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Study for restoring bank protection functions of longitudinal dikes existing in the river with alternate bars

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ABSTRACT: Alternate bars are formed in the main channel of the Kurobe River on the alluvial fan. Patterns of the alternate bars are controlled by the Aimoto ground sill which is directed slightly toward the right bank at the apex of the alluvial fan. At flow attacking points, longitudinal dikes have been installed for bank protection. However, the extension of revetments at the downstream of the ground sill brought bed scouring along the new revetments, resulting in changes in the pattern and the flow attacking points. Therefore, the longitudinal dikes are not able to work effectively against flood flows. In this study, we propose river improvement works for restoring pattern of alternate bars and maintaining functions of the existing longitudinal dikes by using sandbars with boulders and improving main channel. Stability of the proposed channel was investigated by applying the two-dimensional flood flow and bed variation analysis.

1 INTRODUCTION

The Kurobe River, Japan, is a steep river and forms alternate bars in the reach between 13.4 km and 6.0 km on the alluvial fan. The channel slope in this reach results in change of flow attacking points at the downstream of the Aimoto ground sill. The ground sill located at the apex of the alluvial fan is directed slightly toward the right bank for protections of the left banks (see Fig. 1). The free meander experiments of Friedkin (1945) and Kinoshita (1957) showed that the direction of flow at upstream ends controlled patterns, widths and lengths of alternate bars. Flood flow and meander pattern in the Kurobe River were controlled by the obliquely installed Aimoto ground sill. At the flow attacking points, a series of longitudinal dikes have been constructed for bank protection since 1991 (see Fig. 2). The longitudinal dikes were designed based on pattern of the alternate bars by the large-scale hydraulic model experiments (Public Works Research Institute 1993). However, since flow attacking points have changed after 1995 flood which was the largest flood in the past 40 years, most of the longitudinal dikes have not been effective for bank protection (see Fig. 2). This flood caused severe bank erosions and bed scouring along the outer bank at the downstream of the Aimoto ground sill. After the flood, the revetment at downstream of the ground sill was extended to prevent the outer bank from erosions. The extended revetments accelerated scouring of river bed along new revetments. Therefore, developments of the bed scoring along the revetments have brought changes in the pattern of alternate bars.

The process of bed scouring by flood flows along the revetments and changes in longitudinal pattern of alternate bars were clarified in the Joganji River (Osada et al. 2007). The improvement work of the Joganji River was executed by installing sandbars with boulders for regulating flood flows along the revetments (see Fig. 11) (Osada et al. 2012; Koikeda et al. 2012). The Sandbar with boulders could navigate flood flow accelerated along revetments and restore original pattern of the alternate bars in the Joganji River.

In this study, we consider that installing the sandbars with boulders is effective method to improve accelerated flows along the revetments in the Kurobe River. Therefore, we propose a river improvement work for

Figure 1. Alluvial fan of the Kurobe Rover (Aimoto observation station) (October 2003).

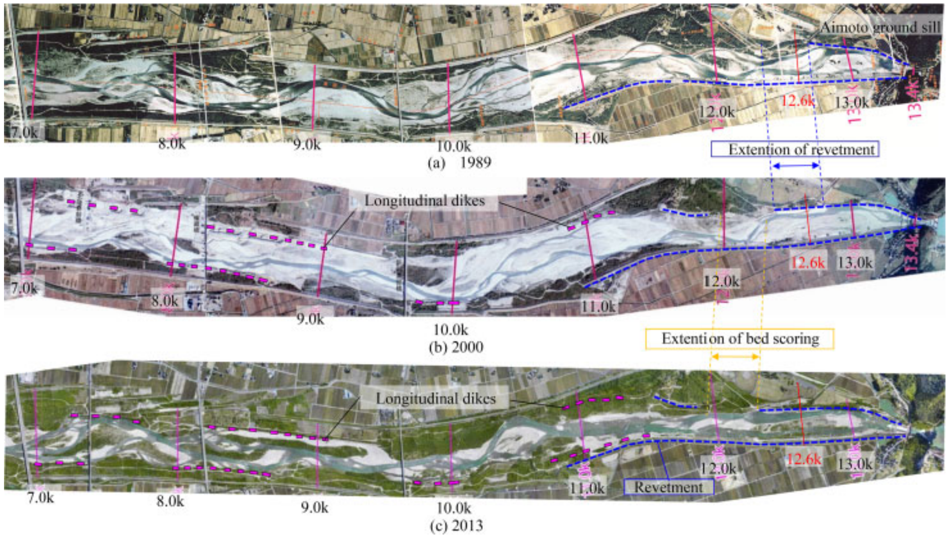

Figure 2. Temporal changes in alternate bars of the Kurobe River.

