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Recently, traditional river methods of construction have been reconsidered from a river landscape and ecological environment perspective. A spur dike is one such method of construction. However, the influence and character of spur dikes are not usually understood. This study uses a model for experiments to examine flows around spur dikes. Moreover, we have observed riverbed levels and flow velocities at a location 8.8 km from the mouth of the Akashi River. We examined the adaptability of the spur dikes to this river.

I. INTRODUCTION

In Japan, where death and injury frequently occur by flooding attributable to geographical and meteorological reasons, diversified banking and bank protection works have been provided from ancient times to protect human lives, property and agricultural crops from flood damage. The nation coexists well with rivers. Although flood control safety has been improved since the Meiji Era together with progress in modern civil engineering technology, in heavily populated urban districts where rivers are artificially straightened, fish and aquatic organisms lose their habitats, thereby accelerating destruction of natural environments. For this reason, today, a trend exists by which river construction methods are richly endowed with natural materials, numerous stones and wooden materials, to retain rich natural environments provided by rivers [1].

The Akashi River flowing through western part of Kobe City and Akashi City is a typical example of this sort of river. Many natural environment type constructions such as stone-lined bank protections, spur dikes and submerged wooden beds are structured from upstream to the river mouth. However, these structures are based mostly on experience and technologies gained centuries ago. Sufficient investigations to see if these river structures are adopted and functioning effectively in the highly developed modern society from flood control and environment viewpoints, have not been carried out yet. Many areas remain badly affected by flooding [2].

In this study, we attempted to clarify characteristics of flows and river bed deformations around spur dikes using field observations and model experiments that specifically examine stone-lined spur dikes constructed downstream from the Hirano bridge of the Akashi River. We investigated a method for reducing and controlling local scouring that occurs during floods to establish a reasonable design and work execution method for stone-lined spur dikes.

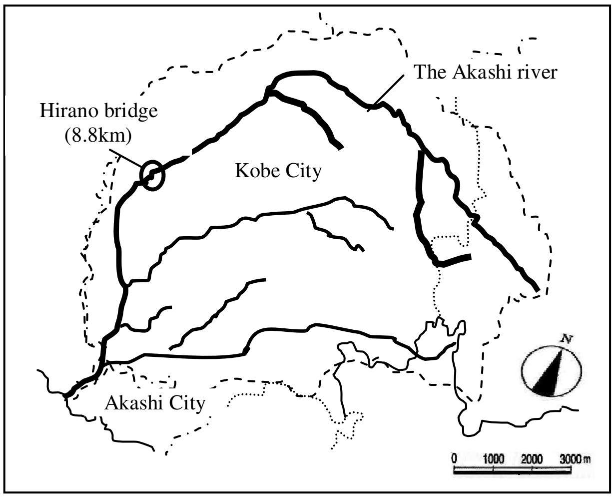


Figure 1. Outline of the Akashi River

II. SPUR DIKES IN AKASHI RIVER

The Akashi River is a main stream of the Akashi River system. Its source is in Kita-ward, Kobe City. Most of its watershed is in Nishi-ward, Kobe City. It is a class B river with river channel length of 26 km and a basin area of 126.7 km^2 (Figure 1).

Spur dikes provided in the Akashi River are of stone-lined impermeable overflow dikes constructed on the right bank downstream from the Hirano bridge located 8.8 km from the river mouth. Before these spur dikes were constructed, the foot protection block provided at the root of the high-water revetment was exposed as the concealed bank protection. Consequently, river bank water protection spur dikes were provided, which were aimed primarily at water turbulence to deepen channel erosion, providing current foot protection to the dike front edge, thereby suppressing velocity along the river bank. These spur dikes are expected to protect green vegetation of areas between spur dikes and provide diversified flow conditions around spur dikes, which engender good effects on ecological systems and water amenity.

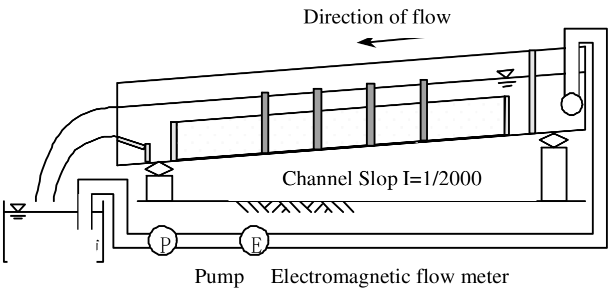
In all, 11 sets of spur dikes are installed outside the bends of the river channel downstream from the Hirano great bridge of the Akashi River (Figure 2). Of those, the current study examines five sets located at downstream division at the jog. To elucidate spur dike hydraulic characteristics, results of hydraulic experiments using scale models are compared with field observations after flooding.

