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Prevention Due to Assembled Boulders Against Local Scouring in Low-head Hydraulic Structures

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Abstract

In low-head hydraulic structures, the prevention against local scouring of the river bed downstream of concrete aprons must be required during flood stages. Generally, protection blocks are installed downstream of the apron, but they do not control the flow passing through the blocks to reduce the velocity near the bottom. In most of river fields, the installation of protection blocks may not help protect the river bed. In the case of low drop-structures, hydraulic jump occurs during flood stages just below the drop-structures. The main flow near the bottom continues far downstream, and a local scouring is formed. In the case of the movable weir, a local scouring occurs downstream of the weir during flood stages. There is little information on the countermeasure against the local scouring below the movable weir during flood stages. Recently, the authors proposed the installation of consecutively assembled boulders instead of protection blocks. This paper presents the effect of installing consecutively assembled boulders on the prevention of local scouring for both low drop-structures and movable weirs. The effect of seepage on reducing flow velocity near the bottom has been shown, the comparison between the installation of protection blocks and the installation of consecutively assembled boulders has been discussed. In the case of the movable weir, the flow velocity near the bottom below the protection blocks is always larger than that below the assembled boulders, in which the effect of the deflected flow formation by the support pier is not negligible.

Keywords: drop structure, movable weir, prevention region, local scouring, assembled boulders

1. Introduction

There are a lot of low-head hydraulic structures (e.g., drop-structure, movable weir, check dam, and etc.) in rivers. In accordance with hydraulic design manual (Japan River Association., 2005), the installation of apron and protection region must be required for both the protection of river bed and the stability of hydraulic structure. But, local scouring and river bed degradation are formed at the downstream of hydraulic structures. Generally, the protection blocks are installed in the protection region.

In the case of low drop-structure, a hydraulic jump including plunging flow is formed at the downstream of the drop-structure during flood stages. In the jump formation, the main flow is located near the bottom (Yasuda & Shinozaki, 2018), because the concave curvature of stream line below the structure is not negligible. The velocity profile in the jump is similar as in the case of wall jet, and the flow passing through the protection blocks may produce a local scouring. Further, a three-dimensional flow is formed at the downstream of the structure, because the local scouring depth becomes larger near the side wall. Kanda et al. (1995) revealed the scouring characteristics of different types of protection blocks in moving river bed experiments. Based on these results, he proposed a method using riprap at the downstream side of the drop.

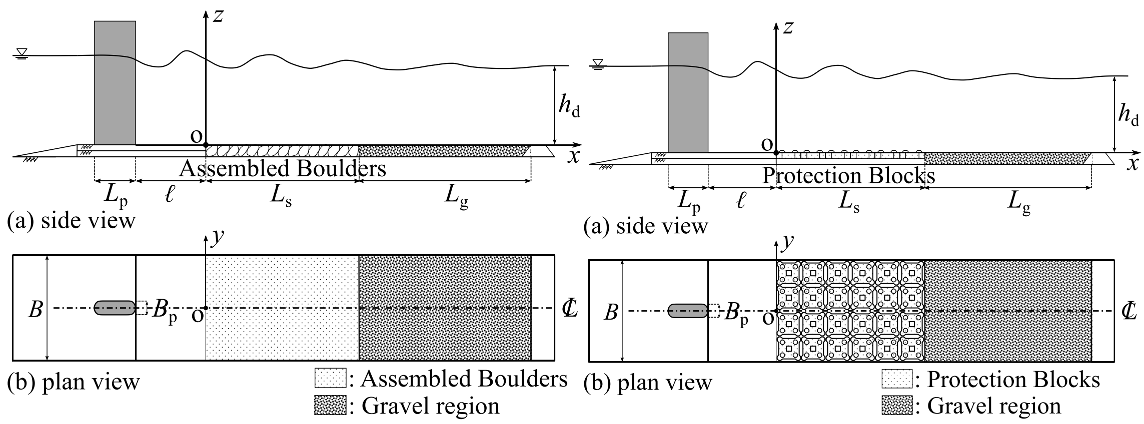
In the case of movable weir, several types of gates are installed for the water level control and supported by piers as guide walls. Many researchers have studied the local scouring of river bed downstream of aprons associated with river structures (e.g., Breusers & Raudkivi, 1991, Hamidifar et al., 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 river bed (Hamidifar et al., 2018), the installation of screens on the river bed (Rajaratnam & Aderibigbe, 1993) and the use of roughness over the surface of stiff apron (Mohammad et al., 2022) to prevent scouring. However, these studies are based on the situation that the sluice gate of the movable weir is not completely opened, that is, the condition in which a hydraulic jump is formed. During flood stages, the gates are opened to prevent from the increasing of water level at the upstream of the weir. In this case, the flow passing through supported piers becomes a three-dimensional flow including deflected flow, and a three-dimensional local scouring is formed at the downstream of the protection region (Yasuda & Suzuki, 2022a). Previous studies have assumed that scour holes will form, and there are no measures to prevent scour. There is a lack of research on preventing scour, including in the recent literature.

As a main problem, the flow passing through the protection blocks cannot rise toward the water surface. Recently, the authors proposed the installation of consecutively assembled boulders instead of the protection blocks as a prevention method against a local scouring (Yasuda & Suzuki, 2022b). As the installation of assembled boulders is not familiar for the normal construction, the gaps between boulders are willing to be filled by concrete in order to stabilize the assembled boulders. But, the effect of gaps between boulders on the velocity field near the bottom is not clear.

