Weir removal and its influence on hydro-morphological features of upstream channel

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This paper presents an experimental study on the upstream channel responses due to partial removal of a weir, focusing on the impacts of the removal shape of the weir on the hydro-morphological features. It is found that the shape of the removal significantly affects the 3D flow structure and the local scour around the weir and poses influences on the propagation process of upstream sandbars. However, the characteristics of the sandbar system at the quasi-equilibrium stage are governed by the removal area rather than the removal shape. Governing parameters characterizing the removal shape is proposed as well. Desirable morphological features could be achieved by a careful selection of those parameters.

Key Words: Dam/weir removal, channel response, sand bar, local scour, 3D flow

1. Introduction

The aging of in-stream barriers such as dams and weirs, coupled with increasing awareness of their environmental costs, has brought dam/weir removal to the attention of scientific communities, management agencies and the general public. In particular, dams/weirs are criticized to disrupt the longitudinal continuity of a river system and are identified as a significant pressure to the aquatic habitat, resulting in severe environmental degradations. In addition, the removal of dams/weirs is driven in part by political agreements, for example, the European Union’s Water Framework Directive, which supports and even pushes the movement of environmental and ecological restorations such as the modification of in-stream barriers in water courses.

There are several alternatives during the modification of an in-stream barrier, for example, a full removal, a partial removal, a gradual removal, relocation of the structure or construction of appendage structures. It is noted that very little documentation related to barrier modifications, is available to the public around the world. Moreover, scientific research up to date is either too preliminary or too qualitative due to the complexity of the problem involved. As a result, although there have been already many modification examples of low-head dams and weirs in practices, whether successful or failed, the understanding on the associated hydro-morphological processes is still poor. In order to reduce the risks and uncertainties in the strategies development for barrier modifications, there is a great demand for expanded research.

In the past several years, the authors’ research group has conducted a series of studies to investigate the upstream channel responses to the modification of a weir, particularly in case of a partial removal. The rationale behind the studies are stated here. The weir removal triggers hydraulic and sediment transport processes which propagate both upstream and downstream, with the former driving the latter. A partial or gradual removal is preferred compared with a full removal, to avoid sudden changes in physical, chemical and biological factors of the river channel. A lot of knowledge has been accumulated on several governing parameters such as the initial weir pool condition, the flow discharge, the discharge hysteresis, the modification area of the weir profile and the upstream channel bed composition. It is found that the weir removal exerts impacts both near the weir and far from the weir, typically in terms of local scour development and sandbar propagation. In general, the influences of the local scour propagate towards upstream, while those of the sandbars propagate towards downstream. As a result, the channel adjusts itself corresponding to these two dominant processes and their interactions. It has been found that the removal area of the weir profile plays an important role in characterizing the sizes of weir pools and the properties of sandbars at the quasi-equilibrium state. If weir pools exist both before and after the removal, the remaining size of the pools is

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almost inversely proportional to the removal area of the weir section. If sandbar fronts already approach the weir section before the removal, the sandbars will enlarge in wavelength and gradually shift from a single system to multiple systems with an increase of the removal area. Therefore, it is very important to select the removal area for a suitable control of the sandbar structure, the channel stability and the habitat quality. In addition to that of the removal area, the importance of the removal shape is also recognized. It is noted that the removal shape influences the proximity of the weir and makes threat to the structure safety. The removal shape affects the propagation of upstream sandbars as well. Unfortunately, the exact role that the removal shape plays is still poorly understood. On the other hand, the choice of a partial removal scheme is largely determined by the selection of the removal area as well as the removal shape in practices. Thus, there is a need to investigate the hydro-morphological features of the post-removal channel under various removal shapes and to clarify the associated underlying processes. The study is aimed to address these problems with experimental methods.

2. Experiments

2.1 Experiment setup

A series of experiments were performed in a straight tilting flume at the Ujigawa Open Laboratory, Disaster Prevention Research Institute, Kyoto University (Japan). The flume has a rectangular cross-section and is 21m in length, 50cm in width and 30cm in depth. An inlet tank and a small reservoir are located at the upstream and the downstream of the flume, respectively, and the water in which is re-circulated with a pump and pipe system. The slope of the flume is kept as 1/200 during the experiments. A model weir of 11.5cm in height, 50cm in width and 2cm in thickness is set at 13m from the inlet tank. The upstream reach of the weir is covered with an 8.5cm-thick layer of silica sediment with a mean diameter of 0.163cm, forming a movable bed area (see Fig.1).

