River improvement techniques for mitigating river bed degradation and channel width reduction in the sandy Hii River where sediment transport occurs at normal times

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Abstract. In the sandy Hii River, a large amount of sediment yield from upper river basin had brought developments of braided channels covered with sand waves. In the braided channels, sediment materials on the river beds are capable to move in normal discharge conditions. In recent years, however, the sediment yield decreases due to constructions of check dams and ground sills in the upper river basin. Thus, the river beds downstream of the ground sill have gradually degraded and the main channel widths have been narrowed with the progressing bed degradation. Firstly, we clarified that the effects of non-equilibrium sediment transports around the ground sill during normal discharge conditions on the bed degradation and the channel width reduction by using annual observed data and numerical simulations for bed variations. In addition, we provided the river improvement techniques for mitigating bed degradation and channel width reduction by improving state of non-equilibrium sediment transports passing through the ground sill.

1. Introduction

The Hii River is located at Shimane prefecture in Japan and flows into the Sea of Japan through the Lake Sinji and the Lake Naka-umi (see Figure 1). The upper basin of the Hii River had yielded a large amount of sediment composed of fine sand materials. It had caused great aggradation of the river bed in the lower Hii River until 1960s. Due to the bed aggradation, the bed elevations of the main channel in the lower Hii River have raised than the ground level of the urban area along the river. And it has brought flood inundation disasters around this area in the past years.

Meanwhile, a large amount of fine sediment yield has formed braided channels which are covered with well developed sand waves. The braided channels in the lower Hii River (around 11.0km) at the normal discharge conditions are shown in Figure 1. In the braided channels, sediment materials on the river bed are capable to move due to normal discharge flows since the river bed materials are almost uniform sizes of fine sands which are approximately 1mm to 2mm in diameter. Figure 2 shows ratio of shear stresses to the critical shear stress in the braided river section (12.4km) during the normal discharge

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condition. Here, the normal discharge in this section is approximately 50m^3/s by the annual observation records. The ratio of shear stresses to the critical shear stress indicates to be about 3 to 5 times at the cross-section.

Fig. 1. Location of the Hii River and the braided channels in the river.

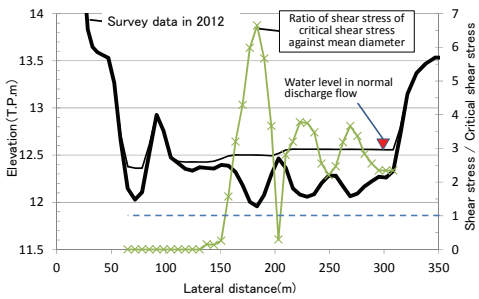

Fig. 2. Ratio of shear stress to critical shear stress in the braded river section.

However, in recent years, the sediment yield from the upper river basin has decreased due to constructing a series of check dams and ground sills since 1960s. It has caused rapidly degradation of the river bed from the downstream of the ground sill in the lower Hii River. The bed degradation has brought to reduce the main channel width in the downstream of the ground sill. Moreover, the narrowed main channel led to advance the further river bed degradation.

In this study, we investigate mechanism of the bed degradation and the channel width narrowing in the sandy Hii River. In addition, we attempt to provide the idea of river improvement techniques for mitigating bed degradation and channel width narrowing in sandy braided rivers where sediment supplies from upper river basins are almost zero at normal discharge conditions.

2. Mechanism of river bed degradation and channel width narrowing

In this section, we investigated mechanism of the bed degradation and the main channel width reduction in the lower Hii River by using annual survey data, hydraulic records and aerial photographs.

Figure 3 shows the aerial photographs and the changes in the main channel widths since 1975 until 2011. Here, the main channel widths shown in Figure 3 were determined by using the cross sectional shapes (see Figure 4). Figure 4 shows cross sectional shapes at

17.0km and 18.6km in the periods. In 1975, the braided channels were formed across the full river width defined by widths between the levees. However, since 1992, the reduction of the main channel widths has begun and gradually progressed toward the downstream from the Igaya ground sill which was installed at 23.3km. Figure 5 indicates the annual changes in the observed mean bed elevations of the main channel. Due to the reductions of the main channel width, the mean bed elevations in the main channel have gradually degraded from the Igaya ground sill toward the downstream. The bed degradation has reached around 14.4km point until 2011.