In this paper, the installation of consecutively assembled boulders for the prevention against local scouring downstream of both low drop-structure and movable weirs was examined on the basis of experimental investigation. The effect of seepage on reducing flow velocity near the bottom has been shown, and the results yield that the installation of the assembled boulders is required within a stable undulation region of water surface in order to prevent local scouring downstream of the protection region. The experimental results on the velocity field near the bottom were compared between the protection blocks and the assembled boulders, the flow velocity near the bottom below the protection blocks is always larger than that below the assembled boulders. Especially, in the case of the movable weir, the effect of the deflected flow formation by the support piers is not negligible. For both low drop-structures and movable weirs, the installation of the assembled boulders is effective for the prevention against local scouring.

2. Experimental Setup

Experiments were conducted in horizontal rectangular channel with 15 m long, 0.80 m wide, and 0.60 m height. Figures 1 and 2 show diagrams defining the symbols used. In the case of the movable weir, a long elliptical pier 0.20 m long, 40 mm thick, and 0.50 m high was installed in the center of the channel, and apron with 30 mm thick and 0.51 m long was installed directly downstream of the long elliptical pier (Figure 1). In the case of the low drop-structure, a drop model (transverse length 0.796 m, drop height H = 0.10 m, downstream length L = 1.00 m) simulating a low drop-structure was installed in a horizontal rectangular channel (Figure 2). For both cases of the low drop-structure and the movable weir, assembled boulders was installed from the end of apron, and gravel region was installed from the end of assembled boulders. The average size of assembled boulders is about 0.05 m. the gravel with an average diameter of about 0.008 m (0.002 ~ 0.015 m) is installed as a gravel region with a thickness of about 0.55 m. Assembled boulders was adjusted to connect smoothly with the upstream of apron and the downstream of gravel region. The velocity profile at each vertical section was recorded by using a I-type probe electrical-magnetic current meter KENEK CO. model VM-806H/VMT2-400-04P (sampling times: 90 sec for the comparison of local scouring downstream of assembled boulders under filled and secured gaps, 120 sec for other cases. sampling frequency: 0.05 sec (20 Hz)) was used to measure the longitudinal (x-direction) u and the lateral (y-direction) v velocity components. The water surface and the gravel bed profiles were recorded by using a point gauge with 0.1 mm reading. The discharge was measured by using wide rectangular sharp-edged weir located at downstream end of channel.



Installation of protection blocks Installation of consecutively assembled boulders

Figure 1. Definition sketch for the movable weir model

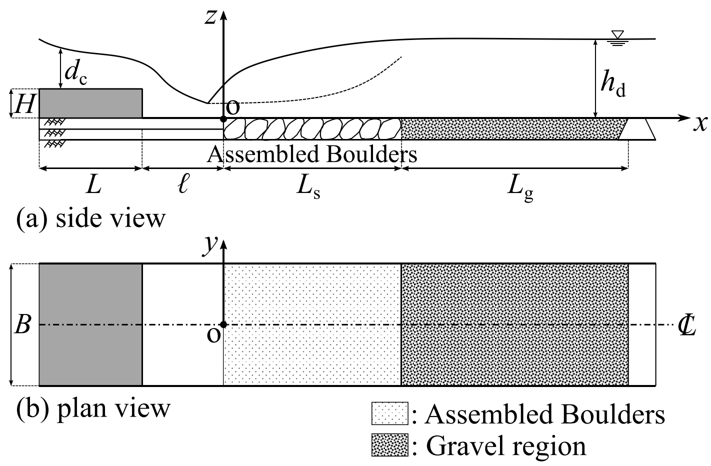


Figure 2. Definition sketch for the low drop-structure model

Table 1. Experimental conditions

Low drop-structure with apron and assembled boulders

q(m^2/s)	H/d_c	F_d	L/d_c	ℓ/d_c	L_s/d_c	L_g/d_c	h_d/d_c	Note
0.114	0.913	0.442	9.13	4.23	7.76	9.13	1.72	Secured gaps

Movable weir with protection blocks

q(m^2/s)	F_d	$B_p/(B/2)$	L_p/d_c	ℓ/d_c	L_s/d_c	L_g/d_c	B/d_c	h_d/d_c
0.180	0.552	0.100	1.34	3.42	5.37	8.05	5.36	1.49

Movable weir with assembled boulders

q(m^2/s)	F_d	$B_p/(B/2)$	L_p/d_c	ℓ/d_c	L_s/d_c	L_g/d_c	B/d_c	h_d/d_c	Note
0.180	0.550	0.100	1.34	3.42	5.37	8.05	5.36	1.49	Secured gaps
0.180	0.553	0.100	1.34	3.42	6.71	8.05	5.36	1.48	Secured gaps Filled gaps

The experimental condition is shown in Table 1. Then, q is discharge per unit width, L_s is length of assembled boulders, and L_g is length of gravel region. In Figure 1, B_b is the pier thickness, L is length of pier, ℓ is the length of apron, B is width of the channel. The coordinate axes of x, y, and z are defined as the downstream direction from the apron, the transverse direction from the center of the channel, and the vertical direction from the apron, respectively. The experimental conditions are set to the relative drop height H/d_c (H: drop height, $d_c = \sqrt[3]{q^2/g}$: critical depth, q: unit width flow, g: gravity acceleration), Froude number defined at the downstream section F_d ($= q/h_d\sqrt{gh_d}$, h_d: downstream water depth).

