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BED DEFORMATION AROUND GROINS IN A RIVER RESTORATION PROJECT

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This paper investigates the flow and bed deformation around groins under flood conditions in a river restoration project with both experimental and numerical methods. The experiments are based on a large-scale physical model and are able to resolve the local flow and sediment transport phenomena with a relatively high accuracy. The numerical models are formulated on an unstructured mesh and allow the exact representation of complex geometries, in particular the restoration structures such as groins. The numerical results have been compared with those of the experimental measurements. Reasonable agreements have been obtained in terms of both flow patterns and bed variations. The study suggests that the flood had significant impacts on the bed morphologies with quantitative evidences. The numerical models may serve as a promising tool for the decision-making and post-assessment in river restoration.

Key Words: *River restoration, groins, bed morphology, large-scale physical model, unstructured mesh*

1. INTRODUCTION

One of the most important tasks in the river restoration is to recover the channel morphological features, e.g. the reinstatement of the substrate, pool-riffle sequences and more natural bank forms[1]. The natural channel morphologies are adaptive evolution results of the long-term fluvial process, hence approaches to return rivers to that condition is expected to bring esthetic enhancements as well as to have a high potential and possibility for the improvements of the biodiversities and ecosystems. The commonly adopted human measures to restore river channels include groins, bank covers, weirs and randomly placed boulders. Amongst these, groins are documented to be the most durable solution and have been enjoying a widespread use in the engineering practice [2].

According to structure permeability, groins are classified into two kinds: impermeable and permeable. The former is generally built of local soils, stones, gravels or rocks and the latter consists of one or several rows of piles [3]. The two kinds of groins affect the flow field and sediment transport in different ways and result in various flow patterns and bed morphologies [4), 5)]. Therefore, impermeable and permeable groins may be organized in a group to achieve the maximum benefits during the design of restoration projects. Unfortunately, the problem is much more difficult than it physically appears. For a sustainable design, researchers and decision-makers need predict and evaluate the river morphodynamics due to restoration action. The river morphodynamics is a quite complex process involving a high degree of interactions between the flow and sediment transport under the influence of restoration structures and riverbed. This process necessitates characterization both qualitatively and quantitatively based on an insight into the underlying physics and mechanisms. Due to the inherent complexity, there is a great shortage of guidelines and analysis tools. It has led to a lot of failures in terms of both money loss and ecosystem damage. A recent example is the failure of a river restoration project on the Kizu River in Kyoto Prefecture. The project locates at about 6km upstream of the confluence where three rivers, i.e. the Uji River, the Katsura River and the Kizu River, joint together (**Fig. 1**).

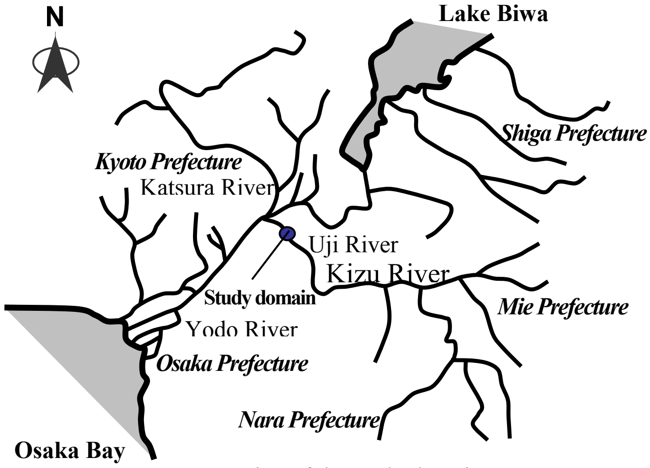

Fig.1 Location of the study domain.

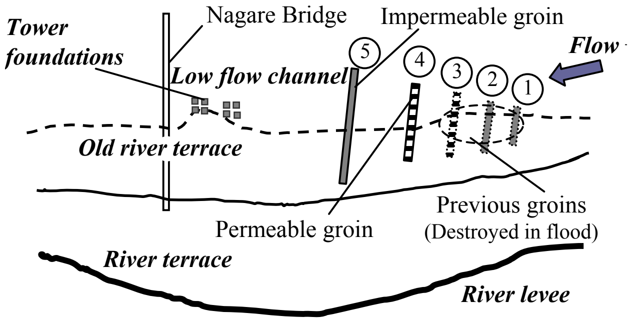

Fig.2 Sketch of the restoration project.