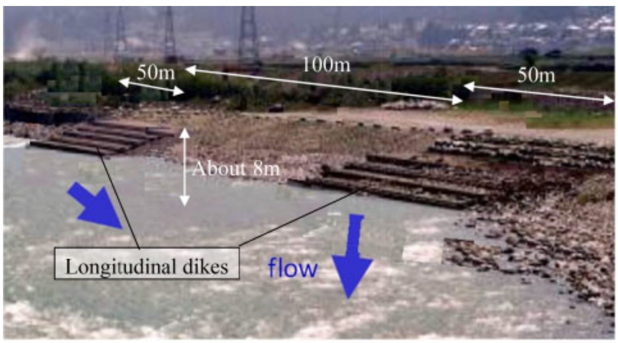

Figure 3. Longitudinal dikes for bank protection.

restoring pattern of the alternate bars and maintaining functions of the existing longitudinal dikes by using the sandbars with boulders.

2 FLOOD IMPROVEMENT WORKS OF THE KUROBE RIVER

2.1 *Temporal changes in the alternate bars*

Figure 1 shows locations of the Aimoto ground sill and the Aimoto weir. The Aimoto ground sill is slightly directed toward the right bank for protection of the left bank. Figure 2 represents temporal changes in patterns of the alternate bars in the Kurobe River from 1989 to 2013. The locations of the revetments and longitudinal dikes are shown in these Figures. The longitudinal dikes with 8m in height and 50 m in length of concrete blocks have been constructed at 100 m longitudinal intervals in 1991 (see Fig. 3). A series of longitudinal dikes were designed according to patterns of the alternate bars in 1989 channel. Then, geometric characteristics of the alternate bars almost agreed with

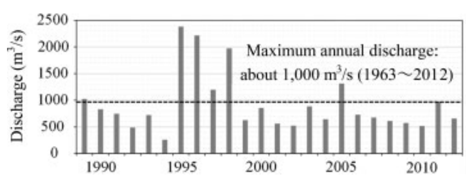

Figure 4. Maximum annual discharges (Aimoto observation station).

those of natural rivers. The amplitude of the alternate bars were almost river width of the main channel and the wave lengths were about 1 km as shown in Figure 2 (a). The effects of the designed longitudinal dikes against flood flows were confirmed by the large scale hydraulic model experiments (Public Works Research Institute 1993).

The July 1995 flood of the Kurobe River was the largest flood in the past 40 years. Figure 4 and Figure 5 show the observed maximum annual discharge and the observed discharge hydrographs of July 1995 flood at Aimoto observation station, respectively. The peak

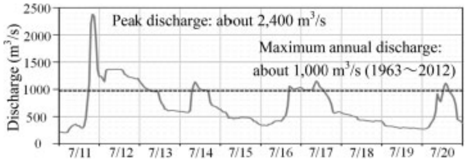

Figure 5. Observed discharge hydrographs in July 1995 flood (Aimoto observation station).

discharge of the flood was about 2,400 m^3/s and the duration time was a few days. The existing longitudinal dikes worked effectively for the river bank protection at the flow attacking points against this flood (Kamada et al. 2001). However, 1995 flood caused the bank erosion about 40m and the river beds scoring about 3m of the right bank at 12.6 km. Figure 6 indicates observed cross-sectional river bed profiles at 12.6 km from 1990 to 2012. After the 1995 flood, the revetment of the right bank was elongated to about 300m downstream at downstream of the Aimoto ground sill as shown in Figure 2 (b). The extension of the right bank revetment brought river bed scoring along the new bank revetments as shown in Figure 6. The bed scoring have gradually extended from 12.6 km to 12.0 km after 1995 flood (see Fig. 2 (b) (c)). Therefore, patterns of the alternate bars and flow attacking points have been also changed by successive floods as shown in Figure 2 (b) and (c). Figure 7 designates the section of the bank erosions around the longitudinal dikes at 10.0 km after 2005 flood. In 2005 flood, changes in patterns between 12.0 km and 10.0 km caused sharp flow attacks to the longitudinal dikes (see Fig. 2 (c)). Consequently, the longitudinal dikes have not become effective for the bank protection due to changes in flow attacking points.