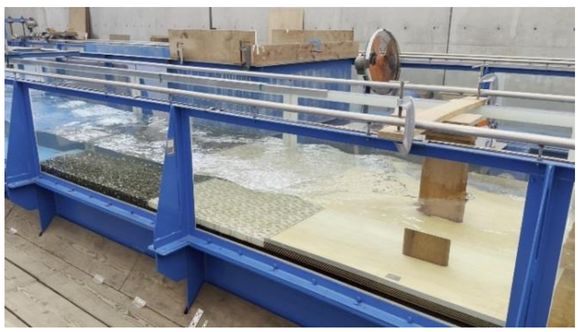
3. Description of Flow Conditions

Photo 1 shows the flow conditions passing through the low drop-structure, the movable weir with protection blocks, and the movable weir with the protection region due to consecutively assembled boulders, respectively. In the case of the movable weir, supported pier was installed at the center part of the weir. As shown in Photo 1 (a), a hydraulic jump is formed at the downstream of the low drop-structure. The toe of the jump is located at the apron, and the end of jump might be located at the immediately downstream of the assembled boulders. The mainstream rises to the water surface at the downstream of the assembled boulders. In the case of the movable weir, a subcritical flow is formed around the weir in order to consider a flood stage. As shown in Photo 1 (b) and (c), stable undulations of the water surface are formed below the supported pier. At the downstream of the protection region, the formation of the undulation shifts to the center part from side wall. In the case of the installation of the protection blocks, local scouring near the side wall is formed at the downstream of the protection blocks. Photo 2 shows that the gravel bed shape below the consecutively assembled boulders differs between the filled gaps and the secured gaps. In the right side toward downstream (right bank side), the gaps between boulders are filled. In the left side, the gaps are secured. As shown in Photo 2, local scouring hole is formed at the downstream of the assembled boulders with filled gaps. This might be explained from the velocity fields near the bottom.

4. Water Surface and Bed Profiles

Figure 3 shows water surface and bed profiles downstream of a low drop-structure at $y/(B/2) = 0$ and 0.75. As shown in Figure 3, the consecutively assembled boulders are installed in the jump region (≈6 times of subcritical sequent depth of jump), and there is no scouring at the downstream of the protection region. The jump formation was controlled in order that the toe of the jump was located at the impingement position of a supercritical flow passing through the low drop-structure. In addition, the gravel bed was measured after 30 hours from the start of the experiment. The main flow in the jump below the low drop-structure becomes three-dimensional deflected flow, but the gravel bed does not affect the three-dimensional flow, because the flow velocity along the assembled boulders might be reduced to rise the main flow toward the water surface until the end of jump.

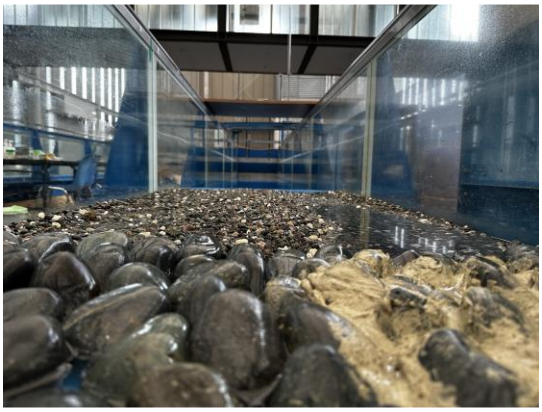
(a) The jump formation below the low-drop



(b) The stable undulation at the downstream of pier

(c) The flow condition downstream of the assembled boulders

Photo 1. Flow conditions passing through the low drop-structure and the movable weir



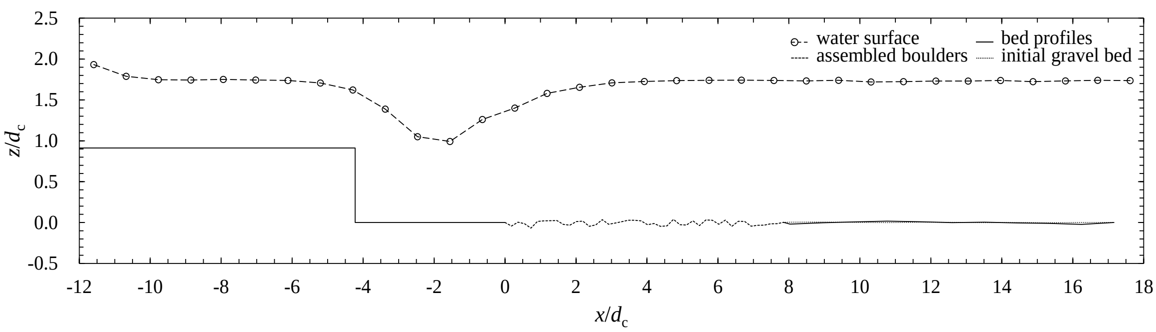
(a) Bottom shape viewed from upstream

(b) Bottom shape viewed from the right bank

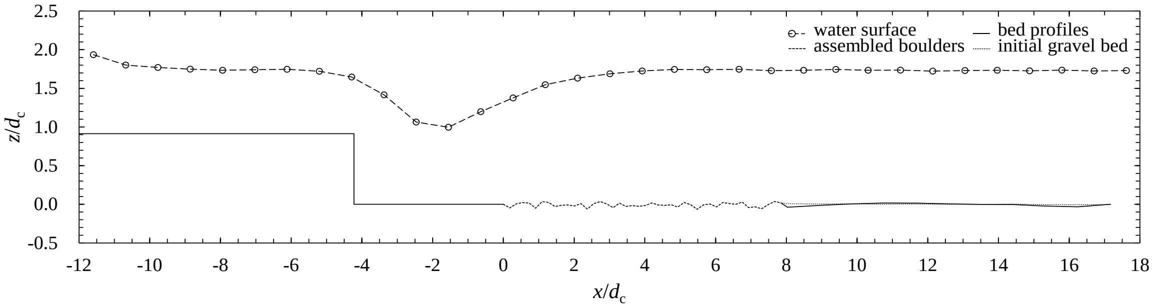
Photo 2. Comparison of local scouring downstream of assembled boulders under filled and secured gaps

