and remained only along the riverside of the floodway in recent years as shown Figure 3 and Figure 4. In the first Ota River improvement planning which was made in 1933, the entire reach of the floodway were designed as a compound cross-sectional channel. Thus the main channel in the lower floodway was constructed by channel dredging of the Fukushima River which had flowed before the floodway was completed (see Figure 1 and Figure 2). In contrast, the riversides designated as the floodplains in the first river improvement planning have been naturally remained in the estuary. Since the riversides are within the intertidal zone which are submerged and exposed by daily tidal changes, the tidal flats develop on the riverside and they have important roles to grow intertidal creatures. Figure 5 shows contours of the river bed topography drawn by using surveying data in each year. Figure 6 shows observed cross sectional bed profiles at -1.0km. In the main channels of the lower floodway, alternate bars with about 1km wavelength are formed and gradually move to downstream by flood flows. The alternate bar movements cause river bed scouring and erosions on the tidal flats along the riversides, which tend to accelerate degradations of the tidal flats as described below.

In 1993, a pool of alternate bars was formed at around -0.4km of the left bank. Due to July and Sept. 1999's floods and Sept. 2005's flood, alternate bars moved to downstream as shown Figure 5(b) and Figure 5(c). Therefore, the tidal flats on the riverside in the left side of -1.0km were scoured by alternate bar movements due to flood flows in 2010 (see Figure 6).

While the floodway has experienced the above deformation processes of the tidal flat shapes, the cross-sectional river bed profiles in the lower floodway have gradually changed to ship-bottom shaped channels from compound channels due to bed scouring and erosions with alternate bar movements by a series of floods in the past years. The characteristics of the ship-bottom shaped cross-sectional channels are that the river bed profiles have a continuous bed boundary and their widths and depth are naturally adjusted by erosions on the riverside and bed variations in main channels. Therefore, the ship-bottom shaped channels formed and adjusted by the bed variations are almost stable for discharges below the channel-forming discharge. Since the Ota River floodway has already experienced the design scale flood in July 1972, the cross-sectional bed profiles are almost stable under the design flood discharge that is considered as a channel-forming discharge of the current floodway. Fukuoka & Yamasaka (1984) described cross-sectional bed profiles in straight stable river bed profiles as Eq. (1). The ship-bottom shaped cross-sectional profiles in the lower floodway are similar to the cross-sectional shapes described by Fukuoka & Yamasaka's equation as shown Figure 6.

$$\frac{h}{H} = 1 - \left\{exp\left(-\frac{b-y}{D}\right) + exp\left(-\frac{b+y}{D}\right) - exp\left(-\frac{2b}{D}\right)\right\} \tag{1}$$

Where h: water depth, b: half of channel width, y: distance from center of channel, H and D: coefficients which were decided by cross sectional area and lateral slope of river beds near riverside.

While the river bed profiles have been formed in the above deformation processes, elevations of the tidal flats on the riversides have gradually lowered. Moreover, the emergency transportation road for earthquake disaster (see Figure 4) is going to be constructed on the tidal flats of the left bank based on the current river improvement planning. Since these road constructions may accelerate degradations of the tidal flats, it is necessary to preserve the tidal flats along the riverside in the lower floodway. In the following sections, we explained and validated our numerical model developed for flood flows and bed variations in the lower floodway with tidal flats. Moreover, we discuss countermeasures for preserving the riverine tidal flats against bed variations.