Figure 2. Spur dikes of the Akashi River

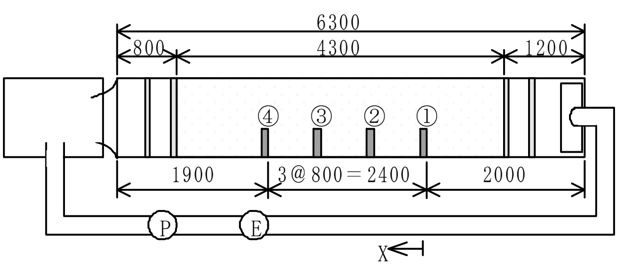
III. OUTLINE OF EXPERIMENTS

A. *Experimental apparatus*

Figure 3 shows an outline of the experimental apparatus. The water channel has a rectangular section that is 6.3 m total long, 0.8 m wide and 0.4 m high. Its sands are almost uniformly shaped, with average particle diameter of d = 0.088 cm, which were placed to form a 15 cm thick river bed of materials. Water suctioned from the underground water tank using a pump is introduced to the water channel via an electromagnetic type flow meter. It flows down the water channel and returns to the underground water tank. A current straightening part using filter materials is provided at the upper stream end of the water channel and a water level regulating plate that can be adjusted to an arbitrary angle is provided at the downstream end. The water channel gradient of the bed is adjustable using a jack, and four spur dike models are placed on the left bank 2 m from the upper stream end at 80 cm intervals.



(a) Elevation view



(b) Plain view

Figure 3. Outline of the experimental apparatus (Unit: mm)

For data arrangement reasons, the origin of the coordinates is placed at 2 m from the upper stream end in the down flowing direction (upper stream end of the first spur dike). The x-axis is set in the flow down direction and the y-axis is set from left bank wall to right bank. The z-axis is set in a vertical direction. The water channel floor bottom is considered as the origin.

B. *Spur dike model*

The spur dike model is made of impermeable material. The basic profile of this model is a rectangular section, as shown in Fig. 4(a). It is 18 cm wide, 20 cm high and 5 cm thick. This basic profile of the spur dike was sloped (1 : 1.5), as shown in Fig. 4(b) to represent actual sections of spur dikes used in the Akashi River. Experiments were carried out using this model.

C. *Experimental conditions and Experimental Method*

Experiments were conducted for seven cases while the flow rate and spur dike profile were changed as parameters. Details of experiments are shown in TABLE Ⅰ. The time for water flowing is 90 min for Run 4 and 120 min. for other cases.

For analyses of surface flow conditions, images taken from an oblique direction were corrected to perpendicular images and then subjected to Large Scale Particle Image Velocimetry (LSPIV) analysis developed by Fujita et al[3]. In the current study, punched refuse of 5 mm diameter was used as the tracer to investigate the relationship between river bed deformations around the spur dikes and surface flow velocity. The surface flow velocity around spur dikes was measured using LSPIV.

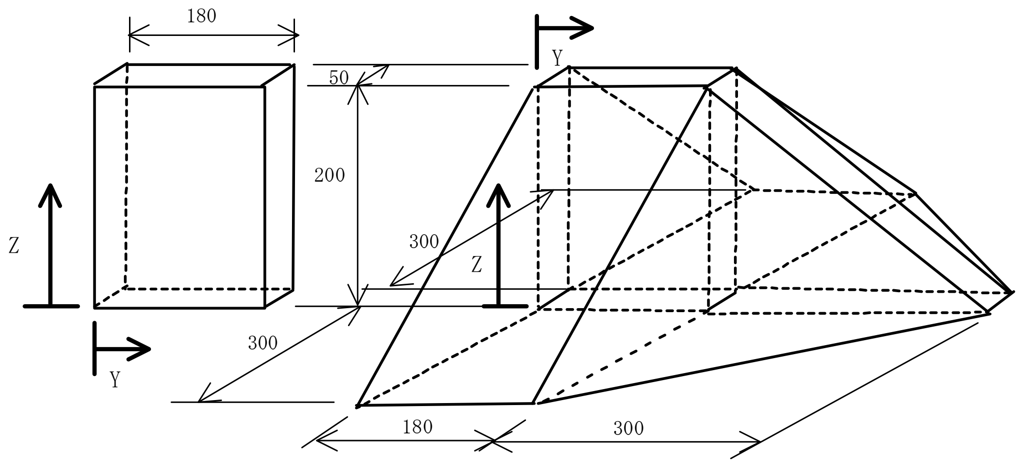
IV. RESULTS OF EXPERIMENTS AND DISCUSSIONS