The project was built around an ancient wooden bridge: the Nagare Bridge, which is one of the most attractive sightseeing and recreation spots in this river basin. The main objectives are to restore beach landscapes and improve the riparian ecotones around the bridge. Restoration measures mainly include cutting down part of the river terrace and constructing 3 groins (①, ② and ③) as shown in **Fig. 2**. The project was completed in 2004 but soon failed in a typhoon-induced flood. The 3 groins were almost washed away. As a remedy, a permeable groin (④) and an impermeable groin (⑤) were constructed in the next year after an investigation of the effects of the two groins on the riparian restoration. However, the knowledge is still very poor on the river morphodynamics caused by these restoration actions. This research intends to evaluate the function of these two groins and seek the most cost-effective solution for possible improvements prior to further restoration actions. Both physical model experiments and numerical simulations were conducted. Some previous results may be found elsewhere [6]. This paper concentrates on the flow and bed deformation in the neighborhood of the two groins during a typical flood process.

2. PHYSICAL MODEL EXPERIMENTS

A large-scale physical model was constructed in the Ujigawa Open Laboratory, Kyoto University. The model represented the river sections from 4.4km to 7.4km with a physical scale of 1:65 (**Fig.3**). Details of the hydraulic structures such as the shape of the impermeable groin, the timber piles of the permeable groin (**Fig.3c**), the complex piers of the Nagare Bridge (**Fig.3d**) were reproduced to scale as well. Along the transverse section, the river consisted of a low flow channel with a floodplain on either side. The floodplain area was treated as fixed bed. The low flow channel was movable and was covered with coal powders after a comprehensive comparison with some other model sediment materials. The model sediment had a mean diameter of 0.83mm and a specific gravity of 1.41.

Continuous sediment supply was guaranteed during the experiments with an automatic sediment supplier installed at the upstream boundary. At the downstream boundary, a tailgate was used to control the water level. At section 4.6km, a point gauge was set to record the downstream water stage. The initial bed configuration was shaped using field data surveyed at some control sections in February 2005. Water level and bed elevation were measured at typical transverse sections during the experiments. In the proximity of the groins, the longitudinal distance between two measured sections was around 7m. The water level was measured with an ultrasonic sensor and the bed elevation was obtained through a sand-surface profiler. The surface flow structure in the groin stretch was also studied with PIV (Particle Image Velocimetry) method.

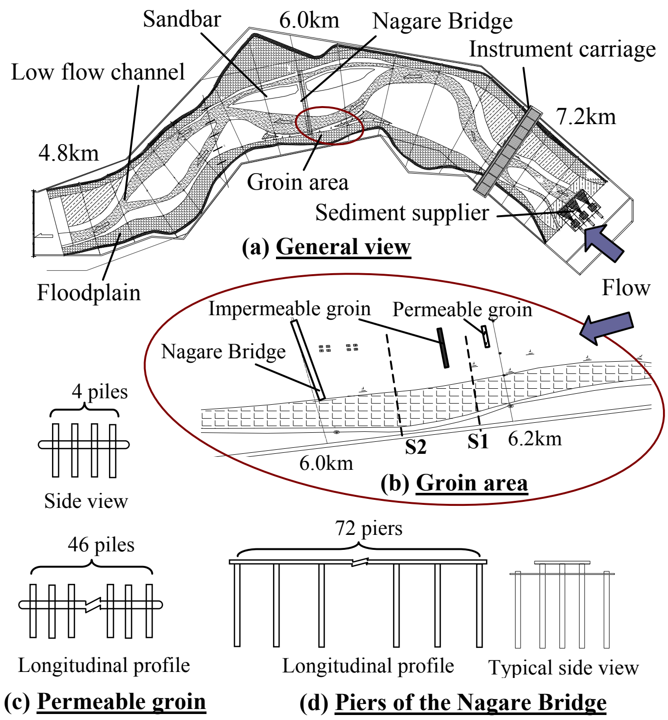

Fig.3 Experimental setup.

3. NUMERICAL SIMULATIONS

(1) Numerical models

A 2D morphological model has been developed to simulate the flow and sediment transport in this study. The model consists of a depth-averaged flow module, a bedload transport module and a bed deformation module.

