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Countermeasure of Protection Against Local Scouring Downstream of Concrete Check Dams

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Abstract

Check dams are planned to control sediment and gravel runoff during floods. In accordance with the planning for the Sabo works, check dams have been constructed in each watershed, which may reduce serious sediment transport during floods. On the other hand, as the ratio of the installation of check dams to the planning is proceeded, sediment transport is limited, and degradation of the riverbed has been observed downstream of check dams. In general, localized scouring was observed downstream of the sub-dam even after protection blocks were installed downstream of the check dam. This may be caused by the lack of functionality to raise the main flow in the protection blocks. In concrete check dams, there are different types of ordinary closed check dams and check dams silted at a center part of dam. In terms of countermeasures against local scouring downstream of the sub-dam, there is no difference of design method for different types of check dams. Recently, the ramp with consecutively assembled boulders was proposed by Yasuda, the installation of the ramp below low drop structure is effective for both protection of river bed during flood stages and migration of multi-aquatic animals for normal stages. This paper presents that the installation of the ramp with consecutively assembled boulders downstream of a sub-dam is effective for different types of check dams. Experimental results show that the thee-dimensional main flow through the sub-dam can be controlled by the formation of seepage flow in the ramp composed by the assembled boulders, and that the main flow always rises toward the water surface at the downstream end of the ramp. The cross section of the ramp has a parabolic shape, and the velocity near the sidewall can be reduced in comparison with the center part of the ramp during flood stages. In addition, the migration for the multi-aquatic animals on the ramp is possible during normal stages as in the case of low drop structure.

Keywords: check dam, local scouring, seepage flow, assembled boulders, flow velocity fields

1. Introduction

The check dams have been installed for either the prevention against debris flow or the reduction of serious sediment transport and driftwood during flood stages. In order to dissipate the high velocity passing the check dam, a stilling basin was installed. In Japan, the riverbed slope is not milder in the installation region of the check dam, and the downstream depth required to form the hydraulic jump below the check dam might not be kept during flooding. The forced jump is formed by installing the sub-dam (Photo 1). From the view point of the protection of riverbed during flooding, the protection blocks were installed at the downstream of the sub-dam (Vischer and Hager, 1995, MILT, 1997, Japan River Association, 2008). But, a local scouring was formed when the gravel and sediment transports were controlled by check dams. Many researchers have studied the local scouring of riverbed downstream of aprons associated with river structures (e.g., Breusers & Raudkivi, 1991, Hamidifar et al., 2010, Guan et al. 2019, Rufira et al., 2021, Chauhan et al., 2022). As a countermeasure against local scouring, the study proposes the use of corrugated aprons in the shape of the apron (Hossam et al., 2014). Other studies propose the installation of a single bed sill in the riverbed (Hamidifar et al., 2018), the installation of screens on the riverbed (Rajaratnam & Aderibigbe, 1993) and the use of roughness over the surface of stiff apron (Mohammad et al., 2022) to prevent scouring. In the case of the check dam, the protection blocks are installed instead of the concrete apron. The protection blocks have not function for rising the main flow toward the water surface, and the main flow is located near the riverbed below the sub-dam during flood stages. The number of the check dams have been installed in accordance with the planning for the countermeasure against disasters, and sediment transports were limited. It might be easy to form a local scouring during flood stages. The results of previous studies do not substantially prevent scouring downstream of check dam. In accordance with the recent research by Yasuda and Fuchino (2023), the installation of the consecutively assembled boulders as the ramp may help for the protection of riverbed downstream of the ramp. In the case of the concrete check dam, there are two kinds of check dams. The ordinary closed check dam is classical check dam installed for both the control of sediment transports and the catchment of debris flow. The slit-type check dam with a depression in the center part of the dam is the check dam for the defense against driftwoods and large rocks transported by the debris flow (Photo 2). The degree of the concave curvature passing through the sub-dam during flood stages is not negligible for both cases, and a three-dimensional deflected flow is formed at the immediately downstream of the sub-dam. Especially, in the case of the slit-type check dam, as the main flow of the forced jump impinges to the upstream face of the sub-dam, strong deflected flows are formed at both sides of the sub-dam.

According to researched by Yasuda et al. (2023), the installation of the consecutively assembled boulders might be effective for both migration route for aquatic animals during normal stages and protection against local scouring around hydraulic structures during flood stages.

In this paper, the authors applied the consecutively assembled boulders to the ramp downstream of the sub-dam in the check dams for both non-slit and slit types. The installation of the assembled boulders may be helpful for reducing the concentration due to three-dimensional deflected flow on the ramp. The installation of the assembled boulders may be helpful for reducing the formation of three-dimensional deflected flow on the ramp. The experimental results by using physical models yield the improvement of the flow condition below the check dam due to the installation of the assembled boulders. The water surface profile around the sub-dam emphasis the concave curvature of the flow passing through the sub-dam, and three-dimensional profiles are recorded downstream of the sub-dam. The installation of the consecutively assembled boulders in the protection region including the ramp is stable during a design discharge. The velocity fields reveal that a high velocity flow near the assembled boulders can be reduced to the downstream end of the protection region by the formation of seepage flow among the boulders. The improvement of the flow condition and the velocity field on the protection region is confirmed by the comparison with the flow condition and the velocity field on the protection blocks downstream of the sub-dam under the same design discharge and the downstream water elevation.

