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An Experimental Study on Bed Degradation Due to Falling Works Improvement

AN EXPERIMENTAL STUDY ON BED DEGRADATION DUE TO FALLING WORKS IMPROVEMENT

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ABSTRACT

There often exists a conflict between flood alleviation and environmental preservation in river management. One of the problems is how to design and construct the river-crossing structures such as dams and falling works. Some attempts in order to restore and/or compensate river consecutiveness divorced by the structure have been adopted, however its effect on river bed morphology is not well explored yet. A series of laboratory experiments were conducted to study effects of falling works improvement on degradation and instability of the bed in their upstream reach. How a pool in the upstream and a sand bar in the non-affected reach is changed according to modifying the falling works are of particular interests. After the modification the pool is shrunk or even disappeared when the weir is totally removed. In this case a sand bar extends in the whole area and the sand wave migration can seen. The results indicate that the falling works improvement can contribute the river scenery being restored into a natural condition.

Keywords: falling works, bed degradation, sand bar, experiment

1. INTRODUCTION

Falling works usually contribute river bed stabilisation, but they at the same time bring some defects especially on river environments. It is well known that falling works yield a pool, stop and deposit sediments in their upstream reach, and sometimes prevent fishes from migrating up- and downstream. Moreover the pool itself changes river scenery and the condition of the habitats quite a lot (American Rivers, 2002). Several engineering schemes can be considered to improve such a situation, i.e. full removal, weir height reduction, redesigning of the body such as slit-type, fish way appendage, etc.

The schemes rebuilding the structure itself, however, naturally cause bed degradation, and possibly introduce instability of the bed. Recently in the United States, dam removal is recognised as a one of effective tools for river environment restoration, and nearly 500 dams have already removed (American Rivers, 1999). Pizzuto (2002) summarises geomorphic processes related to dam removal and scope of further necessary research. Several literatures can also be found treating the channel form and sediment dynamics regarding dam removal (Stanley & Luebke, 2001; Cheng & Granata, 2007). However most of them deduced results from field observations, thus river bed change due to structural rebuilding has not yet been studied well, especially the relation between impact on the structure and response of the river geometry is not systematically explored.

Based on the aforementioned recognition, a series of laboratory experiments were conducted to study effects of falling works improvement on degradation and instability of the bed in their upstream reach. A model falling works was set in a straight flume and uniform silica was filled in the upstream reach as a movable bed. Water surface profiles and quasi-equilibrium bed configurations were measured at the initial and final stages. Velocity distributions at the surface were measured while running the water in order to pursue changing processes of the flow field. Each improvement scheme was evaluated through the data analyses in the viewpoints of effectiveness in environmental restoration and validity in flood alleviation.

2. Experimental Set-up

The experiments were carried out at Ujigawa Open Laboratory, Disaster Prevention Research Institute, Kyoto University. A straight flume of 21m long, 0.5m wide with a rectangular cross section made of glass (side wall) and steel (bed) was used. Bed material was silica whose mean diameter was 1.56mm. A model falling works of 11.7cm height was set at 13m from the flume entrance, and the movable and fixed beds are set in its upstream and downstream reaches respectively. The set-up thickness of the bed material in the movable bed reach was 8.5cm or 11.7cm, in which the former developing a pool in the initial condition (Cases P) and the latter being full deposition of the sediment (Cases D). Firstly an initial equilibrium bed was formed under a stable discharge shown in Table 1, then an improvement was adopted to the model falling works, and the same discharge was again given until a quasi-equilibrium bed configuration was eventually established. The experimental condition on the sediment transport was a live-bed one where τ_*/τ_{*c} was about 2.0. The hydraulic conditions of the experiments are summarised in Table 1. The studied conditions as to the falling works improvement are shown in Table 2. For example, for Case P-F32, initially the weir sticks out of the sand bed, but after the improvement the top of the weir matches with the sand bed, whose height from the flume bed is 8.5cm.

Table 1 Hydraulic conditions.

Discharge: 8,160cm^3/s	Flume bed slope: 1/200	Norm. shear stress: 0.070
Water depth: 4.18cm	Reynolds number: 14,000	Mean d of the sediment: 0.156cm
Sectional velocity: 39.0cm/s	Froude number: 0.66	Norm. critical shear stress: 0.036

Table 2 Experimental conditions – falling works improvement.

