

Formation mechanism of the ship-bottom-shaped channel and its hydraulic functions

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ABSTRACT: The general shape of rivers in Japan is the compound channel consisting of main channel and flood channel. However, gravel-digging and construction of cross-structures have reduced sediment transport, resulting in riverbed degradation and narrowing of the main channel width. Those brought damage to river structures and riverbanks and intense channel forestations. On the other hand, in the middle reach of Tama River, the main channel bed height has been controlled by longitudinal riverbed stabilization works over long period, resulting in widening of the main channel width in response to repetitive flood flows, and this brought change to the ship-bottom-shaped channel where the main channel bed connects gently with the flood channel bed. In this study, the formation mechanism and hydraulic functions of the ship-bottom-shaped channel in the middle reach of Tama River were evaluated by flood flow and riverbed variation analysis. As a result, the following findings were clarified. The ship-bottom-shaped channel is formed by scouring laterally interfacial zones of the flood channel with the main channel so that flood energy is shared properly across the entire channel. This mechanism which makes flood flow downstream carry safely by varying the main channel width within the total width limited by levees is explained physically. In addition, the ship-bottom-shaped channel provides refuge for fish during flooding because the bottom velocity hardly changes as flood discharge increases.

1 INTRODUCTION

The study of river channel shape that floods flow safely and are easy to maintain the environment has been treated as an essential issue in river management. As a concept of such river channel shape, in Europe, river management aiming to close to the natural river channel shape has been introduced since the 1970s in order to take advantage of the self-adjustments function of natural rivers (Binder (2006)). In recent years, in Germany and Switzerland, which have advanced the close-to-natural river construction, the removal of structures that protected riverbanks has allowed river channel width to be widen in response to force of nature, thereby stabilizing riverbed height (Binder (2006), Rachelly et al. (2018)). This has been recognized as effective means in restoring the landscape and ecosystem. In the Netherlands, the room for the rivers program implemented since 2006, is an effort to return floodplains that have been originally river spaces to rivers (Klijn et al. (2018)), and it can be considered river management in harmony with flood control and

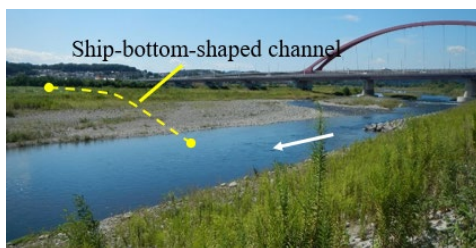


Figure 1. Ship-bottom-shaped channel in the middle reach of Tama River.