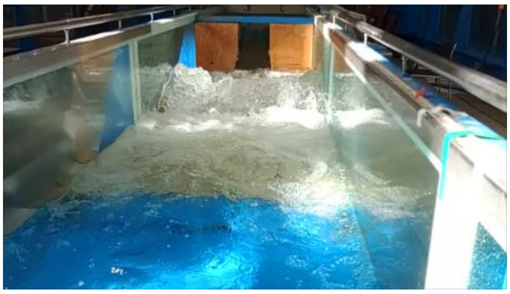
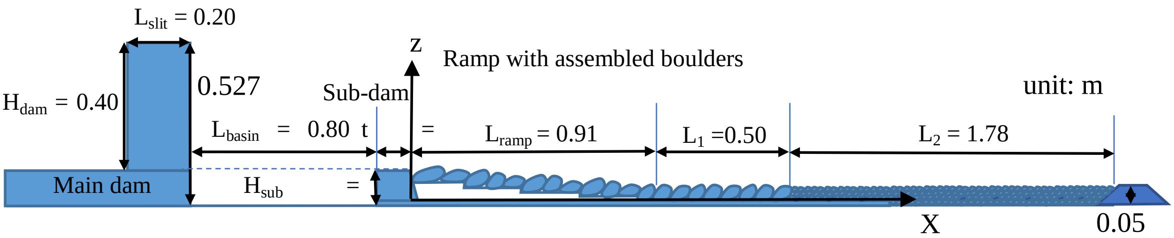


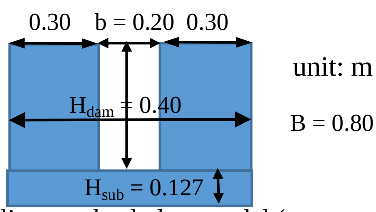
Photo 1. Jump formation downstream of sub-dam in slit-type check dam

2. Experimental Setup

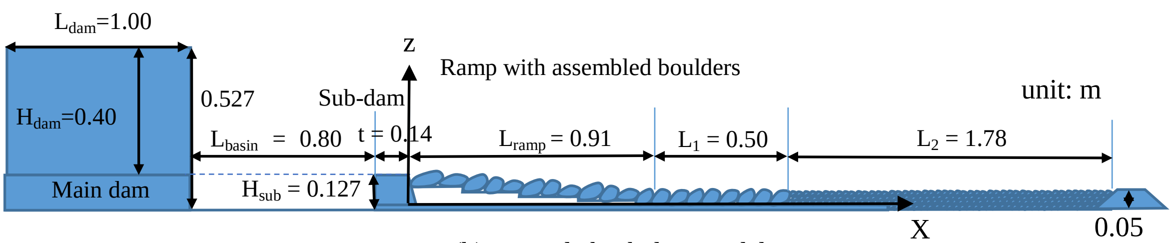
The experiment was conducted in a horizontal channel of rectangular cross section (channel width B = 0.80 m, length 15.5 m, height 0.60 m). The slit-type check dam model and the check dam model without slit were produced in accordance with the Japanese design manual for check dam as scale model (Figure 1). The scale of model was settled as 1/10 scale, and Froude similarity law was applied. The slit is located in the center of check dam. The slit width was settled as b = 0.20 m wide and 0.40 m height in order that the flow upstream of the check dam has been passed through the slit under the design discharge. As shown in Photo 1, consecutively assembled boulders were installed downstream of the sub-dam. Based on the applied check-dam model, the design flood discharge was set to $Q = 0.0755\ m^3/s$, and the length of stilling basin was set to $L_{basin} = 0.80$ m. The slope and horizontal length of the assembled boulders were settled as 1/10 slope and 0.91 m length, respectively. Averaged diameter of 0.09 m was used for the assembled boulders, in which the boulders were arranged to form a parabolic shape in the cross-sectional direction. In addition, the ramp is constructed of boulders on a wooden stepped model. At the downstream end of each step, an L-shaped bracket is installed, on which the boulders are leaned and propped. The boulders are assembled on the steps to stabilize each other, and no fixed materials are used. The assembled boulders were continuously installed as a protection region of gravel bed with L_1 = 0.50 m long (Figure 1). Downstream of the protection region, small crushed stones with an average diameter of 0.016 m were installed with a thickness of 0.05 m and a length of L_2 = 1.78 m to reproduce the riverbed. The downstream water level was adjusted to form a surface flow at the downstream of the sub-dam. In the experiment, ground profiles, water surface profiles, and flow velocities were measured when the design flow rate was applied. A point gauge was used to measure the water levels and ground profiles, and a KENEK two-dimensional I-type electromagnetic anemometer (measurement time per point: 30 sec, sampling interval: 20 Hz) and a KENEK propeller-type anemometer (measurement time: 20 sec) were used to measure the flow velocity.



