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Upstream Channel Responses due to Partial Removal of a Weir

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Synopsis

This paper presents an experimental study on the hydraulic and morphological responses of a channel due to partial removal of a weir. In particular, the impacts of the removal shape of the weir and the properties of the bed sediment are focused on. It is found that weir removal promotes local scour and sandbar development in the upstream channel. The removal shape significantly affects the three dimensional flow structure and the local scour around the weir and poses influences on the propagation process of upstream sandbars at the early stage. Nevertheless, the characteristics of the sandbar system at the quasi-equilibrium stage are governed by the removal area rather than the removal shape. The mean grain size and the geometric standard deviation of the bed sediment mixtures are two practical parameters in characterizing the local scour and the sandbar structure in non-uniform sediment beds. Sand ribbons are observed in non-uniform sediment beds due to the lateral sediment sorting and the ribbons also influence the bed morphologies.

Keywords: dam/weir removal, channel response, sandbar, local scour, sand ribbon

1. Introduction

The aging of 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 (Doyle et al., 2003). Over the past several decades, there have been a significant amount of low head dam or weir removal examples around the world, either successful or failed, e.g. Wildman and MacBroom (2005), De Leaniz (2008), Walter and Tullos (2010). In general, there are several alternatives during the modification of a dam or weir, for example, a full removal, a partial removal, a gradual removal, relocation of the structure or construction of appendage structures. Up to now, most of the research related to dam/weir removal are based on limited field survey and/or post-removal monitoring and the results obtained are generally site-specific and problem dependent, e.g. Doyle et al. (2005), Rumschlag and Peck (2007), Kibler et al. (2010). Research with numerical methods is also carried out by some engineers and scholars (Cui et al., 2006, Cantelli et al., 2007, Zhang et al., 2009), but the applicability and reliability of those models remain questionable due to the hypotheses and simplifications introduced during the model formulations. Consequently, the understanding on the associated hydro-morphological processes of post-removal rivers is still fairly poor and the existing knowledge is quite insufficient to guide considerations of dam/weir removal in practices. In order to reduce the risks and uncertainties in the strategies development for dam/weir removal, there is a great demand for expanded research (Doyle et al., 2003).

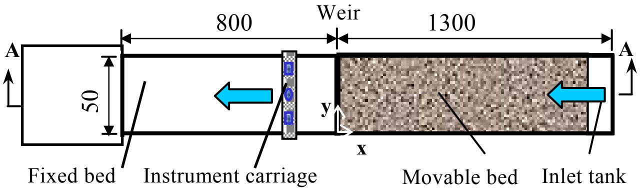
A weir to be removed generally persists for years, hence the river channel typically has adjusted to the altered hydrologic, hydraulic and sediment transport regimes that the weir imposes and the channel is usually in a quasi-equilibrium state (Doyle et al., 2003). Since the weir blocks the river and causes river water to back up, the upstream and the downstream of the weir usually exhibit completely different sceneries and characteristics, typically in terms of a water pool and sediment storage upstream and associated sediment coarsening and bed degradation downstream. Removal of the weir will trigger hydraulic and sediment transport processes that propagate both upstream and downstream. The changes in the flow and geographic parameters furthermore exert impacts on the biogeochemistry and stream habitat. Therefore, removal of a weir, like the presence of a weir, represents a disturbance to the river channel. Moreover, the fluvial process provocated by the weir construction and weir removal may not always be reversible (Doyle et al., 2005). It is hence necessary to characterize and quantify the post-removal channel dynamics and associated underlying processes.

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 (Zhang et al., 2008, Zhang et al., 2009, Muto et al., 2009, Muto et al., 2010). A lot of knowledge has been accumulated on several governing parameters such as the initial weir pool condition, the flow discharge, the discharge hysteresis and the modification scheme of the weir section. 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 sand bar propagation. Soon after the removal, the local flow and/or bed conditions in the proximity of the weir change correspondingly. This change triggers sediment movement and bed variation in the upstream channel and the change in the upstream channel then gradually affects the neighborhood of the weir. In general, the influences of the local scour propagate towards upstream, while those of the sand bars propagate towards downstream. As a result, the channel adjusts itself corresponding to these two dominant processes and their interactions. The dominant discharge of the river is mainly responsible for the longitudinal bed features and meso-scale sandbar systems in the upstream channel. After the weir removal, low flows have a potential to trigger minor channels while high flows likely to promote bed forms of dunes/anti-dunes. Irrespective of the initial bed conditions resulted from different flow discharges, the channel beds at the quasi-equilibrium states exhibit similar geographic features after a continuous running of the dominant discharge. If a weir pool exists before the removal, the remaining size of the pool is almost inversely proportional to the removal area of the weir section and local scour develops near the weir depending on the removal shape to some extent. 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 ones with an increase of the removal area. The local changes near the weir are closely related to the removal shape of the structure. However, the exact role that the removal shape plays is still poorly understood. Moreover, all the aforementioned conclusions are drawn based on relatively uniform sediment beds which are rarely encountered in actual rivers. In fact, as constitute of the bed itself, bed sediment exerts impact on both the fluvial geomorphology and the aquatic ecology since bed materials are used directly by periphyton, benthic species, fishes and plants and serve as an indirect indictor for aquatic habitat (Shields and Milhous, 1992, Milhous, 1998). Therefore, the sediment heterogeneity should also be accounted for prior to any removal action. In view of those arguments, the responses of the upstream channel of the weir due to various removal shapes of the weir section and different types of sediment beds are focused on in this study.

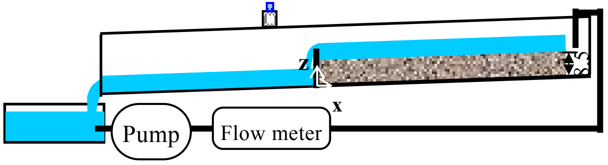
2. Experiments

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 locate at the upstream and the downstream of the flume, respectively, and the water in which is re-circulated with a pump-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 8.5cm-thick silica sediment with a mean diameter of 0.163cm, forming a movable bed area (see Fig.1). The experiment setup is sketched in Fig.1 and the photo of the experiment flume is shown in Photo1.



