Effect of opening depth of oblique weir with an opening on river bed morphology

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Abstract. In this study, we focused on the fact that an oblique weir with an opening activates the fluidity of the sediment compared with a conventional continuous fixed one and examined the removal function of the sediment deposited upstream of the weir. Experimental results showed that the weir with the opening increased the fluidity of the sediment deposited upstream of the weir and lowered the riverbed. The scouring section upstream of the weir was divided into a gradually varied flow section and a local flow section based on the bed topography. In the gradual flow section, the descent of water level and riverbed increases linearly as the opening depth increases. In addition, it was shown that the local scour shapes upstream and downstream of the weir were similar to each other as a result of normalization on the representative scale of vertical and transverse shapes. By creating the opening of the oblique weir, the magnitude of the downward flow generated near the left bank was reduced from 45% to 34% of the non-open weir.

1. Introduction
Cross-river structures such as dams and weirs have been installed for diversion to main rivers and tributaries, irrigation, water intake such as hydroelectric power generation, water depth maintenance, and salt damage prevention.

However, around these structures have been pointed out geo-environment degradation due to a discontinuity of sediment transport. For example, the flow velocity decreases upstream of the river crossing structure due to backwater. Moreover, river-bed levels rise because sediment transport is interrupted by these structures. On the downstream side of the fixed weir, physical and biological environments disappear and tend to suppress natural disturbance. The riverbed on the downstream side is eroded because the supply of sediment from upstream of the fixed weir is interrupted by the weir.

In order to solve these problems, the authors [1], [2] proposed to create an opening in the weir. The following effects can be expected by providing an opening and approaching a natural river.

1) The dredging cost can be reduced by flowing sediment accumulated in the upstream area of the weir for many years at the time of flooding.
2) Reduction of sediment accumulation on the upstream side leads to a decrease in water level at the time of flooding, and improvement of flood control safety can be expected.
3) Due to sediment transport from upstream, improvement of environmental functions can be expected on the downstream side due to recovery of physical and biological environment and increase of natural disturbance.
On the other hand, it is necessary to study the effect of weirs with openings on riverbed variation and flow. However, few studies have examined the effects of weirs with openings on riverbed changes in previous studies. Zhang et al. [3] conducted a series of experiments using a flume bedded with various materials having different grain sizes and specific gravities and various weirs with an opening and investigated scour characteristics of the channel bed upstream of a submerged weir and local flows over the weir. Sumida et al. [4] performed experiments using a flume having a relatively large width-to-height ratio and investigated the effects of weir opening geometry and size on the channel bed processes upstream of the weir resulting from scouring.

By the way, weirs are generally installed orthogonal to the river channel, but some weirs are installed obliquely to the river channel. Oblique weirs have some advantages as follows [5].

1) In the upstream of the weir, the oblique weir has a lower water level than the orthogonal weir.
2) In the normal stage of water, oblique weir can smoothly withdraw water.
3) If an oblique weir is suitably made, it is possible to prevent side banks during floods.

However, if the oblique weir is not installed properly, it may promote side bank erosion downstream of the weir. As shown in Figure 1, there is also an oblique weir in the Shirakawa River that flows through Kumamoto Prefecture. There are concerns about the rise of the riverbed upstream of the weir and local scouring along the downstream riverbank.

There are several previous studies on oblique weirs. The prediction of the overflow of oblique weirs has also been investigated, Nguyen [6] and Kabiri-Samani [7] have investigated the effects of the geometrical characteristics of the weir and the overflow morphology on the flow coefficient. However, the effect of oblique weirs to riverbed morphology and river flow discharge have not been studied. On the other hand, in the examination of the flow around the oblique weir, Otoshi et al [8] conducted a hydraulic model experiment on the technical grounds related to the linear determination of the "Miyagawa river" in the Matsuda River flowing through Kochi Prefecture. Fukuoka et al. [9] focused on the relationship between the position of the oblique weir and channel shape, examined the effect of the oblique weir on water level and riverbed deformation.