![Fig.1 Sketch of experiment setup (Unit: cm)](image)

2.2 Experiment procedures

The experiment conditions are shown in Table1. Based on knowledge and experiences from previous experiments, the flow discharge is kept constant as 8.16l/s, representing a shear stress ratio of $\tau*/\tau_{c}* = 2.0$. Here, $\tau_*$ and $\tau_{c}$ are dimensionless shear stress and dimensionless critical shear stress, respectively. The flow discharge, applied on the sediment beds in the current experiments, corresponds to a flood scenario in typical Japanese rivers. This discharge governs the longitudinal bed features and the meso-scale sandbars in the upstream channel according to the previous research of the authors' group. In this study, the partial removal is conducted by making a notch or several notches along the weir section and maintaining the same removal area. Three types of removal schemes, consisting of six cases in total, have been tested in the experiments as sketched in Fig.2. In the figure, the initial flatbed level is also shown for reference. Type1 tests rectangular removal sections with different removal heights, including Case1 and Case2. Type2 uses trapezoidal removal sections with bases of different lengths, and...
including Case1, Case3 and Case4. Type3 adopts various slit-type removal sections, including Case1, Case5 and Case6. For clarity, several governing parameters characterizing the removal shape are sketched in Fig.3. As shown in the figure, \( B \) is the length of the weir across the channel, \( H \) is the height of the weir above the initial flat bed, \( B_0 \) is the removal length, \( H_0 \) is the removal height, \( B_1 \) is the removal length at the upper part, \( B_2 \) is the removal length at the lower position and \( B_s \) is the length of each opening in case of a slit-type removal. In case of a trapezoidal removal section, \( B_0 = (B_1 + B_2)/2 \). In case of a slit-type removal, \( B_0 = NB_s \), where \( N \) is the number of the slits.

Each experiment follows such a procedure: 1) The sediment bed surface is levelled to a flat initial one with a scraper blade; 2) When the desired water depth is achieved upstream of the weir by slowly filling water in the flume, the pump is set to the desired discharge; 3) The propagation process of sandbars in the channel is memorized if necessary until a quasi-equilibrium condition is reached; 4) The water level along the centerline of the flume is recorded with a point gauge and the velocity near the weir is measured with an electromagnetic velocimetry; 5) The pump is stopped and the flume is drained out; 6) The bed level is measured with a laser displacement meter and the setup of the pre-removal condition is completed; 7) The flume is again filled with water until the desired water depth is achieved and the desired discharge is then set properly and the weir is partially removed at the same time; and 8) The propagation processes of sandbars as well as the water level, the velocity near the weir and the bed deformation at the quasi-equilibrium state are investigated following the same procedures as those of the setup of the pre-removal condition. The quasi-equilibrium state is mainly examined based on the propagation properties of sandbars.

During the experiments, no sediment is supplied from the upstream end of the flume. Instead, the bed elevation near the upstream end is made a little higher than the immediately downstream area as sediment reserves.

3. Results

3.1 Temporal variation of bar front

Soon after the pump is activated, sediment movement is observed in the upstream channel. Sandbar develops and a bar front is distinguishable within several minutes. The movement of the bar front before the weir removal is shown in Fig.4, in which the dimensionless distance from the weir is defined as the distance between the bar front and the weir normalized by the width of the channel. From the curvature of the curve, it is evident that the sandbar propagates with a decreasing velocity towards the weir. The bar front becomes almost stagnant with a propagation velocity less than 0.5 cm/min after 160 min. A stable weir pool forms and a quasi-equilibrium condition is assumed.

As soon as the weir is removed, the bar front propagates immediately and the weir pool shrinks rapidly as shown in Fig.5. The bar front moves downstream with an ever decreasing velocity according to the curvature of the curves and approaches the proximity of the weir section finally. The proximity of the weir is occupied by several local scour holes depending on the shape of the removal as to be discussed in the contexts later. The propagation velocity of the bar front, and hence the time to approach the weir, differs from case to case. In general, the bar front arrives at the weir earlier if the removal shape exhibiting a smaller value of \( H^*/B^* \) (Type1), \( B_2/B_1 \) (Type2) or \( B_s/B_0 \) (Type3).

