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MORPHOLOGICAL RESPONSE OF RIVER CHANNEL DUE TO WEIR RECONSTRUCTION

Hao ZHANG[1], Keiichi KANDA[2], Yasunori MUTO[3] and Hajime NAKAGAWA[4]

[1]Member of JSCE, Assistant Professor, Ujigawa Open Laboratory, Kyoto University
(Shimomisu, Yoko-oji, Fushimi-ku, Kyoto 612-8235, Kyoto, Japan)
E-mail:zhang@uh31.dpri.kyoto-u.ac.jp
[2]Member of JSCE, Professor, Dept. of Civil Eng., Akashi National College of Technology
(679-3 Nishioka, Uozumi-cho, Akashi 674-8501, Hyogo, Japan)
E-mail:kanda@akashi.ac.jp
[3]Member of JSCE, Associate Professor, Shirahama Oceanagraphical Observatory, Kyoto University
(Katata, Shirahama, Nishimuro, Wakayama 649-2201, Wakayama, Japan)
E-mail:muto_yas@mbox.kudpc.dpri.kyoto-u.ac.jp
[4]Member of JSCE, Professor, Ujigawa Open Laboratory, Kyoto University
(Shimomisu, Yoko-oji, Fushimi-ku, Kyoto 612-8235, Kyoto, Japan)
E-mail:nakagawa@uh31.dpri.kyoto-u.ac.jp

This paper presents a research result on the change of the flow pattern and sediment transport in a straight channel after the reconstruction of a weir structure. Both laboratory experiments and numerical simulations are conducted. The experiments are carried out under flood discharge scenarios with dominant sediment transport in bedload mode. Numerical simulations are based on a 2D morphological model, which couples a depth-averaged turbulent flow model, a deterministic empirical bedload transport model and a bed deformation model. Different weir reconstruction schemes have been proposed and the morphological impacts of these schemes are characterized and compared with each other. The applicability of the numerical model is also validated by comparing the numerical result with that of the experimental measurements. Based on the research result, some recommendations are made for weir reconstruction.

Key Words : *morphological response, weir reconstruction, laboratory experiment, numerical model*

1. INTRODUCTION

In the past century, river-crossing structures such as weirs were widely constructed in the world. Weirs cause river water to back up and pool behind them. The build-up of water may be used for power generation, recreation, water supply, agriculture irrigation and other purposes. However, these structures are under debate in many countries nowadays. As known, weir structures form artificial barriers and disturb the longitudinal continuity of water and sediment system in a river basin, which generally has more or less negative impacts on the riverine/riparian eco-system and landscape. With the significant increasing of the global environmental concern, reconstruction of weir structures has been highlighted recently. According to the statistics and reports of the River Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan, weirs have been criticized to prevent fishes from free migration in many Japanese rivers and there is a great demand for weir reconstruction (MLIT Website, 2008). In Korea, for example, relocation of a weir was recently investigated under the Kongju Bridge over the Geum River in order to improve the riverside scenery (Lee et al., 2007). A weir reconstruction project was also launched on the Bow River in Calgary, Canada to create a new river amenity and to enhance the fish and wildlife habitat (Government of Alberta, News release, 2007). A lot of schemes may be adopted to reconstruct a weir, including entire removal of the weir, relocation of the weir, change of the weir type, modification on the weir profiles or construction of appendage structures such as fish ladders. Nevertheless, the applicability and sustainability of these schemes have been seldom investigated in scientific communities. As a result, decision-makers and practitioners are in great need of scientific information and methodologies prior to the implementation of reconstruction measures.

It is a crucial task, from the perspective of hydraulicians and morphologists, to characterize the impacts of weir reconstruction measures on the flow structure and sediment transport in the river system and to develop practicable analysis tools to predict and simulate the underlying processes. In this paper, movable bed experiments were carried out to investigate the flow and bed deformation characteristics in the upstream reach of a weir after implementations of different reconstruction schemes. These schemes are focused on the modification of the weir profile. A 2D numerical model is developed to simulate the physical processes in the experiments. Comparisons are also made between the experimental data and the numerical result.