However, no specific solution to the weir problems has been discussed in previous studies. The author [10] investigated the influence of oblique fixed weir with openings on flow and bed fluctuation to improve the flood control and environmental problems of the oblique weir.

As a subsequent study, in this study, this paper is to investigate effect of the opening depth of the oblique weir to on riverbed morphology at the downstream of the weir and sedimentation at the upstream of the weir.
2. Experimental setup

As shown in Figure 2 the experiments were conducted with a 10-m-long, 40-cm-wide, 20-cm-deep variable-slope circulating acrylic flume. The weir shown in Figure 3 is installed at a position 6 m downstream from the upstream end (weir angle $\theta = 30^\circ$), and the average particle size $d_{50} = 0.77$ mm in the section from the weir to 6 m upstream and 4 m downstream. The initial bed thickness upstream of the weir was 17 cm, which is the same height as the weir height. And the initial bed thickness downstream of the weir was 6 cm lower than the upstream initial bed thickness, 11 cm thick.

The depth of the opening (opening depth) of the weir model was set to $D$, and experiments were conducted in 7 cases by systematically changing the depth in the range of 0 cm to 6 cm at 1 cm intervals.

Figure 2. Experimental flume.

Figure 3. Weir shape and size.

Table 1 shows the initial conditions of the experiment. These hydraulic quantities show the values at the position 3 m upstream and 2 m downstream of the weir, respectively. Due to evaluate how much the sediment deposition upstream of the weir is improved, the flow discharge was set that the nondimensional tractive force $\tau_c$ calculated by assuming the law of the wall at 3 m upstream of the weir under the initial conditions was about 3 times the critical nondimensional tractive force $\tau_{c\infty}$ calculated from the mean grain size.

The water level and the bed elevation were measured with a point gauge and an ultrasonic sensor, respectively. The initial water depth downstream of the weir was set to 6.5 cm by manipulating the weir at the downstream end of the experimental channel so that it was below the nondimensional tractive force. The water level and riverbed shape were measured after confirming the equilibrium state of the riverbed. The time to reach equilibrium is 48 hours at an opening depth of $D = 0$ to 1 cm, 72 hours at $D = 2$ to 4 cm, and 96 hours at $D = 5$ to 6 cm, respectively. In order to secure the run-up section, sand was supplied to maintain the continuity of the riverbed surface of the target section in the range of 5 m to 6 m upstream from the weir.

Table 1. Hydraulic Condition.

| Discharge: $Q$(l/s) | 5.4 |
|---------------------|-----|
| Bed slope: $I$     | 1/300 |
| Critical depth(cm) | 2.69 |
| Grain size: $d_{50}$ (cm) | 0.077 |
| Friction velocity: $u_v$(cm/s) | 2.06 |

| Flow depth (cm) | Upstream ($x = -300$cm) | Downstream ($x = 300$cm) |
|----------------|-------------------------|--------------------------|
| Mean velocity (cm) | 47.7 | 21.3 |
| $\tau_c/\tau_{c\infty}$ | 3.0 | 0.45 |
| Froude Number | 0.9 | 0.27 |
In the local flow section, Figure 4 shows the illustration of parameters that were measured to describe the local scour hole in the longitudinal and transversal section. The maximum scouring depths upstream and downstream are $d_{su}$ and $d_{sd}$, respectively. The scouring length in the flow axis direction and the scouring length in the transverse direction downstream of the weir were set to $l_{xd}$ and $l_{yd}$, respectively.

The right-hand coordinate system has its origin at the center of the bottom of the flume, where the opening is located, and the $x$-axis, $y$-axis, and $z$-axis representing the longitudinal direction, the transverse direction, and the vertical direction, respectively. The instantaneous flow velocity components, time average components, and fluctuation components are represented by $u$, $v$, and $w$; $U$, $V$, and $W$; and $u'$, $v'$ and $w'$, respectively. The magnitude of flow velocity $|u|$ was defined by the following equation:

$$|u| = \sqrt{U^2 + V^2} \quad (1)$$

where $|u|$ = magnitude of flow velocity; $U$ = longitudinal velocity component; $V$ = transversal velocity component.