The flow field is obtained by solving the 2D shallow water equations with the depth-averaged k-ε model for the turbulence closure. One of the weakest points of 2D models, i.e. the secondary flow effect, is taken into account by introducing a dimensionless diffusivity coefficient as suggested by Minh Duc et al. [7]. Only bedload transport is considered in this study. The sediment transport rate is evaluated with the Ashida-Michiue formulae [8]. The effect of the local bed slope on the sediment transport has been accounted for by introducing a new bed slope factor [9]. Considering the complexity of the study domain, the model is formulated with FVM (Finite Volume Method) on a collocated unstructured mesh. The details of the model are referred to Zhang et al., 2006.[6]

(2) Computational mesh

The computation is based on the model scale, but the result has been transformed to the prototype scale for clarity. The computation domain covers the same area as that represented by the physical model. A hybrid mesh consisting of both quadrilaterals and triangles is used considering local mesh refinement, mesh quality as well as total mesh numbers. The mesh is very fine in the neighborhood of the groins and becomes rather coarse in the floodplain area. The main part of the mesh is generated by hand and programming. The mesh system in the groin stretch is shown in **Fig.4**.

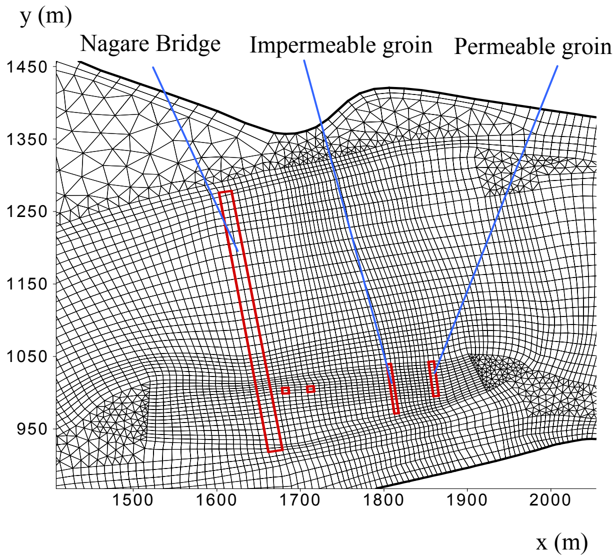

Fig.4 Hybrid mesh in the groin stretch.

So far, the piers of the Nagare Bridge and the piles of the permeable groin are not exactly resolved since they are very huge in amount, small in size and complex in shape. The CVs containing these structures are treated as roughness elements and are assigned relatively larger roughness coefficients.

(3) Computational conditions

The flow and bed deformation during a flood in September 2005 is investigated. The flood process is simplified to a 3-stage process: pre-peak (0~12.2h), peak (12.2~18.7h) and post-peak (18.7~24.5h). At each stage, water discharge and sediment discharge are assumed constant. According to the hydrograph and calibrated sediment discharge by preliminary experiments, the flood parameters are shown in **Table 1** and **Fig.5**. The boundary conditions at the inlet, the outlet and impermeable walls are specified as follows. At the upstream inlet, the velocity u is obtained according to the given discharge. The turbulence kinetic energy k is related to the velocity u and the turbulence intensity I via $k = 1.5uI^2$. The dissipation rate ε is estimated from k and the eddy viscosity ν_t by specifying a viscosity ratio (ν_t/ν) around 10-20. Here, ν is the molecular kinematic viscosity of the water. At the downstream outlet, the water level is assumed to be a constant under a specific discharge. A zero gradient boundary is assumed for other quantities there. Methods are developed to correct the outlet velocity components in order to assure the global mass conservation. The wall function approach is adopted near the bank and non-submerged hydraulic structures. Both dry and wet meshes participate in the computation. The wetting-drying process has been accounted for by introducing a new algorithm[6].

Table 1 Parameters of the modeled flood.

Water discharge (m^3/s)	Sediment discharge (m^3/h)	Duration (h)
500	196	12.2
1,000	491	6.5
500	196	5.8

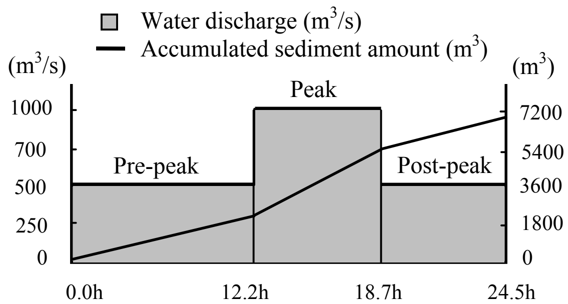

Fig.5 Modeled flood process.