A. *Critical friction velocity*

Local scouring around spur dikes falls into two categories. One is static scouring, by which the drag force is greater than the moving limit of river bed only around spur dikes; only river bed sands around spur dikes are moved. In addition, dynamic scouring occurs, in which the drag force is excessive and quicksand is created over the entire river channel. The moving limit friction speed of river bed materials (average particle diameter d = 0.088 cm) evaluated by Iwagaki's formula is U_{*cr} = 2.201 (cm/s).

TABLE Ⅰ
EXPERIMENTAL CONDITIONS

Run No.	Flow rate Q(l/s)	Time for water flowing t(min)	Overflow conditions	Profile of Spur dike
Run 1	18.20	120	Overflow	Basic profile
Run 2	8.25		Non-overflow	
Run 3	11.75		Partially overflow	
Run 4		90		
Run 5	18.20	120	Overflow	Basic profile + slope
Run 6	8.25		Non-overflow	
Run 7	11.75		Partially overflow	



(a) Basic profile (b) Basic profile + Slope

Figure 4. Profile of model (Unit: mm)

Results of calculation of friction velocity U_*, based on the uniform flow depth h_0, are shown in TABLE Ⅱ. The uniform flow depth used here is an average at the center of water channel (y = 40 cm), which does not traverse the levee crown of the spur dike longitudinally. The TABLE shows that $U_* < U_{*cr}$ in all cases and all are of static scouring.

B. Water Surface Profile

Figure 5 shows the water surface profile of Run 1, Run 2 and Run 3. Figure 6 shows water surface profile of Run 4, Run 5 and Run 6, in which a slope is provided to the basic profile. Measurements were taken at a section traversing center of the levee crown (y = 9 cm) of the spur dike longitudinally 120 min after commencement of water flowing.

Figure 5 shows that for flows overflowing the spur dikes, water splash effects are relaxed as the flow rate increases. It might be said that effects of roughness of the spur dikes are reduced because of the increased flow rate. In addition, for flows not overflowing the spur dikes, reduction of the water level is recognized at the rear of the spur dikes. Comparison of Figure 5 and Figure 6 reveals that when a slope is provided to the basic profile, water splash effects upstream from the spur dikes are relaxed. It might be said that this is attributable to the fact that flows are not concentrated in the upper stream portion of the spur dikes, but are rather dispersed by the slope. The water level in the downstream from the spur dikes is lowered rapidly because of the slope effects.

TABLE Ⅱ

UNIFORM FLOW DEPTH AND FRICTION VELOCITY

Run No.	Flow rate Q(l/s)	Uniform flow depth h_0(cm)	Friction velocity U_*(cm/s)
Run 1	18.20	5.97	1.60
Run 2	8.25	4.29	1.38
Run 3	11.75	5.34	1.52
Run 4			
Run 5	18.20	6.66	1.67
Run 6	8.25	4.44	1.40
Run 7	11.75	5.27	1.51

C. Scouring Characteristics around Spur Dikes

Deformations of the river bed from its initial state for each case 120 min after commencement of water flow are shown in Figure 7 in the form of a contour map. Each contour map shows measurement results: the black area signifies scouring and white areas denote deposition. The darker the color, the more scouring or deposition is generated. The following findings are apparent from Figure 7.

With the basic profile, the maximum scouring depth is developed at the front edge of the first spur dike in an inverted cone shape. It is always generated along with wall surface at upstream from the first spur dike. Scouring around each spur dike maintains a nearly identical shape between spur dikes regardless of the flow rate while its magnitude is decreased. Simultaneously, the maximum scouring depth becomes smaller with spur dikes located more on the downstream side. The maximum scouring depth and range of scouring around each spur dike become greater as the flow rate and time for water flowing increase. The maximum scouring depth of the first spur dike is always approximately twice that of the second spur dike and has a smaller flow rate. Scouring does not occur, except at the front edge of the third spur dike and onward. The maximum scouring depth of the first spur dike at the maximum flow rate (overflow conditions on spur dikes) is approximately twice that of the minimum flow rate (non-overflow conditions on spur dikes). The maximum scouring depth of the first spur dike reaches as deep as 75% of the spur dike height.

