PROPOSAL OF SLOPING ENERGY DISSIPATOR WITH STACKED BOULDERS IN LOW DROP STRUCTURES

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ABSTRACT

For the jump formation just below low drop structures during flood stages, a main flow is located near the bottom, and it might be easy to form local scouring at the downstream of the apron with protection blocks. This might be caused by the curvature of streamline due to the impingement of main flow, and the maximum velocity with high turbulence near the bottom continues far downstream. The protection of river bed against the main flow with high turbulence is not secured by the jump formation. In this study, a sloping energy dissipator installed below low drop structure was proposed. The dissipator has gentle slope (i.e., 1/10 to 1/20 slopes) with stacked boulders. The function may help for both lifting a main flow and preventing local scouring. It is possible to form a surface jet flow without a plunging even if the tailwater level is lower. Also, the formation of the surface jet flow has a high turbulence in the main flow. The flow velocity at water side is lower than that at center part. The velocity measurement yields that the maximum velocity at each vertical section decays in a short distance. For different discharges, tailwater levels, relative drop heights, and inflow conditions, hydraulic conditions required to form a surface jet flow have been made clear. For the formation of surface jet flow, distribution of turbulent intensity at the end of the slope has been discussed from the view point of protection of riverbed.

Keywords: Energy dissipator, Stacked Boulders, Surface jet flow, Drop structure, Mainstream position

1. INTRODUCTION

In Japan, there is a guide line for hydraulic design of low drop structure (Japan River Association. 2008). The hydraulic jump is a phenomenon well known as useful method of energy dissipation (Hager. 1992 and Yasuda. 2017). In order to stable the toe position of jump below the drop structure, the formation of plunging flow might be effective for the change of tailwater level corresponding to discharge (Ohtsu and Yasuda. 1991). In addition, a main flow is located near the bottom for the formation of hydraulic jump below the low drop structure if the value of Froude number at the toe of the jump is smaller than 3 (Yasuda and Shinozaki. 2018). For the jump formation just below low drop structures during flood stages, it might be easy to form local scouring at the downstream of the apron with protection blocks. As an energy dissipation due to the jump formation, it might not be economical to keep the approaching supercritical flow and jump formation within concrete apron and protection block, even if the toe of the jump is not plunging. Recently, a sloping energy dissipator with stacked boulders below low drop structure was proposed by Yasuda and Masui (2019). The dissipator has gentle slope (i.e., 1/10 to 1/20 slopes). The hydraulic condition for the formation of surface jet flow was discussed, but velocity in the surface jet flow was not made clear. Also, as a small drop at downstream end of stacked boulders was remained to fix the stacked boulders, the surface jet flow was not formed if the tailwater level became lower. The plunging flow is formed as in the case of abrupt drop.

This paper presents hydraulics on the sloping apron with stacked boulders. The slope of the stacked boulders is settled as 1/10 slope. The downstream end of stacked boulder was connected to the downstream bottom smoothly without small drop. The method for the installation of stacked boulders has been discussed. The flow condition of surface jet flow has been explained for different inflow conditions and tailwater depths. The hydraulic condition required to form the surface jet flow has been shown experimentally. Also, the stabilization of river bed has been discussed from the comparison between abrupt low drop and sloping apron with stacked boulders. The velocity profiles including turbulent intensity and the maximum velocity decay at downstream of stacked boulders have been shown. The experimental results revealed that the installation of sloping apron with stacked boulders might be effective as the energy dissipator below low drops.

2. EXPERIMENTAL SETUP

Experiments were conducted in rectangular horizontal channel with 15 m long, 0.80 m wide, and 0.60 m height. In the channel, drop model with 0.796 m wide, 0.10 drop and 1.00 m long was installed. The water resistant boards with 0.0320 m and 0.0210 m thickness were used in order to adjust the difference level at the upstream and downstream of drop. Also, stacked boulders were installed in 0.89 m length for the sloping portion of 1/10 slope (Photo 1). The average size of stacked boulders is about 0.05 m. The small stones with about 0.010 m to 0.020 m were used for the stabilization of stacked boulders. The downstream end of stacked boulders was adjusted at abrupt rise to connect smoothly at the downstream of the bottom by installing boards with 0.796 m wide, 0.0320m height, and 1.00 m long. The velocity profile at each vertical section was recorded by using a two-dimensional electromagnetic current meter with I type probe (0.004 m diameter) of KENEK CO. LTD to measure both the streamwise x and the transverse y directions (sampling time 30 s, sampling frequency 20 Hz). The discharge was measured by using wide rectangular sharp edged weir located at downstream end of channel.