2. EXPERIMENTAL METHODS

A series of experiments were carried out in a 21m-long, 50cm-wide and 30cm-deep tilting flume at the Ujigawa Open Laboratory, Kyoto University. The sketch of the experimental setup is shown in Fig.1. The slope of the flume was adjusted to 1/200. A model weir of 12cm-height, 50cm-width and 2cm-thickness was set at 13m from the inlet tank. The upstream reach of the weir was covered with 8cm-thick silica sediment, having a mean diameter of 0.156cm. Before each experimental run, water was pumped into the flume with a constant discharge of 8.16 l/s, corresponding to a flood discharge scenario in a river. The hydraulic condition is shown in Tab 1. Due to the existence of the weir, sediment movement was confined in the area far enough from the weir. Sand bar developed in the upstream part of the flume and slowly propagated. The front of the sand bar became almost stagnant after 2hours and a relatively stable pool formed behind the weir with a longitudinal length of about 4m. This condition was considered as initial condition for the examination of various weir reconstruction schemes.

Four kinds of schemes were proposed and tested in the experiments as shown in Fig.2. In Case1 and Case2, the height of the weir is 4cm-reduced and 2cm-reduced, respectively. In Case3 and Case4, the middle 1/3 part of the weir is 4cm-reduced and 2cm-reduced, respectively. Case1 and Case2 might be considered as measures to modify the area of the weir section, while Case3 and Case4 were measures to modify both the area and the shape of the weir section. In Case1, sand bar developed quickly in the whole area and the pool morphology behind the weir completely disappeared after 30 minutes. Then the pump was stopped. In other cases, the pool area gradually deceased with the invasion of the sand bar front. When the movement of the sand bar front became sufficiently slow, i.e. less than 2cm per minute, the pump was stopped. The change of the weir pool length (i.e. the distance between the sand bar front and the weir) with time is shown in Fig.3. It is very obvious that different reconstruction schemes have different impacts on the sand bar front (hence, the weir pool) in terms of movement velocity and distance. However, there is a common point that the front moves quickly at the first several minutes and approaches the weir at a very small velocity at the later stage in all these cases.

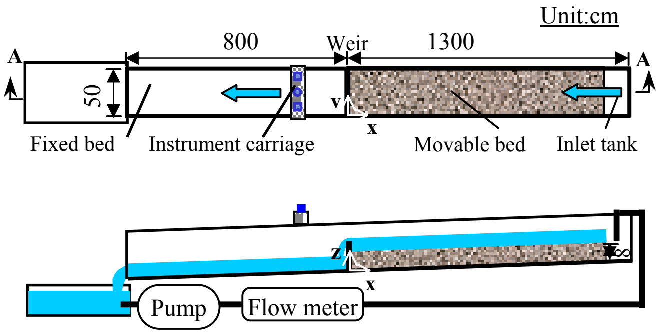

Fig.1 Experiment setup (Planview: Top; Section A-A: Bottom)

Table 1 Experiment conditions

Discharge	8.16 l/s	Sediment size	1.56 mm
Bed slope	1/200	u_*/u_{*c}	1.40
Flow depth	4.18cm	Re. number	12,651
Mean velocity	39.04 cm/s	Fr. number	0.61

where u_*= friction velocity and u_{*c}= critical friction velocity.