(a)-1 Slit type check dam model (side view)



(a)-2 Slit type check dam model (cross section of slit)



(b) Normal check dam model

Figure 1. Definition Sketch of Experimental model (side view)

3. Description of Flow Conditions

Photos 3 and 4 show the flow conditions downstream of check dam. For both slit type and normal check dams, a forced jump is formed in the stilling basin for the design discharge in order that a high velocity flow passing through the check dam is dissipated. The main flow in the jump impinges to the upstream face of the sub-dam, and a boiling flow is formed near the side of the sub-dam. A three-dimensional deflected flow is formed on the ramp. In the case of slit type check dam, the degree of the boiling flow is larger than that for the normal check dam.

In this experiment, as shown in Photos 3 and 4, in order to investigate the effect of the installation of the assembled boulders on the protection against a local scouring downstream of the protection area, a supercritical flow is formed on the ramp. Also, the space among the assembled boulders on the ramp is secured, and a seepage flow is formed on the ramp. The seepage space in the assembled boulders is complicated, and the flow velocity near the assembled boulders can be reduced. In the protection area below the ramp, the flow passing through the ramp transits to subcritical flow, and a surface jet flow is formed. The assembled boulders are consisted as parabolic shape at the cross section on the ramp, and the main flow is located at the center part of channel. At the downstream of the protection area, the main flow is located near the water surface, and the gravel bed is not scouring for a long time (more 50 hours).

If the protection blocks are installed downstream of the sub-dam, a hydraulic jump is formed at the downstream part of the protection blocks under the same downstream water level and discharge (Photo 5). As a high velocity flow passing over the sub-dam impinges to the blocks is accelerated on the blocks, a supercritical flow is formed at the upstream part of the protection blocks. A local scouring is formed at the downstream of the protection blocks. The stability of the blocks in range of the formation of supercritical flow cannot be kept for a long time.

Photo 3. Flow condition downstream of sub-dam in slit-type check

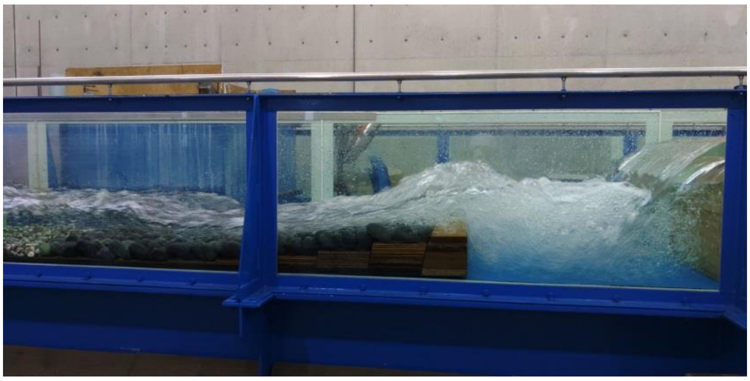
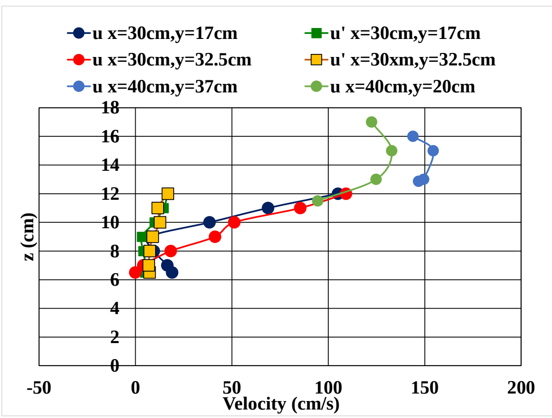


Photo 4. Flow condition downstream of sub-dam in normal check dam

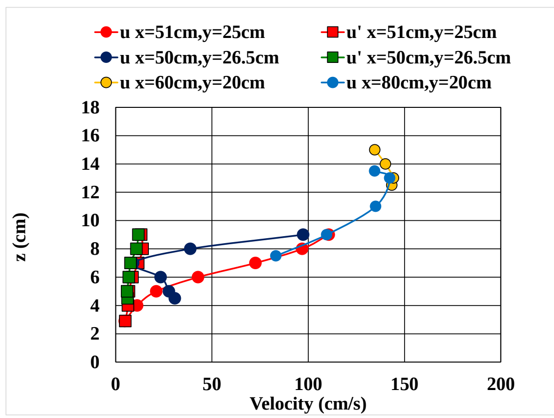
Photo 5. Jump formation downstream of sub-dam in slit-type check dam