As it will be discussed later, those values show strong relations with the maximum local scour depth around the weir. On the other hand, the local scour around the weir has a potential to alter the downstream boundary conditions such as the water stage, channel thalweg and bed slope. These conditions play important roles in the propagation process of sandbars. However, there is also an exception, i.e. Case3 and Case4. Although the value of \( B_2/B_1 \) in Case3 is larger than that in Case4, the
propagation velocity in Case3 is faster than that in Case4. It suggests that the removal shape should influence the sandbar properties in a rather complex way and the maximum scour depth along would be not enough to explain the development of the bar fronts.

When the bar front meets the local scour near the weir, it loses its identity and the aggraded bed in the proximity of the weir gradually becomes lower. After the disappearance of the dominant bar front, bars in the more upstream area develop towards downstream and repeat the life cycle of the dominant one. A quasi-equilibrium condition is assumed after another continuous running of about 180 min based on the examinations of the transport properties of the bar systems.

3.2 Bed deformation

The detailed changes in the bed level from the initial flatbed to the final bed at the quasi-equilibrium condition are shown in Fig. 6. Comparing the post-removal cases (Fig. 6, b-g) with the pre-removal one (Fig. 6, a), it is evident that the partial removal of the weir triggers sediment movement both near and far from the weir. A weir pool exists before the removal, but disappears after the removal. Sandbars occupy almost the whole domain of the movable bed area and the local scour develops at the proximity of the weir section after the removal of the weir. The area of the weir pool formed at the pre-removal stage is significantly aggraded due to the invasion of the sandbars in all the cases. The structure of the alternating sandbar is very similar in each case irrespective of the differences in the removal shape. These sandbars own a larger wavelength compared with those at the pre-removal stage. It provides further evidences on the authors’ previous findings, i.e. it is the removal area, rather than the removal shape, that plays the dominant role in the determination of the properties of the meso-scale sandbar system.

3.3 Water level and bed slope

The water stage and the bed elevation along the centerline of the flume are shown in Fig. 7 and Fig. 8.
Before the weir removal, the pool area is obviously distinguishable according to either the water surface profile or the bed level in the longitudinal direction. The pool area is characterized by a rather big water depth. After the removal, water level decreases, particularly in the previous weir pool area. On the other hand, the bed in the previous weir pool area is greatly aggraded. Therefore, the reduction in water depth is expectable. Both the slope of the water surface and the longitudinal bed slope become much steeper than the pre-removal condition. It is known that all these changes promote sediment movement and the propagation of sandbars. Moreover, representative angles of the scour hole surface along the left side of the channel are also listed.

It is found that the scour depth increases with an increase of either $H^*/B^*$, $B_2/B_1$ or $B_s/B_0$. In other words, deeper scour holes may be intendedly created by increasing the removal height or the removal length at the lower part of the weir or by simply decreasing the number of openings in case of a slit-type removal. These findings should be well explained by considering the mechanism of the formation and the development of the local scour holes, especially the complex vortices in the proximity of the weir section as to be described in the next section.

### 3.4 Local scour at the weir

In order to clarify the relationship between the local scour and the removal shape of the weir, the typical scour hole around the weir along the left side of the flume is sketched in Fig.9. In this figure, several important parameters and representative cross-sections are defined according to the location of the maximum scour. Angles $\alpha$, $\beta$ and $\gamma$ stand for the local slopes of the scour hole surface along the longitudinal and transverse (towards the centerline and towards the side of the flume) directions, respectively. Sections A and B are transverse and longitudinal cross-sections crossing the point where the maximum scour is located, respectively. As has been mentioned before, the number of the scour holes is generally larger than one in case of a partial removal. The scour holes may also change their geometries periodically according to the shifting of sandbars immediately upstream of them. In this study, the mean values of the scour hole depths in each case are selected to characterize the local scour phenomena and the maximum and minimum values of the scour hole depths are also listed for reference. These values are denoted as $d_1$, $d_2$ and $d$ correspondingly as shown in Table2. Moreover, representative angles of the scour hole surface along the left side of the channel are also listed.