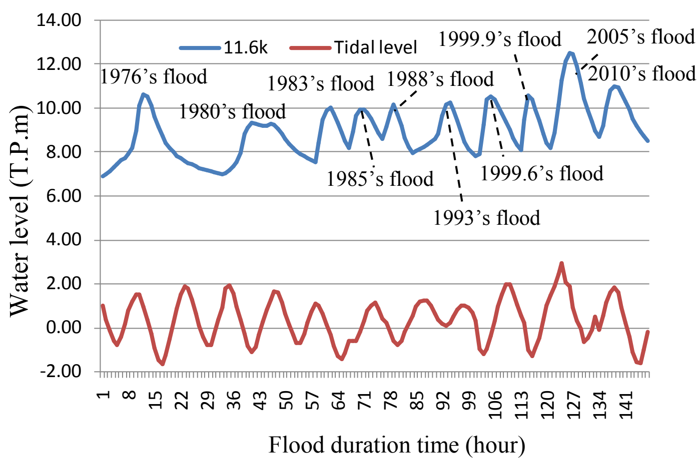


Figure 7. Boundary conditions of upstream end and downstream end in the past about 30 years

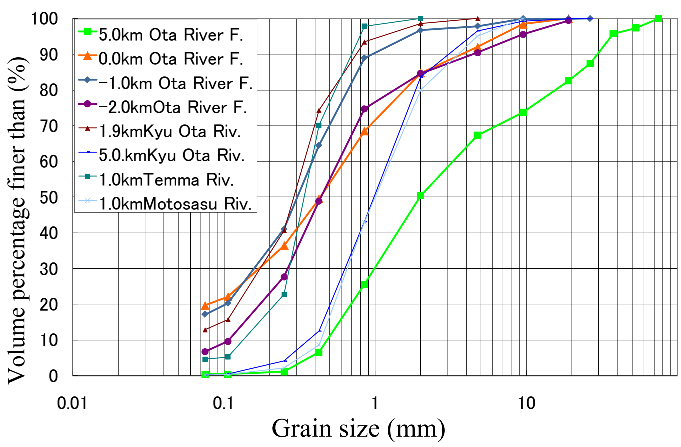


Figure 8. Grain size distributions in the channels on the Ota river delta

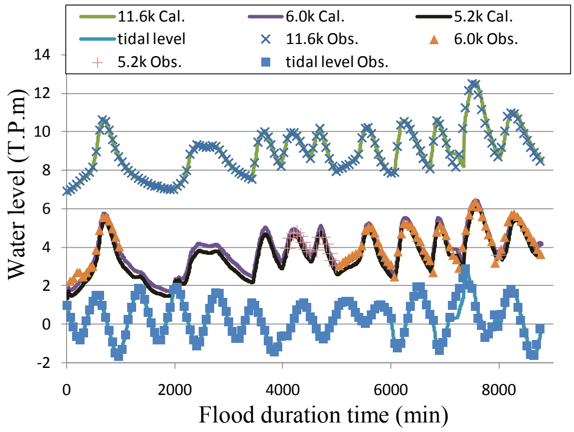


Figure 9. Comparison between observed and calculated water level hydrographs

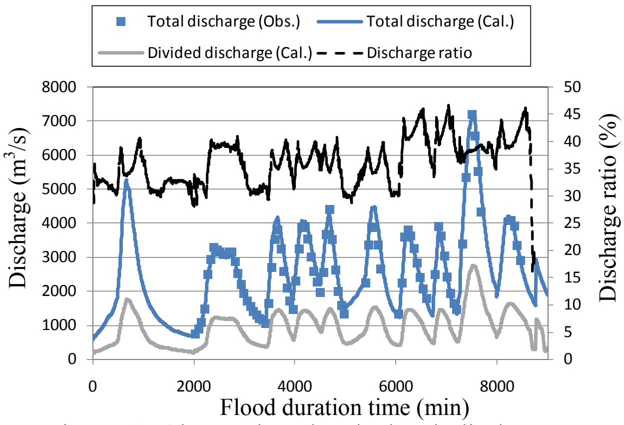


Figure 10. Observed and calculated discharge hydrograph and discharge ratios

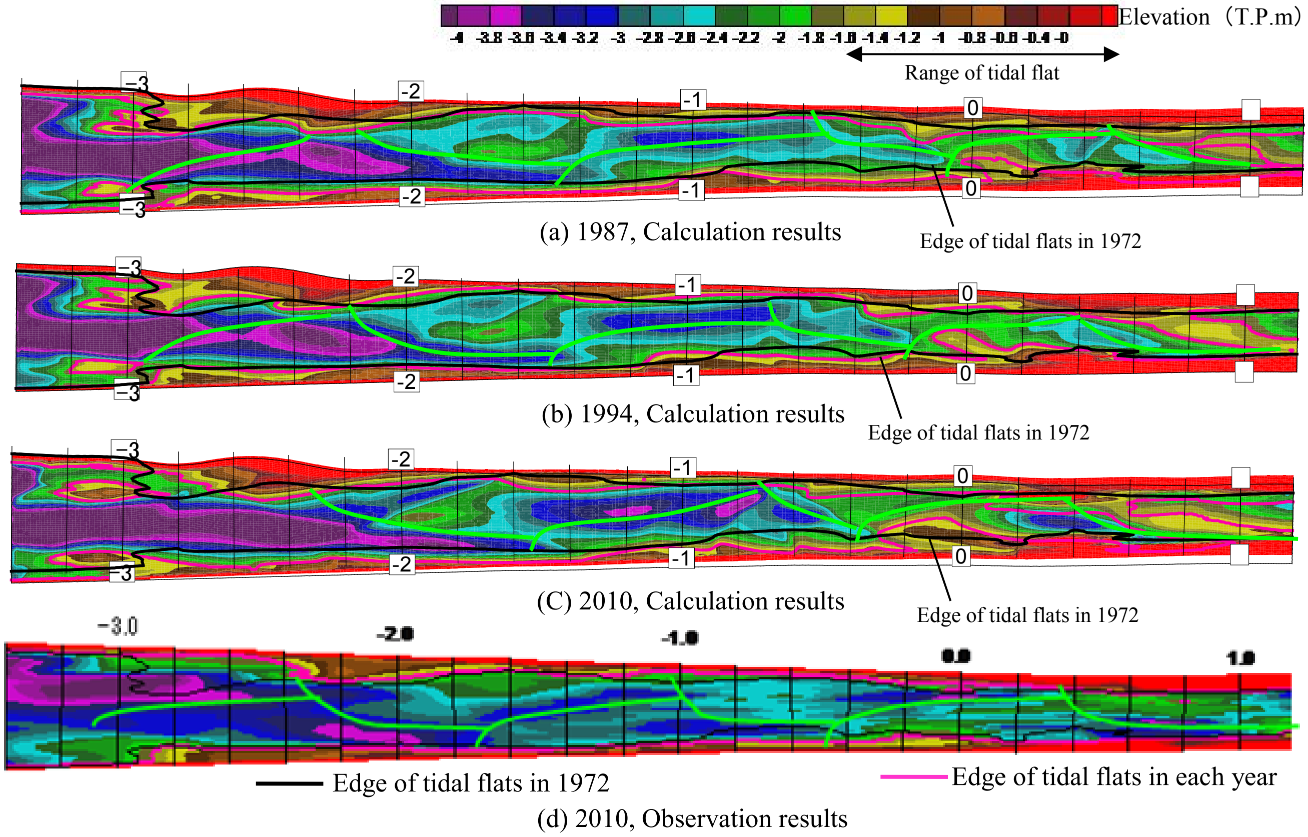


Figure 11. Comparison between observed and calculated river bed topographic changes by a series of flood until July 2010's flood from July 1972's flood in the lower floodway

3 EVALUATION OF DEFORMATION PROCESSES OF THE TIDAL FLATS IN THE SHIP-BOTTOM SHAPED CHANNELS IN THE LOWER OTA RIVER FLOODWAY

In the previous studies, Author et al. (2011) have developed numerical model which was able to reproduce the flood discharge distributions and bed variations in the channel network on the Ota River delta by using time series of observed water surface profiles. The concept of the numerical model is that we conduct numerical simulations for flood flows and bed variations so as to agree with time series of observed water surface profiles because effects of flood discharge distributions, bed variations, flood flows and so on appear in the time series of observed water surface profiles (Fukuoka et al. (2004)). Therefore, in July 2010's flood, we observed time series of water surface profiles in detail by installing water level gages in main and branch streams as shown Figure 1. The numerical model also made possible to evaluate the changes in the tidal flats due to the alternate bar movements in July 2010's floods (Author et al. (2013)). Therefore, it is necessary to develop numerical model for understanding and evaluating the tidal flat deformations by a series of floods in the past years.