In the case of the movable weir, as shown in Figures 4 and 5, the different bed profiles between the installation of protection blocks and the installation of consecutively assembled boulders in the same protection region. In these conditions, the installation length might be short for the protection against local scouring. If the protection blocks are installed in the protection region, the main flow passing through the protection blocks is located near the bottom of side wall by a deflected flow due to the pier, a local scouring is formed at $y/(B/2) = 0.75$ as shown in Figure 4. While, if the consecutively assembled boulders are installed in the protection region, the local scouring can be reduced (Figure 5 (b)). At the center of channel, there is no scouring at downstream of the protection region (Figures 4 (a) and 5 (a)). As in the case of the low drop-structure, the gravel bed was measured after 30 hours from the start of the experiment. The water surface profile is similar for both cases, and the stable undulation of water surface is formed. In the protection region, the undular surface is formed near the side wall. At the downstream of the protection region, the undular surface is formed at the center of channel (Figures 4 and 5). This might be caused by the rectangular shape of channel and aspect ratio of water depth to the width of the flow passing through the pier. The local scouring is formed in the region in which the stable undulation of the water surface is formed directly from the pier, and the assembled boulders should be installed until the dissipation of the stable undulation from the support pier.

As shown in Figure 6, comparing the profile of the gravel bed in the area of consecutively assembled boulders with filled and secured gaps shows that the local scouring formed by the deflected flow due to the pier is different. The flow velocity passing through the filled gaps becomes faster at $y/(B/2) = 0.75$, and the local scouring depth is greater than that for the secured gaps. In the case of the assembled boulders with secured gaps, comparing the bed profiles shown in Figure 5 with those in Figure 6, a local scouring might be formed by the greater unevenness of the assembled boulders.