Weir removal size	Initially forming a pool	Initially fully deposited
(Initial)	Case P0	Case D0
32mm, full width remove	Case P-F32	Case D-F32
16mm, full width remove	Case P-F16	--- (not conducted)
32mm, 1/3 width remove	Case P-P32	Case D-P32
16mm, 1/3 width remove	Case P-P16	Case D-P16

When the initial and final quasi-equilibrium bed conditions were established, water surface profiles were measured at the centre of the flume by a pointer gauge. Subsequently the bed configurations were measured by a laser range finder after the pump stopped and the water fully drained. While running the water, flow patterns on the surface visualised with the aid of PVC powder were captured by a digital video camera. Then velocity distributions were calculated by a self-developed PIV software (Fujita, 1998).

3. Results and Discussions

As shown in the followings, the changing processes of bed configurations and their final conditions are somewhat different between Cases P, initially forming a pool in the upstream, and Cases D, initially sediment fully deposited. In order to secure the clarity on the phenomena and the effect of falling works improvement, these cases are separately discussed in this chapter.

3.1 Cases P: initially forming a pool in the upstream

Figure 1 shows water surface profiles before and after the falling works improvements for Cases P. It is clear that the water depth decreases after the improvements for all the cases. Reduction of the water depth is larger as closer to the weir. As a result a pool initially formed in the upstream is shrunk, or even totally disappeared in Case P-F32 judging from the water surface gradient.

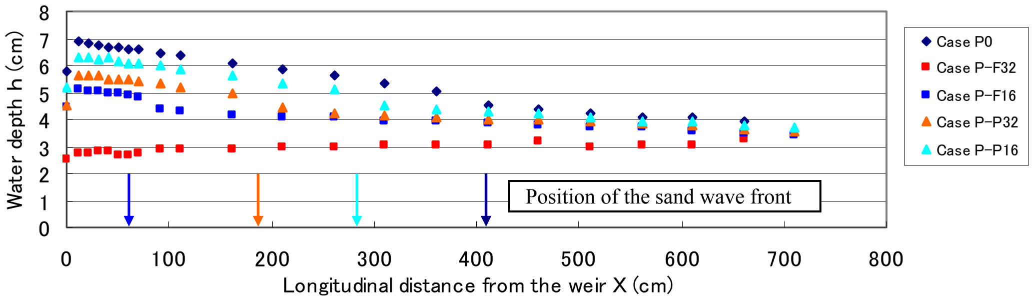

Figure 1 Water surface profiles in the upstream of the weir for Cases P.

As to a general relation between the change of the depth and the improvements, the depth decreases larger when the amount of the weir removal is larger. In this study the removal is considered in both the vertical (height) and lateral (width) directions, a removed cross-sectional projection area of the weir is introduced in order to deal with the effect of the improvement synthetically. The relation between the removed cross-sectional projection area and the depth reduction is shown in Figure 2. The figure clearly shows that they have a strong positive correlation, and a correlation curve is also drawn in the figure.

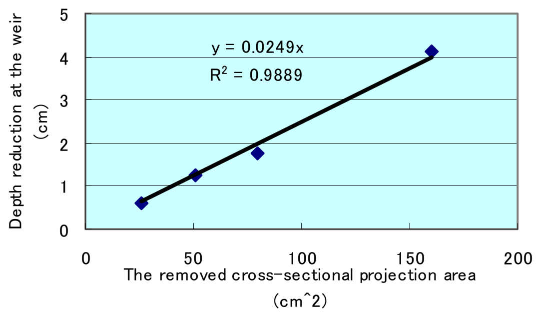

Figure 2 Removed projection area of the weir vs. depth reduction for Cases P.

Bed geometry contours for Cases P are shown in Figure 3. At the initial condition, Case P0, an alternating bar can be seen but only in the upstream reach apart from the weir with some distance, because of the existence of the pool. A sand wave front is formed at around the entrance of the pool. The position of the front is indicated in Figure 1. This front plays a role of a kind of boundary, i.e., a live bed and a developing bar in the upstream, but a static flat bed in the downstream. After the weir is removed the bar develops toward the downstream, particularly for Case P-F32 the bar even reaches the weir. The area where the alternative bar newly developed is partly degraded as forming a thalweg, and becomes unstable due to the sand wave migration.