Figure 8 shows longitudinal and temporal changes in main channel widths which are defined as widths of water surfaces in the maximum annual discharge (about 1,000 m^3/s). The main channel width has been decreasing between 12.0 km and 10.0 km due to changes in the pattern of the alternate bars after 1995 flood.

2.2 *River improvement works for restoring the alternate bars and functions of the existing longitudinal dikes*

We executed river improvement for restoring original pattern of the alternate bars and maintaining functions of the existing longitudinal dikes by several improvement works. Figure 9 presents locations of proposed two sandbars with boulders to control flood flows flowing from the Aimoto ground sill. The contour diagrams indicate differences from averaged bed elevations in 1993 and 2012, respectively. Installing two sandbars with boulders at the downstream of the Aimoto ground sill were executed in order to reproduce longitudinal arrangement of the alternate bars in 1993 which had an original pattern. Situations of the sandbars with boulders at 12.6 km are shown in Figure 10 (a). The height of the sandbars with boulders was determined with heights of surrounding natural sandbars. Boulders about 1,000 mm in size are put in front of the sandbars (see Fig. 11 (a)). Figure 11 shows photographs of the sandbars with boulders constructed in the Jyoganji River. In stony Jyoganji River, Koikeda et al. (2012) proved that sandbars with boulders were able to direct flood flows concentrated along the river banks toward the main channels and were effective for controlling flood flows (see Fig. 11 (b)).

Sandbars in the sections between 12.0 km and 9.0 km were excavated for widening the main channel. The main channel widths were widened similar to these of 1989 and 1995 channel (see Fig. 8 and 10 (b)).

3 STABILITY OF PROPOSED CHANNEL

3.1 *Calculation method*

For investigating stability of the proposed channels, we conducted the two-dimensional flood flow and bed variation analysis in stony bed rivers (Osada et al. 2013). The Kurobe River has a wide range of particle-size distributions including large stones. Osada & Fukuoka (2013) developed the numerical model of two-dimensional river bed variations in stony-bed

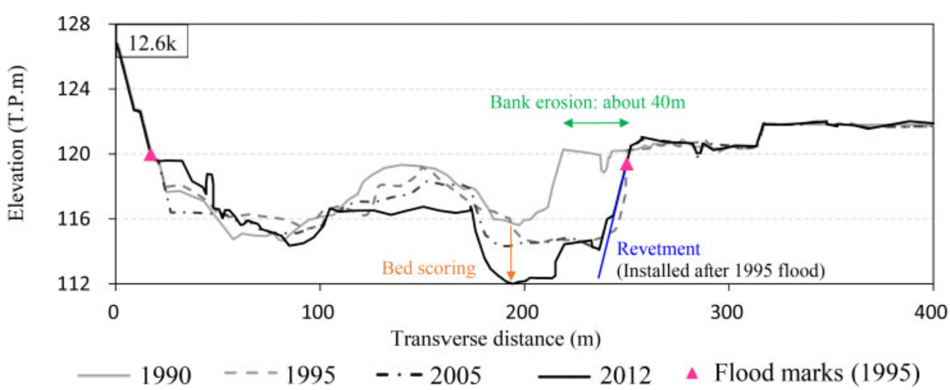

Figure 6. Cross-section at 12.6 km point.

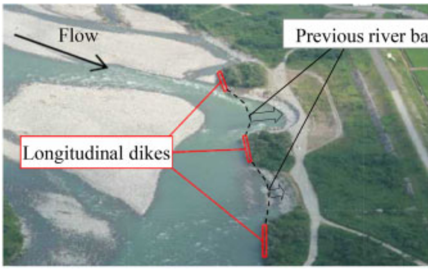

Figure 7. Bank erosion around the longitudinal dikes after 2005 flood (10.0 km point).

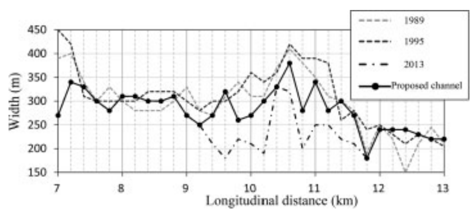

Figure 8. Longitudinal and temporal changes in the main channel width.

rivers. Figure 12 shows the numerical analysis procedure of the two-dimensional riverbed variations. The numerical analysis model was validated by the Satsunai River (Fukuoka 2013) and large-scale field experiments in the Jyoganji River (Osada et al. 2013).