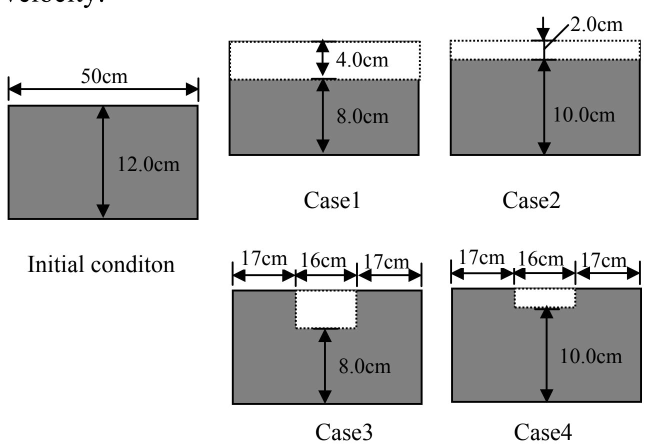

Fig.2 Weir reconstruction schemes in the experiment

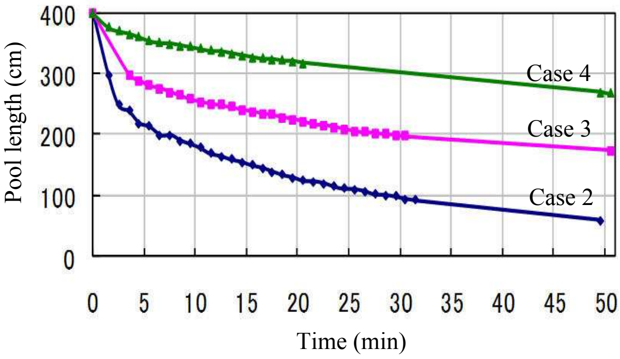

Fig.3 Temporal variation of the weir pool length

The instantaneous flow velocity on the water surface was measured with PIV (Particle image velocimetry) techniques every one minute after the modification of the weir. Before stopping the pump, the water level along the centerline of the flume was collected with a point gauge. After the flume was completely drained out, the detailed bed configuration was measured with a high-resolution laser displacement meter.

3. NUMERICAL MODEL

A 2D morphological model was developed to investigate sediment transport and morphological process in river channels. The model simulates the 2D flow velocity by solving the unsteady shallow water equations. The depth-averaged Reynolds stresses are estimated based on the introduction of the eddy viscosity. The near-bed shear stresses are closely related to the near-bed velocity field. The deviation between the near-bed velocity and the mean velocity is considered in the model. The resistance of the movable bed is estimated with a comprehensive parameter, i.e. the Manning's roughness coefficient. Since the vertical velocity component is considered to be negligible, the approach of the shallow water equations cannot simulate the flow accurately around a weir. The flow over a weir may be a free weir flow or a submerged weir flow. By using empirical weir flow formulae, the flow over the weir section is modeled in this study. The bed evolution process is obtained through the sediment continuity equation with the formula proposed by Ashida and Michiue (1972) for the bedload transport rate. The flow field, sediment transport and bed deformation in the model are coupled and solved in a quasi-steady way, i.e. when one of them is under calculation, the others are considered as unchanged. The numerical model is formulated on an unstructured mesh with the finite volume method. A detailed explanation on the discretization methods and solution processes are referred to Zhang et al. (2006b, 2007).

Two kinds of simulations have been conducted: fixed bed and movable bed simulations. Due to limited space, only some of the results are selected and presented in this paper. In case of movable bed simulations, representative bed deformation process after the weir reconstruction is focused on. While in case of fixed bed simulations, the final flow field corresponding to each reconstruction scheme is emphasized. For the movable bed simulations, the initial bed level is interpolated from the measured bed level before weir reconstruction. The initial velocity field is obtained from a steady flow simulation on the initial bed. For fixed bed simulations, the bed level is interpolated from the measured bed level in each case. In all these simulations, the Manning's roughness coefficients are taken a constant value of 0.019. This value is tuned to assure that the predicted flow field well agrees with that of the experimental measurements before weir reconstruction.

4. RESULTS

(1) Bed deformation

The bed configuration in the experiments before/after weir reconstruction is shown in Fig.4. Before reconstruction, alternate bars developed on the flat bed at the upstream part of the flume as a result of sediment erosion and deposition. The front of the sand bar kept a distance of 4m from the weir. In-between the sand bar front and the weir, the bed was almost maintained flat and a weir pool formed there. The modification in Case1 caused sediment movement in the whole movable bed area and a lot of sediment was transported to the downstream of the weir. Since there was no sediment supply at the inlet boundary, the movable bed upstream of the weir was significantly degraded. It is found in Fig.4b that alternate bars occupied the whole movable bed area and the weir pool disappeared. The situations were quite different in Case2, Case3 and Case4. In all the latter cases, the weir pool area was maintained but shrank with the expanding of upstream sand bars. Due to the existence of the weir pool, sediment was re-distributed in the movable area but was not transported to the downstream of the weir. The remaining pool length showed insignificant relation with the final shape of the weir section but seemed related to the removal area of the weir section. Plotting the pool length against the removal area of the weir section in Fig.5, it is found that the former variable is almost reversely proportional to the latter one. Hence the removal amount should be prudently selected during weir reconstruction. However, more evidence from experiments and simulations is needed. Moreover, it is noticed that severe scour hole formed behind the weir in Case3 due to the complex local flow there. It demonstrates that the modification on the weir shape may result in local bed degradation even if it may not directly affect the size of the weir pool. Since the local bed degradation may undermine the foundation of the weir itself, modification on the weir shape should be paid much attention as well.