It is found that the scour depth increases with an increase of either $H^*/B^*$, $B_2/B_1$ or $B_s/B_0$. In other words, deeper scour holes may be intendedly created by increasing the removal height or the removal length at the lower part of the weir or by simply decreasing the number of openings in case of a slit-type removal. These findings should be well explained by considering the mechanism of the formation and the development of the local scour holes, especially the complex vortices in the proximity of the weir section as to be described in the next section.

<table>
<thead>
<tr>
<th>Case</th>
<th>$H^<em>/B^</em>$</th>
<th>$B_2/B_1$</th>
<th>$B_s/B_0$</th>
<th>$d_1$(cm)</th>
<th>$d_2$(cm)</th>
<th>$d$(cm)</th>
<th>$\alpha$(°)</th>
<th>$\beta$(°)</th>
<th>$\gamma$(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>3.125</td>
<td>0.781</td>
<td>-</td>
<td>8.50</td>
<td>6.01</td>
<td>7.26</td>
<td>32.0</td>
<td>30.0</td>
<td>24.0</td>
</tr>
<tr>
<td>Case2</td>
<td>0.781</td>
<td>-</td>
<td>0.333</td>
<td>2.86</td>
<td>1.63</td>
<td>2.25</td>
<td>32.0</td>
<td>33.0</td>
<td>7.7</td>
</tr>
<tr>
<td>Case3</td>
<td>-</td>
<td>0.333</td>
<td>0</td>
<td>7.70</td>
<td>6.58</td>
<td>7.14</td>
<td>32.0</td>
<td>21.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Case4</td>
<td>-</td>
<td></td>
<td>-</td>
<td>4.13</td>
<td>1.15</td>
<td>2.64</td>
<td>33.0</td>
<td>12.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Case5</td>
<td>-</td>
<td></td>
<td>0.5</td>
<td>5.72</td>
<td>5.19</td>
<td>5.47</td>
<td>31.0</td>
<td>19.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Case6</td>
<td>-</td>
<td></td>
<td>0.333</td>
<td>4.92</td>
<td>4.08</td>
<td>4.45</td>
<td>28.0</td>
<td>21.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>
The local slopes of the scour hole surfaces also deserve special attention. In each case, the slope in the longitudinal direction (α) is generally steeper than that in other directions and the slope towards the centerline of the flume (β) is generally steeper than that towards the side of the flume (γ). The slopes of the scour holes are closely related to the local flow structure, particularly the strength of the circulating flows in the scour area.

3.5 Velocity profiles near the weir

The flow field around the weir is an important key to understand the sediment transport and bed variation processes in the channel. When local scour occurs, the flow generally becomes three-dimensional and is composed of complex vortex systems according to research on local scour around other types of hydraulic structures\(^{20,21}\). Therefore, the detailed 3D velocity data is collected and analyzed in this study. The velocity profiles in typical transverse Section A and longitudinal Section B (as sketched in Fig.9) in each case are shown in Fig.10 and Fig.11, together with the bed profiles and weir profiles.

An investigation on both the transverse (Fig.10) and the longitudinal velocity profiles (Fig.11) at the pre-removal stage demonstrates that a strong upward flow with almost no transverse velocity component forms when the flow approaches the weir section. Due to the existence of the weir, the flow is significantly accelerated over the crest of the weir. However, near the bed, the flow is blocked and the velocity is quite small. As a result, although flow is much rapid on the water surface, almost no near-bed sediment movement could be observed in the proximity of the weir at this stage. After the partial removal of the weir, the flow velocity and the local bed near the weir dramatically change and strongly interact with each other. Both the velocity field and the scour geometry evidently exhibit three-dimensional features.

Comparing the flow vectors of difference cases in Fig.10, the linkage between the velocity vectors and the scoured bed as well as the weir profile becomes evident. After the partial removal of the weir, the lateral velocity components are significantly intensified. It is found that the direction of the velocity is towards the opening in the weir section. The magnitude of the velocity generally becomes larger near the opening. As a result, if there is more than one opening in the weir section, the flow pattern becomes much sophisticated. For example, the emerging of two flows at the opening is obviously shown in Case5, while the separation of the flow into two parts is well detectable in Case6. Moreover, if the opening is much narrow in width, the flow may suffer from rapid changes when two flows join with each other. By comparing Case1 with Case2, one may note that the velocity changes gradually in Case2 but reduces near the centerline of the flume within a very short distance in Case1 in the projected opening area. The complex flow patterns described above may result in heavy energy loss and exert influences on the local scour processes. Consequently, the transverse velocity plays a crucial role in the initiation and the controlling of the scour processes around the weir.