4. Velocity Distribution on the Ramp

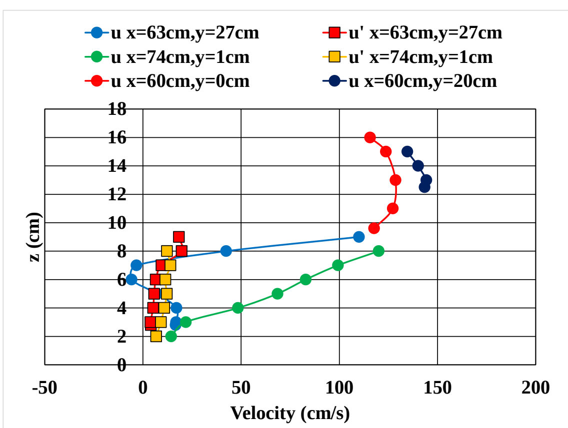
The velocity distributions on the ramp for both cases of normal check dam and slit-type check dam are shown in Figures 2 and 3. In these figures, the time averaged velocity and the standard deviation for longitudinal direction are expressed as circle symbol and squire symbol, respectively. Then, u is time averaged velocity for X component, u' is standard deviation for X component, X is longitudinal axis from downstream end of sub-dam, y is transverse axis from center of channel, and z is vertical axis from channel bottom. The positive direction of z is upward direction, and the direction from the center to the left side is positive for y-direction. The velocity in the main flow was measured by propeller type anemometer, and the velocity near the bottom was measured by electromagnetic anemometer. As shown in these figures, the time average velocity and standard deviation are always small in the assembled boulders. The shape of the velocity distribution differs between the near-bottom and mainstream areas. Near the bottom, the velocity distribution tends to be convex upward due to flow control by seepage flow, while in the mainstream area, the velocity distribution is exponential, except near the water surface. Velocity gradient in z-direction varies with the uneven shape of the assembled boulders in the ramp. In some measurement locations, the flow velocity near the surface of the step installed as a foundation may be greater than that at the top of the slope because the way the boulders are assembled makes it easier for the flow to enter the assembled boulders. The standard deviation of the velocity among the assembled boulders is always smaller than that on the ramp due to the control of the seepage flow in the consecutively assembled boulders. It should be noted that this is a feature indicated by the presence of gaps among the assembled boulders, as opposed to filled gaps by concrete.



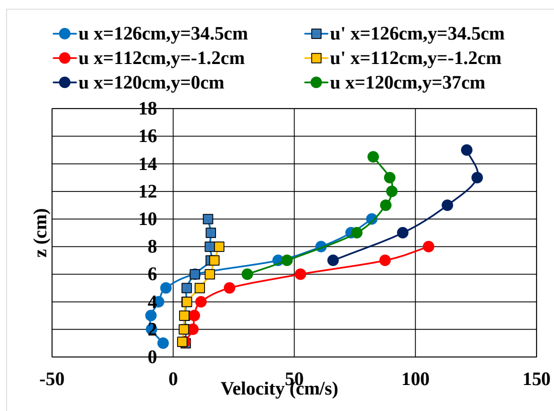
(a) 30 ≤ X (cm) ≤ 40



(b) 50 ≤ X (cm) ≤ 80

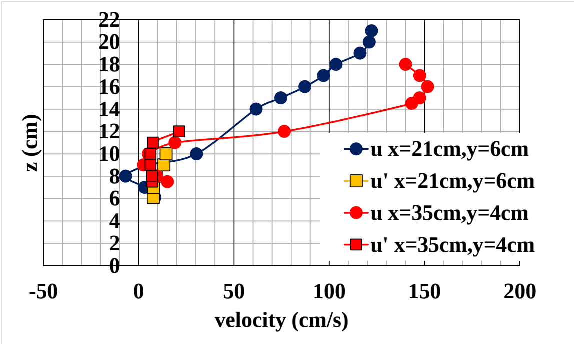


(c) 60 ≤ X (cm) ≤ 74

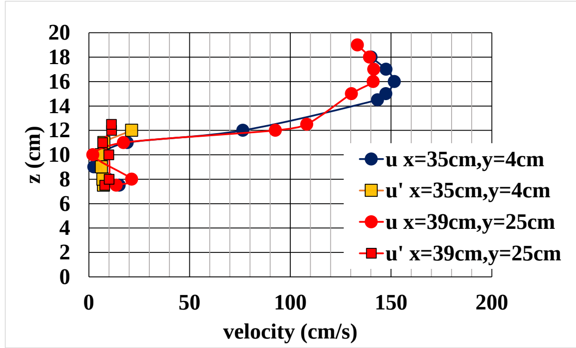


(d) 112 ≤ X (cm) ≤ 126

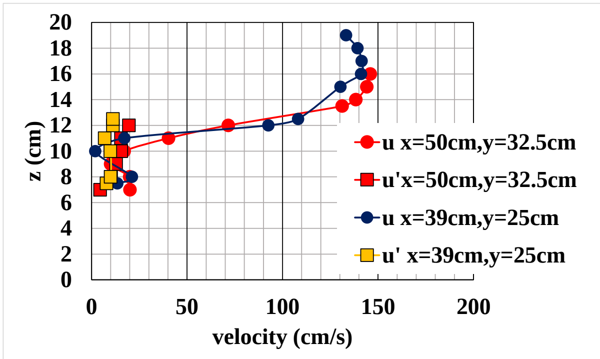
Figure 2. Velocity profiles on the assembled boulders downstream of slit type check dam