The experimental condition is shown in Table 1. Then, i *is* slope of stacked boulders defined as h_m/L(h_m= Height difference, L= horizontal installation length of stacked boulders). ε is the roughness height of stacked boulder. The inflow condition above the drop was settled by Froude number F_1 and relative drop height s/h_1. Here, h_1 is the inflow depth defined in the flow passing over the drop (located in 3.5 times of h_1 upstream from drop), s is the drop height, and F_1 is the inflow Froude number defined as $V_1/(gh_1)^{1/2}$; V_1 is average velocity. If the inflow Froude number is unity, a free over flow type was assumed. The relative drop height s/h_1 (=s/d_c; d_c is critical depth) was settled as 0.79. If the flow above the drop is supercritical (F_1 > 1.00), the relative drop height h_m/h_1 was settled as 1.32. The flow conditions were recorded by a digital camera.

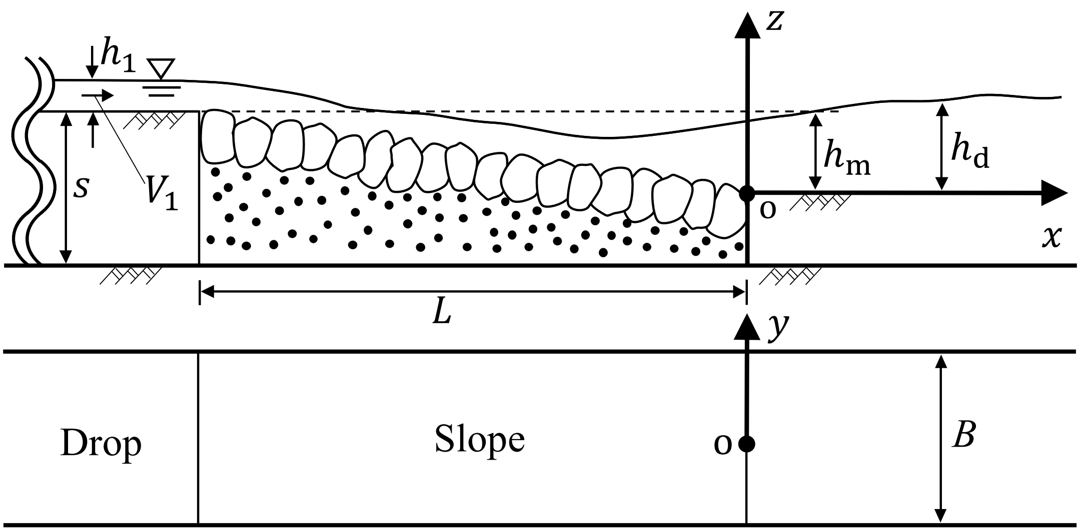


Figure 1. Definition sketch of sloping energy dissipator with stacked boulders below low drops

Photo 1. Installations of drop model, stacked boulders, and boards for abrupt rise in rectangular channel.

Table 1. Experimental conditions.

	h_m/h_1 (-)	ε/d_c (-)	F_1 (-)	i (-)	$R_e \times 10^4$ (-)
Stacked Boulders	**0.79**	**0.09~0.18**	**1.00**	**1/10**	**11.7~12.2**
	1.32	**0.09~0.18**	**2.16**	**1/10**	**11.7~12.2**