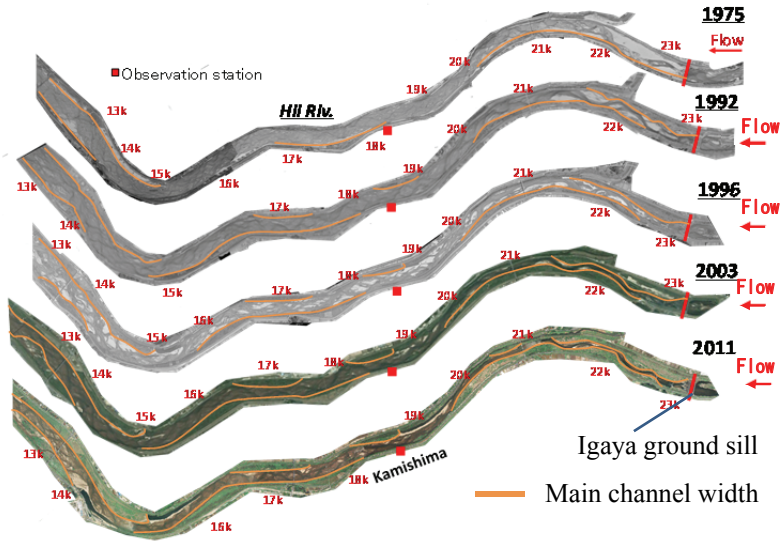

Fig. 3. Annual changes in main channel width in the Hii River.

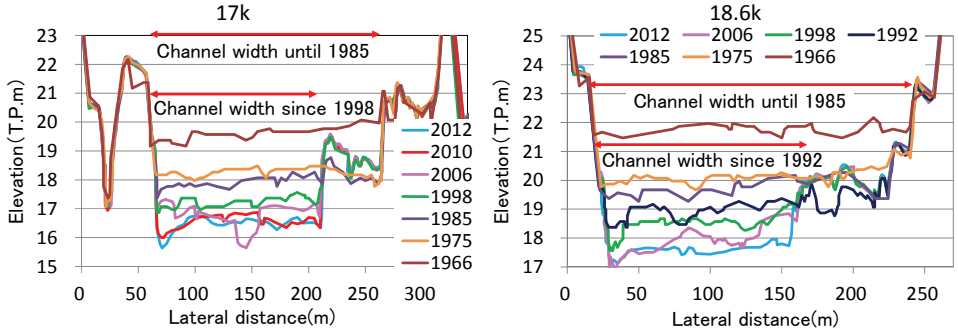

Fig. 4. Annual changes in cross sectional bed profiles and definition of main channel widths.

Figure 6 indicates the annual changes in observed water levels in the normal discharge at Kamishima observation station (18.6km) which is located about 5km downstream from the Igaya ground sill. The observed data shows that the water levels in the normal discharge have gradually declined with the river bed degradation. The declining of water levels per year since 1993 until 2011 is approximately -7.2cm. It seems to be almost independent from frequency and scale of the past flood events shown in Table 1. Table 1 indicates the history of main flood events in the past about 50 years. Figure 7 shows observed cross sectional shapes at upstream and downstream of the Igaya ground sill (23.4km, 23.0km). At the upstream section of the ground sill, the bed elevations of the main channel in recent years became lower than the elevation of the ground sill which was 29.05 T.P.m, T.P. :

Tokyo peil, Japanese datum of leveling. Therefore, the ground sill has prevented sediments transported from the upstream section during the normal discharge conditions and small scale floods. At the cross section of 23.0km downstream of the ground sill, the river bed in the main channel was scoured during the period from 2006 to 2010 although large scale floods did not occur in this period (see Table 1). It means that the river bed degradation has progressed due to effects of non-equilibrium sediment transports passing across the ground sill during the normal discharge conditions and small scale floods.

On the other hand, in large scale flood of 2006 flood, flood flows were able to transport sediment materials across the ground sill and the sediment materials were deposited downstream of the ground sill (see Figure 7). Therefore, we found that the sediment passing through the ground sill during large scale floods mitigated the bed degradation and the reduction of main channel widths in the downstream of the ground sill. It was found that improving the state of non-equilibrium sediment transports passing across the ground sill was important to mitigate the bed degradation and the channel width narrowing.

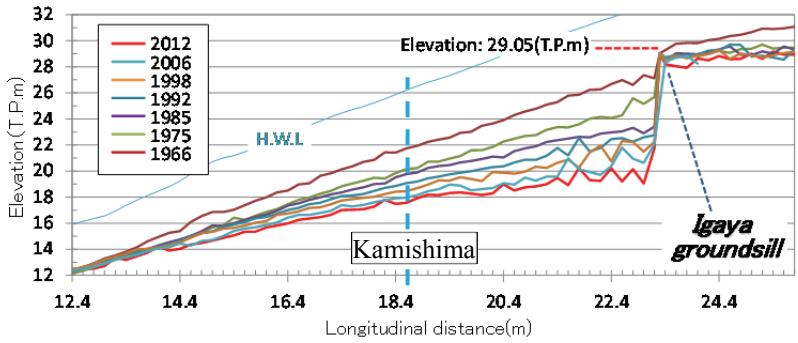

Fig. 5. Annual changes in longitudinal distributions of observed mean bed elevations in the main channel.