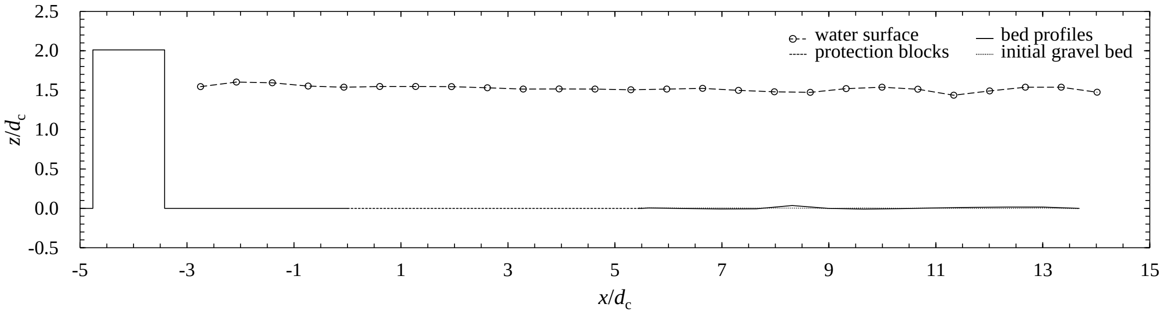


(a) $y/(B/2) = 0$

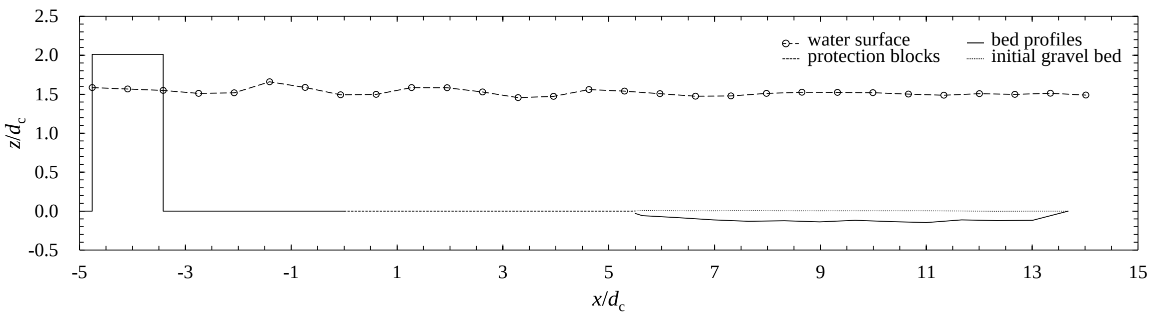


(b) $y/(B/2) = 0.75$

Figure 3. Water surface and bed profiles around low drop-structure

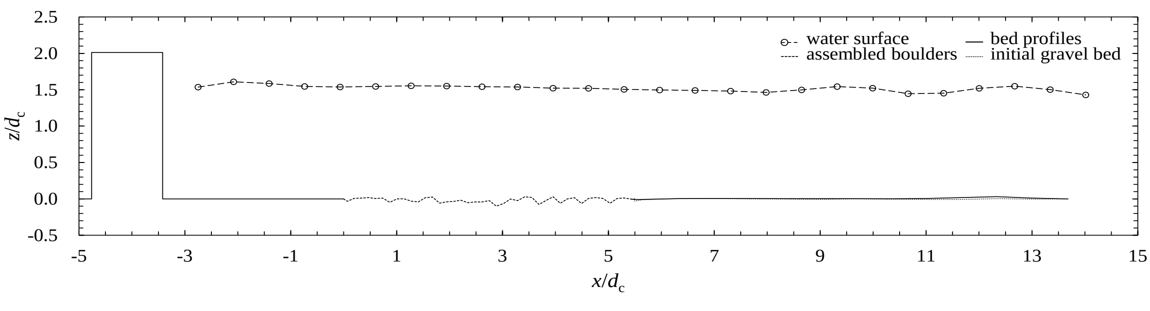


(a) $y/(B/2) = 0$, $L_s/d_c = 5.37$

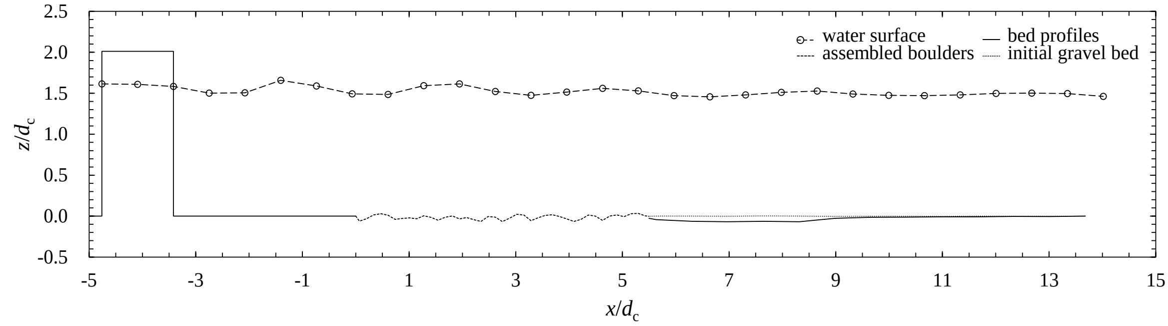


(b) $y/(B/2) = 0.75$, $L_s/d_c = 5.37$

Figure 4. Water surface and bed profiles around movable weir with installation of protection blocks



(a) $y/(B/2) = 0$, $L_s/d_c = 5.37$



(b) $y/(B/2)$ = 0.75, L_s/d_c = 5.37

Figure 5. Water surface and bed profiles around movable weir with installation of assembled boulders

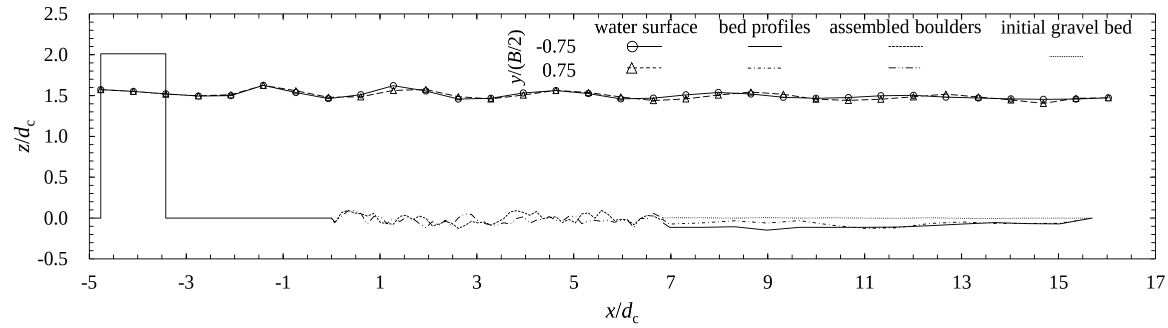


Figure 6. Comparison of water surface and bed profiles downstream of assembled boulders under filled and secured gaps

5. Velocity Fields of Main Flow and the Flow Near the Bottom

The velocity field was measured for longitudinal and lateral components. The velocity profiles at center of channel and near the side wall were analyzed for each vertical section, and the maximum velocity u_{max} was defined under a given transverse location.

In the case of low drop-structure, the longitudinal change of the maximum velocity is arranged under the following relation (1).

$$\frac{u_{max}}{V_c} = f\left(\frac{x}{d_c}, \frac{y}{B/2}, \frac{h_d}{d_c}, \frac{B}{d_c}, \frac{L_s}{\ell}\right) \quad (1)$$

Here, d_c is critical depth, h_d is downstream depth, V_c is critical velocity.

As shown in Figure 7 (a), the difference of the maximum velocity decay is small between $y/(B/2)$ = 0 and 0.75, and the change of the maximum velocity becomes smaller at the downstream of the protection region. Regarding the longitudinal change of the main flow, the relationship of z_{max}/d_c (2) can be organized as shown in Figure 7 (b), where z_{max} is the location of the maximum velocity. The water surface and bed profiles at $y/(B/2)$ = 0.75 are included.

$$\frac{z_{max}}{d_c} = f\left(\frac{x}{d_c}, \frac{y}{B/2}, \frac{h_d}{d_c}, \frac{B}{d_c}, \frac{L_s}{\ell}\right) \quad (2)$$

As shown in Figure 7 (b), the main flow rises toward the water surface at the downstream of the protection region. Accordingly, the installation of the consecutively assembled boulders might be effective as the protection region if the assembled boulders are installed within the jump region (≈6 times of subcritical sequent depth of jump).

The velocity near the bottom is arranged under the following relation (3). Figure 8 shows the longitudinal change of the time-average velocity u_b and the standard deviation u_b'.

$$\frac{u_b}{V_c}, \frac{u_b'}{V_c} = f\left(\frac{x}{d_c}, \frac{y}{B/2}, \frac{h_d}{d_c}, \frac{B}{d_c}, \frac{L_s}{\ell}\right) \tag{3}$$

As shown in Figure 8, the region of consecutively assembled boulders has acceleration and deceleration regions with the time-average velocity u_b, and the longitudinal change of u_b and u_b' is small at the downstream of the protection region. Also, the difference of the velocity near the bottom between $y/(B/2) = 0$ and 0.75 is small for both the time-average velocity and standard deviation. This might be caused by the reduction of three dimensionality due to the installation of the consecutively assembled boulders.