(a) Plan view



(b) Section A-A

Fig.1 Sketch of experiment setup (Unit: cm)

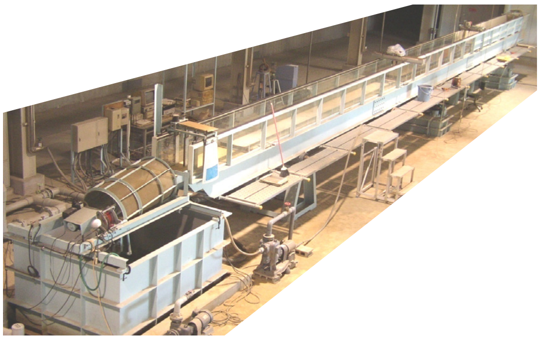


Photo 1 Experiment flume

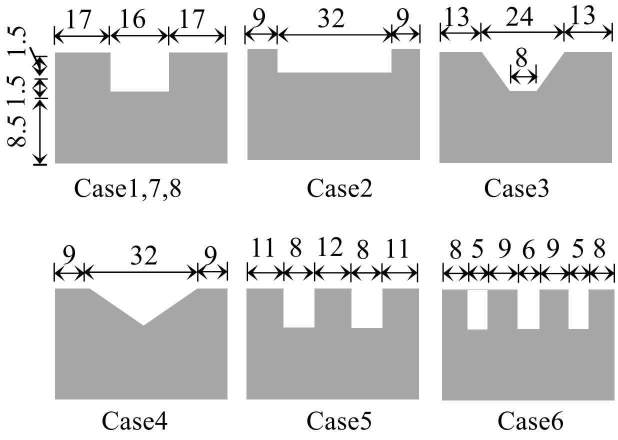
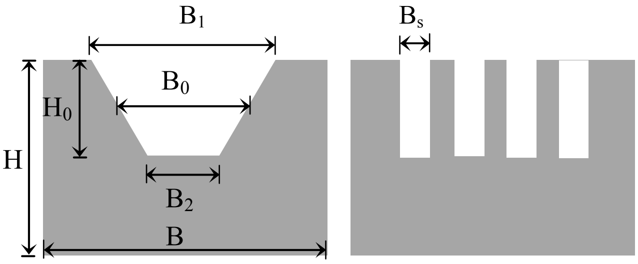


Fig.2 Weir section post- removal (Unit: cm)



Relative removal width B^* and height H^*

$B^*=B_0/B, H^*=H_0/H$

Fig.3 Definition of governing parameters

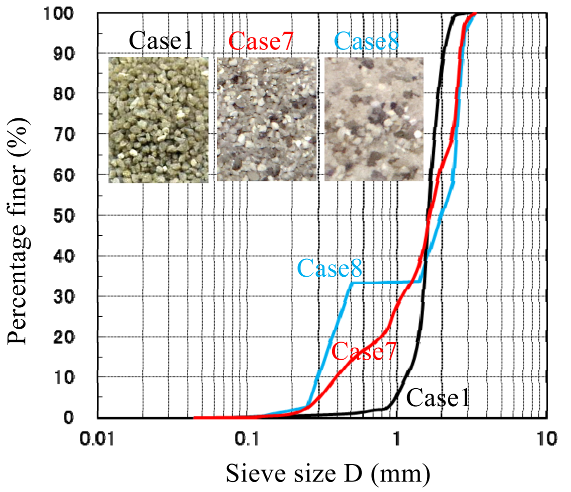


Fig.4 Sieve analysis curves of sediment samples

2.2 Experiment conditions

In general, two kinds of experiments are performed consisting of 8 cases in total. In all these cases, the weir is partially removed with the section being lowered both across the channel and in the vertical plane. The first kind (Case1 to Case6, hereafter referred to as the U-series) tests the impacts of the removal shape on the upstream channel processes. In these experiments, the movable bed is composed of uniform sediment materials with a mean diameter of 0.163cm. The removal area is fixed, while the removal shape varies from case to case. The post-removal weir sections are sketched in Fig.2. In general, they can be categorized into three types. Type1 tests rectangular removal section with different removal heights (Case1 and Case2). Type2 uses trapezoidal removal section with bases of different lengths (Case1, Case3 and Case4). Type3 adopts various slit-type removal sections (Case1, Case5 and Case6). For clarity, several governing parameters characterizing the removal shape are sketched in

Fig.3. The second kind (Case1, Case7 and Case8, hereafter referred to as the M-series) tests the impacts of the bed composition on the upstream channel processes. The removal shape and the mean diameter of the movable bed is kept the same, while the bed composition differs in each case. Three types of sediment beds are prepared for the experiments by mixing uniform silica sands of different sizes. The sieve analysis curves of the sediment samples taken from the initial flatbeds are shown in Fig.4 and several characterizing parameters are listed in Table1. It is evident that the sediment mixtures may be categorized as uniformly graded (Case1), well graded (Case7) and gap graded (Case8), respectively.

Based on the knowledge and experiences from previous studies of the authors, the water discharge in the flume is kept constant as 8.16l/s, representing a shear stress ratio of $\tau_*/\tau_{*c}=2.0$. Here, τ_* and τ_{*c} are dimensionless shear stress and dimensionless critical shear stress, respectively. This flow condition, applying on the sediment beds in the current experiments, corresponds to a dominant discharge scenario in typical Japanese rivers according to Yamamoto (1997). The hydraulic conditions are detailed in Table2.

Table 1 Sediment properties

Parameters ╲ Case	Case1	Case7	Case8
Maximum grain size D_{90} *(cm)*	0.204	0.250	0.252
Geometric standard deviation σ_g	1.200	2.151	2.953
Uniformity coefficient *Cu*	1.453	5.932	8.815
Curvature coefficient *Cc*	1.286	1.968	0.168

Table 2 Hydraulic parameters

Discharge *Q (l/s)*	8.16
Bed slope *I*	1/200
Flow depth *h (cm)*	4.18
Mean velocity *U (cm/s)*	39.0
Sediment size *D (cm)*	0.163
u_*/u_{*c}	1.40
Reynolds number	12,651
Froude number	0.61

In Table1 and Table2, σ_g is the geometric standard deviation and is obtained from $(d_{84}/d_{16})^{1/2}$, C_u is the coefficient of uniformity and is defined as d_{60}/d_{10}, C_c is the coefficient of curvature and is expressed by $d_{30}^2/(d_{60}d_{10})$, u_* is the friction velocity and u_{*c} is the critical friction velocity.

Near the inlet of the flume, the bed elevation is made a little higher than the immediately downstream area as sediment reserves. While during the experiments, additional sediment supply is not made from the upstream end.

2.3 Experiment procedures

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 (Model ACM250-A, JFE Alec Co., Ltd); 5) The pump is stopped and the flume is drained out; 6) The bed level is measured with a laser displacement meter (Model LK-500, Keyence, Co., Ltd) 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; 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 procedure as that of the setup of the pre-removal condition. The quasi-equilibrium state is mainly examined based on the propagation characteristics of sandbars. In Case7 and Case8, sediment samples are taken from the bed surface at several representative points with a sampling spoon soon after the bed elevations are surveyed. The sampling depth is about 2.5mm, corresponding to the maximum grain sizes of the sediment materials used in the experiments. The samples are analyzed with a nested column of sieves after being completely dried, together with a high-resolution balance scale (UW220H, Shimadzu Co., Ltd).