We developed the numerical model for flood flows and bed variations for past about 30 years in the ship-bottom shaped channel with the tidal flats on the Ota River delta. In addition, we validated the numerical model by reproducing observed river bed topographic changes in the lower floodway within the past about 30 years (July 1976's flood-July 2010's flood). In order to evaluate appropriate bed variations during the floods, we applied the BVC method developed by Uchida & Fukuoka (Uchida & Fukuoka (2013)) which can evaluate proper bed surface velocities and vertical velocity distributions by applying depth averaged horizontal vorticity equations with depth averaged horizontal momentum equations and continuity equation. The vertical velocity distributions in the numerical model assumed by a cubic curve were determined by using depth averaged horizontal vorticity and difference between water surface velocities and bottom velocities. The bed variation analysis was used the conventional method which consisted of bed load formula (Ashida & Michiue (1972)) and continuity equations for sediment and grain sizes (Hirano (1971)). The suspended sediment transport were calculated by depth averaged continuity equation of suspended load concentrations which vertical distributions were assumed to be equilibrium conditions provided by Lane & Kalinske formula (Lane & Kalinske (1941)). The pick up rate of suspended load from river bed were calculated by Kishi & Itakura formula (Itakura & Kishi (1980)). The critical tractive forces for *dk* and mean particle size *dm* were calculated by the modified Egiazaroff formula (Egiazaroff (1965), Ashida & Michiue (1972)) and Iwagaki formula (Iwagaki (1956)), respectively. In order to estimate proper inflow discharge hydrographs of the floodway, it is necessary to evaluate discharge distributions of the channel network on the Ota River delta. Therefore, the calculation model had two kinds of grids composed of coarse grids and fine grids. The fine grids were used for evaluation of the flood flows and bed variations around the tidal flats along the riverside. The coarse grids were used for evaluation of the flood discharge distributions and bed variations in the channel network on the delta, providing boundary conditions for fine grids region. The water level hydrographs of major flood events in the past about 30 years were given as the boundary conditions of upstream and downstream ends as shown Figure 7. The initial conditions of river bed profiles were made by using survey data in 1972. Figure 8 shows the grain size distributions in the section studied. The bed materials in the Ota River floodway and the other branched rivers mainly consist of sands.

Figure 9 shows the comparison between observed and calculated water level hydrographs in each flood. Figure 10 shows the calculated discharge hydrographs of the Ota River floodway and the branched river, the Kyu Ota River, in each flood. The calculated water level hydrographs were able to reproduce observed ones as shown Figure 9. The calculation results indicated that about 40% amount of total discharge divided to the branched river, Kyu Ota River. These discharge ratios were almost agree with results of our previous study which provided discharge distributions on the delta in July 2010's flood by using detailed time series of observed water surface profiles in the flood. Figure 11 shows contours of the calculated bed profiles in 1987, 1994 and 2010 and observed ones in 2010. The black lines in these figures show the edges of the tidal flats in 1972 that is initial conditions. The red lines show the edges of the tidal flats after each flood. Although calculated displacements of alternate bars were relatively smaller than observed ones, our numerical model was able to explain interactions of erosions on the riverside and bed variations in the main channels. When pools of alternate bars approached to tidal flats on the riverside, bed scourings on tidal flats were induced by movements of pools on the alternate bars. From these figures, it is found that bed scourings on the tidal flats along the riversides are induced by movements of the alternate bars.