When a slope is provided to the basic profile, the maximum scouring depth is developed downstream from the front edge of the first spur dike and at the bottom of slope of the spur dike in inverted cone shape. It is generated along with the slope at front edge of the spur dike. Scouring around each of spur dikes maintains a similar shape regardless of the flow rate, but its magnitude is decreased. The maximum scouring depth becomes less with spur dikes located more on the downstream side, while it is stabilized on the third spur dike and onward regardless of flow rate. Therefore, at least three sets of spur dikes are necessary to form a group.

The maximum scouring depth of the first spur dike is reduced by about two times if the rectangular section is

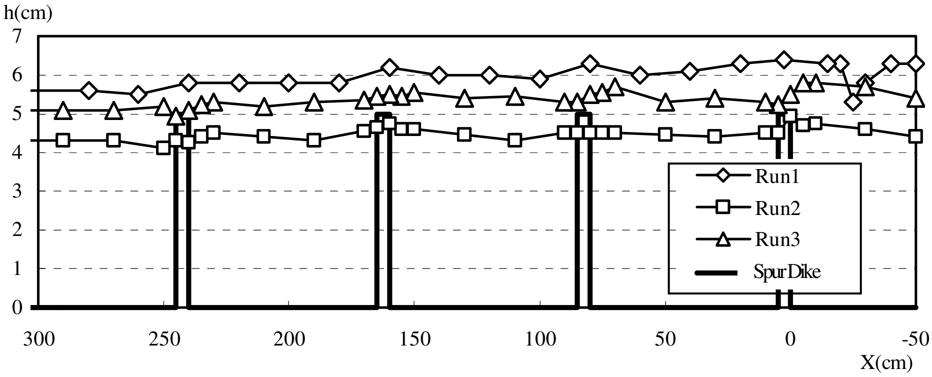


Figure 5. Water surface profile (Basic model, T=120min, Y=9cm)

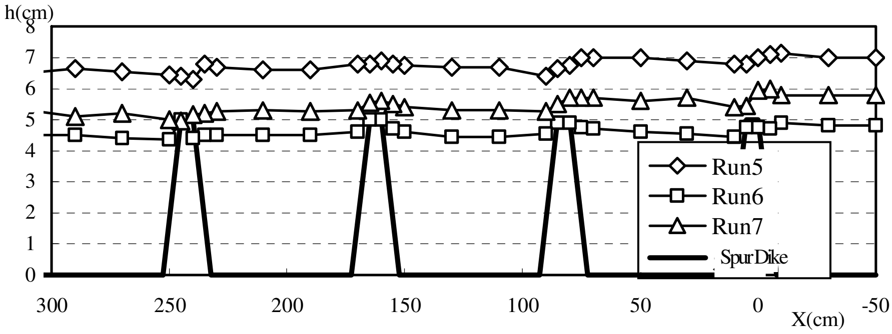


Figure 6. Water surface profile (Basic model+ slope, t=120min, Y＝9cm)

