Improvement of flow condition in channelized river due to stacked boulders

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Abstract. Recently, a channelized river was constructed in natural rivers from the point of flood control, and the river fell into drainage channel. During flood stages, it might be impossible for aquatic animals to stay at channelized river. Also, degradation and disappearance of gravel bed might be formed easily, because flood flow was concentrated into the same route for normal stage. The improvement of flow condition in channelized river must be required as soon as possible. As a short-terms of construction for the improvement, the installation of stacked boulders might be helpful for both habitat and refuge of aquatic animals. The installation of stacked boulders with about 1 m size was conducted at channelized portion with 20 m wide and1/200 slope in Kando River, Shimane Prefecture, and a surface jet flow with three dimensional could be formed in both normal and flood stages. After the installation, several kinds of aquatic animals could be observed around stacked boulders, and movable gravels with 3 mm to 100 mm diameters were deposited below stacked boulders. The stability of stacked boulders during flood stages was investigated experimentally by using 1/15 scale model. Further, the possibility of refuge space in stacked boulders was investigated in proto scale by using 25 eels.

1. Introduction
For flood control in residential area, natural gravel river was constructed as a channelized river. In a straight channelized river, in steep slope, a high velocity flow is formed during flood stages, and it might be easy to transport a lot of gravels from downstream of gravel region (Beretta, et al. [1]). The formation of naked rock in the channelized river might cause disappearance of refuge region and habitat space of aquatic animals. In order to preserve habitat for aquatic animals in channelized river with steep slope, refuge area must be kept from a high velocity flow with sediment transfer. The stability of gravel region in the channelized river might be caused by the installation of fixation at downstream end of gravel region, a stacked structure of gravel, gravel thickness, and gravel size.

The flow resistance on gravel bed was investigated by Bathurst[2],[3],[4], Bray[5], Griffiths[6], Hey[7], and Thorne and Zevenbergen[8], and et al. In these cases, the effect of stacked boulders on the flow resistance was not discussed. Regarding the installation of stacked boulders in subcritical flow as a ground sill, the application of the momentum equation reveals that the drag force acting on stacked boulders depends on the combination of stacked boulders for different discharges (Yasuda[9]). Also, the experimental investigation on velocity distributions yields that the main flow passing over optimal stacked boulders lifts to the water surface for large discharges.

In Kando River (82.4 km long) located in Shimane prefecture, as gravel-bed river was partly constructed as a channelized river for flood control (about 20 km upstream from river mouth). In
channelized region of Kando River (Photo 1), a high velocity flow with strong turbulence was formed near the river bed after the construction, and it was impossible to preserve habitat area and refuge for aquatic animals.

This paper presents practical approaches for the improvement of channelized river in Kando River. In Kando River, three ground sills with stacked boulders were installed within three weeks. The channelized river could be improved quickly after the construction in accordance with the field observations in which swimming and benthic fishes in abundant habitat area could be found around ground sills. In this area, several sizes of gravels and rocks could be transported after floods, aquatic insects could be observed in space in rocks. Further, it has been confirmed experimentally that the stability of gravel region in the channelized river might be caused by the installation of fixation at downstream end of gravel region, a stacked structure of gravel, gravel thickness, and gravel size. By using eels, velocity field in stacked boulders has been characterized as a refuge region in prototype.

![Photo 1. Channelized area in Kando River.](image1)

![Photo 2. Installation of Stacked Boulders.](image2)

![Photo 3. Flow conditions passing over stacked boulders in normal stage.](image3)

2. Field observation for channelized river in Kando River

2.1. Background for approach
Kando River is branch of Hi River, Izumo city, Shimane Prefecture. As shown in Photo 1, a channelized river was constructed, because there was flood accident in this region 14 years ago. The compound cross section with 20 m bottom was formed in order to prevent from bank erosion. The slope of river was varied from 1/200 to 1/400, and the position of main flow was fixed under a wide range of discharges. Impacts of riverbed armouring in the channelized region were developed. In order to extend top width of water during flood stages and to keep the refuge area in the channelized region, the installation of ground sills was proposed. In this case, the construction must be finished in a short period. Also, the boulders must be brought from the same catchment area.