3.1.1 *Unsteady 2-D flood flow analysis*

General coordinate systems are employed for flood flow analysis. Since boulders bring dominant flood flow resistances in stony-bed rivers, the flow resistances are evaluated by a boulder of diameter d_{90} as follows:

$$\begin{pmatrix} F_\xi \\ F_\eta \end{pmatrix} = N_{D90} \frac{\varepsilon_{D90}}{2} \rho C_D A_{D90} u_{D90}^2 \frac{1}{\sqrt{u_x^2 + u_y^2}} \begin{pmatrix} u_\xi \\ u_\eta \end{pmatrix} \tag{1}$$

where $F_\xi, F_\eta = \xi$- and η- components of form resistance of d_{90}; N_{D90} = number of d_{90} on the bed surface defined as $N_{D90} = 0.2/\alpha_2 d_{90}^2$; ε_{D90} = shielding coefficient of d_{90} (=0.48); ρ = water density; C_D = drag coefficient (=1.0); A_{D90} = projected area of d_{90}; u_{D90} = flow velocity acting on d_{90} which is determined by logarithmic velocity distributions.

3.1.2 *Average height and particle size fraction on the bed surface*

Average height of each particle size $\overline{Z_{Pk}}$ is related to pick-up rate V_{Pk}, deposit rate V_{Dk} and each particle size fraction on the bed surface P_k by Equation (2).

$$\frac{\partial \overline{Z_{Pi,j,k}}}{\partial t} = -\frac{\alpha_2}{\alpha_3} \frac{(V_{Pi,j,k} - V_{Di,j,k})}{P_{i,j,k}} \tag{2}$$

where subscript i, j indicates computational grid number and k indicates particle numbers; α_2, α_3 = two-dimensional and three-dimensional shape factors of the particles ($=\pi/4, \pi/6$), respectively. Each particle size fraction on the bed surface P_k is estimated by pick-up rate V_{Pk} and deposit rate V_{Dk}. Average elevation of riverbed $\overline{Z_B}$ is calculated by subtracting average particle radius from average height of particles.

3.1.3 *Estimation of sediment transport rate*

Sediment transport rate of each particle size is evaluated by products of the volume of sediment transport V_m and particle velocity u_{pk}.

$$q_{B\xi i,j,k} = V_{mi,j,k} \overline{u_{p\xi i,j,k}}, \quad q_{B\eta i,j,k} = V_{mi,j,k} \overline{u_{p\eta i,j,k}} \tag{3}$$

The volume of sediment transport per unit of area V_m is calculated by differences of sediment transport rate, pick-up rate and deposit rate in each control volume.

$$\frac{\partial V_{mi,j,k}}{\partial t} + \frac{\partial q_{B\xi i,j,k}}{\partial \xi} + \frac{\partial q_{B\eta i,j,k}}{\partial \eta} = V_{Pi,j,k} - V_{Di,j,k} \tag{4}$$

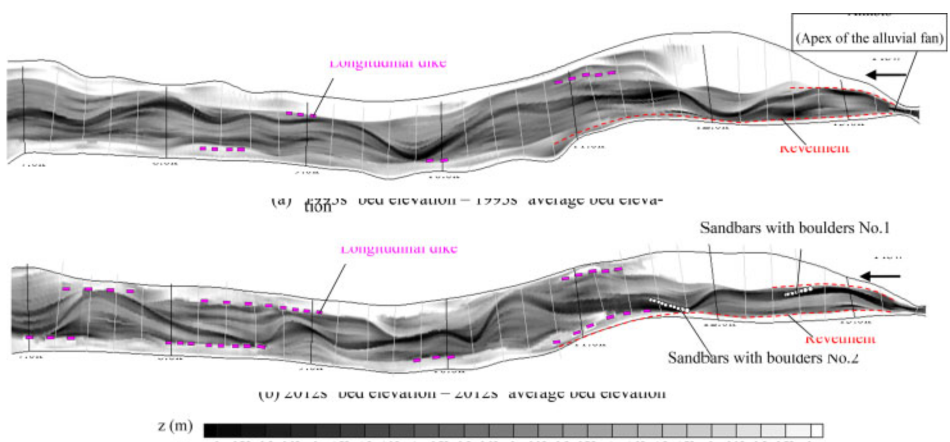

Figure 9. Contour diagrams of bed elevations differences from average bed elevations.