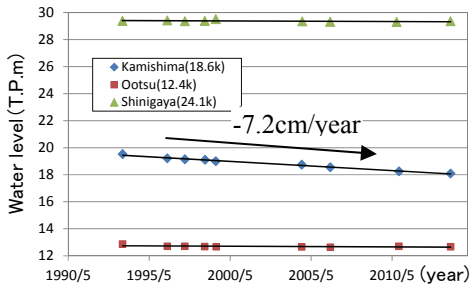

Fig.6. Annual changes in observed water levels in normal flow condition.

Table 1. History of flood events in the past 50 years of the Hii River.

Year/Month	Peak discharge(m^3/s)	Year/Month	Peak discharge(m^3/s)
1971/7	1,500	1998/10	1,700
1972/7	2,300	2006/7	2,400
1979/10	1,600	2011/5	1,500
1983/9	1,500	2011/9	1,500
1993/9	1,600		

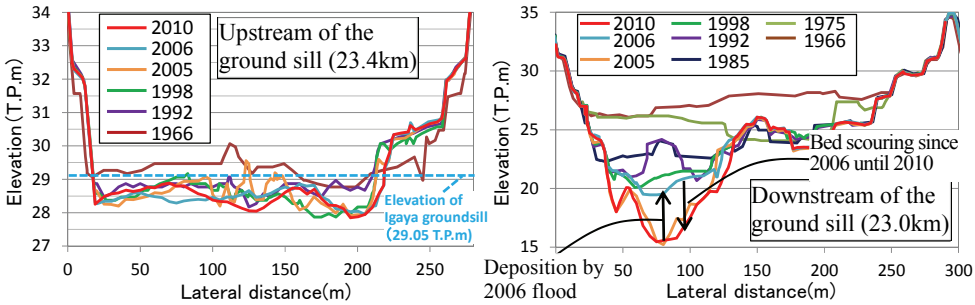

Fig. 7. Annual changes in observed cross sectional shapes of upstream and downstream of the Igaya ground sill (23.4km and 23km).

3. River improvement techniques for mitigating river bed degradation and channel width narrowing in the sandy Hii River

3.1. The idea of river improvement technique

In this section, we proposed river improvement techniques for mitigating bed degradation and channel width narrowing downstream of the Igaya ground sill on the basis of the mechanism clarified in the section 2. The idea of the river improvement technique was composed of lowering the elevation of the ground sill for improving the state of non-equilibrium sediment transports and widening the main channel widths in downstream of the ground sill. Effects of the proposed river improvement technique were examined by conducting numerical simulations of river bed variations under conditions of a series of flood flows and normal discharge flows.

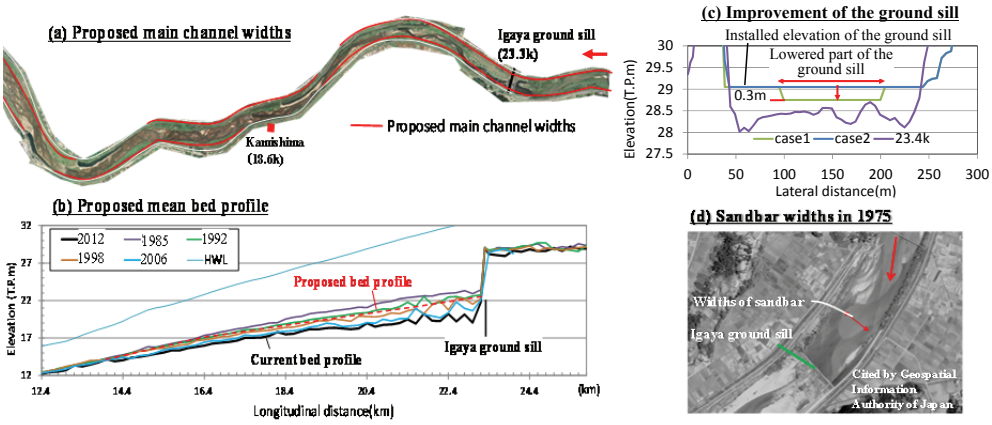

Fig. 8. River improvement techniques.