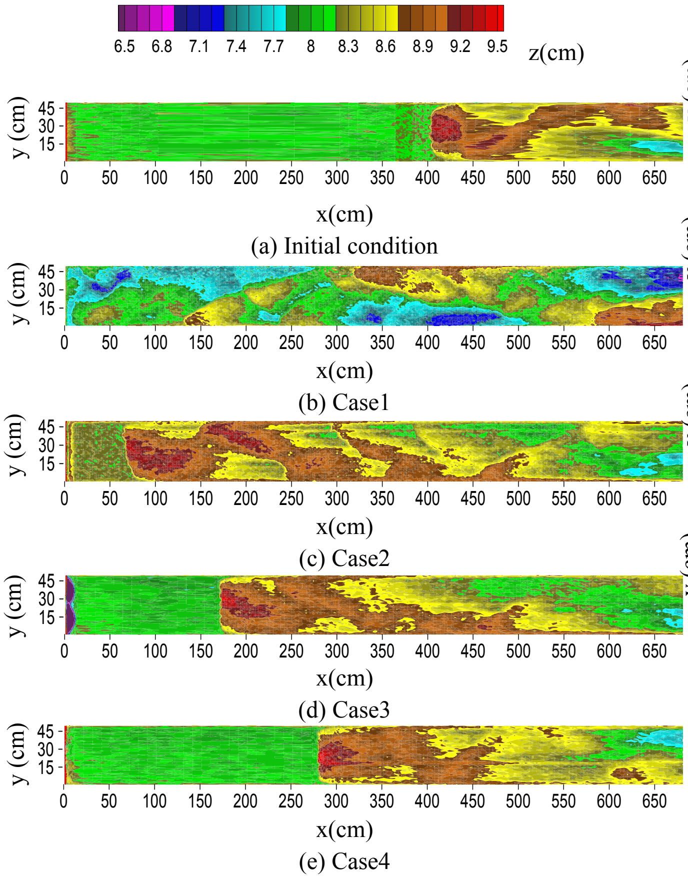

Fig.4 Bed deformation after weir reconstruction (Experiment)