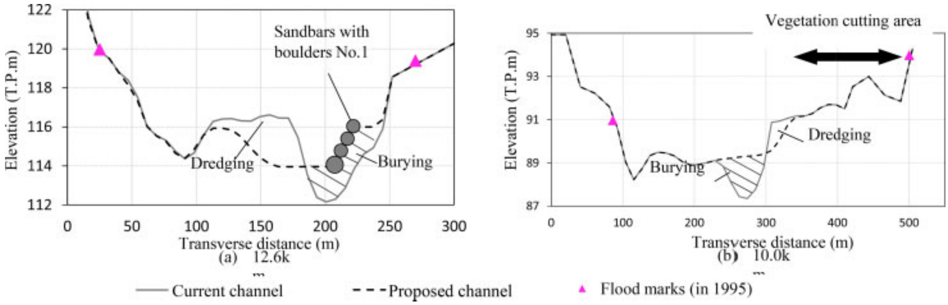

Figure 10. Cross-sections of the current channel and the proposed channel.

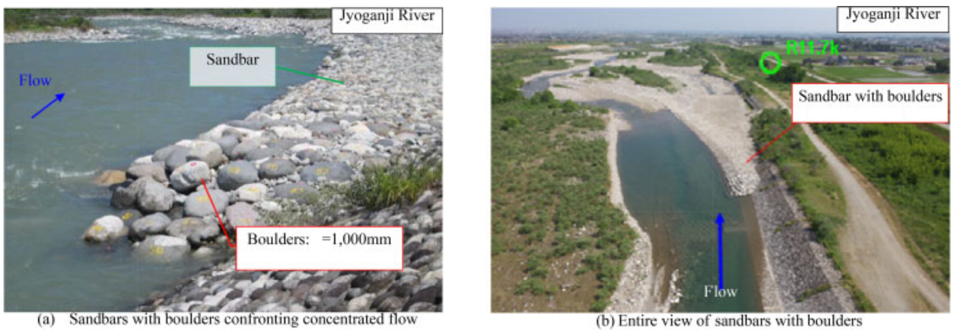

Figure 11. Sandbars with boulders (Jyoganji River, 2012).

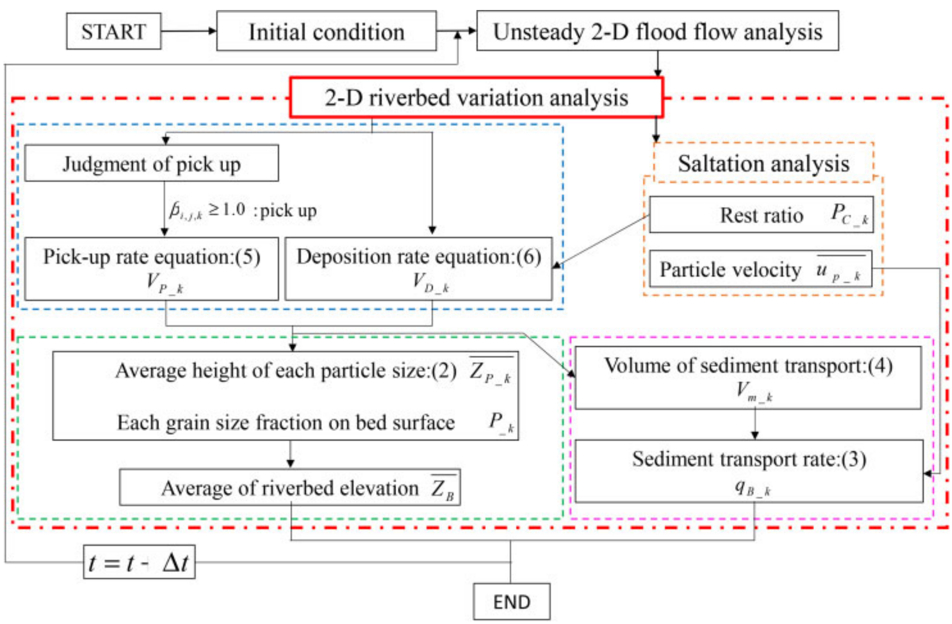

Figure 12. Procedure of the 2-D riverbed variation analysis.