Figure 8(a) and (b) show the proposed main channel widths and the longitudinal mean bed elevations of the main channel. The main channel widths and the mean bed elevations were determined so as to agree with those in 1992 when the reduction of the main channel was not noticeable problems for the river managements. In addition, for increasing sediment replenishments from the upstream of the Igaya ground sill, we attempted to lower the elevation in the central part of the ground sill as shown in Figure 8(c). The width of the

lowered part of the ground sill was determined based on the width of sand bars in 1975 when the river bed profiles were relatively stable (see Figure 8(d)). The height of the lowered part of the ground sill was 0.3m. It was determined by taking into account elevations of sand bars at the upstream sections of the ground sill and elevations of water intake facilities upstream of it.

3.2. Calculation method and conditions

The BVC Method, the Bottom Velocity Computational Method[1], which was able to estimate vertical velocity distributions of flows based on the depth integrated model were employed for simulating flows and bed variations. The vertical velocity distributions in the numerical model were calculated by using depth averaged horizontal vorticity and difference between water surface velocities and bottom velocities. The bed variation was estimated by calculating sediment transport of bed load and suspended load. The bed load transport was calculated by using bed load formula of Ashida and Michiue. The suspended sediment transport was calculated by three dimensional convection–diffusion equation of suspended load concentrations. The entrainment rate of suspended load from river bed was calculated by Kishi & Itakura formula[2].

A series of discharge hydrographs based on the past observation records were given as the boundary conditions of upstream ends (see Figure 9). The normal discharge of rainy seasons and snowmelt seasons were considered in this simulation. The observed water level hydrograph in the Lake Shinji was given as boundary conditions of downstream end. Manning's roughness coefficient in the main channel was 0.027($m^{-1/3}s$) which was determined by using temporal changes in observed water surface profiles during 2013 flood in our previous studies[3] in the Hii River.

The simulation cases were as follows. In Case1, channel widths and bed elevations downstream of the ground sill were improved as described in Figure 8(a), (b) and the central part of the ground sill was lowered as shown in Figure 8(c). In Case2, channel shapes were same as Case1. But the elevation of the ground sill remained as the current conditions.

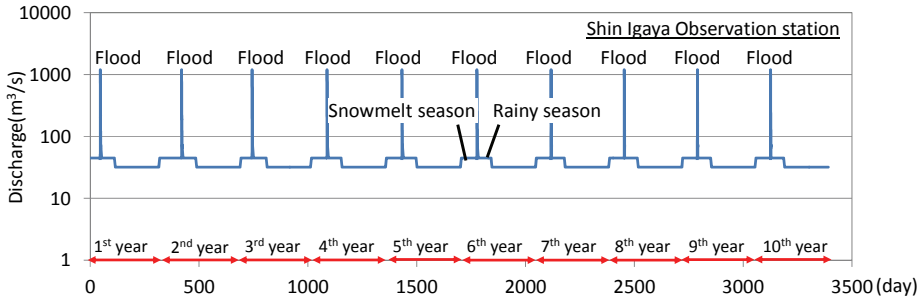

Fig.9. A series of discharge hydrographs given at the upstream end.

3.3. Calculation results

Figure 10 shows the calculated contour of bed profiles downstream of the ground sill in each case. In Case2, the numerical results show that the bed profile downstream of the ground sill was obviously channelized due to the repetitions of flood flows and normal discharge flows. At the upstream section of the ground sill, the sand bar gradually developed and it gave rise to meandering pattern of the main channel in the downstream of the ground sill. On the other hand, by lowering elevation of the ground sill shown in Case1,

the normal discharge flows were able to transport sediment materials smoothly across the ground sill without sand bar developments at the upstream section. Hence, the channelized bed morphology did not form clearly in downstream section of the ground sill. Figure 11 shows calculated cross-sectional shape at 20.6km and 22.9km after the repetition of flood flows and normal discharge flows for 10 years period. In the calculation results of Case2 which formed channelized river bed morphology, the differences of bed elevations between main channel and sand bars became larger than those of Case1. And the maximum height of the differences was more than 2m.