3. INSTALLATION OF SLOPING ENERGY DISSIPATOR WITH STACKED BOULDERS

The sloping apron with stacked boulders was proposed in order to prevent from degradation of river bed during flood stages as an energy dissipator (Yasuda and Masui. 2019). The lift of main flow into the water surface is significant for the prevention of river bed below drop structure. If the drop structure is consisted as an abrupt drop, there is the range of the tailwater level in which a plunging flow is formed (Ohtsu and Yasuda. 1991). By installing sloping apron with the stacked boulders below drop structure, the surface jet flow is formed easily even if the tailwater level is the same as that for the formation of plunging flow under given relative drop height s/h_1 and inflow Froude number F_1. In this case, the sloping apron should be settled as 1/10 or 1/20 slope (Yasuda and Masui. 2019). Also, the shape resistance due to stacked boulders is important for both the reduction of high velocity on the slope and the production of strong turbulence on the stacked boulders. The sloping apron with stacked boulders was proposed in order to prevent from degradation of river bed during flood stages as an energy dissipator (Yasuda and Masui. 2019). The lift of main flow into the water surface is significant for the prevention of river bed below drop structure. If the drop structure is consisted as an abrupt drop, there is the range of the tailwater level in which a plunging flow is formed (Ohtsu and Yasuda. 1991). By installing sloping apron with the stacked boulders below drop structure, the surface jet flow is formed easily even if the tailwater level is the same as that for the formation of plunging flow under given relative drop height h_m/h_1 and inflow Froude number F_1. In this case, the sloping apron should be settled as 1/10 or 1/20 slope (Yasuda and Masui. 2019). Also, the shape resistance due to stacked boulders is important for both the reduction of high velocity on the slope and the production of strong turbulence on the stacked boulders.

Photo 2. Stacked boulders (i = 1/10).

4. FLOW CONDITION ON PROPOSED ENERGY DISSIPATOR

The flow condition at the sloping apron with stacked boulders depends on inflow Froude number above the drop F_1, relative drop height h_m/h_1, slope of stacked boulders i, relative protruding height of stacked boulders ε/h_1, and relative downstream depth h_d/h_1 (Yasuda and Masui. 2019). Photos 3 and 4 show the flow pattern with the change of the tailwater level under given F_1, h_m/h_1, i, and ε/h_1.

4.1 Free over flow type

The toe of the surface jet flow moves upstream by raising tailwater level as shown in Photos 3. The main flow in the surface jet flow is located near the water surface, and a low velocity flow is formed near the bottom at downstream of the stacked boulders. A surface jet flow is formed below the stacked boulders, even if the transition from supercritical to subcritical flows is started from the downstream end of the stacked boulders. Because, the approaching Froude number can be reduced to less than 2.5 by the flow resistance on the stacked boulders and a fully developed inflow is formed.

4.2 Supercritical flow type

If the flow passing over the drop is supercritical ($F_1 > 1$) under the experimental condition shown in Table 1, the approaching velocity can not be reduced to less than 2.5. In this case, the jump with a surface roller is formed (Photo 4 (a)), because the relative length in the stacked boulders might be shorter for the reduction of high velocity at the downstream end of the stacked boulders. If the tailwater level is raising, a jump with surface roller is partly formed on the stacked boulders (Photo 4 (b)). Further, by increasing the tailwater level, at a certain stage, as shown in Photo 4 (c), a surface jet flow is formed. The change of the flow condition might be similar to that at an abrupt drop (Ohtsu and Yasuda. 1991).

a) $h_d/h_1 = 1.37$.

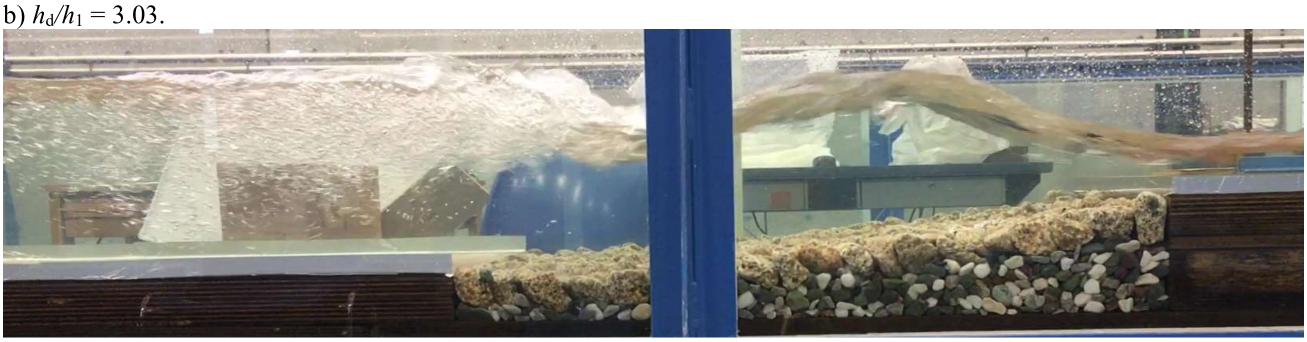
b) $h_d/h_1 = 1.70$.

c) $h_d/h_1 = 2.03$.