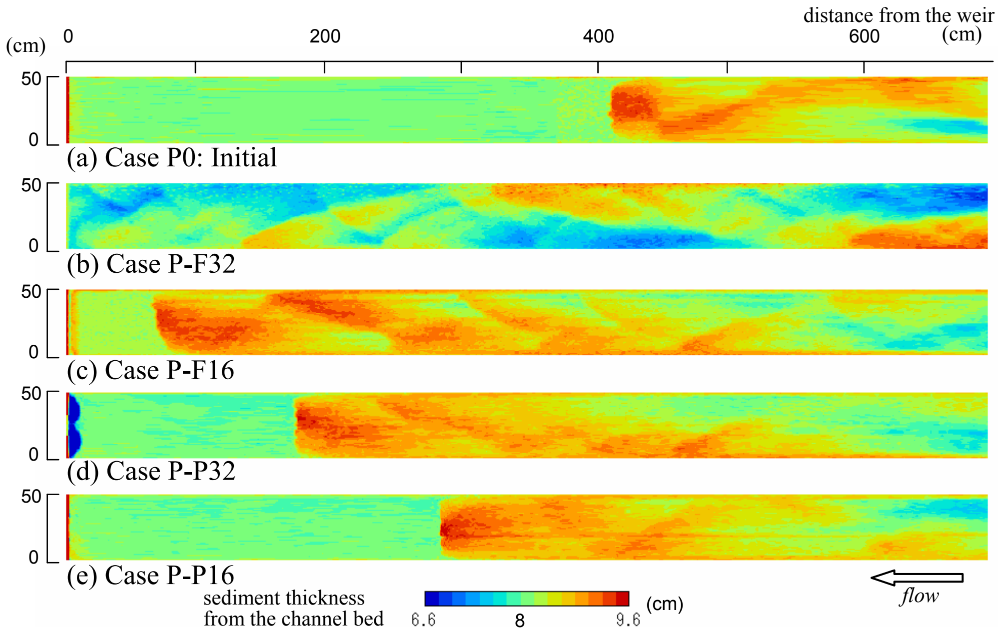

Figure 3 Bed geometry contours in the upstream of the weir for Cases P.

However, for the cases other than Case P-F32, the sand wave front still exists on the way and bed conditions are different across the front. Figure 4 shows passages of the front migration for Cases P-F16, P-P32 and P-P16. Each experiment was finished when the passage of the front is recognised almost stopping (migration speed less than 1cm/min). The bed contours shown in Figure 3 were taken at this timing. The relation between the removed cross-sectional projection area and the left length of the pool is shown in Figure 5. The figure shows a strong positive correlation between these two parameters.

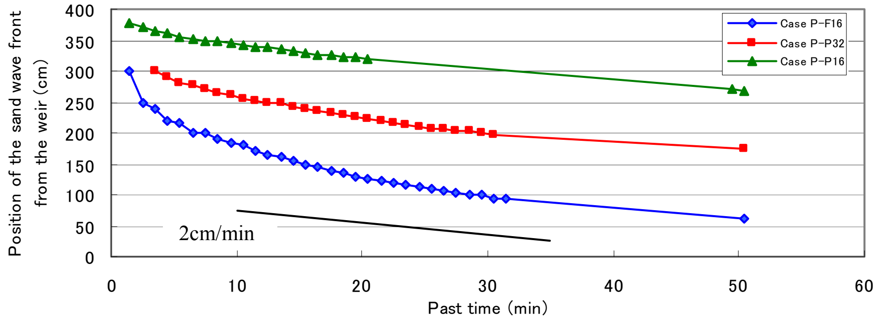

Figure 4 Passages of the front migration for Cases P.