In the case of the movable weir with the installation of the protection blocks, the longitudinal change of the maximum velocity is arranged under the following relation (4).

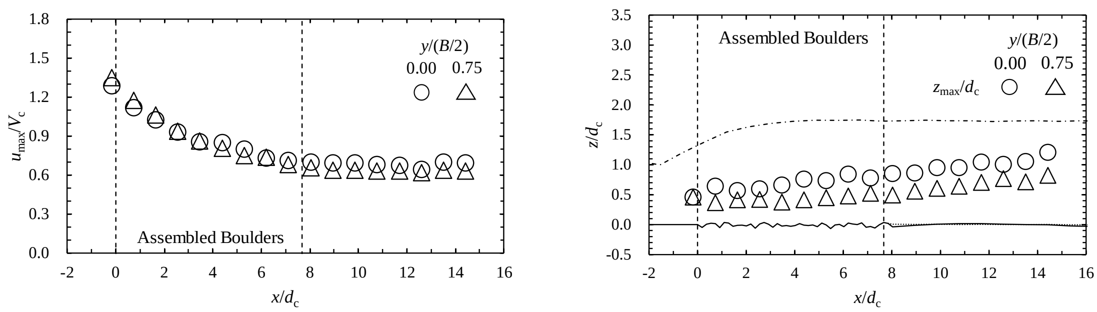
$$\frac{u_{max}}{V_c} = f\left(\frac{x}{d_c}, \frac{y}{B/2}, \frac{h_d}{d_c}, \frac{B}{d_c}, \frac{B_p}{B/2}, \frac{L_s}{\ell}, \frac{L_p}{\ell}\right) \tag{4}$$

Here, the symbols of B_p, L_s, and L_p are refers in Figure 2. The definition of the other symbols is similar to the case of low drop-structure.

As shown in Figure 9, the maximum velocity u_{max}/V_c for $y/(B/2) = 0.75$ is larger than that for $y/(B/2) = 0$ under given x/d_c, and the maximum velocity is accelerated in the protection region. The change of the maximum velocity is small at the downstream of the protection region. Regarding the longitudinal change of the main flow, the relationship of z_{max}/d_c (5) can be organized as shown in Figure 10, where z_{max} is the location of the maximum velocity.

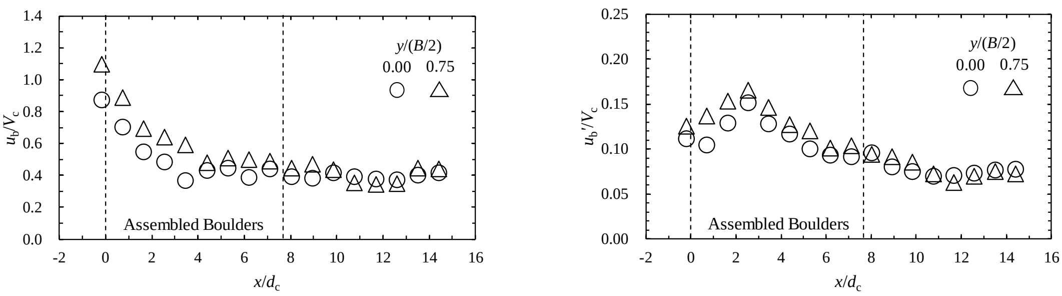
$$\frac{z_{max}}{d_c} = f\left(\frac{x}{d_c}, \frac{y}{B/2}, \frac{h_d}{d_c}, \frac{B}{d_c}, \frac{B_p}{B/2}, \frac{L_s}{\ell}, \frac{L_p}{\ell}\right) \tag{5}$$

The main flow at $y/(B/2) = 0$ rises toward the water surface gradually (Figure 10). While, the location of the main flow at $y/(B/2) = 0.75$ is almost constant.



(a) Maximum velocity decay (b) Position of main flow at each section

Figure 7. Maximum velocity decay and position of main flow for low drop-structure



(a) The time-average velocity (b) Standard deviation for longitudinal direction

Figure 8. Longitudinal change of flow velocity near the bottom

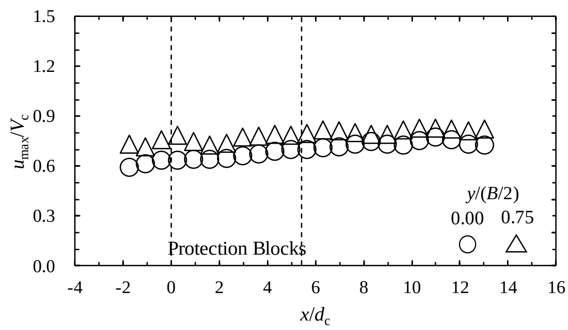


Figure 9. Longitudinal change of maximum velocity for installation of protection blocks