Photo 3. Flow condition of surface jet flow ($F_1 = 1$, $h_m/h_1 = 0.84$, $i = 1/10$, $\varepsilon/h_1 = 0.09 \sim 0.18$).

a) h_d/h_1 = 2.78.

b) h_d/h_1 = 3.03.



c) h_d/h_1 = 3.28.

Photo 4. Flow condition of surface jet flow (F_1 = 2.16, h_m/h_1 = 1.32, i = 1/10, ε/h_1 = 0.09 ~ 0.18).

5. HYDRAULIC CONDITION FOR FORMATION OF SURFACE JET FLOWS

In order to investigate the hydraulic condition for formation surface jet flows, the tailwater level h_d was determined from the inflow depth, and it was arranged by the following relation Eq. (1).

$$\frac{h_d}{h_1} = f\left(\frac{x}{h_1}, F_1, i, \frac{h_m}{h_1}, \frac{\varepsilon}{h_1}\right) \quad (1)$$

The hydraulic condition required to form plunging condition at an abrupt drop has been clarified by Ohtsu and Yasuda (1991), For F_1 = 1.0 and h_m/h_1 = 0.79, the plunging flow formed below abrupt drop can be changed into the surface jet flow by installing the stacked boulders with i (=h_m/L) = 1/10 and ε/h_1 = 0.09 ~ 0.18. While, for F_1 = 2.16 and h_m/h_1 = 1.32, the flow condition on the stacked boulders with i (=h_m/L) = 1/10 and ε/h_1 =0.09 ~ 0.18 includes the jump formation with surface roller, and the plunging flow is formed at a certain condition (Photo 4). In this case, the slope on the stacked boulders must be milder than 1/10 (e.g., 1/15, 1/20).

6. MAXIMUM VELOCITY DECAYS SURFACE JET FLOWS

In order to investigate the maximum velocity decay below the stacked boulders, the maximum velocity U_{max} was determined from the profile of the mean velocity at each vertical section, and the velocity was arranged by the following relation Eq. (2).

$$\frac{U_{max}}{V_1} = f\left(\frac{x}{h_1}, F_1, i, \frac{h_m}{h_1}, \frac{h_d}{h_1}, \frac{\varepsilon}{h_1}\right) \quad (2)$$

Figure 2 shows the maximum velocity decay of the surface jet flow. For the case of free over flow type, as the flow passing over the drop transits from critical to supercritical flows, and the velocity on the slope is accelerated. As shown in this figure, the maximum mean velocity decays slightly in the range of 0 < x/h_1 < 15.0. Also, the change of U_{max}/V_1 depends on the relative downstream depth h_d/h_1. If the relative downstream depth becomes larger, the transition zone moves upstream, and the maximum velocity is smaller than the critical flow velocity for h_d/h_1 = 2.03.