3. Results

3.1 Temporal variation of bar front

(1) Pre-removal stage

Soon after the flow passes the initial flatbed, sediment particles move. But the movement is generally confined in the area a little far from the weir at the beginning of each experiment. Sandbar develops quickly and the bar front is obviously distinguishable within several minutes. The movement of the bar front is depicted in Fig.5.

In the U-series experiment cases, the bar front propagates towards downstream with a decreasing propagation velocity and becomes almost stagnant with a propagation velocity less than 0.5cm/min at a location about 2m away from the weir after 160min. A stable weir pool forms and a quasi-equilibrium condition is assumed.

In the well graded case (i.e. Case7), Bar front mainly consisting of fine particles appears soon after the start of the experiment and propagates downstream with a decreasing propagation velocity. During the propagation of the bar front, new bar front consisting of coarse sediment forms in the upstream area. The new bar front moves faster than the old one. It overlies on the old one and propagates ever downstream with a decreasing propagation velocity. The new bar front is not the only competitor, a newer bar front composed of even coarser particles was born before the first front is colonized by the second one. The newer one propagates downstream and soon replaces the position of the second one. The process is not finished yet, the fourth and the fifth bar fronts emerge one by one, consisting of coarser and coarser sediment particles. The fifth bar front becomes the final winner, it becomes almost stagnant at a place around 1.5m away from the weir after 210min. It has to be mentioned that five kinds of relatively uniform sediment particles are used to prepare the mixed sediment in this case, with a mean size of 0.31, 0.48mm, 1.03mm, 1.61mm and 2.38mm, respectively. The development of the bar fronts gives evidence on the sediment sorting process of these different size fractions.

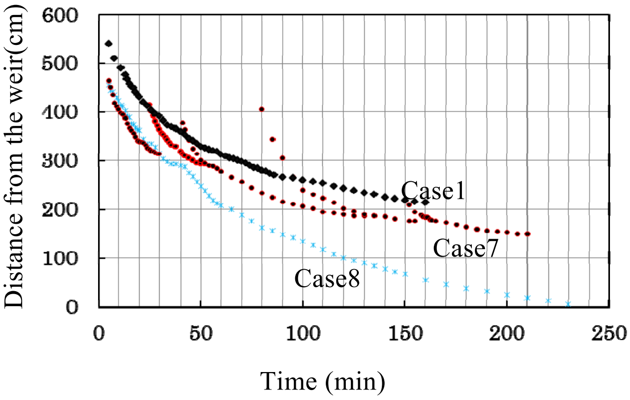


Fig.5 Movement of bar front before removal

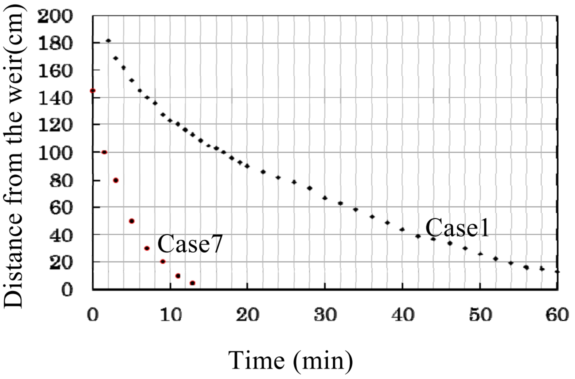
In the gap graded case (i.e. Case8), sediment consists of obviously distinguished two size fractions: a fine fraction with a mean size of 0.31mm and a coarse fraction with a mean size of 2.38mm. Ripples of fine sediment particles immediately appear after the start of the experiment. After that, bar front mainly consisting of fine sediment is observed, but the front expands towards downstream and soon becomes invisible to the naked eye. Therefore, the obviously distinguished front consisting of coarse fraction sediment is recorded. It is very clear that zigzags are observed on the path down to the weir as shown in Fig.5, especially at the initial stage. It indicates that the bar front propagates downstream following such a pattern as fast, slowly, fast again and slowly again and this pattern is repeated until the front approaches the weir. In this process, the accumulation of fine sediment plays a crucial role. The existence of thin fine sediment layers reduces the local bed resistance and results in the movement of coarse sediment. In fact, the rapid movement of coarse particles on fine sediment stripes is evidently observed during the experiments. The overlay of fine sediment stripes on the coarse sediment texture is termed sand ribbons in this paper and is discussed later in the context. When the bar front propagates close enough to the weir after 230min, particles on the upper part of the front is transported over the weir to the downstream by the local flow and the height of the front is lowered. After that, such process is repeated that the sediment from upstream is transported to the front and is carried by the local flow to the downstream of the weir. It has to be mentioned that the bar front maintains a shape like a chin although it expands to the weir section. The experiment finally lasts 300min when the sand bar structures and sand ribbons in the flume show insignificant changes.

(2) Post-removal stage

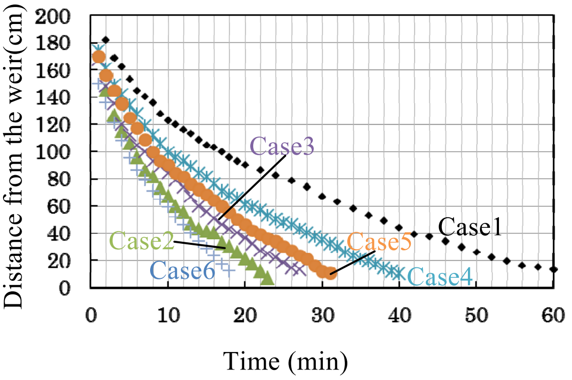
As soon as the weir is removed, the bar front propagates immediately and the weir pool shrinks rapidly as shown in Fig.6. The bar front moves downstream with an ever decreasing velocity, approaches the proximity of the weir section and loses its identity finally. The propagation velocity of the bar front, and hence the time to approach the weir, differs from case to case. 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.

In the M-series experiment cases, the bar front approaches the weir section earlier if σ_g is larger. Moreover, sand ribbons also gradually change with time. The variations of the sandbars and the sand ribbons are not two independent processes, but exhibit linkages to some extent. The quasi-equilibrium conditions are assumed after a 180min-running (Case7) and a 90min-running (Case8) based on examinations of the propagation characteristics of the bars and the sand ribbons.