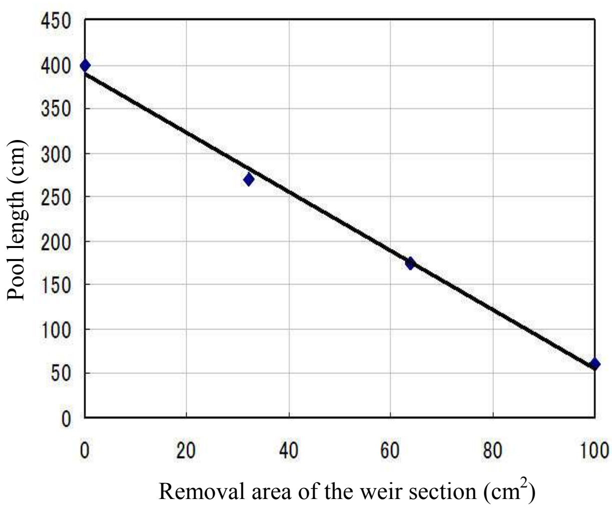

Fig.5 Weir pool length against removal area

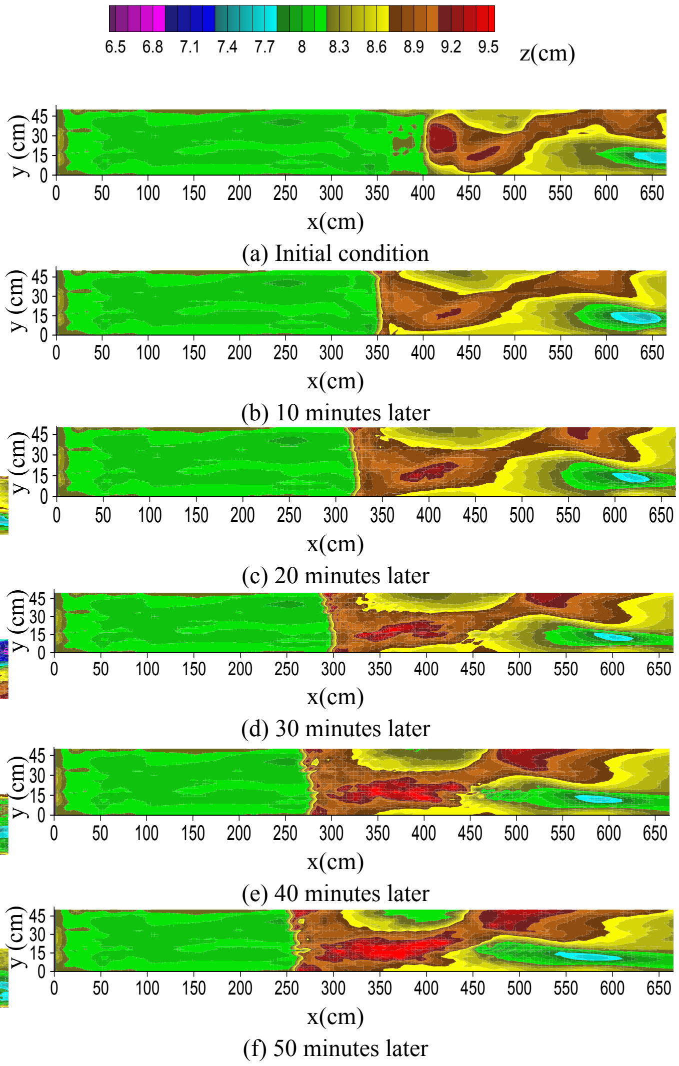

Fig.6 Bed deformation process in Case4 (Simulation)

The bed deformation process in Case4 predicted with the morphological model is shown in Fig.6. Compared with the experimental data, the simulation result is quite encouraging. The expanding process of the sand bar and the advancing of the sand bar front have been reasonably reproduced in the simulation. It is very obvious that the expanding velocity of the sand bar to the downstream is very big at the first 10 minutes but is significantly decreased after that. This coincides with the observation in Fig.3. The change of the wavelength of the sand bar with time is also obviously observed. Since it is much easier to set the weir shape and removal area of the weir section in the numerical simulation, the numerical model will be a powerful tool to quantify the relationships between the key parameters characterized from the laboratory experiments.

(2) Velocity field

Before weir reconstruction, the flow field and the bed configuration are almost in a state of equilibrium. This equilibrium state is disturbed when the weir section is modified. Consequently, the flow field and the movable bed adjust themselves in order to establish a new balance. The predicted mean velocity based on the fixed bed simulations is shown in Fig.7 in the same scales. It is found that the iso-vels are closely related to the bed configuration in Fig.4.

Before weir reconstruction, the velocity field may be divided into two different parts at the front of the sand bar. In the weir pool area, the velocity is very low and shows insignificant difference in the transverse direction. While in the stretch where sand bar develops, the flow shows some meandering features. It indicates that the pool area and the sand bar area are completely different not only in terms of bed configurations but also in view of flow conditions. In Case2, Case3 and Case4, the meandering flow becomes more and more evident with the expanding of the sand bars. At the same time, the magnitude of the mean flow velocity in the flume becomes larger and larger. In Case1, the weir pool disappears and the meandering flow occupies the whole movable bed area. In Case3 and Case4, the local flow velocity behind the opening of the weir is very big. Especially in Case3, this local flow erodes a great amount of sediment behind the weir and leads to severe local scour.