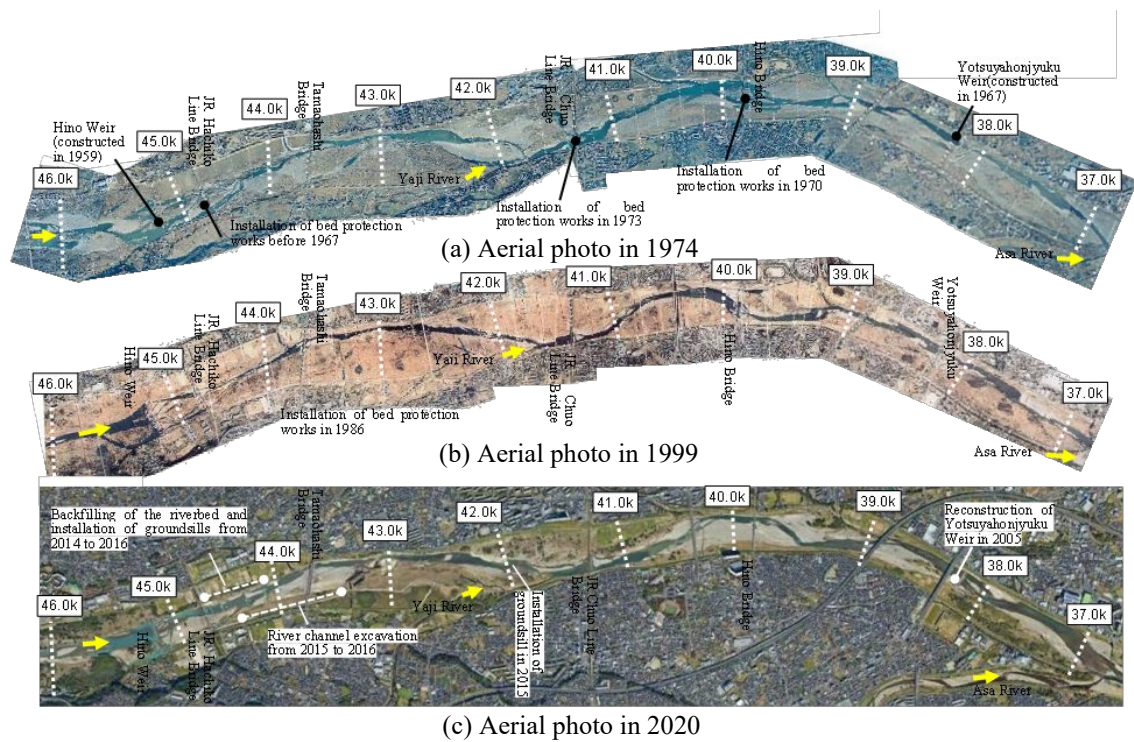


Figure2. Annual changes of the river channel in the middle reach of Tama River.

environment restoration.

On the other hand, in Japan, the close-to-nature river works based on European case studies has been started in 1990. Japanese rivers are steep and have large sediment transport, while channel widths restricted by levees are narrow because population and residential areas are concentrated in alluvial plains. Therefore, the close-to-natural river works have been promoted under severe natural and social conditions. Meanwhile, Fukuoka (2012) has focused on the dynamic relationship of channel formation in natural rivers and has proposed the relation equations of dimensionless river width and water depth against dimensionless channel-forming discharge called “Fukuoka’s equation” by dimensional analysis method using data of alluvial rivers in Japan and overseas. Furthermore, it has clarified that the ship-bottom-shaped channel where the main channel bed connects gently with the flood channel bed such as the original natural river channel shape as shown in Figure 1, satisfies Fukuoka’s equation and is a desirable river channel shape in harmony with flood control and environment (Fukuoka (2012) and Sasaki et al. (2015)). Since then, practical studies on the ship-bottom-shaped channel have been conducted in various rivers (Sasaki et al. (2015)).

Figure 2 shows annual changes of river channel in the middle reach of Tama River. In the 1940s, a vast sandbar channel with a rich natural environment was formed, but sediment transport decreased due to mass gravel-digging and construction of fixed weirs during the period of rapid economic growth (1950s to 1960s). The discontinuity of sediment transport caused channel bipolarization with river bed degradation, narrowing of the main channel width and immobilization of sandbars, resulting in loss of the characteristic sandbar channel. Therefore, in the middle reach of Tama River, river improvement works have been implemented to improve the bipolarized channel and stabilize the longitudinal profile of the main channel bed level. As a result, scouring of immobilized sandbar banks has been promoted by large floods in recent years, and the sandbar channel has been recovering as the main channel width has been widened (Gotoh et al. (2023)).

In this study, the transformation of river channel shape into the ship-bottom-shaped channel with stabilization of the main channel bed level was investigated by long-term observation data in the middle reach of Tama River. Next, the formation mechanism of the ship-bottom-shaped channel was clarified and it was evaluated that the ship-bottom-shaped channel was stable channel shape from viewpoint of flood flow energy distribution by flood flow and riverbed variation analysis for the 2019 flood was equivalent to the design-flood discharge. In addition, the function of low velocity area formed in the ship-bottom-shaped channel during flooding, which contributed to formation of fish refuges were hydrologically evaluated.

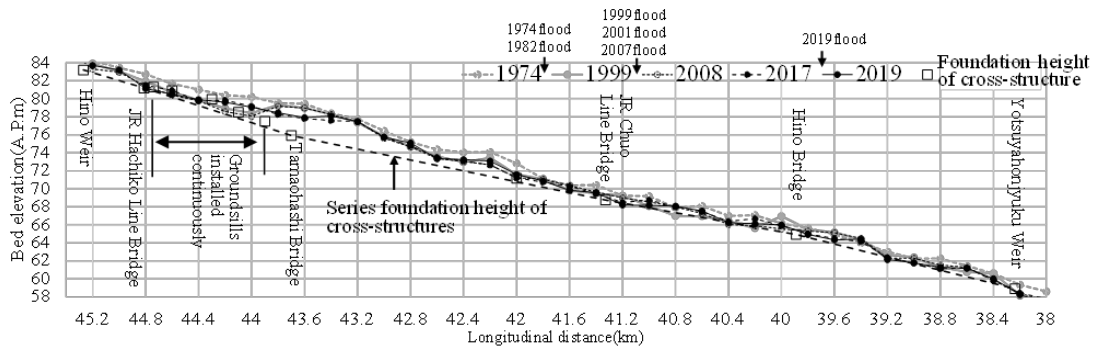


Figure 3. Annual changes in longitudinal distributions of the mean bed level of the main channel.