4. RESULTS AND DISCUSSIONS

(1) Bed deformation

In the experiments, the bed evolution in the whole year of 2005 has been investigated. **Fig.6** shows the resulted bed contour before the flood season in the stretch of interest. This serves as the initial bed condition for the numerical simulation. The scour and deposition due to the impermeable groin are evident, locating around the tip and in the wake of the groin correspondingly. This scour-deposition pattern coincides with the results from many flume experiments and numerical simulations [4,5]. In this section, however, we concentrate on the change of the bed morphology during the flood period.

The bed contour after the flood is shown in **Fig.9** and **Fig.10** according to experimental and numerical results, respectively. Compared with the bed contour before flood as given in **Fig.6**, the bed morphology changes after the flood. The results also demonstrate the reasonable agreement between the experimental measurement and the numerical simulation. In some area, the scour and bed degradation seem to be under-estimated. It is probably caused by the inherent defect of the 2D modeling methods. A 2D model is not able to resolve the vertical velocity component, which contributes a lot to the sediment transport in scour area and around groins.

From **Fig.6** to **Fig.8**, the simulated bed evolution process has been plotted. The flood discharges almost trigger sediment movement in the whole channel. Deposition of sediment in the upstream part of the big sandbar has increased the sandbar height obviously. Moreover, the stream way on the right side of the channel is almost colonized by the head of the sandbar. The local scour at the head of the impermeable groin is filled with sediment transported from upstream. Behind the impermeable groin, the bed is degraded significantly. This is due to the flow separation as well as overtopping. These observations suggest that flood conditions should be prudently considered in groin designs.

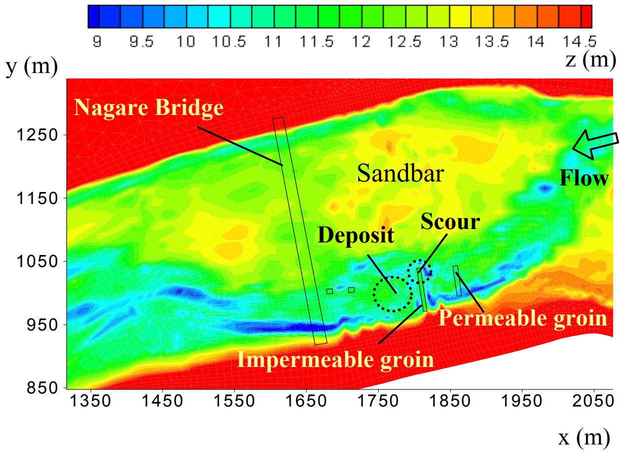

Fig.6 Bed contour before flood (Experiment & Simulation, 0h).

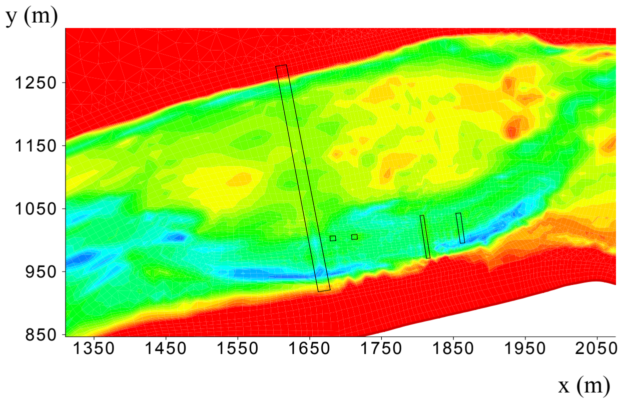

Fig.7 Bed contour before flood peak (Simulation, 12.2h).