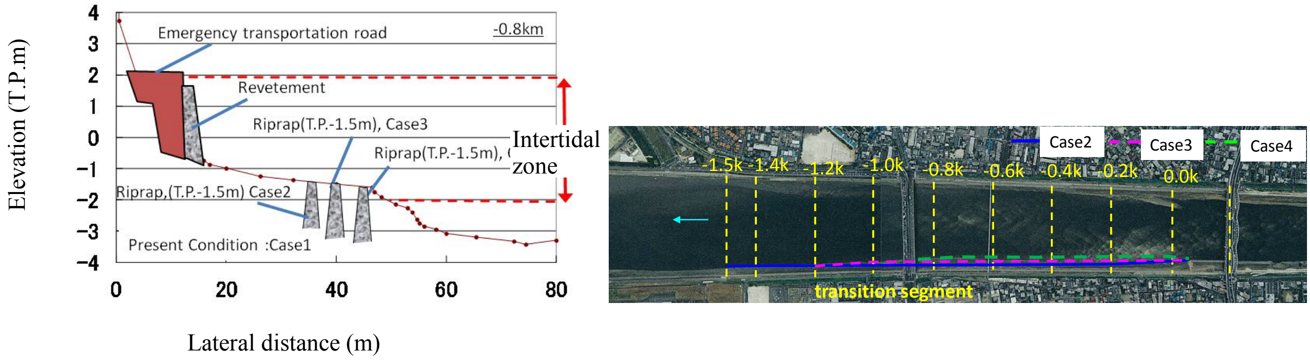
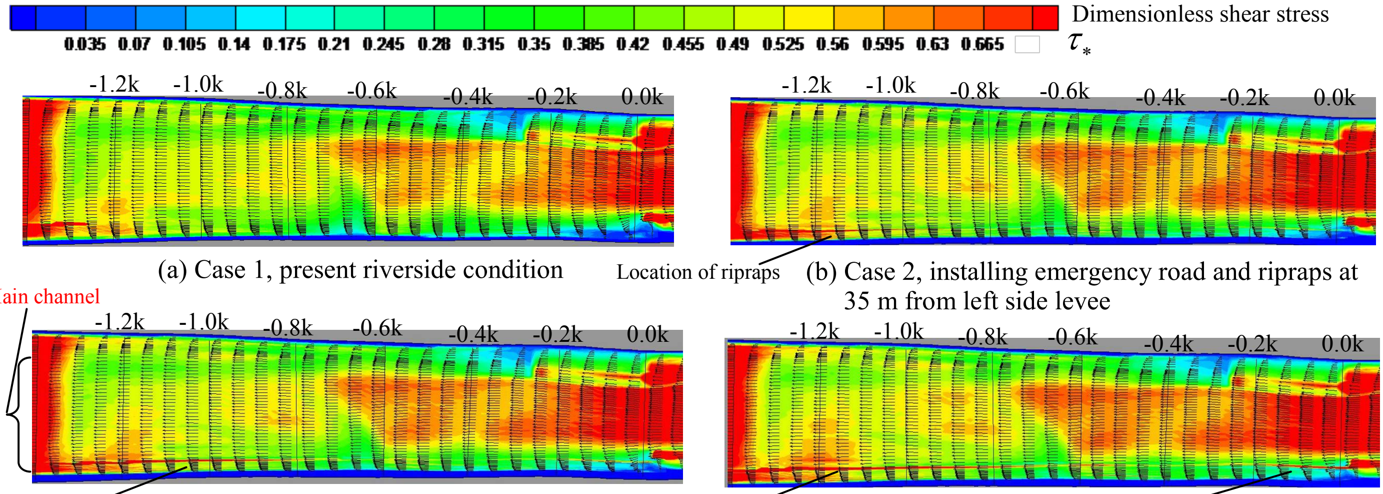