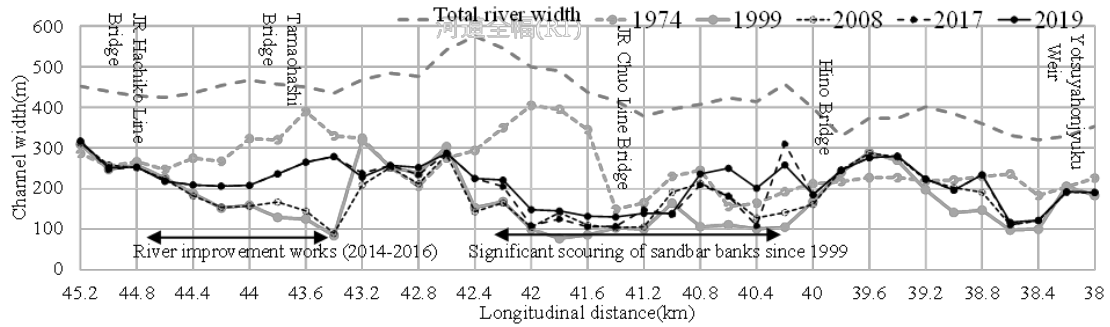


Figure 4. Annual changes in longitudinal distributions of the main channel width.

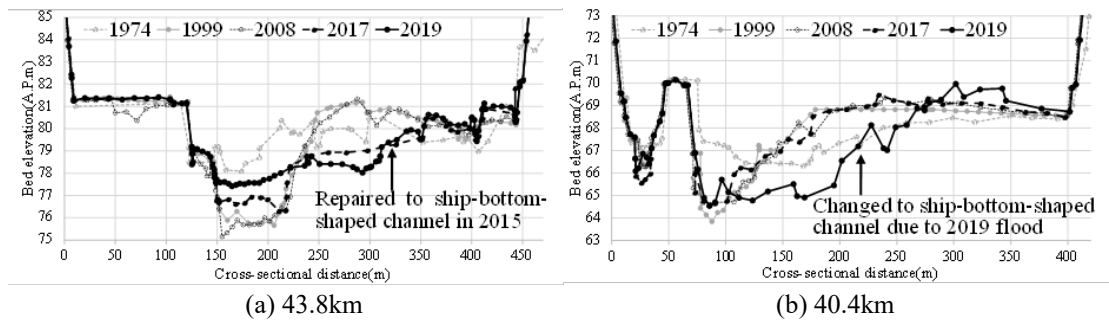


Figure 5. Annual changes in cross-sectional profiles.

2 STABILIZATION OF THE MAIN CHANNEL BED LEVEL AND FORMATION OF THE SHIP-BOTTOM-SHAPED CHANNEL IN THE MIDDLE REACH OF TAMA RIVER

Figure 3 shows annual changes in longitudinal distributions of the mean bed level in the main channel, Figure 4 and Figure 5 show annual changes of the main channel width, and cross-sectional profiles, respectively. In the middle reach of Tama River, as shown in Figure 3, 4 and 5, the main channel bed level was progressively lowered due to mass gravel-digging and construction of fixed weirs in the 1950s and 1960s, the sandbars were immobilized and turned into flood channel beds, narrowing the main channel width, resulting in loss of the characteristic sandbar channel, as shown in Figure 2(b).

However, in recent years, the main channel bed level has been controlled by foundation heights of cross-structures, such as weirs, bed protection works around bridge piers and ground sills, which have been installed and reconstructed in a planned manner, as shown by the black dashed line in Figure 3. With the stabilization of the main channel bed level, changes in the river channel caused by large floods since 1999 have become apparent in changes of the main channel width as shown in Figure 4, and scouring of immobilized sandbar banks has been promoted, and dominant sandbar channel has been recovering as the main channel width has been widened, as shown in Figure 2(c). The 2019 flood, which was equivalent to the design-flood discharge, caused significant scouring of immobilized sandbar banks in the section upstream and downstream of the JR Chuo Line bridge (42.2 km-40.4 km), and the main channel width changed back to that of the