![Figure 4. Parameter at local scour hole downstream of the weir.](image)

To investigate the flow structure, point measurement, and multi-point simultaneous measurement of water surface profile and flow velocity were conducted in Case D=0cm and D=6cm shown in Table 1. The surface flow measurement was made by the PIV (particle image velocimetry) method using a video camera system capable of multi-point simultaneous measurement of flow velocity. The point measurement of flow velocity was made with I type and L type two-component electromagnetic current meters. In the flow velocity measurement by the PIV method, the surface flow was shot with the camera positioned directly over the flume. The flow velocity measurement duration was 20 seconds, and nylon particles having a diameter of 100 $\mu$m and a specific gravity of 1.02 were used as tracers. Image data were recorded on the hard disk as 59.94-fps (frame per second) 1920 $\times$ 1080-pixel monochrome video image data and processed by the PIV method. Following analogue-to-digital conversion, output signals (100 Hz) from the electromagnetic current meters were statistically processed so that 4,096 data sets were used for each measurement point.

3. Experimental results

Figure 5 shows the longitudinal in riverbed and water level. It can be seen that the longitudinal bed level rapidly changed in the range of $x = -30$ to 200 cm around the weir, but it was relatively gradual in the range of $x = -300$ to -30 cm. Therefore, the range of the gradually varied flow section and the local flow section was set to $x = -300$ to -30 cm and $x = -30$ to 200 cm, respectively. The average riverbed height upstream of the weir decreases as the opening depth $D$ increases in both the gradual change section and the local flow section.
The average riverbed height of the non-open weir \( D = 0 \) m at \( x = 0 \) to 120 cm in the local flow section is significantly lower than that of the open weir \( D = 1 \) to 6 cm. In the range of opening weir \( D = 1 \) to 6 cm, the average bed height decreases as the opening depth increases. In the upstream of the weir, the amount of decrease in the water level increases as the opening depth \( D \) increases, but downstream of the weir, the change in the water level due to the difference in the opening depth \( D \) is not significantly.

3.1. Gradually varied flow section

Figure 6 shows the relationship between the riverbed degradation and the depth of the opening. Figure 6 (a) shows the effect of the weir opening depth \( D \) on the amount of riverbed degradation averaged in the gradual flow section. In the figure, the average riverbed reduction of the orthogonal weir is shown by the black line. As can be seen from the figure, the average riverbed reduction amount \( \Delta z_D \) of the oblique weir increases linearly as the opening depth \( D \) increases.

In the case where the weir opening depth \( D \) is 60 mm and equal to the riverbed height difference, the amount of decrease from the initial riverbed is 30.3 mm, which corresponds to about 51% of the riverbed height difference. Compared with the orthogonal weir, the average bed height of the oblique weir is...
about 2 mm, which is about 10% larger than that of the orthogonal weir. It is considered that the critical water depth at the top of the weir is smaller in the oblique weir than in the orthogonal one.

Figure 6 (b) shows the effect of the weir opening depth $D$ on the relative water level degradation and the relative riverbed degradation. The opening depth $D$ is nondimensionalized by the initial riverbed height difference $\Delta Z = 60$ mm. As can be seen that both the relative water level degradation and the relative riverbed degradation at the oblique weir increase linearly as the opening depth $D / \Delta Z$ increases. The relative riverbed degradation in the oblique weir is larger than the relative water level degradation, and the difference tends to increase slightly as the opening depth $D / \Delta Z$ increases. This shows the same tendency as the result with the orthogonal weir. In the case where the weir opening depth $D$ is 60 mm and equal to the riverbed height difference, the relative riverbed reduction amount corresponds to 23% of the riverbed height difference, which is about 15% larger than the relative water level reduction amount. Compared to the orthogonal weir, in the case where the weir opening depth $D$ is 60 mm and equal to the riverbed height difference, the relative riverbed reduction is about 14% larger at about 1.7 mm and the relative riverbed reduction is about 12% smaller at about 1.2 mm. From these results, the oblique weir has a higher sand removal function than the orthogonal weir.