In addition to the transverse velocity component, the velocity component in the vertical direction shows great changes as well. A downward flow is visible in most of the cases after the partial removal of the weir. This flow is not present in the pre-removal stage. The downward flow is generally stronger in deeper-scour hole cases, but shows certain relation with the local slope of the scour hole surface. The downward flow may be very weak even the scour hole is very large if the local slope of the scour surface is mild enough. It may be confirmed from the plots in Fig.10. It is also noted in Fig.10 that the bed level at the openings of the weir section is generally higher than that of the surrounding area. As a result, local slopes along the transverse direction are observed. Along the slope, an upward velocity component exist and the flow is directed to the openings by this upward velocity, together with the strong transverse velocity. It is believed that both the downward flow and the upward flow are mainly triggered by the changes in the local bed elevation, particularly the development of the local scour hole.

Along the longitudinal Section B (Fig.11), a circulating flow is evidently observed in each case after the partial removal of the weir. The circulating flow occupies almost the whole domain of the local scour hole. This flow is an engine for the development of the scour hole in the longitudinal direction. Different from the transverse velocity component, the longitudinal component is not directly affected by the removal shape of the weir, but is strongly dependent on the geometry of the scour hole.
Fig. 10 Velocity vectors in transverse Section A (Continued)

Fig. 11 Velocity vectors in longitudinal Section B
4. Discussions

In the previous sections, the main hydro-morphological features in the upstream channel of a model weir after the implementation of several partial removal schemes have been presented.

The removal shape continuously controls the local scour development and influences the propagation properties of the upstream sandbar front before it approaches the weir proximity. Nevertheless, the sandbar characteristics at the quasi-equilibrium condition are found to be somehow independent of the removal shape. Based on the experiment results, there are some probable reasons. Although the weir section provides a downstream control for the upstream hydraulic and morphological processes, the influences of the removal shape are mostly eliminated due to the self-adjustments of the local bed geometry and the local flow field around the weir. As a result, the information on the removal shape is almost lost when the influences of the weir removal propagate towards the upstream of the channel at the quasi-equilibrium stage. As it takes time for the self-adjustments of the flow and the bed, the removal shape has a chance to make influences but on limited area and within limited time before the completion of the self-adjustments.

Three dimensionless parameters H*/B*, B2/B1 and Bs/B0 have been proposed to characterize the removal shape of the weir. According to Fig.10 and Fig.11, one may conclude that those parameters make a well control on the local flow structures near the weir although the flow field is highly three dimensional. With those parameters, one may obtain some general idea on how many circulating cells may occur, where the flow circulation may take place and what kind of scour phenomenon may be expected. In addition, it also sheds a light on the possible prediction of the local scour depth. Unfortunately, the limited experiment data at the current stage does not allow the derivation of a reliable scour formula for the time being. However, the results suggest that a removal shape of a shallow rectangular or a triangle, or a removal by introducing a lot of slits is recommended in order to reduce the local scour around the weir.

5. Conclusions

This research investigates the impacts of the removal shape of a weir on the hydro-morphological features in its upstream channel with a series of laboratory experiments.

The removal shape directly affects the local flow structure and local scour depth around the weir. The removal shape initiates and, to some extent, provides an important boundary for the development of the local flows. The local flow is generally highly three dimensional. Moreover, the local flow and the local scour are strongly coupled parameters. They adjust themselves according to the changes in each other. The removal shape also exerts impact on the propagation properties of upstream sandbars before the disappearance of the weir pool but does not exhibit significant influences on the final characteristics of the sandbar system at the quasi-equilibrium stage. The removal shape can be characterized with three dimensionless parameters, i.e. H*/B*, B2/B1 and Bs/B0. It is found that the local scour depth shows positive relationship, while the propagation velocity of the sandbar front shows negative relationship with the three parameters.

The findings in this research encourage the development of practicable scour prediction formulae and possible methods to quantify sandbar properties such as bar types, wavelength and wave height. However, more experiment data is required to further the understanding on and to characterize the flow structure and the movement of sediment.

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