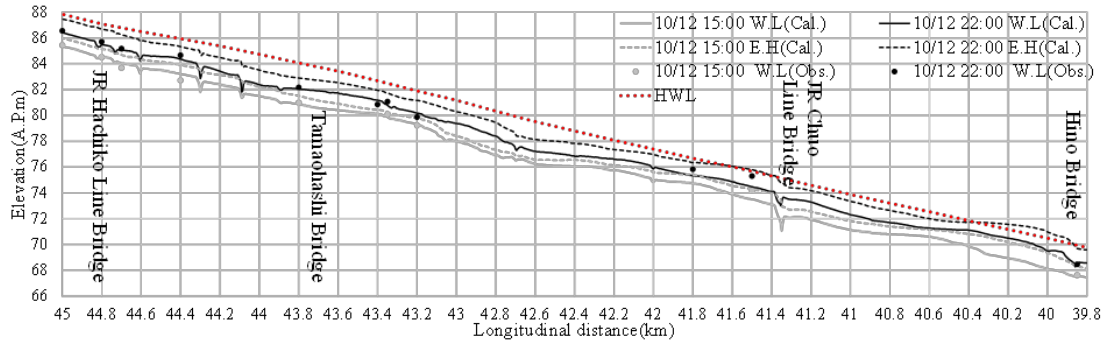


Figure 6. Longitudinal distributions of observed and calculated water levels and energy heads in the 2019 flood.

1960s before channel bipolarization, as shown in Figure 4 and Figure 5(b). As a result, river channel has been changed to ship-bottom-shaped channel where the main channel bed connects gently with the flood channel bed.

On the other hand, in the section around the Tamaohashi bridge (44.8 km-43.4 km), where channel bipolarization was pronounced, the river channel was repaired to ship-bottom-shaped channel by backfilling the main channel bed with gravel, excavating immobilized sandbars, and installing longitudinally continuous groundsills between 2014 and 2016, as shown in Figure 1 and 5(a). Since then, both bed level and width of the main channel have been mostly controlled. This is because the river improvement works have secured sufficient main channel width, and the ship-bottom-shaped channel has been maintained.

3 FORMATION MECHANISM OF THE SHIP-BOTTOM-SHAPED CHANNEL BY SCOURING OF IMMOBILIZED SANDBAR BANK

In this chapter, focusing on the ship-bottom-shaped channel repaired by river improvement works and that formed by floods, the formation mechanism of the ship-bottom-shaped channel was evaluated by the flood flow energy distribution (Fukuoka (2023)) and the dimensionless equation for stable river channel by Fukuoka (2012).

3.1 Analysis method and results

The non-hydrostatic quasi three-dimensional flood flow analysis model (Q3D-FEBS) by Takemura et al. (2019), and the riverbed variation analysis model with bed load and suspended load considering non-equilibrium sediment motion by Gotoh et al (2020) were employed for the simulation of the 2019 flood. Figure 6 shows longitudinal distributions of observed and calculated water levels and energy heads in the 2019 flood. Figures 6 shows that the analysis results are sufficient to reproduce temporal changes of observed flood water surface profile.

3.2 Formation mechanism of the ship-bottom-shaped channel by scouring of immobilized sandbar banks

Figure 7 and Figure 8 show temporal changes of calculated bottom velocity distribution contours in the section around the Tamaohashi bridge (44.8 km to 43.2 km) and in the section downstream of the JR Chuo Line bridge (41.6 km to 40.0 km). Figures 9 and 10 show temporal changes of calculated cross-sectional profiles, velocity and energy head distributions at representative cross-sections (43.8 km and 40.4 km). In addition, in order to focus on the energy distribution of flood flow (Fukuoka (2023)), the total energy heads ($(u^2+v^2+w^2)/2g$) are added to the water surface in Figure 6, Figure 9 and Figure 10. The velocities u , v and w are averaged over the cross-section in Figure 6, and averaged over the water depth in Figures 9 and 10.

In the section around the Tamaohashi bridge, where has been repaired to ship-bottom-shaped channel, as shown in Figures 7 and 9, the distribution of flow velocity and total energy head for each discharge remain gently continuous across the main channel and the flood channel, and don't change significantly during peak flood. This indicates that the ship-bottom-shaped channel is desirable channel shape that can share flood energy properly across the entire channel.