Particle velocities of each particle size $\overline{u_{P\xi k}}, \overline{u_{P\eta k}}$ are calculated by saltation analysis using 3D equation of motions of each particle size. The saltation analysis is computed on the bed surface of mean diameter. Longitudinal and cross-sectional bed gradient are considered in the saltation analysis. Restitution coefficient (=0.65) is used for calculating collisions with bed materials.

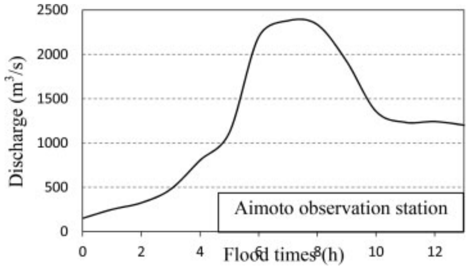

Figure 13. Observed discharge hydrographs in July 1995 flood for the upstream boundary condition.

Pick-up rate V_{Pk} is calculated as follows:

$$V_{Pi,j,k} = \varepsilon'_{Pi,j,k}\varepsilon_{wsi,j,k}\frac{N_{Pi,j,k}a_3 d_k^3}{T_{Pi,j,k}} \tag{5}$$

where ε'_{Pk} = rate of pick up calculated by particle height distribution; ε_{wsk} = rate of pick up controlled by shielding effect of large materials; N_{Pk} = number of particles of each particle size on bed surfaces $(= P_k/\alpha_2 d_k^2)$; T_{Pk} = time required for pick up from bed surfaces.

Deposit rate V_{Dk} is calculated as follows:

$$V_{Di,j,k} = P_{Ci,j,k}V_{mi,j,k} \tag{6}$$

where P_{Ck} is the rest ratio of each particle estimated by the saltation analysis considering particle size distributions and particle height distributions.

3.2 *Calculation conditions*

Meander pattern and bed variations of the proposed channel are compared to those of the current channel. Flood condition for the calculation was July 1995 floods. The boundary condition of the upstream end was given by observed discharge hydrograph of the Aimoto observation station (13.4 km) as shown in Figure 13. Sediment supplies at the upstream end were given by the equilibrium sediment discharge conditions. The downstream boundary condition was given as longitudinal gradients of velocities and water depth being zero. Sediment size distributions in the calculation conditions were given in Figure 14.

3.3 *Calculation results of the proposed channel*

Figure 15 shows contour diagrams of calculated discharges per unit width at the peak discharge (about 2,400 m^3/s) in the current channel and the proposed channel. The calculation result in the current channel indicates that channel straightening along the revetment between 13.0 km and 12.4 km causes the changes in the pattern of the alternate bars. And, the longitudinal dikes are not effective for bank protection due to the changes in flow attacking points (see Fig. 15 (a)). On the other hand, installing two sandbars with boulders improve meander pattern of the main channel by controlling flood flows between 13.4 km and 11.0 km. These meander patterns almost coincide with those of 1993 channel and the existing longitudinal dikes work for bank protection against flood flows. Figure 16 represents contour diagrams of the calculated bed variations after the flood. In the proposed channel, bed scouring along the revetments of the right banks between 12.8 km and 12.4 km section are mitigated by installing the sandbars with boulders.

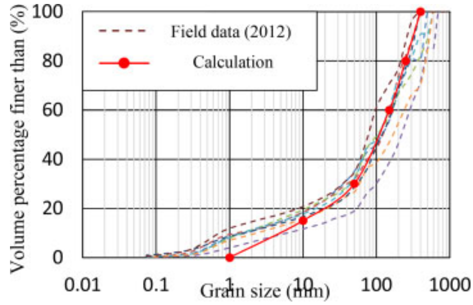

Figure 14. Particle size distributions.

Figure 17 presents calculated water surface profiles and river bed profiles in the current channel and the proposed channel at downstream of the Aimoto ground sill. At the peak discharge (about 2,400 m^3/s), the sandbar with boulders in 12.6 km rise water level between 12.8 km and 12.7 km. Therefore, the water surface profiles of the proposed channel are milder than those in the current channel. Figure 18 shows calculated cross-sectional bed profiles, velocity distributions and water surface profiles in the peak discharge at 12.8 km. The calculation results of the proposed channel mitigate flood flows concentrated along the right bank. Therefore, two sandbars with boulders at downstream of the Aimoto ground sill are found to be effective for restoring patterns of the alternate bars and functions of the longitudinal dikes.