(a) 21 ≤ X (cm) ≤ 35



(b) 35 ≤ X (cm) ≤ 39

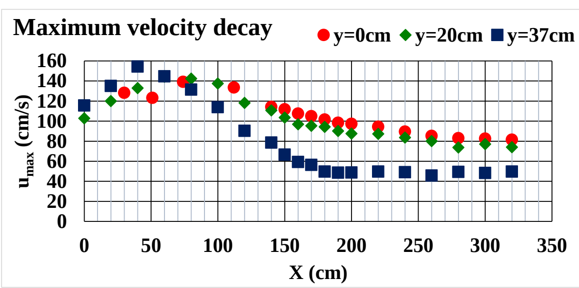


(c) 39 ≤ X (cm) ≤ 50

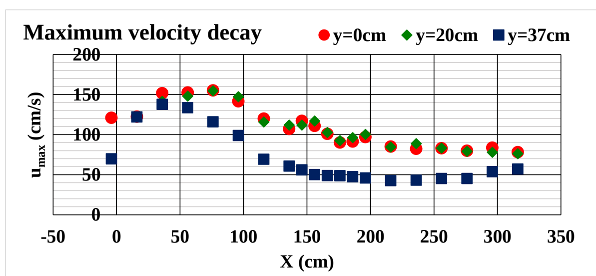
Figure 3. Velocity profiles on the assembled boulders downstream of normal check dam

5. Maximum Velocity Decay Downstream of the Sub-dam

The maximum flow velocity decay is shown in Figure 4. Here, the velocity is time averaged velocity, and the maximum velocity is defined on a vertical velocity distribution for each measurement location of x and y. As shown in this figure, it has been confirmed that the maximum velocity can be reduced by the flow passing over the ramp and the protection area with the consecutively assembled boulders. In the case of the slit type check dam, the maximum velocity decay near the side wall shifts to downstream in the comparison of the non-slit type check dam (i.e., normal check dam). This might be caused by the difference of the formation of the boiling flow between slit type check dam and normal check dam. The maximum velocities near the center part are always larger than those near the sidewalls. The difference of the maximum velocity might be explained by parabolic shape at the cross section on the ramp. At the downstream of the protection area, the difference of the maximum velocity decay is small between slit type check dam and normal check dam.