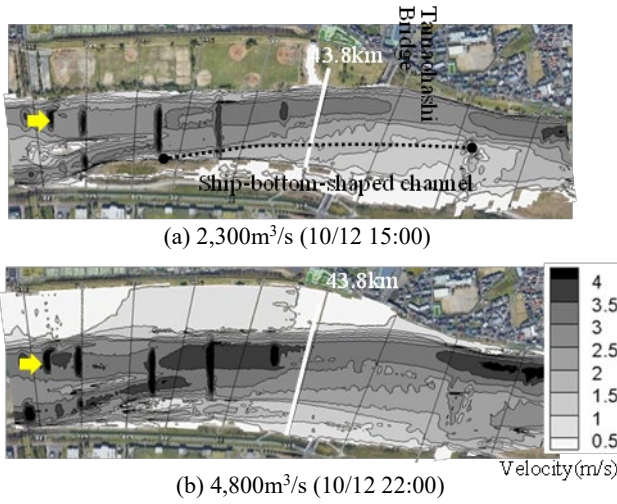


Figure 7. Contours of calculated bottom velocity distribution in the section around the Tamaohashi Bridge.

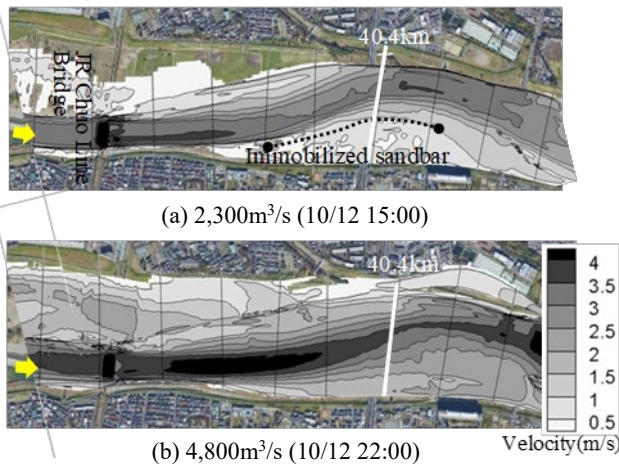


Figure 8. Contours of calculated bottom velocity distribution in the section downstream of the JR Chuo Line Bridge.

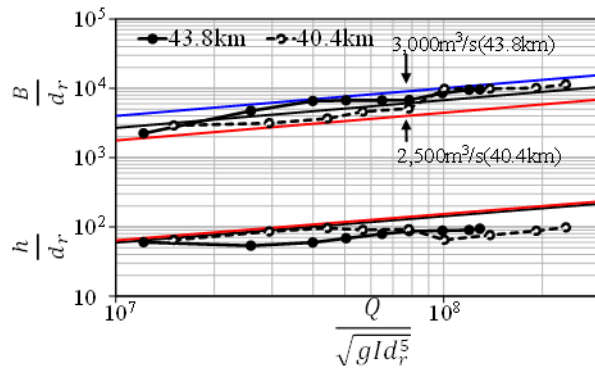


Figure 11. Relationship of dimensionless river width and water depth against dimensionless channel-forming discharge.

Figure 11 shows the relationships of dimensionless river width and water depth against dimensionless channel-forming discharge at 43.8 km and 40.4 km cross-sections based on Fukuoka equations (Fukuoka (2012)), calculated from the analysis results for the 2019 flood. Fukuoka equations for stable river channel are shown in Equation (1) and (2).

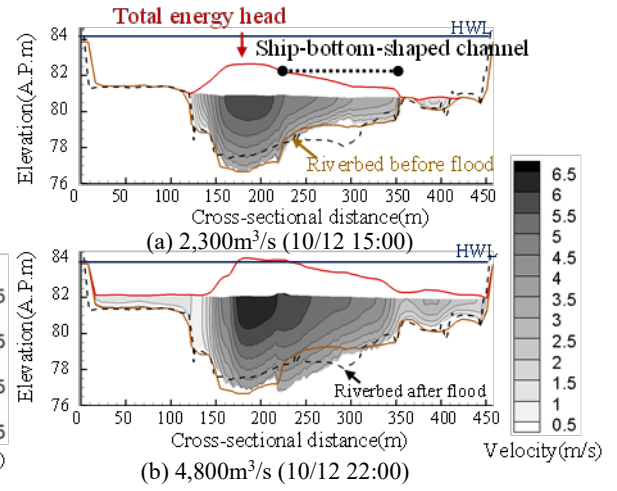


Figure 9. Calculated cross-sectional profiles, velocity and energy head distributions (43.8km).