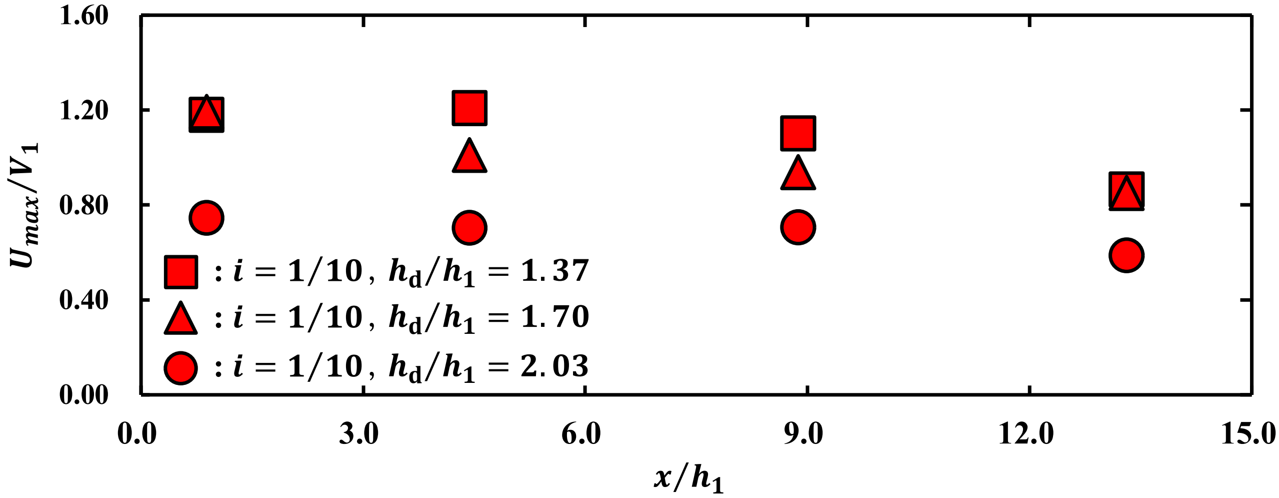
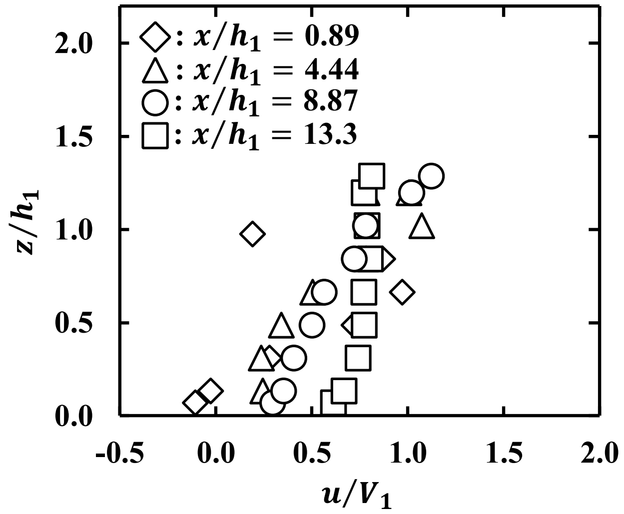
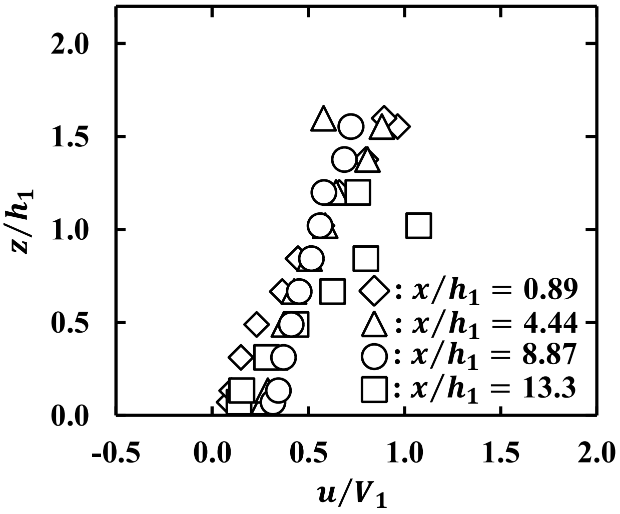


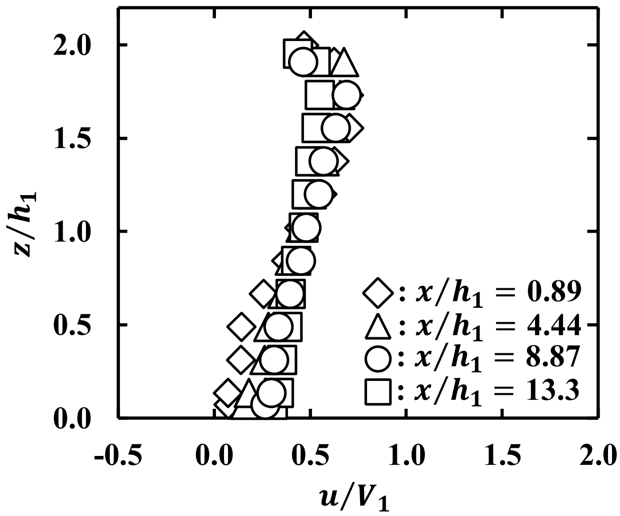
Figure 2. Maximum velocity decay in surface jet flows for $F_1 = 1.00$, $h_m/h_1 = 0.79$, and $\varepsilon/h_1 = 0.09 \sim 0.18$.