3.2. Local flow section

Figure 7 shows the contour of the riverbed in the upstream and downstream of the weir. The contour value is the amount of change from the initial riverbed in mm. In all cases, local scour holes are found around the weir. Significant local scour upstream of both weir sleeve parts occurs except for the non-opening weir $D = 0$ cm.

The depth and area of the scour hole upstream of the weir are larger on the left bank side than on the right bank side, and asymmetry is observed. Also, the depth and area of the scour upstream of the weir increase as the opening depth $D$ increases. It is considered that the sediment upstream is rolled up and transported downstream through the opening.

In addition, as the depth $D$ of the opening increases, the amount of riverbed reduction increases in the gradual flow section, and the height from the riverbed to the weir top increases. As a result, vortices similar to horseshoe-shaped vortices increase the spatial scale and strength. It is guessed that the depth and area of the scour of the scour hole were increased.

On the other hand, a scour hole is observed near the left wall downstream of the oblique weir, and sedimentation is observed near the right wall. The depth and surface spread of the scour hole are the largest at the non-opening weir $D = 0$ cm. The maximum scouring depth decreases as the opening depth $D$ increases in the range of $D = 1 \text{ to } 3$ cm and becomes the smallest when $D = 3$ cm. In the range of $D = 3 \text{ to } 6$ cm, the maximum scouring depth tends to increase as the opening depth $D$ increases.

Downstream of the oblique non-opening weir, as it flows down to the side bank as shown in Figure 7, it converges along the left bank, a concentrated flow occurs, and a vortex with an extraordinarily strong downward flow is formed near the left bank. On the other hand, it is considered that the flow velocity and flow velocity passing through the opening increased in the range of $D = 1 \text{ to } 3$ cm by providing the opening, and as a result, the flow velocity concentrated on the side bank decreased.

However, in the range of $D = 3 \text{ to } 6$ cm, the depth of the opening is large, and it is relatively close to the riverbed downstream of the weir, suggesting that local scouring may have increased. Sediment deposits downstream of the oblique weir occur near the right bank, and the sediment thickness is almost the same as the riverbed height difference in all experimental cases.
Figure 7. The contour of the riverbed at the upstream and downstream of the weir.

Figure 8 shows the longitudinal and cross-sectional shapes of the riverbed at the maximum scour depth downstream of the weir, respectively. In the vertical cross-sectional shape in Figure 8 (a), the scouring depth and the longitudinal direction $x$ were nondimensionalized by maximum scour depth $d_{sd}$ and scour length $l_{sd}$ downstream of the weir, respectively.

The cross-sectional shape in Figure 8 (b) was nondimensionalized by the parameter shown in Figure 4. The longitudinal shape of the riverbed at the maximum scouring depth downstream of the weir is similar to that of the oblique opening weir $D = 1$ to $6$ cm. The maximum scour depth position occurs near $x / l_{sd} = 0.2$ to $0.35$. Scour hole occurs in a wider area in the flow axis direction in the oblique non-opening weir than in the opening weir.
If described with paying attention to the range of $0 < \frac{y}{l_{yd}} < 1.0$, which corresponds to the scouring hole near the left bank, the scouring longitudinal shape of the downstream of the weir is found to be almost similar in all experimental cases.

From Figure 9, the maximum scouring depth $d_{sa}/\Delta Z$ upstream of the weir shows an increasing tendency as the opening depth $D$ increases. The maximum scour depth is the maximum at the opening depth $D = 6$ cm in this experiment, and its size is about 2.3 of the riverbed height difference. The maximum sedimentary thickness downstream of the weir is $d_{sd}/\Delta Z$. It can be seen that sediment deposition downstream of the diagonal weir occurs near the right bank, and the sedimentary thickness is almost the same as the riverbed height difference in all experimental cases.