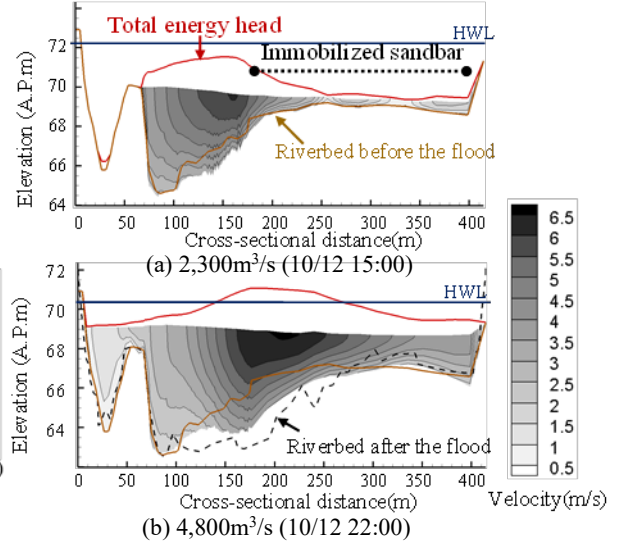


Figure 10. Calculated cross-sectional profiles, velocity and energy head distributions (40.4km).

$$\begin{aligned} \frac{B}{d_r} &= 6.33 \left(\frac{Q}{\sqrt{gld_r^5}} \right)^{0.40} \\ \frac{B}{d_r} &= 4.25 \left(\frac{Q}{\sqrt{gld_r^5}} \right)^{0.40} \\ \frac{B}{d_r} &= 2.80 \left(\frac{Q}{\sqrt{gld_r^5}} \right)^{0.40} \\ \frac{h}{d_r} &= 0.14 \left(\frac{Q}{\sqrt{gld_r^5}} \right)^{0.38} \\ \frac{h}{d_r} &= 0.13 \left(\frac{Q}{\sqrt{gld_r^5}} \right)^{0.38} \end{aligned}$$

$$2.80 \left(\frac{Q}{\sqrt{gId_r^5}} \right)^{0.40} \leq \frac{B}{d_r} \leq 6.33 \left(\frac{Q}{\sqrt{gId_r^5}} \right)^{0.40} \quad (1)$$

$$\frac{h}{d_r} \leq 0.14 \left(\frac{Q}{\sqrt{gId_r^5}} \right)^{0.38} \quad (2)$$

where Q = discharge, B = river width, h = water depth, I = energy gradient, d_r = representative particle diameter (d_{60}), g = gravitational acceleration.

As shown by the solid lines in Figure 11, in the 43.8 km cross-section that has been repaired to ship-bottom-shaped channel, the dimensionless water surface width is plotted between the upper and the lower limit lines of Fukuoka equations, and the dimensionless water depth is plotted below the upper limit line of Fukuoka equations, respectively in desirable ranges for stable river channel. And the dimensionless water surface width and water depth change continuously with increasing the dimensionless discharge, parallel to the average line of Fukuoka equations. When flood discharge exceeds about 3,000 m³/s, the water surface width reaches the entire river width. At this time, the dimensionless river width and water depth satisfy the relation equation for stable channel, and the flood energy distribution shown in Figure 9(b) shows desirable flow that the flood energy is adequately shared between the main channel and the flood channel.

On the other hand, in the section downstream of the JR Chuo Line bridge, where scouring of immobilized sandbar banks has occurred, Figure 8(a) and Figure 10(a) show that when the flood discharge exceeds about 2,000 m³/s, the immobilized sandbar banks around 40.6 km begin to be flooded. At this time, the difference in flow velocity between the main channel and the flood channel becomes large, and the total energy head has steep transverse gradient near the sandbar bank. After that, as the flood discharge increases, the water depth over the flood channel increases, and during peak flood, high velocity area is generated near the sandbar banks, promoting scouring, as shown in Figure 8(b) and Figure 10(b). As a result, the cross-sectional gradient of total energy head becomes lower. Then, scouring of immobilized sandbar banks occurs so that the flood energy concentrated in the main channel is shared properly across the entire channel, changing the river channel to ship-bottom-shaped channel.