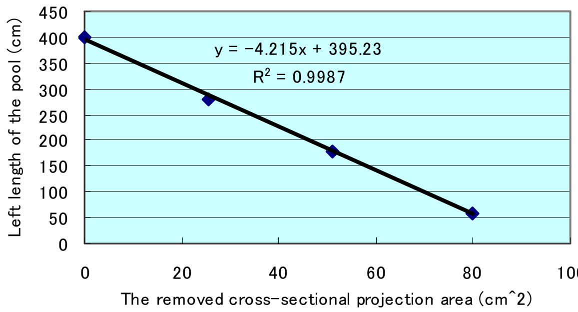

Figure 5 Removed projection area of the weir vs. left length of the pool for Cases P.

It was quite difficult to measure directly the bed evolution process in the experiments. So, velocity distributions at the surface were measured alternatively in order to pursue changing processes of the flow field. It is deemed that velocity distributions reflect to some extent the structure of bed geometry such as a bar formation. Figure 6 shows an example of this relation. Figure 6(b) shows velocity distributions for the lateral component, a blue-coloured area indicates the flow towards the left side bank, and a red-coloured area towards the opposite. One may notice in this figure that a blue area and a red area lie alternately, and its periodic appearing distance well coincides with a wavelength of the sand bar seen in Figure 6(a). Such a relation can also be seen in the longitudinal velocity distributions, Figure 6(c), that is, a faster flow area, indicated with blue-colour, exhibits a so-called wavy shape, which seems to be well correlated with the thalweg formed with an alternating bar (Figure 6(a)).

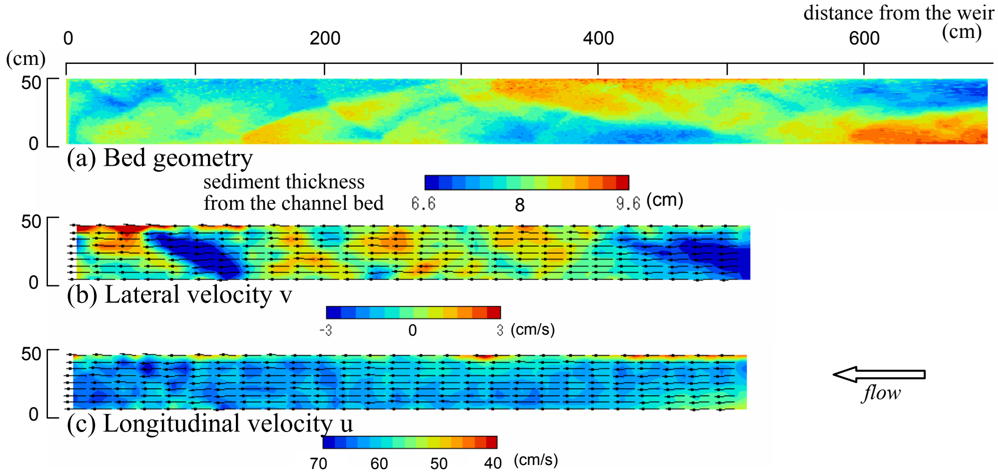

Figure 6 Relation between bed geometry and velocity distributions (Case P-F32).

Figure 7 shows temporal variation of the velocity distributions for Case P-F16. At the initial condition, (a), the fastest flow area is observed at around x=360cm, where just beyond the sand wave front. Velocity is gradually decelerated in the pool as approaching the weir. No wavy distributions indicating an effect of sand bar shown in Figure 6 is seen. As the experiment proceeds, (b) to (d), the concentrated faster flow area disappears, indicating a distinct front is destroyed. However a relatively faster area and a slower area can clearly be