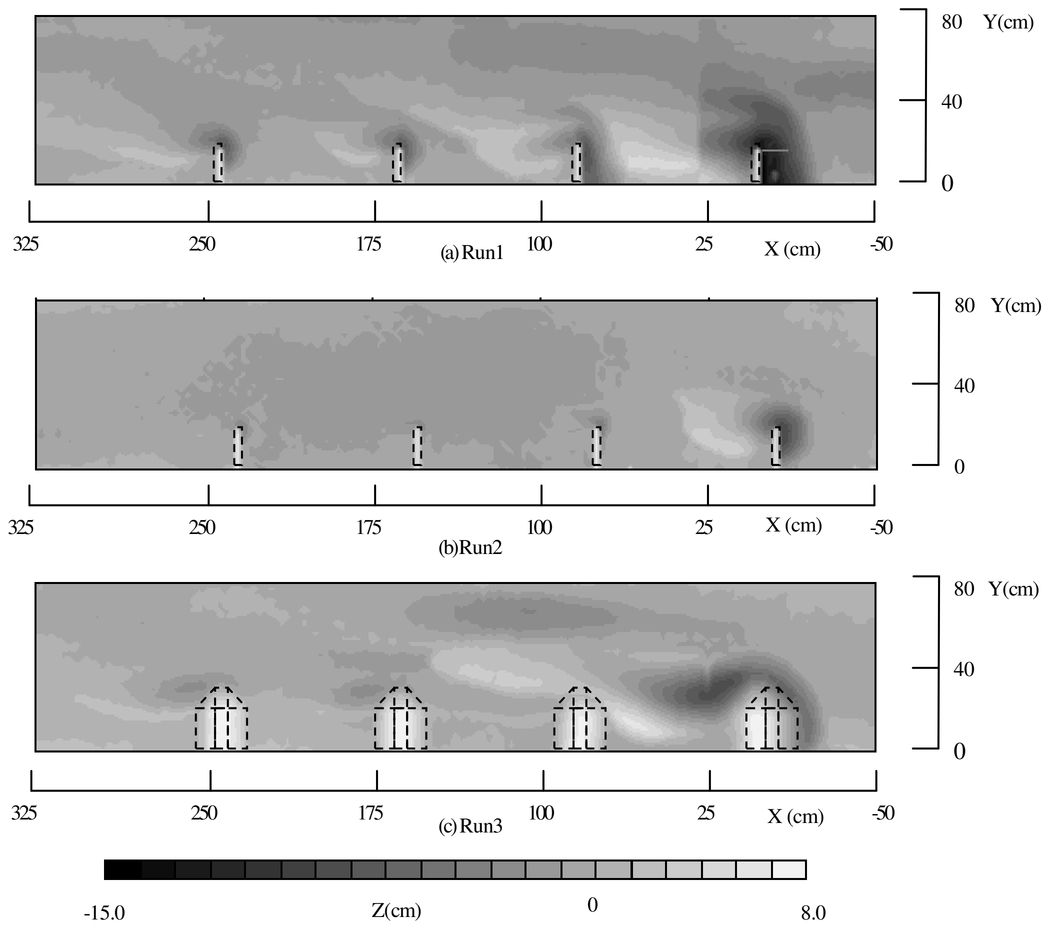


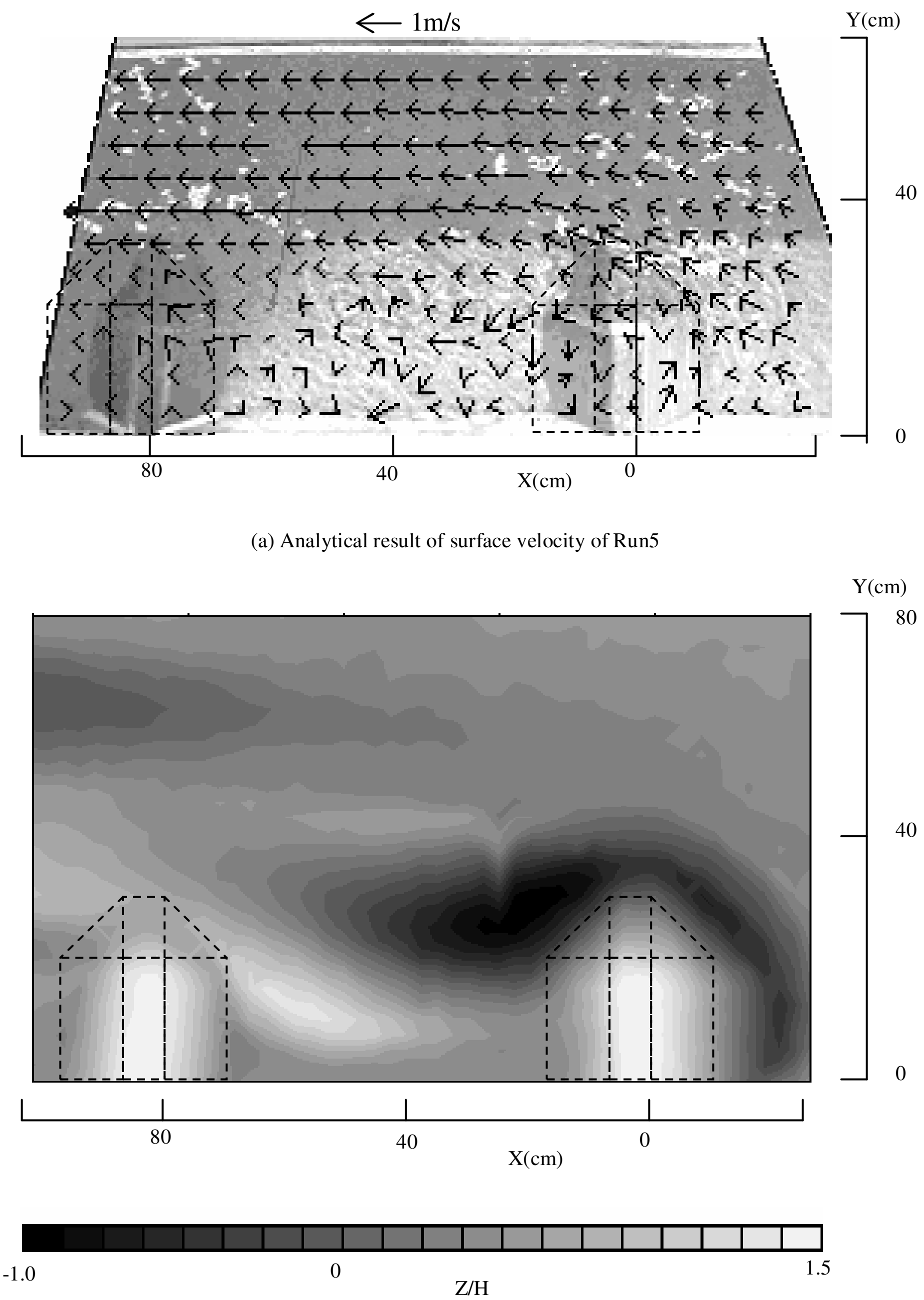
Figure 7 . Contour maps showing river bed deformation from initial state