As shown by the dotted line in Figure 11, in the 40.4 km cross-section where scouring of sandbar bank occurred, the dimensionless water surface width is plotted within desirable range for stable river channel between the averaged and the lower limit lines during low dimensionless discharge. When the flood discharge exceeds about 2,500 m³/s, the water surface width reaches the entire river width, and the dimensionless water surface changes within range between the averaged and upper limit lines. At this time, the water surface width has been sufficiently widened to satisfy the relationship of desirable stable river width, but the sandbar bank has continued to be scoured with widening of the main channel. This mechanism which makes flood flow downstream carry safely by varying the main channel width within the total width limited by levees, resulting in the formation of ship-bottom-shaped channel is explained physically.

4 FORMATION OF LOW VELOCITY AREA AS REFUGE FOR FISH IN THE SHIP-BOTTOM-SHAPED CHANNEL DURING FLOODING

In the ship-bottom-shaped channel repaired around the Tamaohashi bridge, as shown in Figure 1 and Figure 2(c), the sandbar channel of the 1960s has been restored by widening the main channel width and backfilling riverbed with gravel. During normal flow conditions, water route meanders gently, forming riffles and backwaters, which are habitats for diverse organisms. In this chapter, the hydraulic functions of the ship-bottom-shaped channel from the viewpoint of the formation of refuge for fish during flooding was evaluated by the analysis results for the 2019 flood.

Azuma et al. (1999) found from investigation using radiotelemetry in actual rivers that fishes responded to high velocity exceeding their swimmable velocity during flooding by evacuating to low velocity areas near riverbanks and riverbeds. Based on this knowledge, the low velocity area formed in the ship-bottom-shaped channel was evaluated as a refuge for fish during flooding, by bottom velocity calculated from non-hydrostatic quasi three-dimensional flood flow analysis (Q3D-FEBS). As target species, *Plecoglossus altivelis*, a representative fish species of the Tama

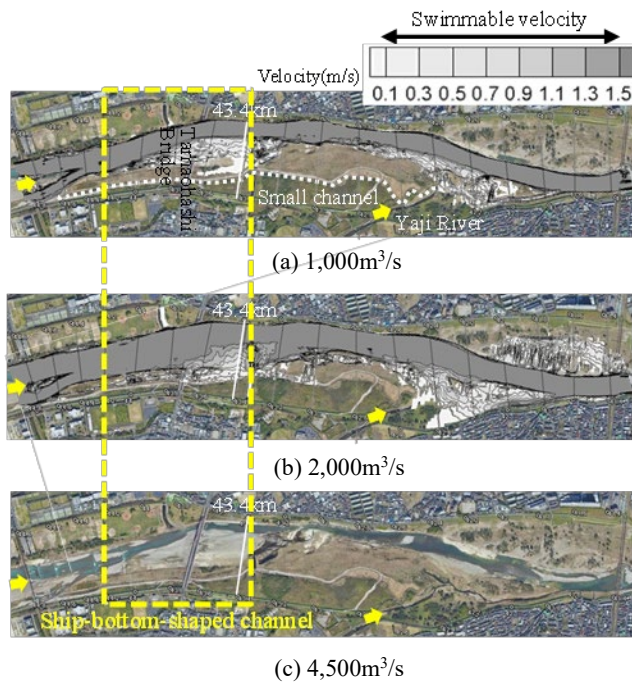


Figure 12. Contours of calculated bottom velocity distribution.

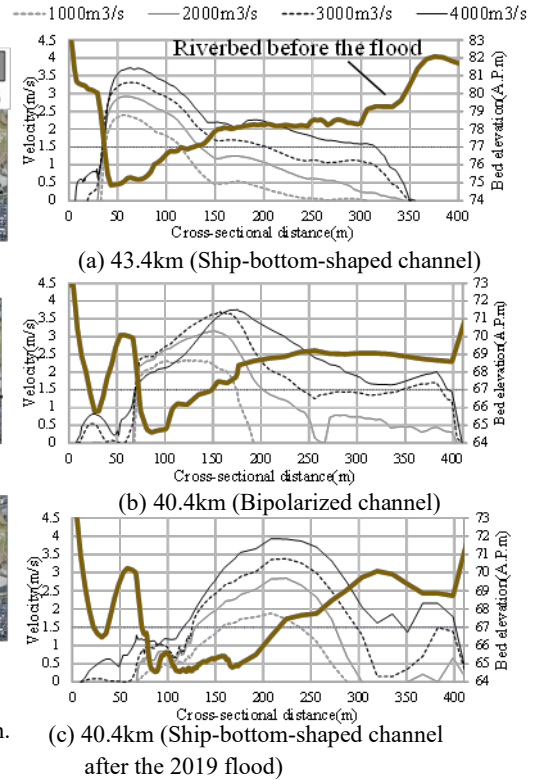


Figure 13. Calculated cross-sectional distribution of bottom velocity.