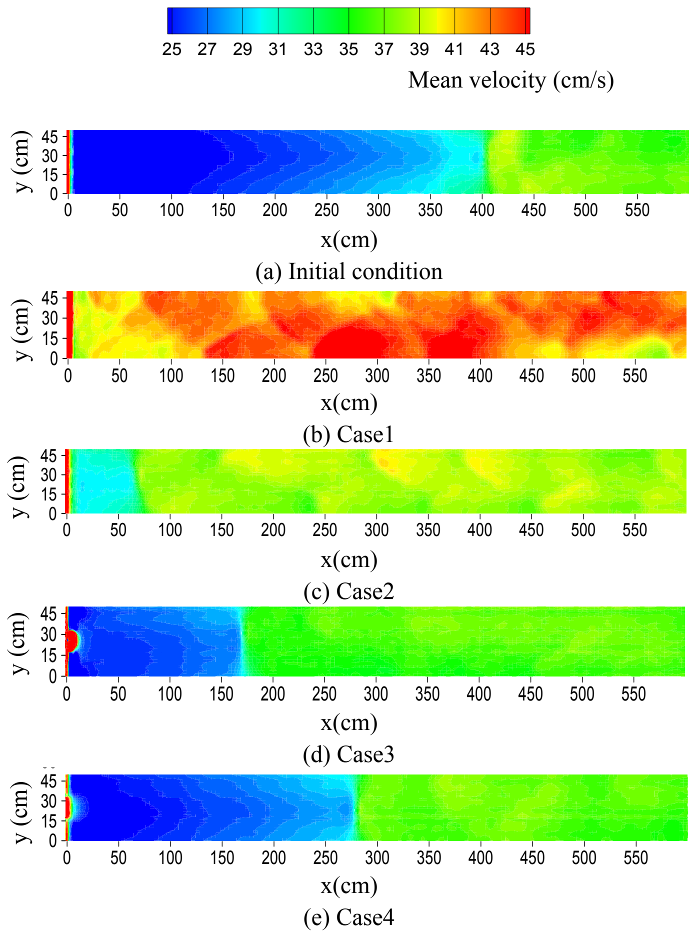

Fig.7 Weir pool length against removal area

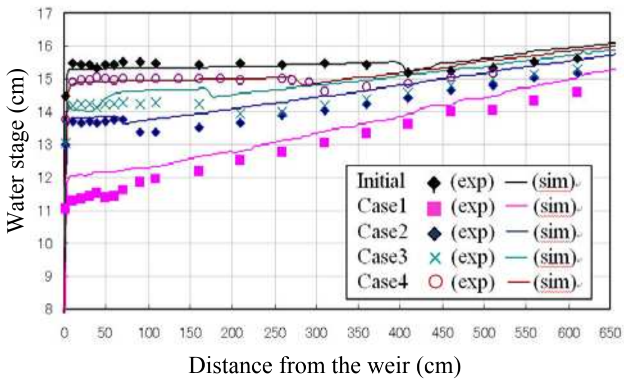

Fig.8 Water stage along the centerline of the flume

(3) Water level

The water stage along the centerline of the flume is shown in Fig.8 with both experimental data and numerical result. The numerical result is reasonably consistent with the experimental data. It is found that the mean slope of the water surface gradually increased with the increasing of the removal area of the weir section (i.e. from Case4 to Case1). In response to the change of the water surface, the movable bed adjusts its configuration through sediment movement. The weir pool area is obviously distinguished from the sand bar area in Case2, Case3 and Case4. The slope of the water surface is very steep just behind the weir in Case3, indicating a high velocity zone there. This local flow is the engine for the severe scour behind the weir as has been mentioned in the previous contexts.

5. CONCLUSIONS

This paper presents a research result on the morphological response of a channel due to weir reconstruction experimentally and numerically. Different weir reconstruction schemes, mainly in terms of the change of the weir transverse-section, have been investigated. It is found that the area change of the weir section plays an important role in the management of sediment and channel morphology upstream of the weir. The remaining size of the weir pool is almost inversely proportional to the removal area of the weir section. On the other hand, the shape of the weir section is more or less a local parameter. A great change on the weir shape may influence the local flow field and sediment transport significantly, resulting in local scour behind the weir. A modification on both the area and the shape of the weir section may result in bed deformation both near the weir and far from the weir. Therefore, desirable channel morphology may be created if suitable modification on the weir section is made.

The numerical simulation results are in good agreements with those of the experimental measurements. It demonstrates the applicability of the numerical model. The impacts of various weir reconstruction schemes may be investigated in the computational domain in the next stage. However, it has to be mentioned that the flow in the neighborhood of the weir shows obvious 3D characteristics, especially in Case3 and Case4. The 3D flow has significant effect on the local bed deformation, which cannot be resolved with a 2D model. A 3D model developed by the authors' group (e.g. Nakagawa et al., 2004 and Zhang et al., 2006a) will be promising and the results obtained with the cuurent 2D model should be compared with those obtained with the 3D model in the near future.

This study is focused on the sediment transport and bed deformation in the upstream of the weir. The impacts of weir reconstruction schemes on the downstream of the weir are also of great concern in practice. Moreover, uniform sediment is investigated in this study. However, sediment materials in actual rivers generally have a wide spectrum of size distribution. These problems are to be included in the future research.

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