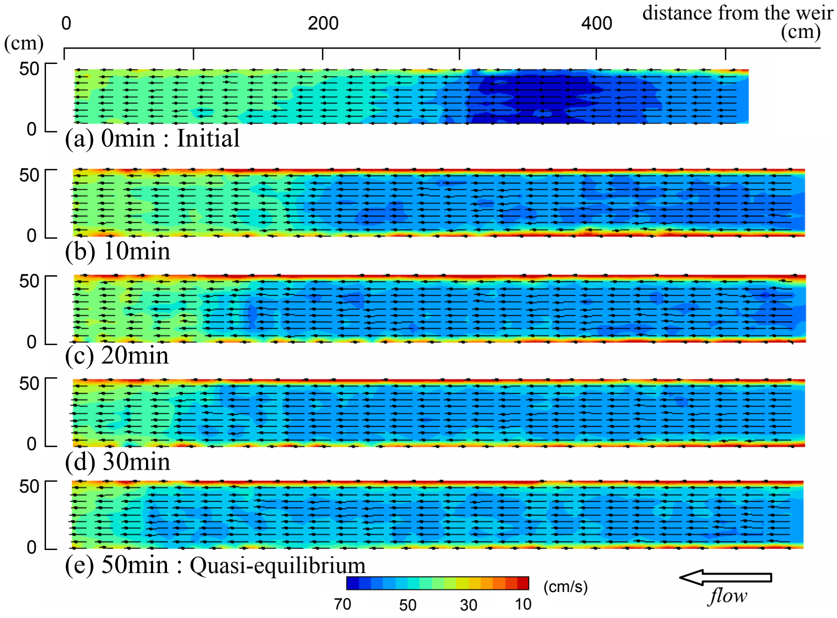

Figure 7 Temporal variation of the velocity distributions for Case P-F16.

recognised, suggesting that the pool still remains although gradually shrinking. After 30min. from the weir removal, (d), a wavy velocity distribution can be recognised a little in the faster flow area. Such a velocity distribution is much clearer in the final quasi-equilibrium condition, (e), indicating a sand bar is well developed in a corresponding area. From these results the bed evolution process after the weir removal can be supposed as follows: firstly the water depth decreases following the removal, then the sand wave front is collapsed and bed-load sediment proceeds into the pool area. Sediment transport takes place nearly evenly across the whole width at first, but an alternating bar develops gradually from the upstream. A new sand wave front is formed at the entrance of a shrunk pool. The other cases show a similar bed evolution process too.

3.2 Cases D: initially sediment fully deposited in the upstream

Figure 8 shows water surface profiles for Cases D. Here the vertical axis is taken from the flume bed, and longitudinal bed profiles at the centre of the channel are also shown. Overall the water depth, subtracting the bed from the surface, is not so much changed before and after the improvement. That is, the measured water depth was within the range of 3 to 4cm everywhere for all the cases, and no tendency to be pointed out was seen. More noticeable is the bed degradations, especially in the area close to the weir. Consequently the longitudinal bed slope, as well as the water surface slope, becomes much steeper than the initial one. Table 3 summarises the averaged bed slope together with the bed degradation measured at the weir. Figure 9 shows a relation between the removed cross-sectional projection area and the measured bed degradation. Here again shows a positive correlation.

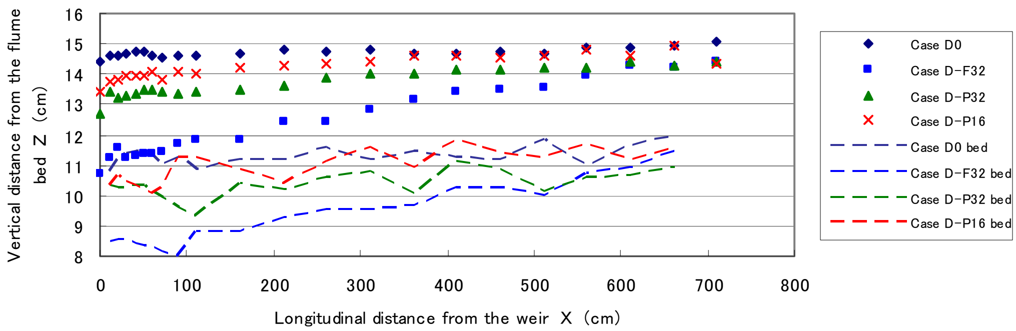

Figure 8 Water surface profiles in the upstream of the weir for Cases D.

Table 3 Bed degradation and bar formation for Cases D.