replaced with trapezoidal section and is stabilized as constant regardless of the flow rate, indicating that scouring is reduced if the front edge angle of the spur dike is reduced. When the flow rate is increased, the maximum scouring depth is increased along with the slope. Accordingly, it is preferable that the downstream gradient should be made more gentle than that of upstream to allow gentle water flow and to prevent scouring downstream.

D. Surface Flow Velocity around Spur Dikes

For flow characteristics of the surface flow in the case of basic profile of spur dike plus slope, the following findings are apparent from Figure 8.

At the main stream part, the flow velocity is high and the direction of flow is nearly constant. Between spur dikes, flow velocity becomes slow and the direction of flow is not constant, thereby causing vortex flow. Upstream from the spur dikes, flow velocity is reduced because of the water splash effect and the maximum scouring depth that occurs on the extension line of fast flow generated along with the upstream slope. Accordingly, relaxation of the angle at front edge of the spur dike is useful for reducing scouring because it prevents the flow from being concentrated in one direction.



(a) Analytical result of surface velocity of Run5

(b) Contour maps showing river bed deformation from initial state in Run 5 (Unit: cm)

Figure 8. Results of LSPIV analysis and contour maps in Run 5 (Around the1-2nd spur dike)

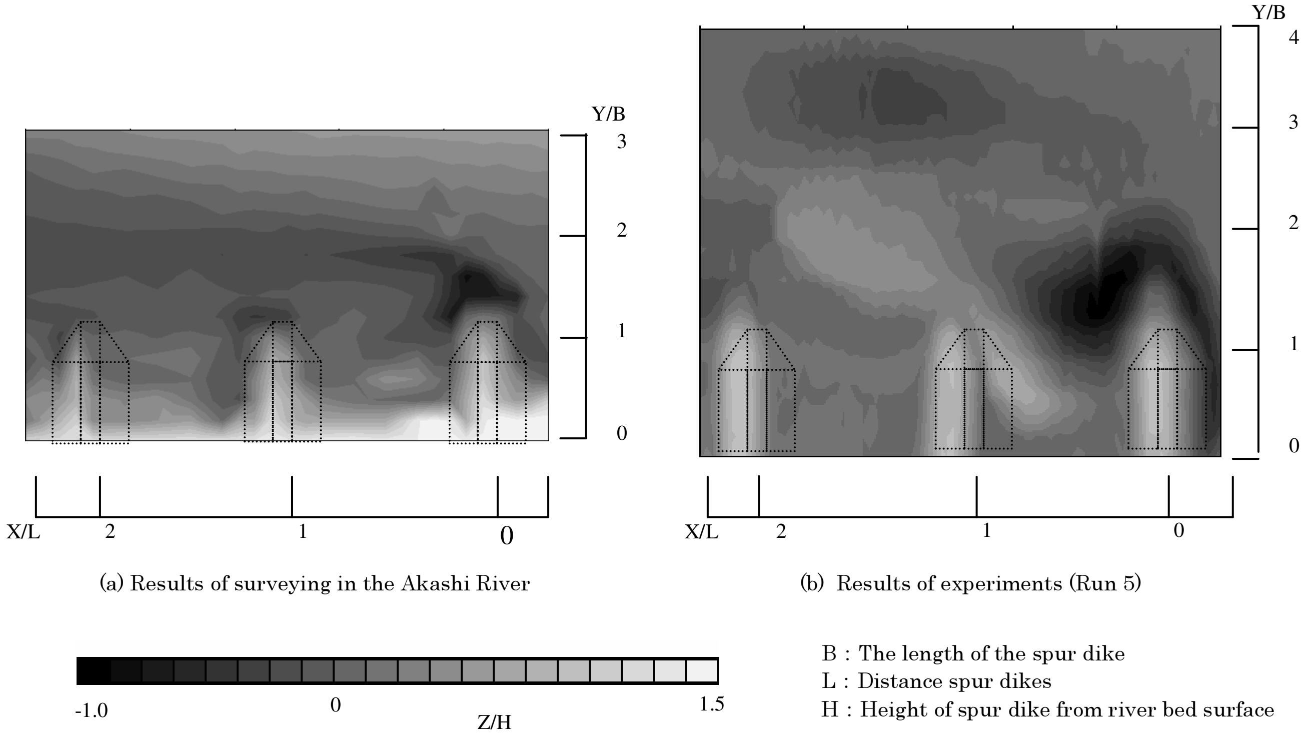


Figure 9. Comparison of dimensionless river bed profile (Around the1-3rd spur dike)

E. Comparison with Results of Surveying in Akashi River

Before our field observations, the Akashi River was heavily damaged by No. 23 typhoon, which hit this area in October 2004. Remarkable scouring phenomena resulting from flooding were apparent around spur dikes downstream from the Hirano greater bridge. The peak flow rate at flooding was calculated using water level data obtained at the Fujiwara observation station located about 4 km upstream from the Hirano greater bridge. The peak flow rate was calculated from the water level and length of the flood channel using Manning's flow rate formula as approximately 350 m^3/s. Meanwhile, the river bed gradient was 1/180 and the roughness coefficient in Manning's formula was set as 0.03.

If Froude's similarity rule is used, the flow rate of 350 m^3/s corresponds to the flow rate 18.20 l/s (actual flow rate 322 m^3/s), which is a condition for overflowing for all spur dikes in model experiments. Subsequently, comparison was made with experimental results (Run 5) relating to river bed deformation for spur dikes with a slope. Figure 9 shows results of the observation of the river bed profile around spur dikes in the Akashi River and experimental results (Run 5) expressed in dimensional form. For initial river bed height of spur dikes in the Akashi River, the average of the river bed height downstream was used; it was considerably less affected by spur dikes in the Akashi River.

Contour maps showing river bed deformation of the Akashi River shown in Figure 9(a) revealed that the maximum scouring depth was caused downstream from the front edge of the first spur dike. The maximum scouring depth in dimensionless form is Z/H = 1.0 while the same obtained from experimental results is Z/H = 1.5. Therefore, an identical tendency as that noted with model experiments was obtained. Reasons for that position of deposition and scouring configurations are different are attributable to that shape and materials of the river bank differ, sands are supplied constantly from upstream in the Akashi River. Furthermore, the river bed configuration is changed because of flooding that occurred in the past. Consequently, we infer that river bed deformation around the spur dikes can be predicted to a certain extent by model experiments in which local hydraulic conditions are examined.

V. CONCLUSIONS

In this study, for prediction of flow around stone-lined spur dikes and river bed deformation, river bed deformation because of the flow was elucidated using experiments with scale models. The relationship between flow and scouring characteristics was elucidated from surface flow velocity obtained by LSPIV method. For discussion, results of experiments were compared with results of observations of the actual river (Akashi River). Experimental results of position of scouring and dimensionless scouring depth exhibit similar characteristics to those observed with the river at the site, considering flow rate conditions and uncertainty.

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