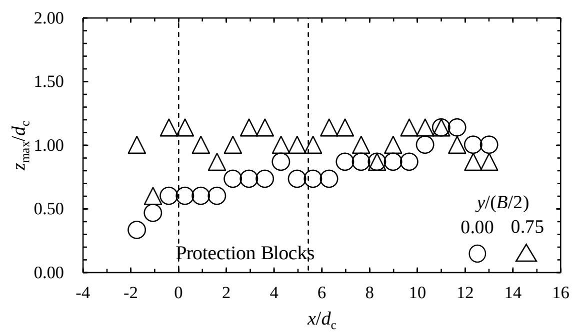


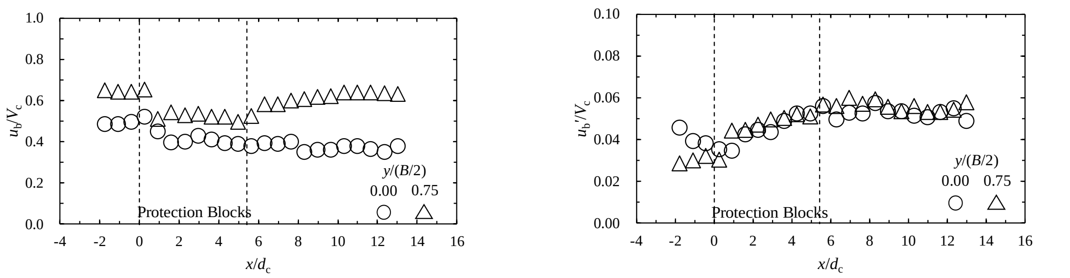
Figure 10. Longitudinal change of position of main flow for installation of protection blocks

The velocity near the bottom is arranged under the following relation (6). Figure 11 shows the longitudinal change of the time-average velocity u_b and the standard deviation $u_b{}'$.

$$\frac{u_b}{V_c}, \frac{u_b{}'}{V_c} = f\left(\frac{x}{d_c}, \frac{y}{B/2}, \frac{h_d}{d_c}, \frac{B}{d_c}, \frac{B_p}{B/2}, \frac{L_s}{\ell}, \frac{L_p}{\ell}\right) \tag{6}$$

The time-average velocity u_b at $y/(B/2) = 0.75$ is accelerated at the downstream of the protection blocks, and the longitudinal change of u_b at $y/(B/2) = 0$ is small (Figure 11). While, the standard deviation $u_b{}'$ is accelerated in the protection region, and the longitudinal variation of $u_b{}'$ is small at the downstream of the protection region. Also, the difference of the standard deviation near the bottom between $y/(B/2) = 0$ and 0.75 is small. The local scouring due to the installation of the protection blocks may be formed at the downstream of the protection region. Accordingly, the installation of the protection blocks may not be helpful for the protection of gravel bed.

In the case of the movable weir with the installation of the consecutively assembled boulders, as shown in Figure 12, the longitudinal change of the maximum velocity is similar to that for the installation of the protection blocks.



(a) The time-average velocity (b) Standard deviation for longitudinal direction

Figure 11. Longitudinal change of the time-average velocity and standard deviation near the bottom for installation of protection blocks

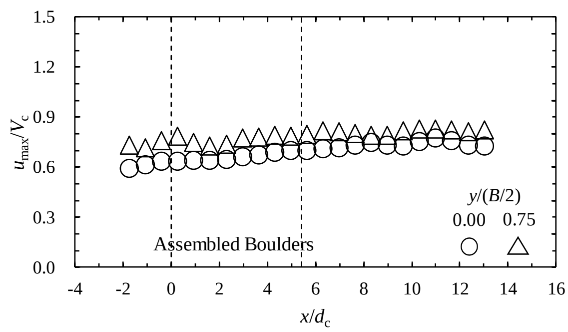


Figure 12. Longitudinal change of maximum velocity for installation of assembled boulders

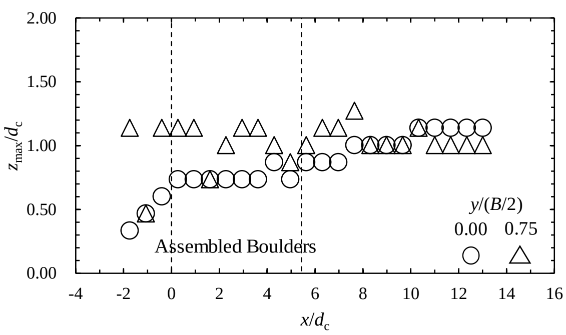
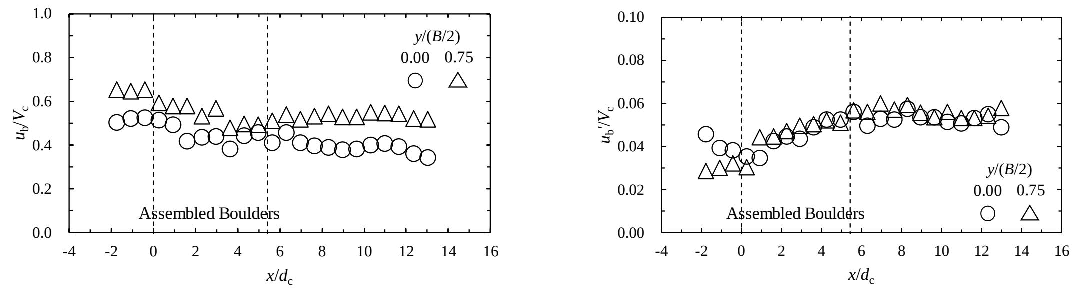


Figure 13. Longitudinal change of position of main flow for installation of assembled boulders

The location of the maximum velocity z_{max}/d_c is also similar to that for the protection blocks as shown in Figure 13. As shown in Figure 14 (a), the longitudinal change of the time-average velocity near the bottom differs from that for the protection blocks. The time-average velocity u_b decays within the protection region, and the longitudinal change of u_b is smaller at the downstream of the protection region. At the downstream end of the protection region, the value of u_{max}/V_c at $y/(B/2) = 0.75$ is smaller than that for the protection blocks. As shown in Figure 14 (b), the standard deviation u_b' is similar to that for the installation of the protection blocks. Accordingly, the flow passing through the consecutively assembled boulders will serve to control the time-average velocity near the bottom, and the installation of the assembled boulders may be helpful for the protection of gravel bed.