(a) Slit type check dam

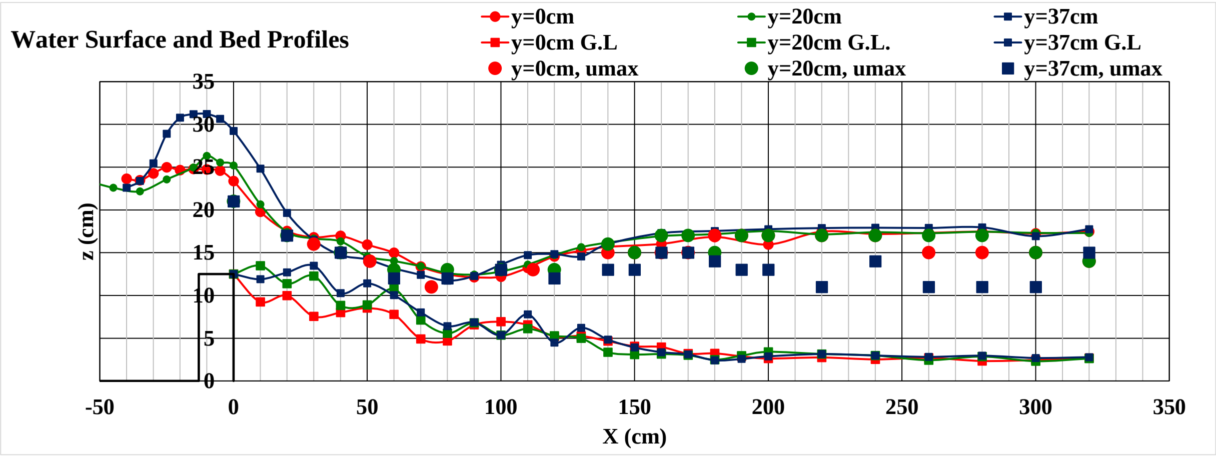


(b) Normal check dam

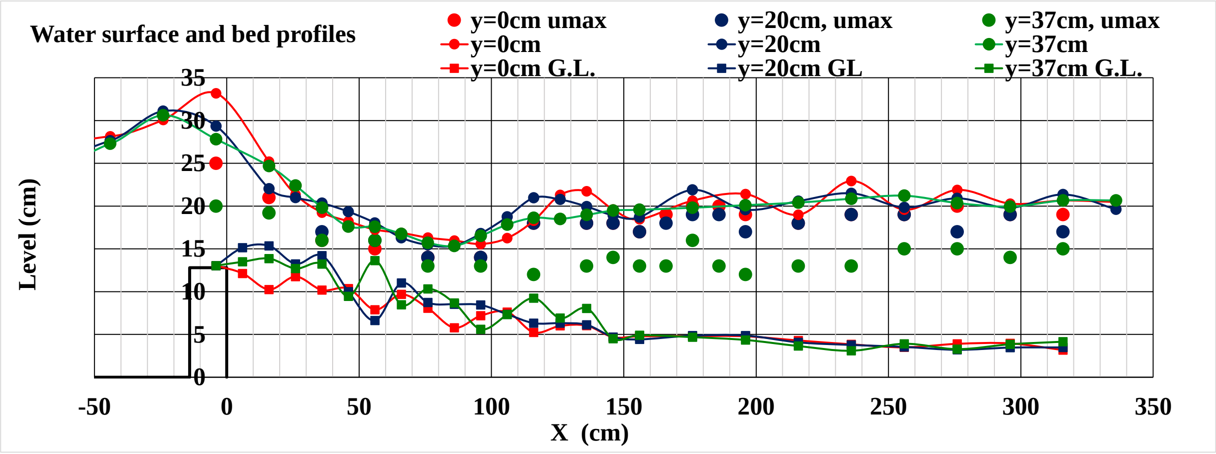
Figure 4. Maximum velocity decay downstream of sub-dam

6. Longitudinal Change of Mainstream Position

The longitudinal change of the location of the mainstream position shown in water surface and bottom profiles at the downstream of the slit-type check dam are shown in Figure 5. Here, the location of the mainstream position is defined as the location of the maximum velocity evaluated in each vertical section. The high velocity flow passing over the slit impinges to the center part of the sub-dam, and the formation of a boiling flow makes the different water surface profiles between the center part and side wall. The position of the main flow is changed with longitudinal and transversal directions by the formation of three-dimensional deflected flow. At the center part, the main flow is located near the water surface. While the main flow near the side wall is located between the water surface and the bottom. This might be caused by the formation of the three-dimensional deflected flow passing over the sub-dam. In the case of normal check dam, the difference of the water surface profiles between the sidewalls and the center part is small, as shown in Figure 3. The longitudinal change of the mainstream position at the center part is similar to that of the slit-type check dam. The mainstream position near the sidewall is higher than that at the center part of the ramp in the case of the slit-type check dam. This might be caused by the different formation of the boiling flow passing through the sub-dam between the normal check dam and the slit-type check dam.



(a) Slit type check dam

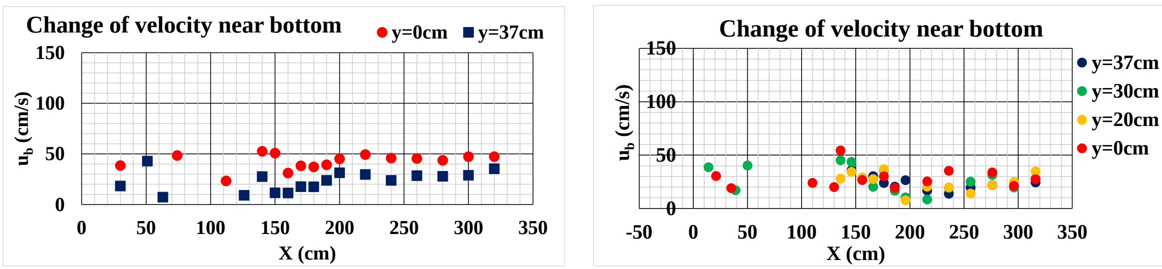


(b) Normal check dam

Figure 5. Water surface and bottom profiles and mainstream position

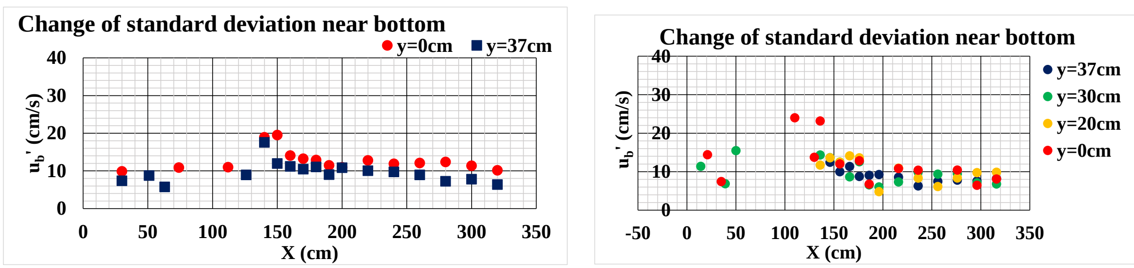
7. Velocity Near the Bottom Downstream of the Sub-dam