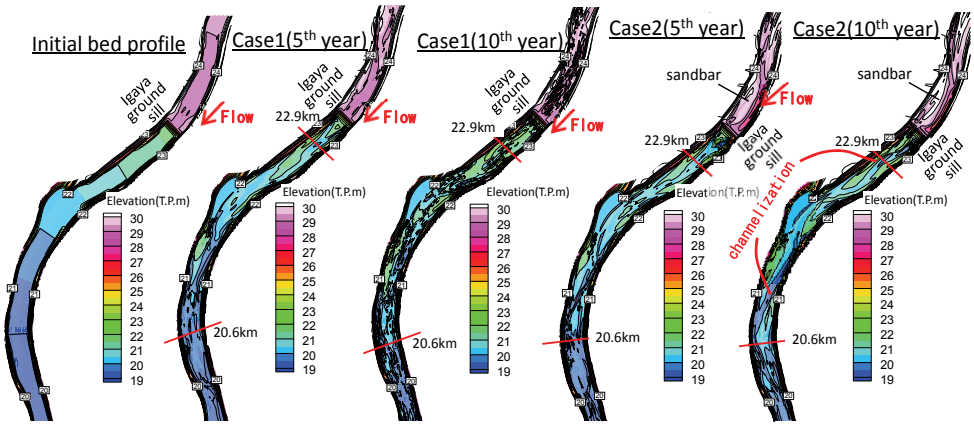

Fig.10. Contour of the initial and calculated bed profiles of Case1 and Case2.

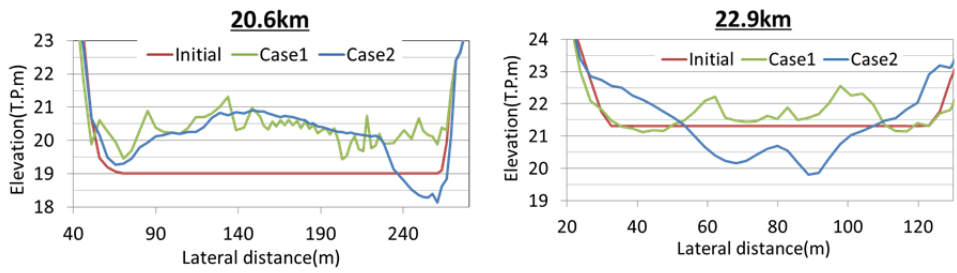

Fig.11. Calculated cross sectional bed profiles of Case1 and Case2.

Figure 12 presents the calculated longitudinal distributions of accumulated sediment discharge during a year. The sediment discharge of Case2 rapidly decreased at the downstream of the Igaya ground sill. However, in the results of Case1, the sediment discharge at the downstream of the ground sill was increased by lowering elevation in the central part of the ground sill compared with Case2. The calculation results showed that the river improvement techniques of Case1 were able to mitigate the state of non-equilibrium sediment transports around the ground sill and channelization and channel incisions downstream of the ground sill.

As a result, the numerical simulations demonstrated that the lowering elevation in the central part of the ground sill were effective for mitigating bed degradation with main channel width reduction.

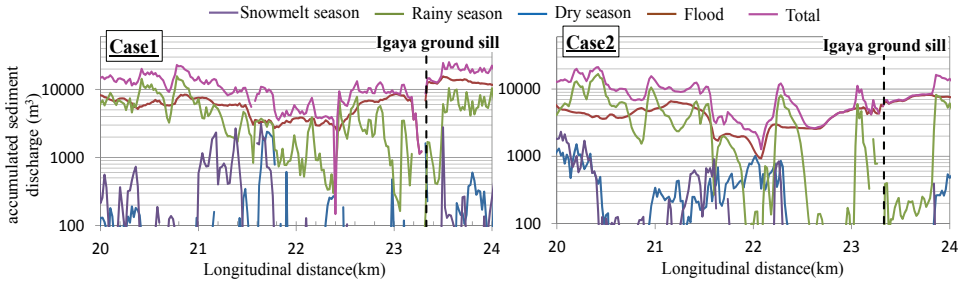

Fig.12. Longitudinal distributions of accumulated sediment discharge for a year in 10th year.

4. Conclusions

In this paper, firstly, we investigated mechanism of the bed degradation and the main channel width reduction in the sandy Hii River by using annual observed data. Secondary, we proposed river improvement techniques for mitigating bed degradation and channel width narrowing. The main conclusions in the study are as follows.

1. The normal discharge flows were able to transport sediment materials on river bed in the braided channels in the sandy Hii River. Meanwhile, the ground sill prevented sediment transports from the upstream during the normal discharge flows and small scale floods. These non-equilibrium conditions of sediment transports across the ground sill caused the bed degradation and the main channel width reduction. The channel width reduction induced further bed degradation in the main channels.
2. The proposed river improvement technique was composed of lowering elevation in the central part of the Igaya ground sill and widening of the main channel width based on the past river conditions downstream of the ground sill. The numerical simulations applying the BVC Method demonstrated that lowering elevation in the central part of the ground sill improved the state of non-equilibrium sediment transports over the ground sill. As a result, we were able to mitigate river bed degradation and channel width narrowing in the sandy Hii River where sediment transports occurred at normal discharge flows.

References

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