	Bed degradation		Sand bar formation	
	Averaged bed slope	ΔZ at the weir (cm)	λ_B/B	Z_B/B
Case D0	1/180	---	1.32	0.023
Case D-F32	1/100	2.96	2.35	0.026
Case D-P32	1/150	1.24	1.23～1.63	0.023
Case D-P16	1/170	0.53	3.57	0.063
λ_B : wavelength of the bar, Z_B : height of the bar				

Bed geometry contours for Cases D are shown in Figure 10. At the initial condition, in contrast to Case P0, no pool is seen but an alternating bar is already formed in the whole reach. After the improvements the bar formation changes, however, how much it changes seems to depend on how far the weir is modified. For Case D-F32, removed in full width for example, the bar formation is still an alternating one but its wavelength increases. Whereas for Case D-P32, removed in 1/3 width, the formation partly changes to a double raw bar. For Case D-P16, removed in 1/3 width but the removed depth smaller, an alternating bar with a

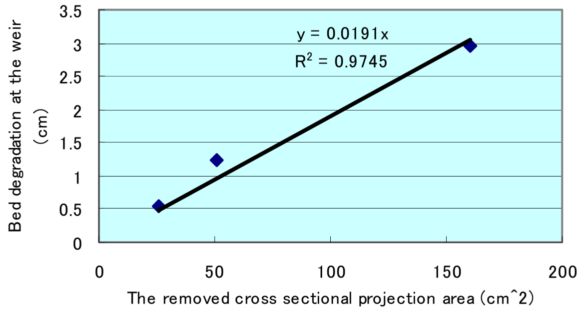

Figure 9 Removed projection area of the weir vs. bed degradation for Cases D.

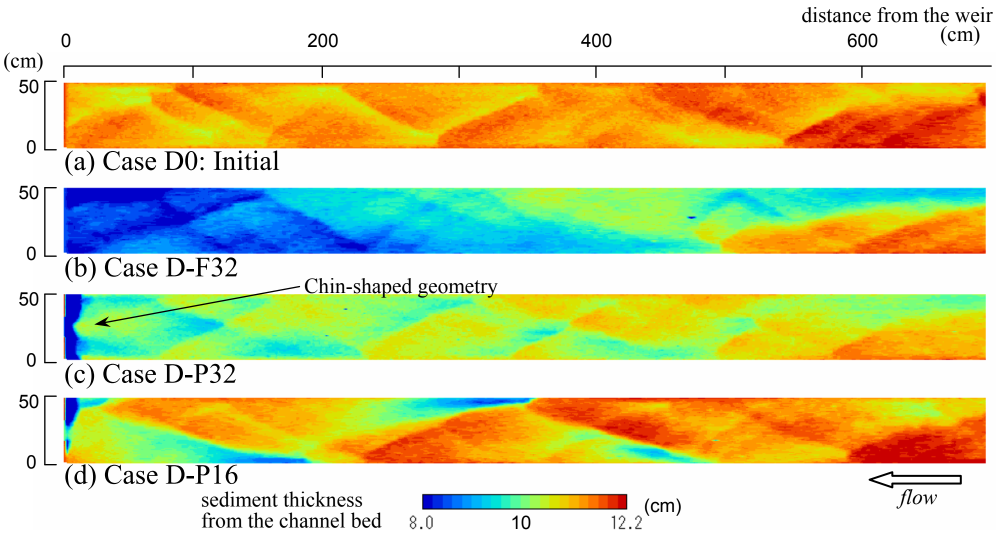

Figure 10 Bed geometry contours in the upstream of the weir for Cases D.

longer wavelength is formed too. More notably, the height of the bar becomes larger and the thalweg is much clearer than those of the initial condition. Characteristic parameters as to the shape of the sand bar are summarised also in Table 3.

The bed slope change shown in Figure 8, and a resultant water depth change, is considered to regulate the character of the bar described above. Figure 11 shows categories of the bar formation and their boundaries deduced by Muramoto & Fujita (1977). In the figure the results of this study are also plotted. The figure indicates that the expected bar formations under the experimental conditions adopted here fall into the category of semi bar or alternating bar, but not including the double raw bar. A phenomenological consideration which explains the result in Case D-P32 should be necessary.