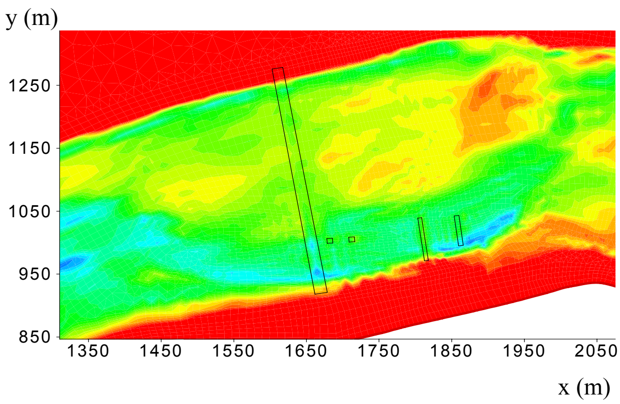

Fig.8 Bed contour after flood peak (Simulation, 18.7h).

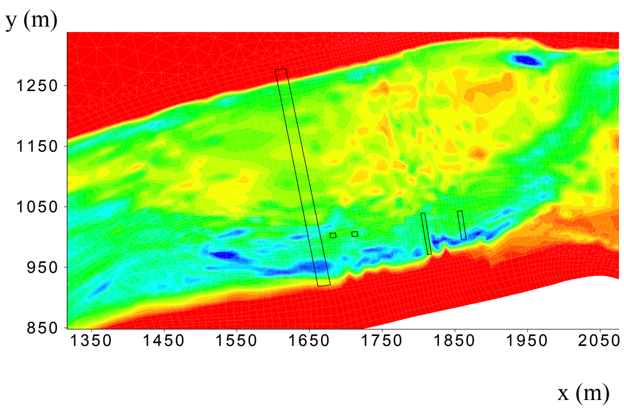

Fig.9 Bed contour after flood (Experiment, 24.5h).

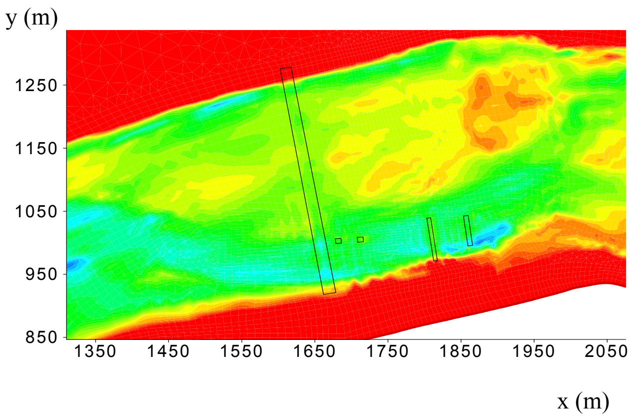

Fig.10 Bed contour after flood (Simulation, 24.5h).

The bed deformation at typical transverse sections is shown from **Fig.11** to **Fig.13**. The locations of the sections are depicted in **Fig.3**. Due to the wavy bed of ripples, the measured bed profiles exhibit great irregularity. Irrespective of this, the computational result is quite encouraging. **Fig.13** deserves special attention. Again, the scour-deposition pattern (i.e. pool-riffle morphology) caused by the impermeable groin before the flood is found to be destroyed during the flood. Both experiment and simulation show that the scour hole is filled with sediment and that the erosion area on the left side of the channel is obviously enlarged. It gives quantitative evidence to previous observations in the change of bed contours.

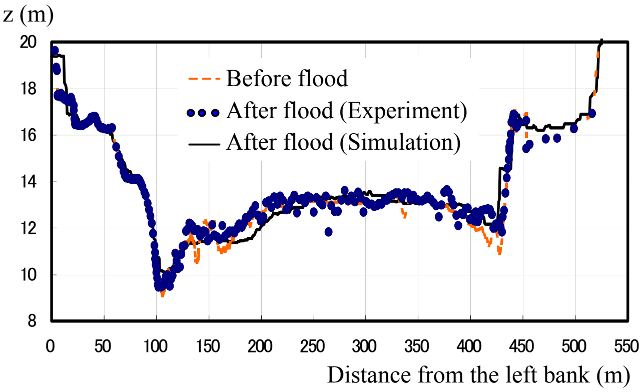

Fig.11 Bed deformation in front of permeable groin (6.2km).