In the U-series cases, the bar front generally 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 governing the propagation of sand bars such as the water stage, channel thalweg and bed slope. However, there is also an exception, i.e. Case3 and Cas4. 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. In the uniform bed cases, the quasi-equilibrium condition is assumed 180min after the bar front arrives at the weir section based on the examinations of the transport properties of the bar systems.



(a) Non-uniform bed cases



(b) Uniform bed cases

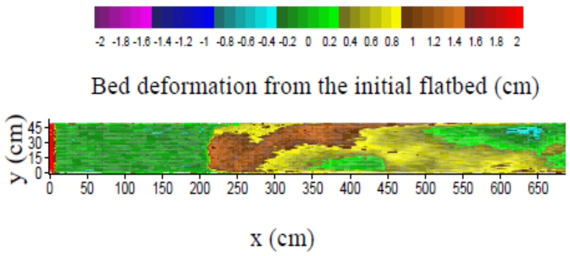
Fig.6 Movement of bar front after removal

3.2 Bed deformation

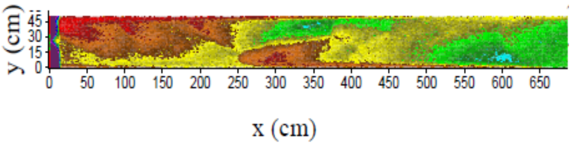
The changes of the bed level from the initial flatbeds to the pre-removal and final stages are shown in Fig.7 and Fig.8.

(1) Influence of removal shape

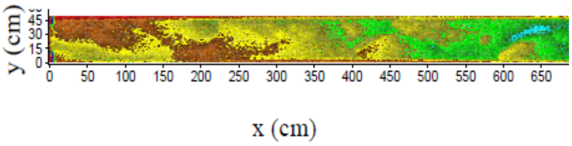
Comparing the post-removal cases with the pre-removal one in Fig.7, it is evident that the weir removal triggers sediment movement both near and far from the weir. It is very clear that sandbars occupy almost the whole domain of the movable bed area and the local scour develops at the proximity of the weir section after the partial removal of the weir. The weir pool formed at the pre-removal stage is significantly aggraded due to the invasion of the sandbars. Alternating bars are evident in all the experiment cases. The properties of the alternating bar after the removal are very similar in each case irrespective of the differences in the removal shape. 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.



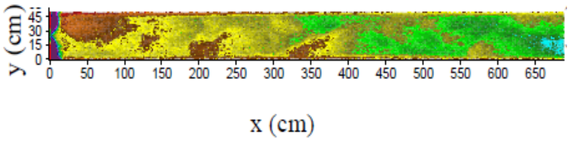
(a) Bed deformation at initial stage



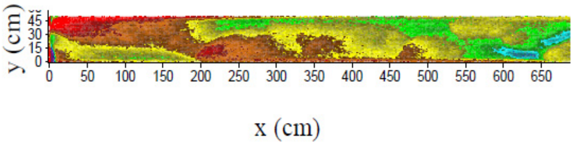
(b) Bed deformation in Case1



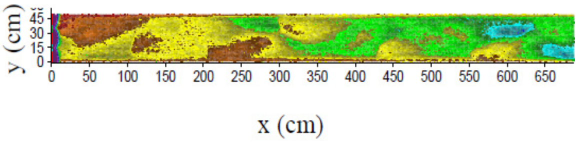
(c) Bed deformation in Case2



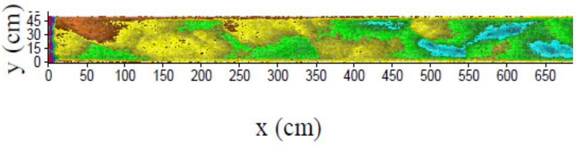
(d) Bed deformation in Case3



(e) Bed deformation in Case4



(f) Bed deformation in Case5

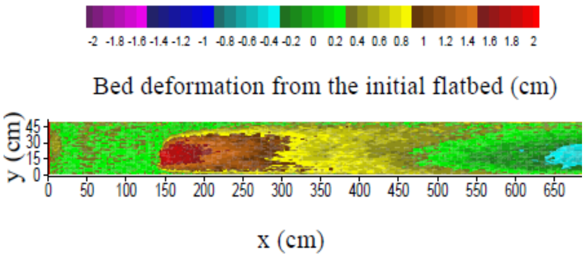


(g) Bed deformation in Case6

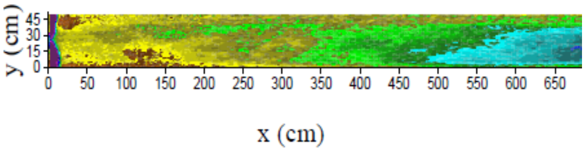
Fig.7 Bed deformation from the initial flatbed pre- and post- weir removal (Case1-6)

(2) Influence of sediment heterogeneity

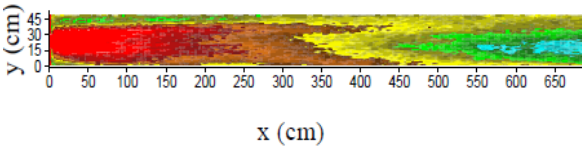
Comparing the pre- and post-removal cases in Fig.7 (a), (b) and Fig.8 (a)-(d), one may recognize significant differences in the bed morphologies among them. The differences are observed in terms of not only the size of the weir pool but also the properties of the sandbar system.



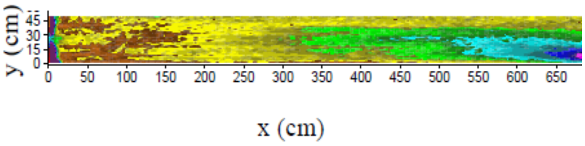
(a) Bed deformation at initial stage (Case7)



(b) Bed deformation at final stage (Case7)



(c) Bed deformation at initial stage (Case8)



(d) Bed deformation at final stage (Case8)

Fig.8 Bed deformation from the initial flatbed pre- and post- weir removal (Case7-8)

If simply quantifying the non-uniformity of the bed sediment with σ_g, there are several interesting findings. At the pre-removal stage, the weir pool area decreases with an increase of σ_g. Moreover, the head of the sandbar protrudes into the weir pool and the protruding length increases with an increase of σ_g. In addition, the elevation of the bar head is higher if the value of σ_g is larger. Due to the protruding of the bar head, the weir pool exists only along the two sides of the channel in Case8. As to the sandbar system in the upstream channel, alternating bar is clear in the uniform case, i.e. Case1, while the bar system in the non-uniform cases is a bit difficult to be characterized. On the other hand, longitudinal streaks are visible from the figures, especially in Case8. These streaks are almost parallel to the side of the flume channel and show certain relationship with sand ribbons which will be discussed later. It may also indicate that sand ribbons influence both the bed composition and the bed morphology.