2.2. Setting for installation
In June 2019, three ground sills were constructed by using boulders with averaged diameter of 1 m. The installation of stacked boulders was constructed in 3 days. The stocked boulders were installed in
accordance with the experimental results on the stability of stacked boulders (Yasuda\textsuperscript{9}) as shown in Photo 2. The top level of stacked boulders was adjusted in order to keep the difference of water level around ground sill as 0.20 m difference in normal stage. The main flow lifts to the water surface easily even if the plunging flow is formed at the immediately downstream of stacked boulders (Photo 3). After the construction, small velocity flows in which small fishes could swim gracefully behind the ground sills were formed. The region was extended to more 100 m long. The velocity near the gravel bed was recorded as less than 0.40 m/s.

2.3. \textit{Flow conditions around ground sills with stacked boulders}
As shown in Photo 4, in the end of August 2019, a big flood was happened by the occurrence of typhoon, and the water level of river was increased up to 1.2 m in the improved region. The installation of ground sills was stable after floods. Also, several sizes of gravels were accumulated below the ground sills during flood stages (Photo 5). The size of the sediments was distributed from 2 mm to 100 mm diameters. After floods, in the improved channelized river, swimming fishes (Ayu fish, Pale chub, Japanese dace, Loach, and etc.), benthic fishes (Eel, Goby), crustacean (Prawn and Swamp shrimps, Mitten crab), and aquatic insects (Nymph) could be found (Photo 6).

3. \textit{Discussion on the improvement of channelized river}
For the improvement of channelized river in Kando River, the installation of ground sill was conducted. From point of flood control, the ground sill with stacked boulders shown in Photo 3 might be effective for the prevention of riverbed, because the surface jet flow was formed during flood stages. In normal stages, as the flow passing over stacked boulders has seepage flows through the space of stacked boulders, aquatic animals can select favorite flow by considering their habitat. Unfortunately, as the hydraulic design method for stacked boulders was not established, it might be difficult for engineers to design the structure of stacked boulders. Also, the application of stacked boulders might be restricted by the place of origin for the boulder. The installation of the ground sill should be noted for the formation of the surface jet flow during flood stages.

\textbf{Photo 4.} Flow conditions during flood stage in 29\textsuperscript{th} August 2019.

\textbf{Photo 5.} The statement of gravel bed after improvement and Eating marks for river snail and Ayu fish.
4. Experimental Investigation

4.1. Experimental setup
The experiments were conducted in a rectangular channel with 15 m long, 0.60 m height, and 0.80 m width. The boulders with 1.6 cm averaged size were installed in 4.70 m long (from x = 3.00 m to x = 7.70 m) and about 0.04 m thickness (2.5 times of averaged gravel size) as shown in Photo 7, 8, 9. Figure 1 shows gravel averaged size distribution and probability curve for averaged gravel size. By considering stability of gravels, crushed stones were used. Also, a steel mount with a trapezoidal shape (0.04 m height, 0.10m top width, 0.25 m bottom width) was installed at the downstream end of gravel region in order that gravels would not be slipped on smooth channel bed. In addition, the test discharge was settled as 0.0585 (Case 1), 0.0864 (Case 2), 0.114 (Case 3), and 0.143 (Case 4) m$^3$/s. The slope of channel was adjusted as 1/100.

4.2. Experimental results
Photo 10 shows flow condition and statement of gravel bed for all cases. As shown in Photo 10, there is no stable undulation in water surface even if the value of Froude number in gravel region is about 0.9. Also, transported gravels were limited (0.03, 0.17, 0.26, and 2.2 % [weight of transported gravel/total weight for installed gravels×100 (%)] for Cases 1, 2, 3, and 4, respectively). In Case 4 (0.143 m$^3$/s), the transported gravels were measured after 4 hours. As shown in Photo 11, installed gravels were stacked in order to stabilize gravels. For Case 4, velocities with plan components were measured by using electric current meter with I type probe (sampling time: 30 s and sampling frequency: 50 ms). Figure 2 shows velocity profiles at x = 3.90, 5.30, and 6.50 m. In the mean velocity profiles for x-component (streamwise direction), the value of the mean velocity near the gravel bed is 0.7 to 0.8 m/s, and difference of the velocity in the test sections was small. In this figure, the turbulent intensity for x-component was represented by a standard deviation, and the value is about 0.10 to 0.13 m/s near the gravel bed. From these results, the effect of configuration of gravel on the stability should be considered under a gravel layer with 0.04 m thickness. In order to demonstrate instability of gravel bed without the fixation at the downstream end of gravel region, the steel mount was removed for Case 4, and most of gravels were transported in a short period (within 20 minutes after the extraction), and undular surface was formed as shown in Photo 12. Also, transported gravels were trapped in each wave crest.
Figure 1. Gravel averaged size distribution and Probability curve for averaged gravel size.