a) $h_d/h_1 = 1.37$



b) $h_d/h_1 = 1.70$



c) $h_d/h_1 = 2.03$

Figure 3. Velocity profiles below stacked boulders for $F_1 = 1.00$, $h_m/h_1 = 0.79$, $i = 1/15$, and $\varepsilon/h_1 = 0.09 \sim 0.18$.

7. MEAN VELOCITY PROFILES IN SURFACE JET FLOWS

The mean velocity below stacked boulders was measured, and the velocity profile at each vertical section was arranged by equation (3).

$$\frac{u}{V_1} = f\left(\frac{x}{h_1}, \frac{z}{h_1}, F_1, i, \frac{h_m}{h_1}, \frac{h_d}{h_1}, \frac{\varepsilon}{h_1}\right) \tag{3}$$

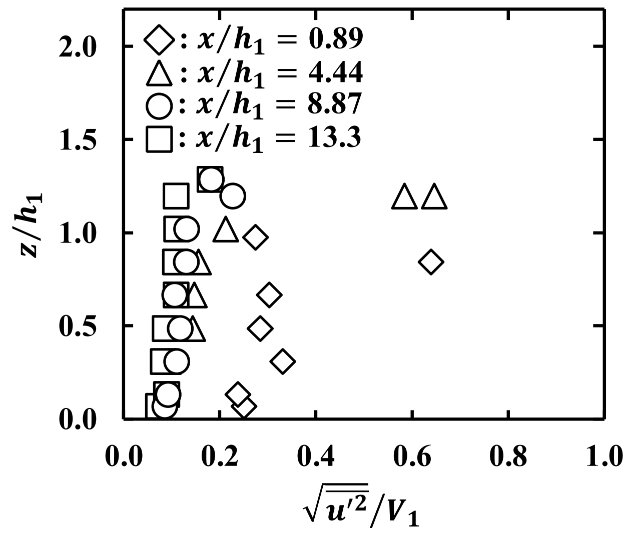
Figure 3 shows the velocity profiles at downstream of the stacked boulders for $F_1 = 1.00$, $h_m/h_1 = 0.79$, and $\varepsilon/h_1 = 0.09 \sim 0.18$. For the formation of the surface jet flow, as shown in Figure 4, it has been confirmed that the main flow lifts into the water surface. Also, the velocity near the bottom is smaller than that near the water surface for the formation of the surface jet flow. For $h_d/h_1 = 1.37$, the bed velocity is accelerated, but the velocity profile transits to that for a gradually varied flow at $x/h_1 = 13.3$.

8. TURBULENT INTENSITY PROFILES IN SURFACE JET FLOWS

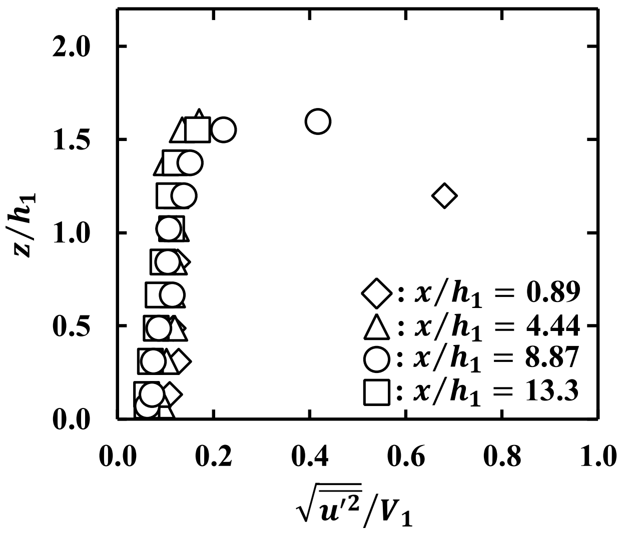
The turbulent intensity below stacked boulders was measured at each vertical section, and the velocity profile was arranged by the following relation Eq. (4).