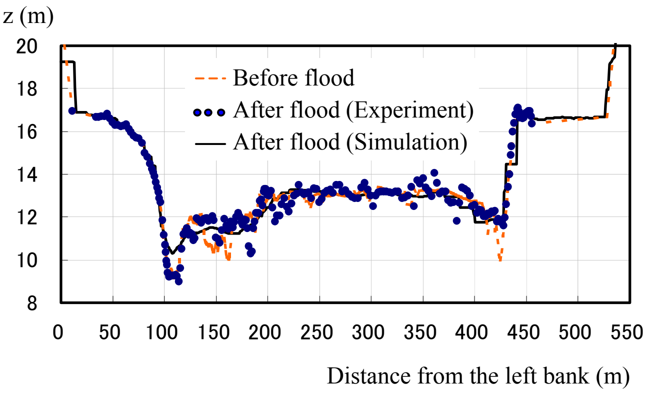

Fig.12 Bed deformation in-between the two groins (S1).

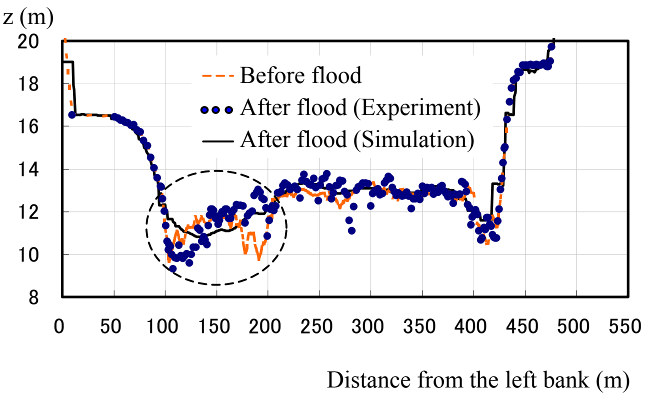

Fig.13 Bed deformation downstream of impermeable groin (S2).

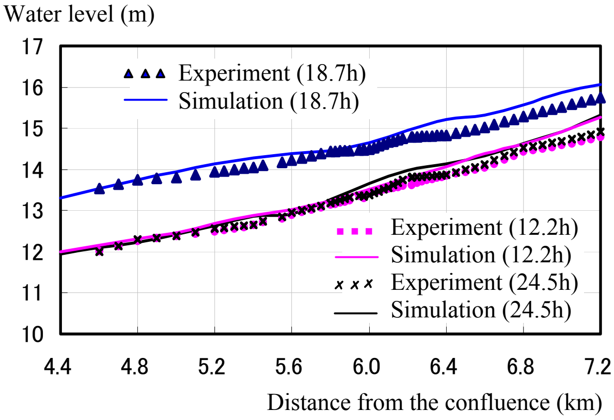

Fig.14 Water level variation in the flood process.

(2) Water level

The computed water levels along the centerline of the low flow channel are compared with those of the experiments as shown in **Fig. 14**.

In general, water levels exhibit no significant differences at the end of the pre-peak stage (12.2h) and at the end of the post-peak stage (24.5h). Higher water level is observed at the end of the peak (18.7h) due to the higher flood discharge. Simulation results are in reasonable agreement with those of the experiments. Nevertheless, slight over-estimation is found upstream, in particular under the peak discharge. It may be attributed to the use of the same set of Manning's roughness coefficients. The development of ripples and its effect on the bed resistance are not accurately accounted for in the model. The roughness, in the upstream area and in case of higher discharges, has probably been over-estimated.

(3) Velocity field

Since the water depth is very small compared with the width of the channel, only the surface velocity was measured in the experiment using PIV method. The surface velocity fields around groins at the end of the flood peak (18.7h) and at the end of the flood (24.5h) are shown in **Fig.15** and **Fig.17**, respectively. The computed mean velocity fields at corresponding time are also plotted in **Fig.16** and **Fig.18**. It was found that the measured surface flow patterns are quite similar to the computed mean flow patterns. The flow fields are closely related to the bed morphologies and water depths. The high velocity zone basically follows the river thalweg. Since the groins are submerged during the flood, they do not have significant influence on the flow directions. However, the flow was accelerated over the groins, in particular the impermeable one. This will result in very high shear stress in the proximity of the groins, which even has a potential to undermine the groin structures themselves.