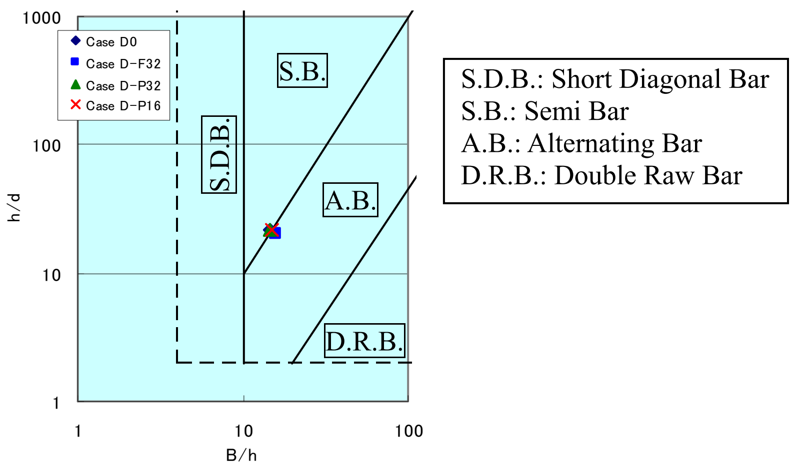

Figure 11 Categories of the bar formation by Muramoto & Fujita (1977).

From the observation for Case D-P32 during the experiment, a local scour in front of the weir is rapidly formed after the weir improvement because of flow concentration into the removed central area. At the same time a chin-shaped geometry, slightly higher than the ambient, is eventually developed in the centre of the flume, then remains there with some distance from the weir (indicated with an arrow in Figure 10). This geometry is fairly stable, and seems to play a trigger for developing a double raw bar. If watching carefully Figure 10, geometry for Case D-P32 is a mixture of an alternating bar and a double raw bar, and transition from the latter to the former can be seen towards the upstream.

Another fact which supports the chin-shaped geometry being the trigger is shown in Figure 12. The figure shows bed geometry contour for an additional case not listed in Table 2, where the improved scheme for the weir is the same as that of Case D-P32, but additionally a channel was made in the upstream to fit the geometry to the improved weir, making a so-called complex cross-section as an initial condition. One can notice that a simple alternating bar, quite similar to Case D0, is formed, but it is much different from the result in Case D-P32. It should be stressed that in this additional case the area to be forming a chin-shaped geometry is removed beforehand when constructing the complex channel, this may lead to the different result although the weir removal shape is the same as Case D-P32.

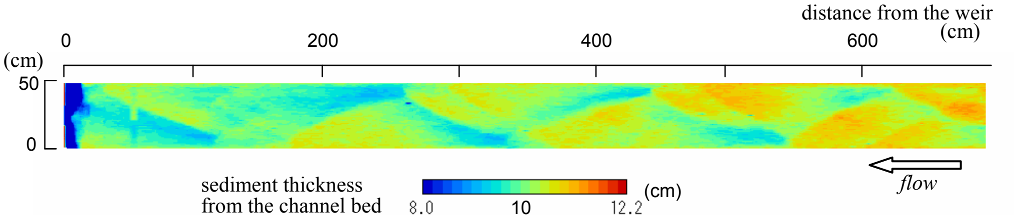

Figure 12 Bed geometry contours in the upstream of the weir for the additional case.

On the other hand, the results in Case D-F32 and Case D-P16 coincide with the categories indicated in Figure 11, an alternating bar. However, the bar in Case D-P16 can be recognised more developed, but that of Case D-F32 seems to be diminished. Naturally the shape of the weir influences the bar formation. In other words, there exist some conditions in the weir removal which enhance/deteriorate the development of thalweg. The effect of the bed slope, which is currently considered not as a major determinant for bar formation, should also be explored. Further experiments should be necessary in order to study more closely the relation between the removed shape of the weir and how the sand bar develops.

4. Concluding Remarks

The effects of falling works improvement on bed evolution processes and bed degradation in their upstream reach are studied experimentally. If a pool is formed initially in the upstream reach, backwater effect due to the weir does not disappear unless the weir is fully removed. A new parameter of the removed cross-sectional projection area is introduced for estimating reductions of the depth and length of the backwater area following the improvement, and shows a good performance. On the other hand, for cases initially sediment fully deposited in the upstream, the removed shape of the weir has close relation with the final bar formation. The hydraulic condition adopted here simulates that under floods, thus fine geometry regarding thalweg may not properly be reproduced, especially for an area near the weir. Further investigations are necessary including a small discharge condition, and/or effect of unsteadiness.

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