In the consecutively assembled boulders shown in Photo 2, as shown in Figures 15, 16 and 17, the longitudinal change of u_{max}/V_c, z_{max}/d_c, u_b'/V_c is independent of whether the gaps are filled or secured. The time-average velocity near the bottom u_b/V_c depends on the gaps as shown in Figure 17 (a). Accordingly, if the gaps are secured, the time-average velocity near the bottom can be reduced at the downstream end of the assembled boulders. The seepage effect on the reduction of time-average velocity near the bottom is not negligible, and the function of protection region against the serious local scouring can be kept during flood stages. Care should be taken in the consecutively assembled boulders to avoid increasing the uneven shape of the boulders, thereby minimizing their impact on the gravel bed downstream of the protected reach.



(a) The time-average velocity (b) Standard deviation for longitudinal direction

Figure 14. Longitudinal change of the time average velocity and standard deviation near the bottom for installation of consecutively assembled boulders

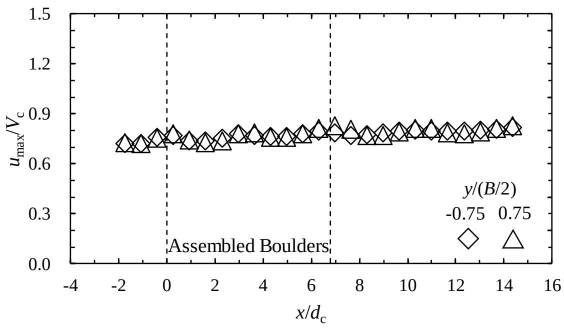


Figure 15. Longitudinal change of maximum velocity for installation of assembled boulders

y/(B/2) = 0.75: secured gaps, -0.75: filled gaps

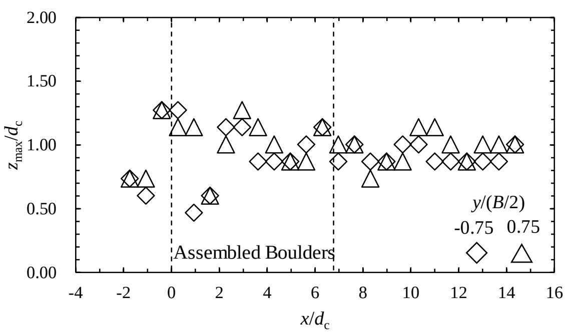
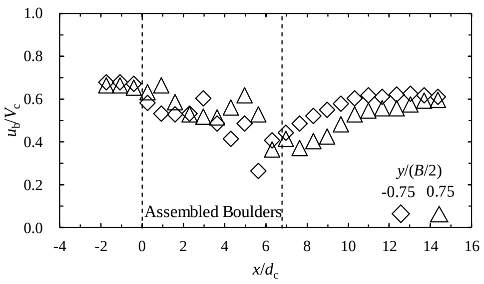
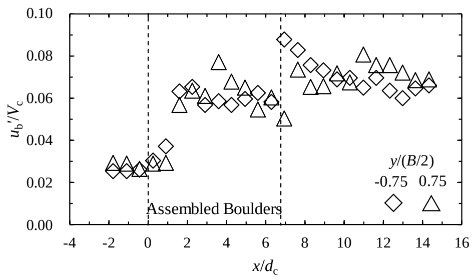


Figure 16. Longitudinal change of position of main flow for installation of assembled boulders

$y/(B/2)$ = 0.75: secured gaps, -0.75: filled gaps



(a) The time-average velocity



(b) Standard deviation for longitudinal direction

Figure 17. Longitudinal change of the time-average velocity and standard deviation near the bottom for installation of consecutively assembled boulders [$y/(B/2)$ = 0.75: secured gaps, $y/(B/2)$ = -0.75: filled gaps]

6. Conclusion

Experimental investigations were carried out on low drop-structure and movable weirs with protection region as a countermeasure against local scouring downstream of the protection region. In the case of the movable weir, a comparison was carried out with conventional protection blocks. The effect of gaps in the assembled boulders on the reduction of the velocity near the bottom was also investigated. The main results in this study are summarized as follows:

a) In the case of the low drop-structure, no scouring was observed at the downstream of the consecutively assembled boulders even if 30 hours have been passed from the start of the experiment. The results indicated that the installation of the assembled boulders in the jump length (≈6 times of subcritical sequent depth of jump) may be effective in preventing local scouring downstream of the protection region.

b) In the case of the movable weir, a deflected flow caused by the support pier makes the flow velocity near the bottom becomes faster. If protection blocks are installed in the protection region, the reduction of the time-average velocity near the bottom is small in this region, and a local scouring is formed at the downstream of the protection region. On the other hand, if the consecutively assembled boulders are installed, the flow velocity near the bottom can be reduced within the protection region, local scouring is minimized. The installation of the assembled boulders is effective for the prevention against local scouring downstream of the protection region. As the local scouring is formed in the region in which the stable undulation of the water surface is formed directly from the pier, the assembled boulders should be installed until the dissipation of the stable undulation from the support pier.

c) In the case of the assembled boulders with filled gaps, the depth of local scouring was greater than that for the assembled boulders with secured gaps, although it did not lead to serious scouring. The formation of the seepage flow through the secured gaps is important to reduce the time-average velocity near the bottom. Care should be taken in the consecutively assembled boulders to avoid increasing the uneven shape of the boulders, thereby minimizing their impact on the gravel bed downstream of the protected reach.

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