After the partial removal of the weir, the local scour develops at the proximity of the weir and the sandbar front approaches the local scour area in each case. In the uniform case, i.e. Case1, the wavelength of the alternating bar increases. In the non-uniform cases, i.e. Cases7 and 8, the bed level of the head of the sandbar is significantly lowered and the weir pool area is aggraded. As a result, weir pools are not distinguishable at the post-removal stage. The sandbar system in the non-uniform cases is not readily recognizable from the figures. However, the similarities of the contours suggest that there seem no inherent changes in the bar structures except certain changes in the wavelength and the wave height.

3.3 Water level and longitudinal bed slope

The water level and the bed elevation along the centerline of the flume are shown in Figs.9-11. For clarity, the impacts of the removal shape (U-series experiments) and the bed sediment heterogeneity (M-series experiments) are discussed separately.

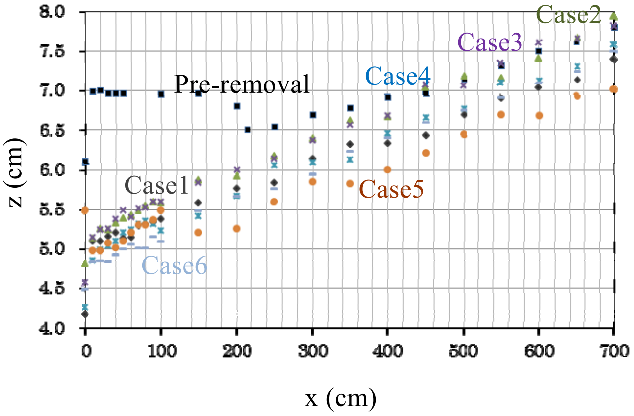


Fig.9 Water level along the centerline of the flume (Cases 1-6)

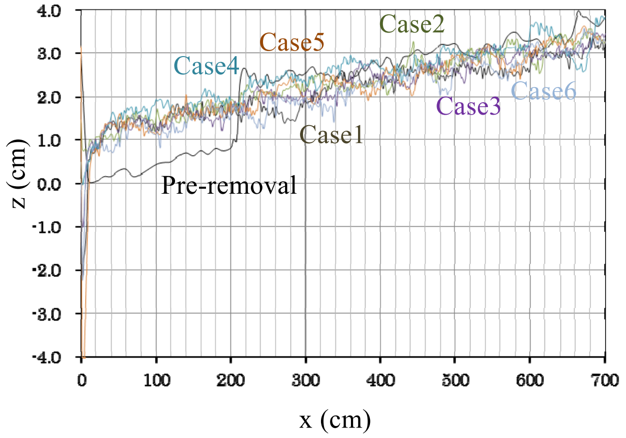


Fig.10 Bed level along the centerline of the flume (Cases 1-6)

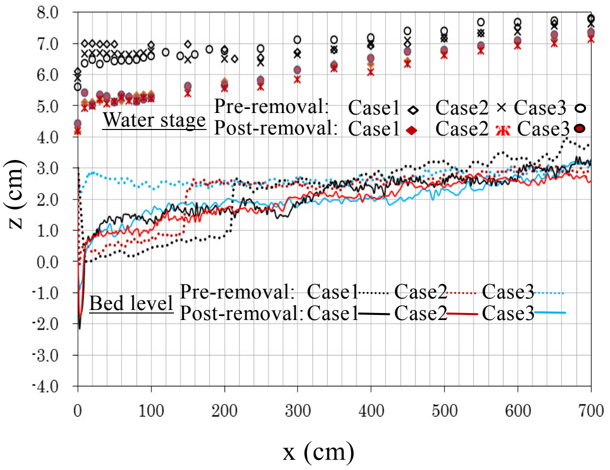


Fig.11 Water level and bed elevation along the centerline of the flume (Cases 1, 7 and 8)

Before the weir removal, the pool area is obviously distinguishable according to either the water surface profile or the bed level as shown in Figs.9 and 10. 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. 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, the slopes of the water surface and the longitudinal bed are very similar in the area a little far from the weir in all the post-removal cases, while discrepancies are recognized in the proximity of the weir. The observations and findings here well coincide with those in Fig.7.

Concerning the M-series experiments, the bed elevations vary a lot from case to case before the weir removal. A bigger σ_g generally corresponds to a higher bed elevation. The dominant bar front at the pre-removal stage is evident in each case. Immediately upstream of the bar front, the local bed slope becomes negative. Compared with the non-uniform cases, this slope is much steeper in the uniform case. The bar system is recognizable in the uniform case, but is not evident in the non-uniform cases. After the partial removal of the weir, the bar front propagates downstream and the negative slope area is enlarged in the uniform case. In the non-uniform cases, bed slopes become much steeper with the disappearance of dominant sandbar fronts and severe bed degradations. Bed level and bed slope are similar in the area far from the weir in the two non-uniform sediment cases. But near the weir, bed level is higher and bed slope is steeper in Case8 if compared with those in Case7.

Despite the great differences in the bed elevations, the water levels near the weir are very similar in all the M-series experiment cases, indicating that the weir structure plays an important role in controlling the water stage in its neighborhood. In the far upstream area, the impact of the weir becomes weak and the water level profile follows that of the longitudinal bed elevation in each case. Before the weir removal, the slope of the water surface is almost 0 or even negative, corresponding to the weir pool or the negative bed slope area following the dominant bar front. After the removal of the weir, water levels decrease. The decreasing amount is particularly large near the weir due to the significant change in the weir elevation there. Since the decreasing amount gradually increases from the upstream to the downstream, the slope of the water surface becomes steeper than that at the pre-removal stage either near the weir or far from the weir.

3.4 Local scour near the weir

It has been found in Figs. 7 and 8 that partial removal of the weir will promote local scour near the weir. The typical scour hole is sketched in Fig.12. Although the local scour covers a very limited area, it exhibits great differences from case to case according to Figs. 7 and 8. It is also found from the figures that the number of scour holes generally equals to the number of openings plus one in case of a partial removal. The scour holes may also change their geometries periodically according to the shifting of sand bars immediately upstream of them. In this study, the mean values of the scour hole depth of each case are selected to characterize the local scour phenomena and the maximum and minimum values are also listed for reference. These values are denoted as d, d_1 and d_2 correspondingly as shown in Table3. Moreover, representative angles showing the surface slope of the left-side scour hole are also listed.