Figure 6 shows the longitudinal change of the time averaged velocity near the bottom downstream of the sub-dam in both cases of the slit type check dam and the normal check dam. The deflection due to the impingement of the main flow to the upstream face of the sub-dam depends on the flow passing over the check dam, and the velocity near the bottom at the downstream of the sub-dam changes with longitudinal and transversal directions. In the case of the slit type check dam, the main flow concentrates to the center part, and the time averaged velocity is larger than that near the side wall. In the installation region of the consecutively assembled boulders, the controlled velocity is continued for both cases of the slit check dam and the normal check dam, because a seepage flow is effective for the velocity decay with small turbulence. Figure 7 show the longitudinal change of the standard deviation of downward velocity. The standard deviation near the bottom is controlled by the formation of seepage flow through the assembled boulders. When the supercritical flow along the ramp with the assembled boulders transits to subcritical flow, the main flow lifts toward the water surface (X = 130-140 cm), and the standard deviation near the bottom is increased locally. Accordingly, the installation of the consecutively assembled boulders on the ramp and the protection region is effective for the protection of riverbed.



(a) Slit-type check dam (b) Normal check dam

Figure 6. Longitudinal change of the time averaged velocity near the bottom downstream of the sub-dam



(a) Slit-type check dam (b) Normal check dam

Figure 7. Longitudinal change of the standard deviation near the bottom downstream of the sub-dam

8. Discussion

The physical model was performed on a 1/10 scale model. Froude similarity is applied to the experiments, and the discharge and flow velocity in the prototype are calculated as $10^{2.5}$ and $10^{0.5}$ times the measured values, respectively. At the design discharge in this model, the flow velocity is up to 5 m/s on the ramp, but can be reduced to about 1.5 m/s near the bottom by installing the consecutively assembled boulders. The formation of the supercritical flow on the ramp with the assembled boulders could control the deflected flow passing through the sub-dam for both cases of slit-type check dam and the normal check dam, and the river bed downstream of the protection region might be prevented against local scouring. Then, it should be noted that crashed stones were installed downstream of the protection region. Crushed stones have a greater interlocking effect and are less likely to transport than cobble stones under same size of stone. If the protection blocks were installed at the downstream of the sub-dam, a hydraulic jump might be formed (Photo 5). The downstream water elevation for the jump formation is somewhat larger than that for the formation of the transition flow shown in Photos 2 and 3. If the jump is formed at the immediately downstream of the sub-dam, the main flow is located near the bottom at the end section of the jump (Figure 8). As shown in Figure 9, the maximum velocities evaluated at each vertical measurement cross section decay downstream, but the maximum velocity evaluated at y=37 cm near the sidewall is greater due to the deflected flow from the sub-dam. The time-averaged velocity near the bottom is also greater at y=37 cm near the sidewall, as shown in Figure 10. The flow velocity near the bottom accelerates, because the flow passing over the sub-dam impinges to the bottom. The velocity at the end of the jump (X = 100 cm) is greater than the velocities downstream of the assembled boulders shown in Figure 5. The velocity distribution at the end of the jump (Figure 10) is different from the velocity distribution downstream of the aggregate rock (Figure 11). If the jump is formed downstream of the sub-dam, the length from the sub-dam to the end of the jump is shorter than the length of the ramp with the assembled boulders, but riverbed protection downstream of the end of the jump should be required, making it impossible for aquatic animals to migrate upstream.

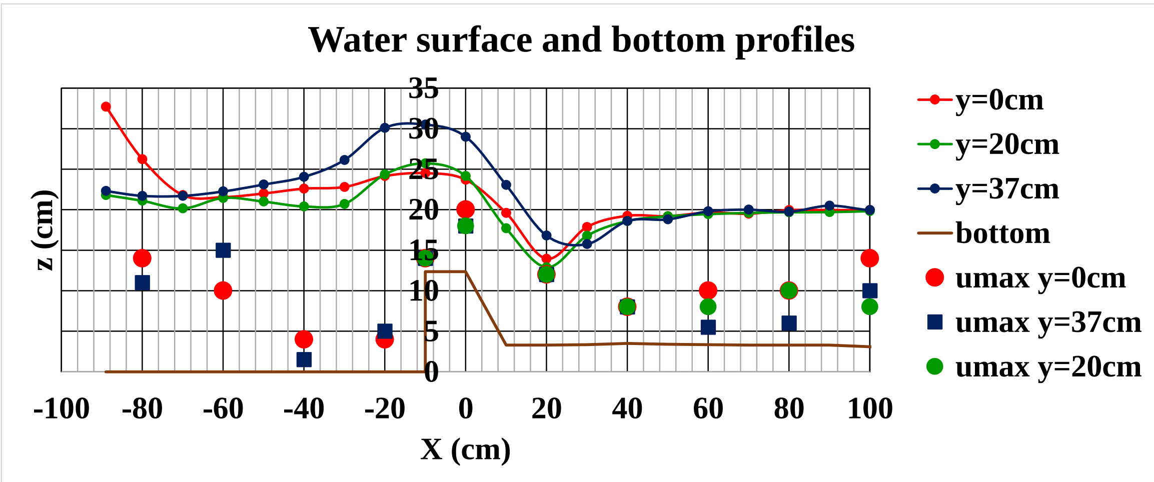


Figure 8. Water surface profiles and the mainstream position in jump formation below sub-dam