Figure 12. Calculation conditions of the riverside at the left bank



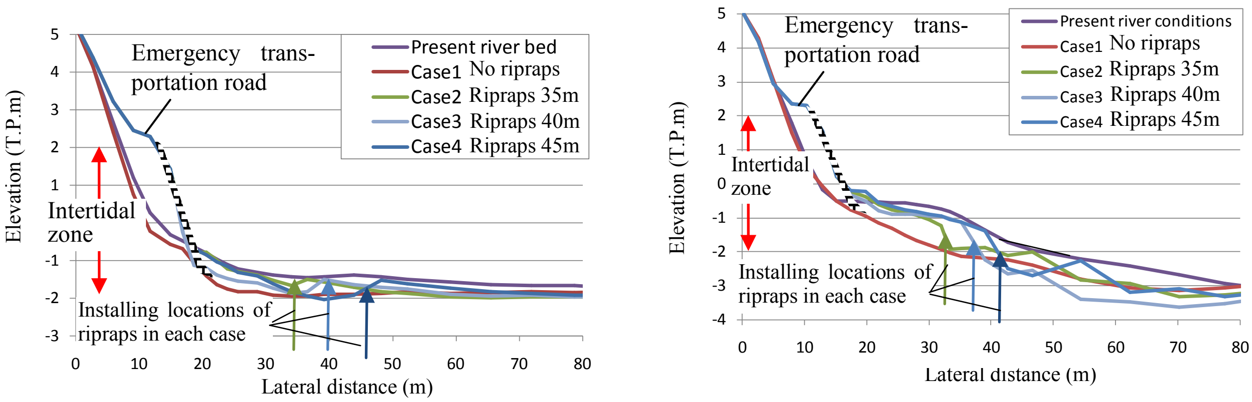
(a) Case 1, present riverside condition

(b) Case 2, installing emergency road and ripraps at 35 m from left side levee

(c) Case 3, installing emergency road and ripraps at 40m from left side levee

(d) Case 4, installing emergency road and ripraps at 45 m from left side levee

Figure 13. Calculated dimensionless shear stresses in case which the largest flood (Sep.2005's flood) occurred in current bed profiles in the lower floodway



(a) -0.2 km, Left side bank

(b) -1.0 km, Left side bank

Figure 14. Calculated cross-sectional bed profiles after a series of floods within next about 60 years

4 COUNTERMEASURES FOR PRESERVING THE TIDAL FLATS AGAINST FLOOD FLOWS IN THE SHIP-BOTTOM SHAPED CHANNELS

In this section, we estimated effects of the construction of the emergency transportation road and ripraps (see Figure 12) on the topographic changes in the tidal flats and determined appropriately locations and elevations of the ripraps for preserving the tidal flats on the ship-bottom shaped channels in the lower floodway. We simulated flood flows, bed variations and tidal flat deformations within next about 60 years under various riverside conditions. Thus, the major flood events in the past 30 years were repeatedly given at the upstream and downstream ends. Figure 12 shows calculation conditions in each case as described below.

Case1 is the present conditions which are no emergency transportation road and no ripraps. The conditions of Case2, Case3 and Case4 are that the emergency transportation road is installed along the riverside of the left bank from 0.0km to -1.5km and ripraps are installed in front of the tidal flats on the current river bed profiles. In the each simulation case, the ripraps are installed on the tidal flats at about 35m (Case2), 40m (Case3) and 45m (Case4) from the left side levee. The elevation of the installing ripraps in all cases is -1.5(T.P.m). These conditions show that the ripraps of Case3 are installed so as to minimize difference from the current bed profiles and the ripraps of Case2 and Case4 are posteriorly and anteriorly displaced from the location of Case3, respectively.