**Figure 8.** The similarity of local scour hole downstream.

**Figure 9.** The characteristics of bed deformation and opening depth.
On the other hand, the maximum scouring depth $d_{sd}/\Delta Z$ downstream of the weir decreases as the opening depth $D$ increases in the range of $D = 1$ to $3 \text{ cm}$ and becomes the smallest when $D = 3 \text{ cm}$. In the range of $D = 3$ to $6 \text{ cm}$, the maximum scouring depth tends to increase as the opening depth $D$ increases. The maximum scouring depth $d_{sd}/\Delta Z$ is the largest when the non-opening weir $D = 0 \text{ cm}$, and the maximum scouring depth is about twice as large as the riverbed height difference of $60 \text{ mm}$. On the other hand, in the range of $D = 1$ to $3 \text{ cm}$, the maximum scour depth decreases as the opening depth $D$ increases. The case of $D = 3 \text{ cm}$ shows a minimum value, which is $25\%$ compared to the non-opening weir $D = 0 \text{ cm}$.

3.3. Local flow on the downstream of the weir opening

Figure 10 shows the contour of the horizontal plane of the magnitude of flow velocity $|u|$. The synthetic vector of the main velocity $U$ and the transverse component $V$ of the secondary flow is shown in this figure. By overflowing the weir, it is accelerated at the top of the weir, and a high-velocity region is formed. On the downstream side of the weir, the high-speed region where the average cross-sectional flow velocity in the equilibrium state is greater than $|u| > 35 \text{ cm/s}$ converges along the left bank is observed. On the right bank side downstream of the weir, it can be seen that a backflow area is formed by the vortex separated from the flow concentrated on the left bank side. When $x > 100 \text{ cm}$, it becomes an acceleration region again as the riverbed rises. The flow velocity is relatively small on the right bank side directly downstream of the weir and in the range of $x = 30 \text{ cm}$ to $100 \text{ cm}$ and $y = -14 \text{ cm}$ to $0 \text{ cm}$.

![Figure 10. The contour of the horizontal plane of the magnitude of flow velocity $|u|$.](image)

Figure 11 shows the vertical plane contour of the magnitude of flow velocity $|u|$ where maximum scour depth occurred. In the figure, the synthetic vector of the transverse component $V$ and the vertical component $W$ of the secondary flow is shown. A significant vortex is formed in the range of $y = -18 \text{ cm}$ to $0 \text{ cm}$. The magnitude of the downflow near the left wall is about $45\%$ of the average cross-sectional flow velocity of $35 \text{ cm/s}$, and a strong downflow is generated.

![Figure 11. The vertical plane contour of the magnitude of flow velocity $|u|$.](image)

A remarkable vortex is formed in the range of $y = -18 \text{ cm}$ to $-6 \text{ cm}$ near the left bank. The magnitude of the downward flow near the left bank is about $34\%$ of the average cross-sectional flow...
velocity of 31 cm / s, indicating that the downward flow near the left bank is smaller than that of the non-opening weir. It is considered that as the high-speed region formed in the center of the channel flowed down due to the influence of the opening, the high-speed region was formed over a wide area on the left bank side due to the concentration on the left wall.

4. Conclusions
In this study, the sedimentation function of sediments upstream of the opening depth of the oblique weir and the riverbed fluctuations downstream of the weir were investigated. The main results obtained are as follows.

1) Both the relative water level degradation and the relative bed degradation at the diagonal weir increase linearly as the opening depth increases. Compared with the orthogonal weir, the relative riverbed reduction is about 14% larger in the case where the weir opening depth D is 60 mm and the riverbed height difference is equal. From this, from the viewpoint of the sand removal function upstream of the weir, the diagonal weir has a higher sand removal function than the right-angled weir.

2) The local scour shapes upstream and downstream of the diagonal weir were dimensionless on the representative scales of the longitudinal shape and the transverse shape, and as a result, similar figures were found.

3) The maximum scouring depth is the largest in non-opening weirs, and in particular, the maximum scouring depth is approximately twice as large as the riverbed height difference of 60 mm. On the other hand, it can be seen that the maximum scour depth has a minimum value when D = 3 cm and is reduced by 25% compared to the non-opening weir D = 0 cm.

4) For both the diagonal non-opening weir and the open weir, it was confirmed that there is a strong positional relationship between the maximum value of the vertical component W of the secondary flow and the sandbar.

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