Taking a look at the U-series experiments, 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. This may be explained by considering the mechanism of the formation of local scour holes, especially the strength of the vortex systems in the proximity of the weir section. It is understandable that stronger vortices are easily induced by the removal schemes with larger values of H^*/B^*, B_2/B_1 or B_s/B_0 as will also be seen in the plots of the velocity profiles later. The local slopes of the scour holes also deserve special attention. In each case, the slope in the longitudinal direction is generally steeper than that in other directions and the slope towards the centerline of the flume is generally steeper than that towards the side of the flume. The slopes of the scour holes are closely related to the local flow structure, particularly the strong circulating flows in the scour area.

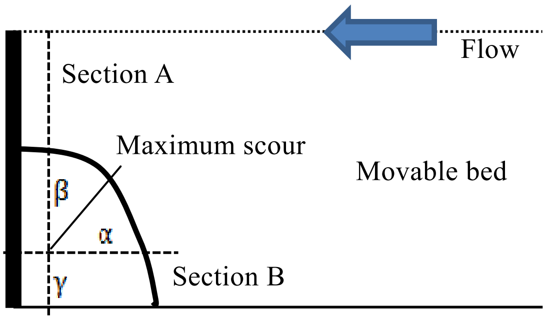


Fig.12 Sketch of scour dimensions

Table 3 Local scour dimensions

	Case1	Case2	Case3	Case4
H^*/B^*	3.125	0.781	-	-
B_2/B_1	1	-	0.333	0
$B_s/B0$	1	-	-	-
d_1(cm)	8.50	2.86	7.70	4.13
d_2(cm)	6.01	1.63	6.58	1.15
d(cm)	7.26	2.25	7.14	2.64
α(°)	32.0	32.0	32.0	33.0
β(°)	30.0	33.0	21.0	12.0
γ(°)	24.0	7.7	7.5	10.0

Table 3 Local scour dimensions (continued)

	Case5	Case6	Case7	Case8
H*/B*	-	-	-	-
B_2/B_1	-	-	-	-
$B_s/B0$	0.5	0.333	-	-
d_1**(cm)**	5.72	4.92	7.14	5.72
d_2**(cm)**	5.19	4.08	6.49	5.61
d**(cm)**	5.47	4.45	6.82	5.67
α(°)	31.0	28.0	27.0	30.0
β(°)	19.0	21.0	29.0	22.0
γ(°)	16.0	20.0	16.0	11.0

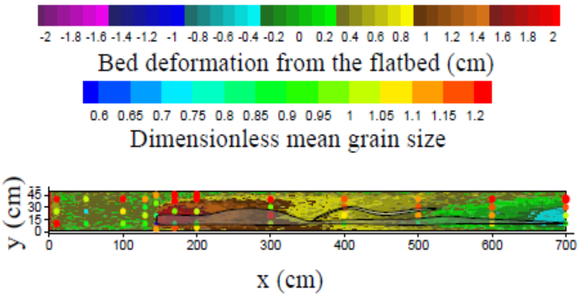
In the M-series experiments, the scour depth decreases and the local slopes increases with an increase of σ_g. The findings are similar to those of scour holes around a spur dyke as observed by Zhang et al. (2012) based on a series of experiments with non-uniform sediment. The sediment sorting process in the proximity of the weir is mainly responsible for this phenomenon. Similar to the results of the U-series experiments, the local slope of the scour surface in each case generally follows the sequence of α>β>γ , in which α, β and γ are local slopes of the scour hole in three representative directions as depicted in Fig.12.

3.5 Bed composition and sand ribbons

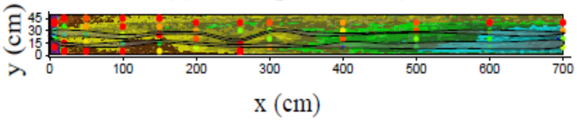
In the M-series experiments, the sediment transport not only promotes changes in the bed topography, but also results in changes of the bed composition. The appearance of sand ribbons as mentioned before is a phenomenon that requires special attention. The typical sand ribbons are shown in Photos 2 and 3 for Case8. During the experiments, the fine sediment stripes which are distinguishable with a naked eye are memorized and are sketched in Fig. 13, together with the bed contour maps. It has to be mentioned that the fine sediment here is not readily defined by a specific grain size. If the particles are obviously finer than the surrounding ones, they are termed fine sediment. Moreover, sediment particles in sand ribbons are not necessarily uniform. The dimensionless grain sizes, i.e., the ratios of the mean grain sizes of the quasi-equilibrium bed to those of the flatbed, at representative locations are also plotted in Fig.13.

Photo 2 Sand ribbons in Case8 (pre-removal)

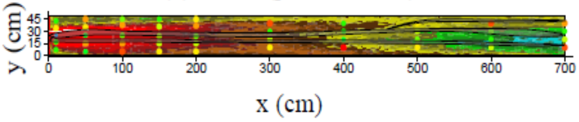
Photo 3 Sand ribbons in Case8 (post-removal)



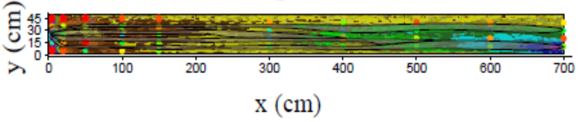
(a) Case7 (pre-removal)



(b) Case7 (post-removal)



(c) Case8 (pre-removal)



(d) Case8 (post-removal)

Fig.13 Dimensionless grain size distribution (scatters), sand ribbons (belts) and bed deformation (background maps)

The spatial variation of the mean grain size is evident according to Fig.13, which is a direct result of the sediment sorting process. The sediment sorting process occurs both longitudinally and laterally, triggering bed changes in terms of both configuration and composition. The sorting process is furthermore affected by the sandbar systems and sand ribbons. Consequently, the distribution of the mean grain sizes exhibits a very complex pattern. In general, sediment is coarser in the bed surface with a relatively higher elevation where the water is shallow and the flow is rapid. Due to the propagation of sandbars, the bed is generally degraded in the upstream part and is aggraded in the downstream part from the pre-removal stage to the post-removal stage. Correspondingly, the grain sizes generally become smaller in the upstream part and turn larger in the downstream part if one compares the post-removal stage with the pre-removal stage. However, the occurrence of sand ribbons makes the situation rather complex. It is found in Fig.13 that relatively fine sediment also appear in the bed with a very high elevation due to the existence of sand ribbons.