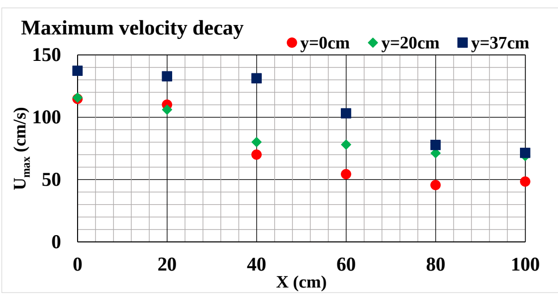


Figure 9. Maximum velocity decay in the jump

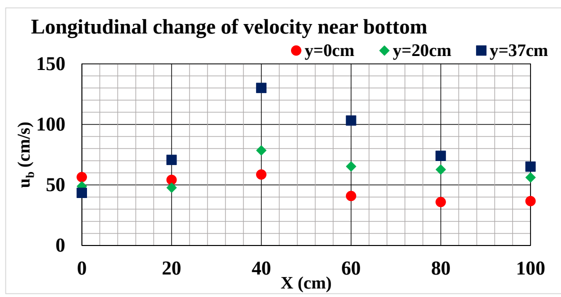


Figure 10. Change of mean velocity near the bottom

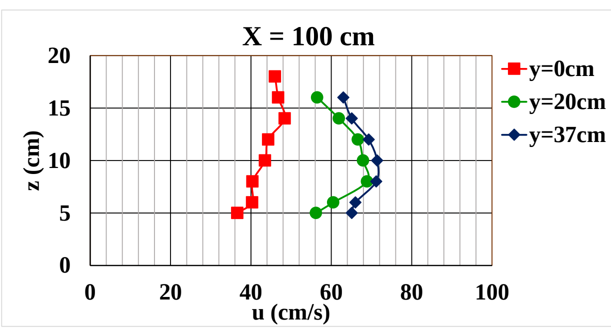


Figure 11. Velocity profiles at the end section of jump

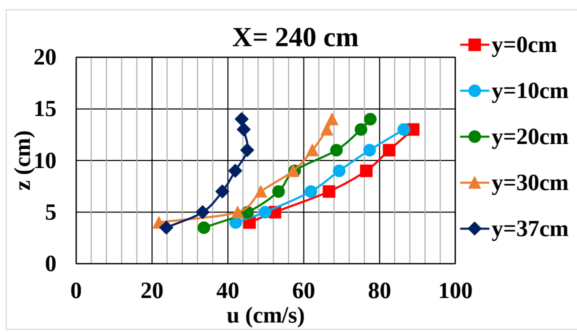


Figure 12. Velocity profiles downstream of assembled boulders

9. Conclusion

The authors proposed the installation of the ramp with the consecutively assembled boulders downstream of the sub-dam in the check dams for both non-slit and slit types. The flow passing through the sub-dam downstream of check dam makes the deflected flow because of the limited stilling basin. The experimental results by using physical models yield the improvement of the flow condition below the check dam due to the installation of the assembled boulders. Jump formation on the protective block downstream of the sub-dam is not recommended according to the velocity field and the main flow is recommended near the water surface in the transition from supercritical to subcritical flow.

This can be accomplished by installing an assembled boulder ramp with a one-tenth slope. The cross-sectional shape of the assembled boulders on the ramp should be parabolic to reduce the flow velocity near the sidewalls. The installation of the consecutively assembled boulders in the protection region including the ramp is stable during a design discharge. The velocity fields during design discharge reveal that a high velocity flow including standard deviation near the bottom can be reduced to the downstream end of the protection region by the formation of seepage flow among the assembled boulders. In accordance with the maximum velocity decay downstream of sub-dam, the installation of the consecutively assembled boulders is effective for the reducing the deflection of the main flow due to the boiling flow passing over the sub-dam. Regarding the mainstream position, the main flow is located near the water surface at the center part. While, the main flow near the side wall is located between the water surface and the bottom. In the installation region of the consecutively assembled boulders, the controlled velocity is continued for both cases of the slit check dam and the normal check dam, because a seepage flow is effective for the velocity decay with small turbulence. In summary, the authors were able to show that substantial scour prevention is possible downstream of the check dam by installing the ramp with assembled boulders at the downstream of sub-dam.

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