$$\frac{\sqrt{\overline{u'^2}}}{V_1} = f\left(\frac{x}{h_1}, \frac{z}{h_1}, F_1, i, \frac{h_m}{h_1}, \frac{h_d}{h_1}, \frac{\varepsilon}{h_1}\right) \tag{4}$$

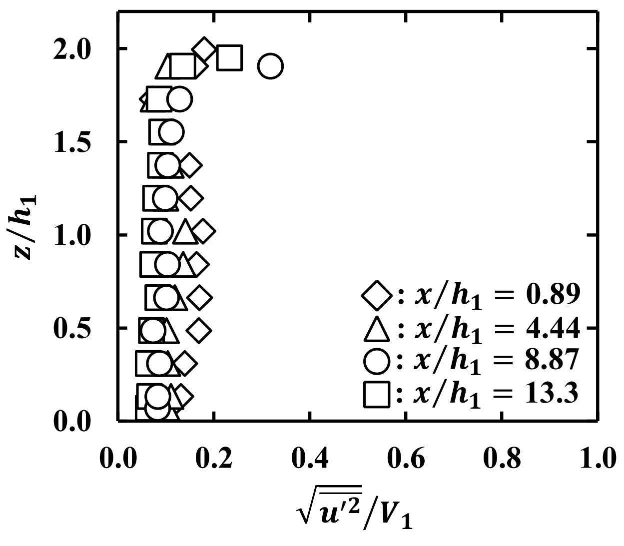
Figure 4 shows the turbulent intensity profiles at downstream of the stacked boulders for $F_1 = 1.00$, $h_m/h_1 = 0.79$, and $\varepsilon/h_1 = 0.09 \sim 0.18$. For the formation of the surface jet flow, as the main flow lifts into the water surface, the turbulent intensity near the bottom can be reduced by comparing with the jump formation. For $h_d/h_1 = 1.37$, the turbulent intensity near the bottom at $x/h_1 = 0.89$ is larger than that at other section ($x/h_1 > 4$), and the bed protection at the immediately downstream of the stacked boulders might be required. Accordingly, the bed velocity of the flow passing over the stacked boulders can be reduced from the velocity profiles shown in Figures 3 and 4 at $h_d/h_1 = 1.37$, 1.70, and 2.03.



a) $h_d/h_1 = 1.37$



b) $h_d/h_1 = 1.70$



c) $h_d/h_1 = 2.03$

Figure 4. Turbulent intensity profiles below stacked boulders for $F_1 = 1.00$, $h_m/h_1 = 0.79$, $i = 1/15$, and $\varepsilon/h_1 = 0.09 \sim 0.18$.

9. CONCLUSIONS

The installation of the sloping apron with stacked boulders below low drop structure is effective for the protection of river bed during flood stages. For free over flow type, the upstream and downstream migrations for the aquatic animal is possible during normal stages. The method for the installation of stacked boulders is the most important for the stability during flood stages. The flow condition of surface jet flow depends on inflow Froude number F_1, slope of stacked boulders i, relative drop height s/h_1, relative roughness hight ε/h_1, and relative tailwater depth h_d/h_1. For $F_1 = 1.00$ and $i = 1/10$, the water surface profiles for both upper and lower limits of tailwater level in surface jet flow are shown. For $F_1 = 1.0$ and $s/h_1 = 0.79$, the surface jet flow is always formed by installing the stacked boulders with i (= h_m/L) = 1/10 and $\varepsilon/h_1 = 0.09 \sim 0.18$. While, for $F_1 = 2.16$ and $s/h_1 = 1.32$, the plunging flow is formed as in the case of abrupt drop, and the slope on the stacked boulders must be milder than 1/10 (e.g., 1/15, 1/20) in order to form the surface jet flow on the stacked boulders. Also, the slope on the stacked boulders must be milder as 1/15, 1/20. For $F_1 = 1.00$ and $s/h_1 = 0.79$, the maximum velocity decays within the range of $0.00 < x/h_1 < 15.0$. The velocity profiles at downstream of stacked boulders yield that the velocity near bottom is always smaller than that near the water surface in the surface jet flow, and that the river bed at the downstream of the drop might be protected by installing the stacked boulders with mild slope (at least, milder than 1/10).

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