Sand ribbons are caused by lateral sediment sorting and are documented to exhibit a strong relation with secondary currents in channels (McLean, 1981, Tsujimoto, 1989, Colombini, 1993, Zhang et al., 2012). Since the formation of sandbar systems in the channel triggers much stronger secondary currents compared with a flatbed, the formation of sand ribbons in both pre-removal and post-removal stages are understandable. The sand ribbons are almost parallel to the side of the flume but show certain changes where bed level changes significantly, demonstrating that the properties of sand ribbons are directly affected by the sandbar structure. On the other hand, the characteristics of the sandbar system in the non-uniform beds are not unambiguous determinable and longitudinal steaks are visible in the bed contour maps as have been mentioned before. It suggests that the sand ribbons exert influences on the properties of the sandbar system. In other words, sandbars and sand ribbons are strongly coupled phenomena in non-uniform sediment beds.

3.6 Velocity profiles near the weir

The flow field around the weir is an important key to understand the sediment transport and bed variation processes. When local scour occurs, the flow generally becomes three-dimensional and is composed of complex vortex system. In this study, the velocity profiles in a typical transverse section A and a longitudinal section B (sketched in Fig.12) in the U-series experiments are measured. The experimental data is plotted in Figs.14 and 15, together with the bed profiles and weir sections.

An investigation on both the transverse and the longitudinal velocity profiles 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. Near the bed, the flow velocity is quite small. As a result, almost no 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 dramatically change and interact with each other. The plots showing the transverse cross section (Fig.14) suggest that the transverse velocity component has been intensified and that the directions of the velocity are strongly dependent on the geometry of the local scour holes. The intensified transverse velocity plays a dominant role in the lateral expanding process of the scour hole. In addition, weak vortices occur in Cases 5 and 6, corresponding to the scour geometries.

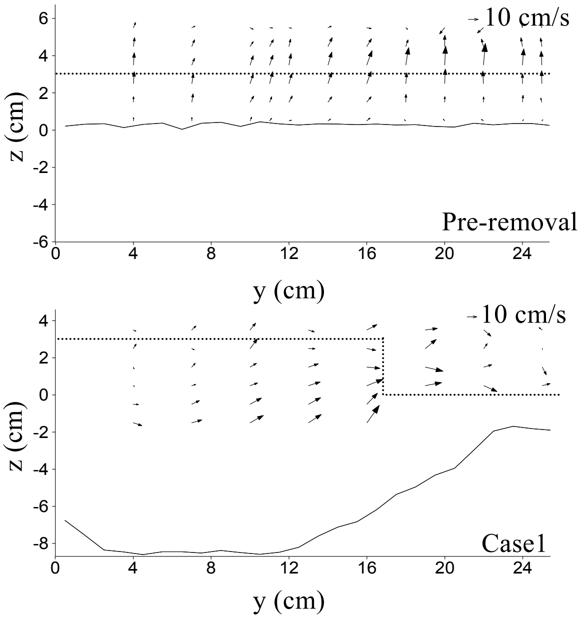


Fig.14 Velocity vectors (*v, w*) in the transverse cross-section A

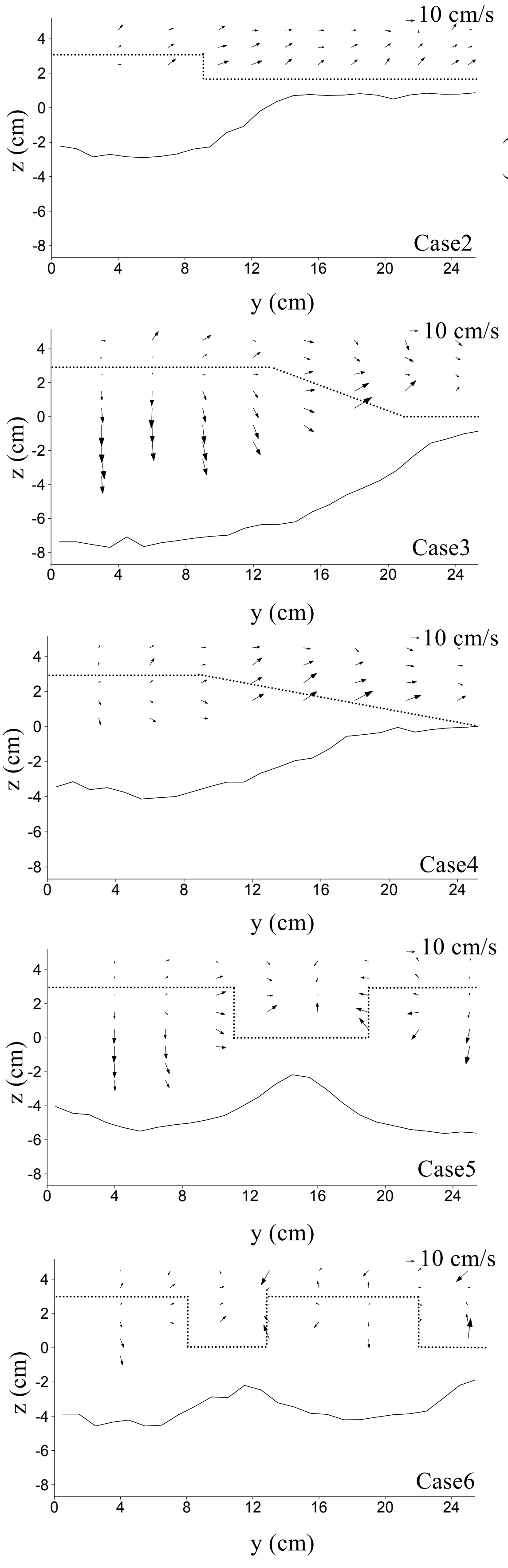


Fig.14 Velocity vectors (*v, w*) in the transverse cross-section A (continued)