Photo 10. Flow conditions for Cases 1, 2, 3, and 4.

Photo 11. Formation of stacked boulders for Case 4.

Figure 2. Velocity distributions for Case 4 at center of channel (y = 0 cm).
5. Possibility of refuge space in stacked boulders

In stacked boulders with about 0.30 m size, there are many spaces where aquatic animals would be able to habitat as a refuge region. As shown in Photo 13, stacked boulders with 0.25 m to 0.4 m sizes were installed in rectangular channel with 15 m long, 0.60 m height, and 0.80 m width. The installation region was settled in 5 m long. The slope of channel was adjusted as 1/200. The discharge was settled as 0.0581 and 0.151 m³/s. 25 eels (Averaged total length 30 cm) were released in gravel region. Most of eels stay in stacked boulders (Photo 14) for Q = 0.151 m³/s (Photo 15). But, favorite space was limited for refuge. Figure 3 shows velocity profiles in stacked boulders in which Japanese eels stay. Figure 4 shows velocity profiles in stacked boulders in which eels do not stay. As shown in Figure 3, the mean velocity in stacked boulders is almost zero near the bottom. Also, the turbulent intensity (in this case, standard deviation) is less than 0.045 m/s. In the case of space in which eels do not stay, as shown in Figure 4, the mean velocity has either positive or negative values near the bottom. Also, the turbulent intensity is larger than 0.045 m/s. From these results, it has been experimentally confirmed that the structure of stacked boulders depends on the possibility for creating refuge region.
6. Conclusions
The ground sill with stacked boulders is effective for the improvement in the channelized gravel river. The balance between flood control and preservation of aquatic habitat was applied to the improvement in Kando River, and field observation might support the effect of the installation of the ground sill with stacked boulders on the improvement of channelized river. In normal stages, the flow passing over stacked boulders has seepage flows through the space of stacked boulders, aquatic animals can select favorite flow by considering their habitat. For flood control, the formation of surface jet flow is significant to lift to the water surface without plunging.

In accordance with Froude similarity, the experimental investigation in 1/15 scale model revealed that the stability of gravel region in the channelized river might be caused by the installation of fixation at downstream end of gravel region, a stacked structure of gravel, gravel thickness, and gravel size from flow observation and measurements of water surface profile and velocity fields.

Furthermore, the experiments on space in stacked boulders were conducted in prototype, and the structure of stacked boulders related to the possibility for creating refuge region by using Japanese eels.

References
[1] Beretta P P, Boes R and Yasuda Y 2020 Installation of alternative gravel banks in channelized river IAHR APD2020 Congress (Zoom meeting)
[2] Bathurst J C 1978 Flow resistance of large-scale roughness Journal of Hydraulic Division- ASCE 104 1587-603
[3] Bathurst J C, Li R M and Simons D B 1981 Resistance equation for large-scale roughness Journal of Hydraulic Division-ASCE 107 1593-613
[4] Bathurst J C 1985 Flow resistance estimation in mountain rivers Journal of Hydraulic Engineers-
[5] Bray D J 1979 Estimating average velocity in gravel-bed rivers *Journal of Hydraulic Engineers-ASCE* 106(9) 1103-21

[6] Griffith G A 1981 Flow resistance in coarse gravel-bed rivers *Journal of Hydraulic Division-ASCE* 107(7) 899-918

[7] Hey R D 1979 Flow resistance in gravel-bed rivers *Journal of Hydraulic Division-ASCE* 91(4) 365-79

[8] Thorne C R and Zevenbergen L W 1985 Estimating mean velocity on mountain rivers *Journal of Hydraulic Engineers-ASCE* 111(4) 616-23

[9] Yasuda Y 2018 Practical approach from experimental investigation on fish passage with stacking boulders installed in weir *Advances in River Engineering-JSCE* 24 125-30