River was selected. The area with lower velocity than the swimmable velocity (1.5 m/s) for the average length of *Plecoglossus altivelis*, which was calculated by the relationship between fish length and swimmable velocity, was evaluated as a potential refuge for fish.

Figure 12 shows temporal changes of calculated bottom velocity distribution contours in the section between JR Hachiko line bridge and JR Chuo line bridge, and Figure 13 shows temporal changes of calculated cross-sectional bottom velocity distribution in the 43.4 km cross-section that has been repaired to ship-bottom-shaped channel, in the 40.4 km cross-section before and after the 2019 flood, when the river channel has changed to ship-bottom-shaped channel. At flood discharge of 1,000 m³/s shown in Figure 12(a), the main channel has become almost high velocity area exceeding 1.5 m/s. However, large low velocity area is formed on the right sandbar banks (44.2 km to 43.4 km) around the Tamaohashi bridge, which has been repaired to ship-bottom-shaped channel. As shown in the grey dotted line (at 1,000 m³/s) in Figure 13(a), in the 43.4 km cross-section of ship-bottom-shaped channel, the main channel bed and the flood channel bed with sandbar are connected gently across the cross-section, so that the low velocity area is also continuously formed. On the other hand, at the 40.4 km cross-section shown in Figure 13(b), where the river channel has been bipolarized, the main channel width is narrow and flood flow is concentrated, resulting in rapid increase in flow velocity, and at 1,000 m³/s, low velocity area is limited around sandbar bank.

Furthermore, when the flood discharge has reached 2,000 m³/s, as shown in Figure 12(b), the flood channel bed around the Tamaohashi bridge begins to inundate. At this time, the water surface on right sandbar along bank and in a small channel installed on the flood channel has been connected transversely, and this small channel has connected longitudinally with old channel site and the Yaji River of tributary downstream, resulted in formation continuous longitudinal and cross-sectional low velocity areas. Even when the flood discharge has reached 4,500 m³/s shown in Figure 12(c), low velocity area remains formed around the small channel on the flood channel. Figure 13(a) shows that in the 43.4km cross-section of ship-bottom-shaped channel, the water surface width is widening as flood discharge increases from 1,000 m³/s (grey dotted line) to 3,000 m³/s (black dotted line), resulting in slow increase in bottom velocity and continuous formation of low flow velocity area. On the other hand, in the 40.4 km cross-section of bipolarized channel, as shown in Figure 13(b), when the flood discharge reaches 2,000 m³/s (grey solid line), the flood channel with sandbar begins to be flooded rapidly and low velocity area becomes discontinuous.

In the 40.4 km cross-section after the 2019 flood, when the river channel has changed to ship-bottom-shaped channel shown in Figure 13(c), the cross-sectional area of the main channel has been enlarged and the water surface width has been widened, forming wider velocity distribution with reduced flood flow concentration. Compared to the bipolarized channel before the 2019 flood shown in Figure 13(b), increase in bottom velocity with increasing flood discharge has become slower, and continuous low velocity area has been formed even when the flood discharge has reached 3,000m³/s (black dotted line).

Based on the above results, hydraulic characteristics of the ship-bottom-shaped channel, which the water surface width widens as the flood discharge increases while the bottom velocity hardly changes were clarified. This indicates that low velocity area formed continuously in the ship-bottom-shaped channel may provide refuge for fish during flooding.

5 CONCLUSIONS

In this study, the formation mechanism and hydraulic functions of the ship-bottom-shaped channel formed in the middle reach of Tama River were evaluated by long-term observation river channel data, and flood flow and riverbed variation analysis. The main conclusions are as follows.

- (1) The ship-bottom-shaped channel is formed by scouring laterally interfacial zones of the flood channel with the main channel so that flood energy is shared properly across the entire channel.
- (2) This is essential mechanism to the ship-bottom-shaped channel, which makes flood flow downstream carry safely by varying the main channel width within the total width limited by levees, according to flood discharges.
- (3) The ship-bottom-shaped channel contributes to the formation of habitats for diverse organisms and refuge for fish during flooding because the water surface width widens as the flood discharge increases while the bottom velocity hardly changes.

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