Fukuoka (2010, 2012) proposed Fukuoka's equations which clarify the relations between dimensionless width, dimensionless depth and dimensionless channel-forming discharge in natural alluvial rivers as Equation (7) and (8),

$$2.80\left(\frac{Q}{\sqrt{gId_r^5}}\right)^{0.40} \le \frac{B}{d_r} \le 6.33\left(\frac{Q}{\sqrt{gId_r^5}}\right)^{0.40} \tag{7}$$

$$\frac{h}{d_r} \le 0.14\left(\frac{Q}{\sqrt{gId_r^5}}\right)^{0.38} \tag{8}$$

where Q = channel-forming discharge; B = river width; h = water depth; g = gravitational acceleration; I = energy gradient; d_r = representative grain diameter (d_{60}). Figure 19 shows the relations between Fukuoka's equation and calculated results of the current and the proposed channel to different discharges in the flood rising period. The dimensionless width of the current channel varies abruptly with increasing of flood discharges. This issue means that hydraulic

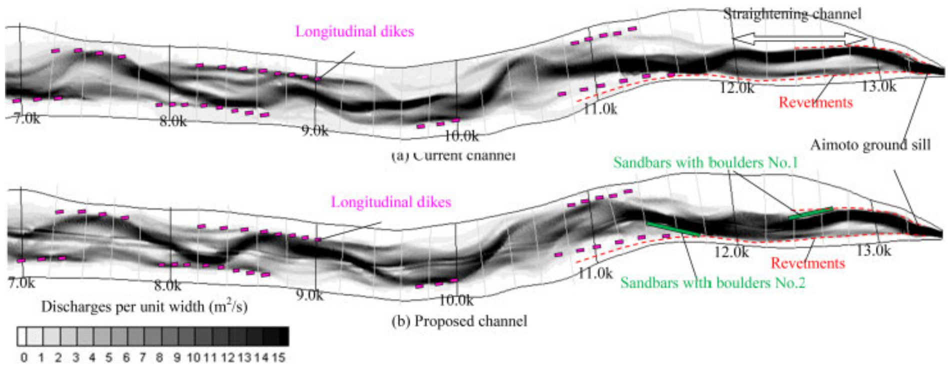

Figure 15. Contour diagrams of discharges per unit width.

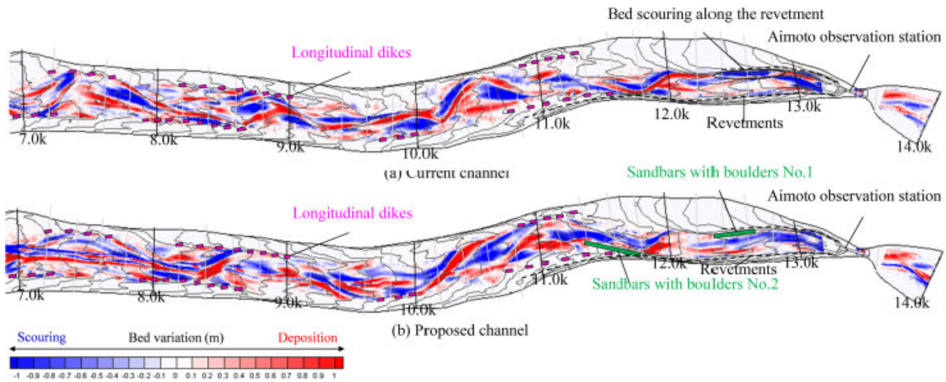

Figure 16. Calculated bed variations after the flood.

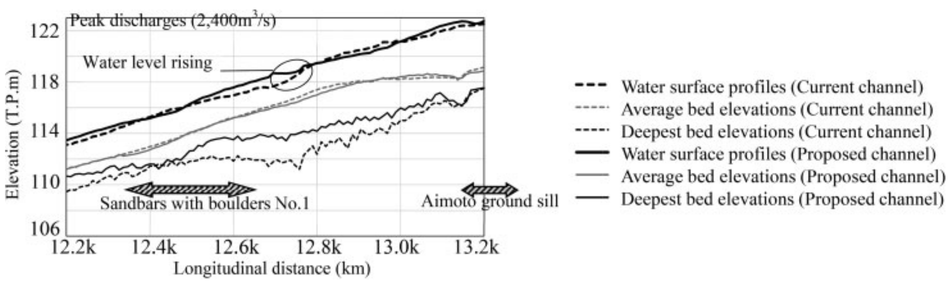

Figure 17. Calculated water surface and river bed profiles in the peak discharge in the current channel and proposed channel.