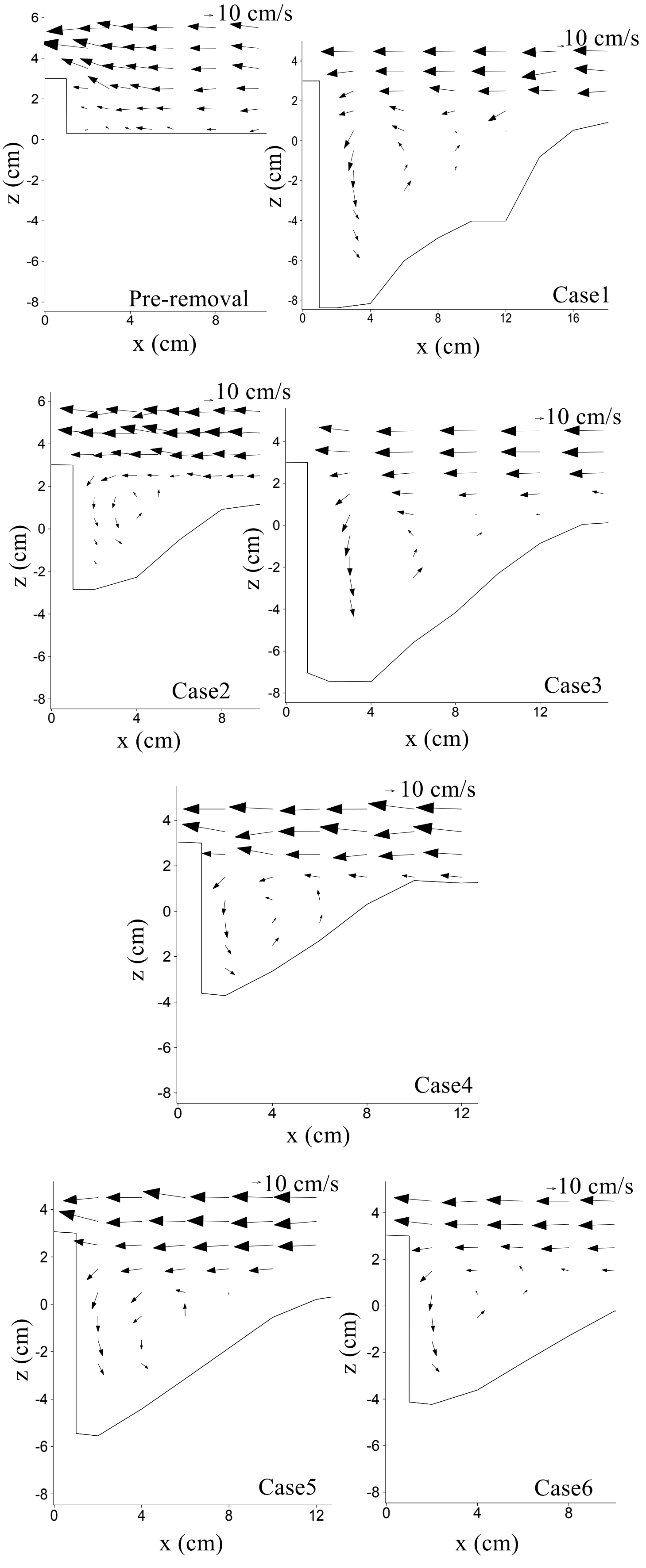


Fig.15 Velocity vectors (*u, w*) in the longitudinal cross-section B

Along the longitudinal section (Fig.15), an evident circulating flow occupying the local scour hole is observed in each case. This circulating flow is an energy source for the development of the scour hole in the longitudinal direction.

It is also found that the bed level at the openings of the weir section is generally higher than the surrounding area. As a result, the flow is directed to the openings with an upward vertical velocity component. The observations suggest that the partial removal of a weir triggers several 3D vortices and these vortices are the major controller of the scour process around the weir. The transverse velocity components are sensitive to the removal shape of the weir. Therefore, by carefully selecting the removal shape, the transverse velocity and the local bed profiles may be altered as desired.

4. Discussions

The results obtained from the experiments demonstrate that the partial removal of a weir structure exerts great impacts on the upstream channel dynamics. The following parameters and processes are considered to be of great importance prior to a removal action.

According to the results of the current experiments, it is found that σ_g is the most dominant parameters to characterize the responses of the upstream channel to a weir removal action in non-uniform sediment beds if the mean grain size is kept constant. Therefore, the mean diameter D and the geometric standard deviation σ_g may be used as simple indicators in the analyses for practical uses.

The experimental observations and quantifiable data indicate that the sediment sorting process is an important phenomenon in non-uniform sediment beds. The dominant flow and the secondary flow trigger sediment sorting both longitudinally and laterally. The sediment sorting processes influence the channel geometry, the bed resistance and the bed composition. Consequently, bed morphology in a non-uniform bed exhibits quite different features from that of a uniform bed. The topographic patterns of sandbars in a non-uniform bed are more irregular than a uniform one and are not easily determinable mainly due to the formation of sand ribbons. Although more quantitative information is needed to understand the weir removal impacts on the sediment sorting process, it is evidently confirmed that the weir removal will likely enhance the lateral sediment sorting process.

The removal shape continuously controls the local scour development and influences the propagation velocity of the sandbar front before it approaches the weir proximity. Nevertheless, the final sandbar properties 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. Since it takes time for the self-adjustments of the flow and the bed, the removal shape has a chance to make influence but on limited area and within limited time before the completion of the self-adjustments.

Three dimensionless parameters H^*/B^*, B_2/B_1 *or* B_s/B_0 have been proposed to characterize the removal shape. According to Figs.14 and 15, 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 hence what kind of scour phenomenon may be expected. In addition, it also sheds a light on possible prediction of the local scour depth. Unfortunately, the limited experiment data in this research 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

A series of experiments on the upstream channel response to the partial removal of a weir structure have been performed.

Weir removal promotes local scour near the removed section and sandbar development in the upstream channel. The two processes dominant the hydraulic and morphological processes in the channel. Both the local scour and the sandbar development are strongly related to sediment non-uniformity. Moreover, sand ribbons appear in non-uniform sediment beds as a result of lateral sediment sorting, which furthermore promote coarse sediment movement and the development of sandbars and hence exert impacts on the flow structure. 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 characteristics of upstream sandbars before the disappearance of the weir pool but does not exhibit significant influences on the final properties of the sandbar system at the quasi-equilibrium stage. The removal shape can be characterized with three dimensionless parameters, i.e. H^*/B^*, B_2/B_1 or B_s/B_0. 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 necessary to further the understanding on and to characterize the flow structure and the sediment movement.

Acknowledgements

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堰の部分撤去による上流河道の応答特性

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要　旨

本稿は，堰の部分撤去による上流河道の水理学及び地形学的な応答特性に関する実験的研究である。特に，堰の改変形状及び河床材料の粒径特性について注目した。堰を部分撤去した場合は，堰周辺には局所洗掘，河道上流域には砂州の移動が生じた。堰の改変形状が堰近傍の三次元流れ場及び局所洗掘を促進し，上流砂州の伝播特性にも影響していることが確認された。準平衡状態においては，砂州の特性は堰の改変形状よりも堰の改変面積との関連性は深いことが示された。混合砂での実験では，河床材料の平均粒径及び標準偏差による河道の応答特性に大きいな違いが見られた。また，河道横断方向の流砂分級現象による河道縦断方向にはサンドリボンと呼ばれる細粒径砂による帯が形成され，そのサンドリボンは河床地形に影響を及ぼすことも確認された。

キーワード：ダム・堰撤去，河道応答特性，砂州，局所洗掘，サンドリボン