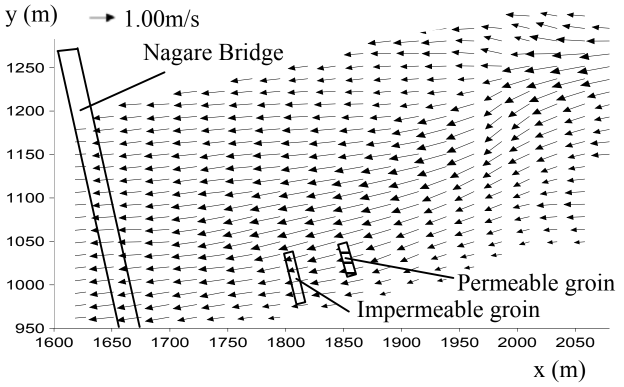

Fig.15 Surface velocity around groins (PIV, after 18.7h).

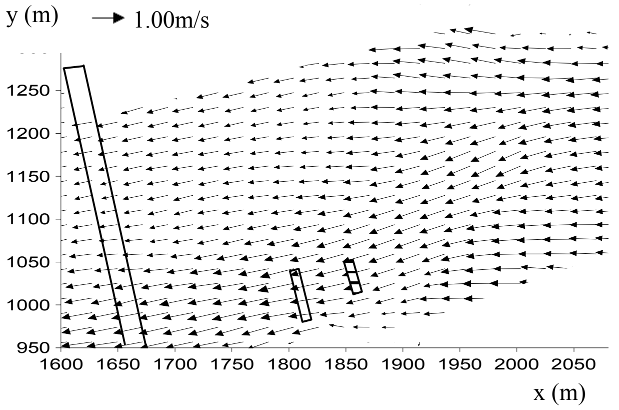

Fig.16 Mean velocity around groins (Simulation, after 18.7h).

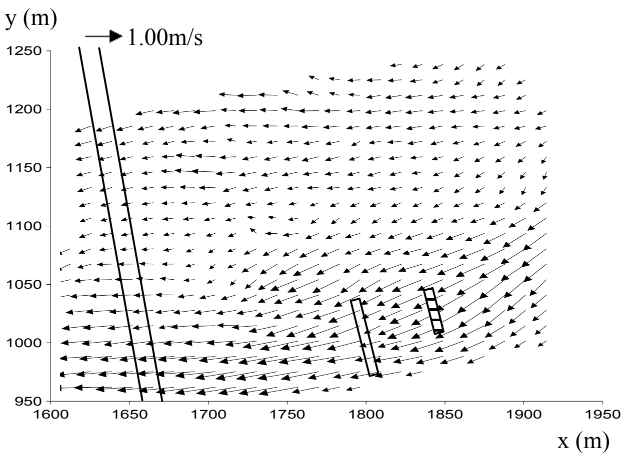

Fig.17 Surface velocity around groins (PIV, after 24.5h).

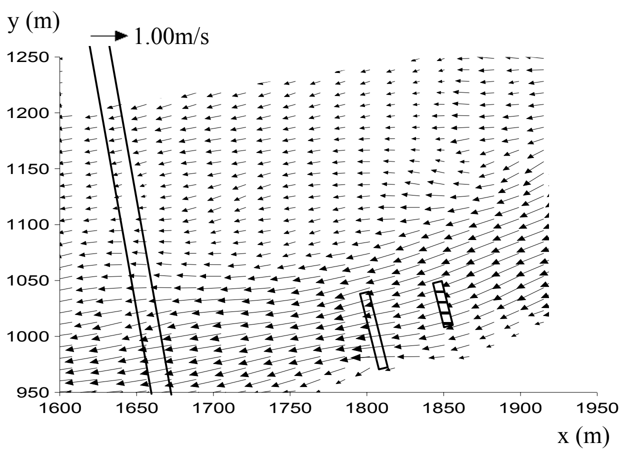

Fig.18 Mean velocity around groins (Simulation, after 24.5h).

5. CONCLUSIONS

This paper presents a result of flow and bed deformation around groins under flood conditions in a river restoration project with both large-scale physical model experiments and 2D numerical simulations. The research results indicate the importance of the flood discharge on the bed deformation around groins with quantitative evidences. Although the flood discharge generally lasts a very short time, it has long-term impacts on the river morphologies and may even lead to failures of restoration projects. However, this study is still of preliminary nature. A comprehensive evaluation of restoration schemes necessitates the consideration of more detailed hydrograph and fluvial process.

The applicability of the numerical model has also been confirmed by the verification data of the experiments. It may serve as a promising tool for the analysis of bed morphodynamics in the design and post-appraisal of river restoration projects.

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