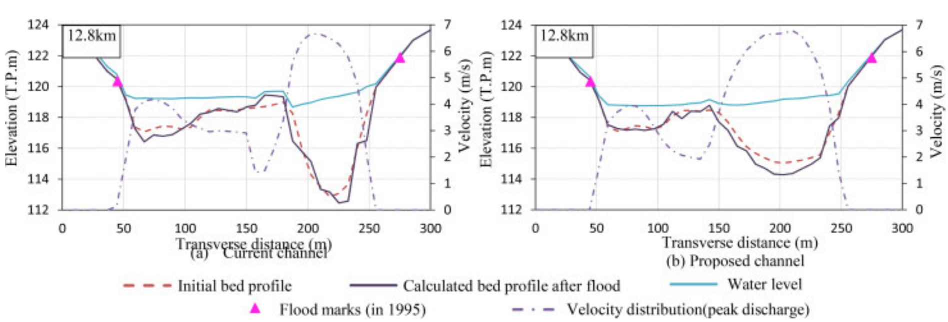

Figure 18. Calculated cross sectional bed profiles before and after the flood, velocity distributions and water level in the peak discharge.

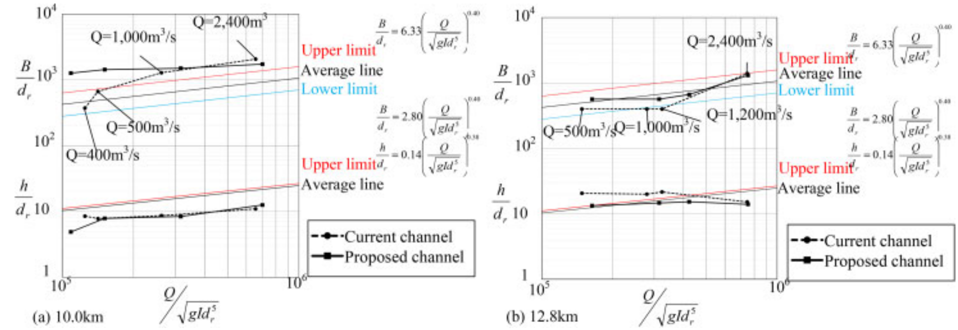

Figure 19. Relationships between dimensionless width, dimensionless depth and dimensionless channel-forming discharge (Fukuoka's equation).

phenomena during a flood such as velocity would not change smoothly with the increase in flood discharges. In contrast, the dimensionless width and dimensionless depth of the proposed channel increase almost parallel to the Fukuoka's equations. Therefore, it is confirmed that the proposed channel has geometric characteristics of natural stable rivers by the improvement works.

4 CONCLUSIONS

The following conclusions were derived in this study.

1. The 1995 flood caused severe bank erosions and bed scouring along the bank revetment at the downstream of the Aimoto ground sill. The extensions of the bank revetments after 1995 flood brought bed scouring along the revetments and caused changes in the pattern and the flow attacking points. As a result, a series of the existing longitudinal dikes have not become effective for the bank protection.
2. We proposed flood improvement works for restoring patterns of the alternate bars and maintaining functions of the existing longitudinal dikes. Two set of sandbars with boulders reproduced longitudinal arrangement of the original pattern in the alternate bars, together with the widening of the main channel width.
3. The two-dimensional flood flow and bed variation analysis was conducted for investigating effects of the proposed improvement works on flood flows. We demonstrated that two sandbars with boulders were able to divert concentrated flows along the revetments toward the center of the channel. The pattern of the alternate bars approached to the original alternate bar pattern in the Kurobe River. The existing longitudinal dikes recover functions for bank protection by the proposed improvement works.
4. We confirmed that the relations between dimensionless width, dimensionless depth and dimensionless channel-forming discharge in the proposed channel almost corresponded to those Fukuoka's equation found in stable alluvial natural rivers.

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