Figure 13 shows contours of calculated dimensionless shear stress in the maximum discharge in each case. From these figures, it is found that dimensionless shear stresses in Case4 are abruptly increased along the ripraps of the left bank at around -0.2km by installing the ripraps. In contrast, dimensionless shear stresses in are still smaller than the results of Case4 and similar to those of Case1. On the other hand, in Case2, Case3 and Case4, distributions of the dimensionless shear stresses in the main channel almost agree with the results of Case1. Figure 14 shows calculated cross-sectional bed profiles after a series of floods in each case. The calculation results of Case1 expected that elevations of the tidal flats were going to decrease due to bed scouring in a series of floods within the next about 60 years, while the cross-sectional bed profiles were going to keep with the ship-bottom shaped channels. However, the calculation results indicated that the installing conditions of the ripraps in Case2 and Case3 were almost able to preserve the tidal flats against river bed scouring and erosions compared with Case1. Neverthless, the installing conditions of Case4 caused large scale bed scouring and erosions at around -0.2km due to increasing of the dimensionless shear stresses along the ripraps. From these results, we decided to install ripraps of locations and elevations of Case3 which was able to protect more extensively tidal flats than Case2. This fact shows that the countermeasure provided by this study for preserving the tidal flats can maintain the stable tidal flats with keeping the functions of self-adjustments of river bed profiles.

5 CONCLUSIONS

The following conclusions were derived in this study.

1) In the lower Ota River floodway, the cross-sectional bed profiles have gradually changed to ship-bottom shaped channels from compound channels due to erosions on the riverside and bed variations in the main channels. Although the ship-bottom shaped channels of the lower floodway are almost stable under the channel-forming discharge, the tidal flats along the riverside gradually lower due to alternate bar movements by flood flows. Therefore, it is necessary to preserve the tidal flats against bed scouring and erosions by installing ripraps in front of the tidal flats as shown Figure 4.
2) Our numerical model developed for flood flows and bed variations was able to reproduce and elucidate the interactions of alternate bars movements and tidal flats deformations in the past about 30 years in the ship-bottom shaped channel of the lower Ota River floodway. Moreover, we estimated topographic changes in the tidal flats under the various riverside conditions within the next about 60 years. As a result, this study indicated that the countermeasure provided for preserving the tidal flats is able to maintain stable tidal flats with keeping the functions of self-adjustments of river bed profiles.

REFERENCES

Chow, V. T. (1964). Handbook of applied hydrology, McCRAW W-HILL.

Darby, S. & Simon, A. (1999). Incised river channels: processes, forms, engineering, and management.

Fukuoka, S. (2012a). Dimensionless width and depth and sediment transport rate in stable rivers, 3rd International Symposium on Shallow Flows (ISSF),CD-R.

Fukuoka, S. (2012b). Study of stable cross-sectional forms harmonizing the flood control and river environment in the satsunai river, Annual Report of River Center of Hokkaido.

Fukuoka, S. & Yamasaka, M. (1984). Shear stress distribution on a continuous boundary and widening process of a straight alluvial channel. Proceedings of JSCE, JSCE, No.351, II-2, pp.87-96.

Fukuoka, S., Watanabe, A., Hara, T. & Akiyama, M. (2004). Highly accurate estimation of hydrograph of flood discharge and water storage in river by using an unsteady two-dimensional flow analysis based on temporal change in observed water surface profiles, J. Hydraul. Coastal & Environ. Engng., No.761(II), pp.45–56.

Gotoh, T., Fukuoka, S. & Miyagawa, Y. (2013). Topographic changes of tidal flats in the Ota River estuary by flood flows, Proceedings of 12th International Symposium on River Sedimentation, ISRS, CD-R.

Gotoh,T., Fukuoka, S. & Tanaka, R. (2011). Evaluation of flood discharge hydrographs and bed variations in a channel network on the Ota River delta, 5th International Conference on Flood Management (ICFM5),CD-R.

Ikeda, S., Parker, G., Chiyoda, M. & Kimura, Y. (1986). Stable channel cross-section of straight gravel rivers with actively transported bed materials, Proceedings of JSCE, JSCE, Vol.375, pp.117-126.

Sasaki, T., Miyahara, K. & Fukuoka, S. (2014). Changes in flood-flow dynamics and bed variatons by repair to ship-bottom-shaped channels from compound channels, Advances in River Engineering, JSCE, Vol.20, pp. 277-282.

Uchida, T. & Fukuoka, S. (2013). Numerical calculation for bed variation in compound-meandering channel using depth integrated model without assumption of shallow water flow, THESIS 2013, USB memory.