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IMPACTS OF FLOOD EVENT ON CHANNEL MORPHOLOGIES AROUND RIVER RESTORATION STRUCTURES

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Flood event has obvious and long-lasting impacts on channel morphologies, posing high risks of damage and/or failure of river restoration projects. This study evaluates the impacts of flood event on the channel morphologies around typical river restoration structures and provides possible management alternatives for a real restoration project. Both laboratorial experiments and numerical simulations have been carried out. The experiments are based on a large-scale physical model, being able to resolve local flow patterns and morphological variations with a high accuracy. The numerical model is formulated on unstructured meshes, allowing the exact representation of complex geometries and boundaries. It is shown that the numerical results are reasonably consistent with those of the experimental measurements. The numerical model might make a powerful tool and the results of this study would be of excellent references for future engineering designs and post-project assessments in the river restoration.

Key Words **:** *Channel morphology, river restoration, flood event, large-scale physical model, unstructured mesh*

1. INTRODUCTION

Flood is one of the most important factors for the failure of river restoration projects. A flood event, although generally short in time, has obvious and long-lasting impacts on channel morphologies. As a result, a flood event may entirely alter the existing aquatic/riparian habitat characteristics, and even worse, cause failures of river restoration structures themselves. In addition, many rivers to date are experiencing increases in flood discharges and frequencies with the significant acceleration of river basin development as well as considerable change of global climate conditions. Therefore, the flood scenario must be accorded a high priority in both the design and the assessment of restoration projects. Unfortunately, it is still an unexploited field to quantify the flood impacts on channel morphologies and restoration efforts. Consequently, there remain a lot of unsuitable project designs and unsustainable management actions.

The Kizu River Waterfront Park project provides a good case study of flood impacts on channel morphologies around restoration structures. It is a river restoration project in Yawata City, Kyoto Prefecture (**Fig. 1**). The objectives of this project are to restore beach landscapes in the neighborhood of an ancient wooden bridge (named *Nagare Bridge*) for public recreation and to increase the diversity of in-stream habitats for aquatic species. During the project, non-native vegetation was removed, part of the river terrace was lowered and several spur dykes were constructed. However, it was not successful due to an under-estimation of flood impacts. All the spur dykes were washed away in a flood in 2004. As a remedy, two new spur dykes were constructed in the next year as shown in **Fig. 1**. One was fabricated with four rows of timber piles (permeable). Another was made of packages of gravels and local sediment (impermeable). Nevertheless, recent studies indicate that the spur dykes are not effective [1), 2)]. They show some advantages of preventing the river terrace from being eroded but are not able to promote the formation of desired local channel morphologies.

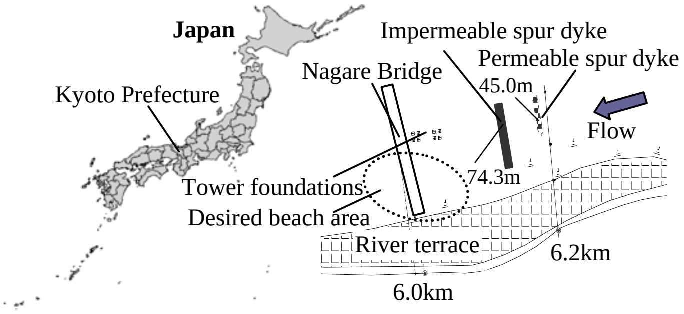


Fig.1 Location and sketch of the restoration project

Intensive study and long-term monitoring are of great necessity. In this study, possible solutions to improve the restoration project are proposed. These solutions are all based on the existing restoration measures but vary in terms of spur dyke types and/or layouts. The morphological consequences of these new solutions under typical flood conditions are investigated and compared. Recommendations are made prior to further restoration actions.

2. METHODS

The complexities of the problem suggest that the experimental or numerical method alone would hardly lead to results of both generality and reliability due to their respective limitations [3]. Hence, a combination of them was adopted.

A physical model was built in the Ujigawa Open Laboratory, Kyoto University [1), 2)]. The model was non-distorted with a physical scale of 1:65. Model sediment was chosen as powdered anthracite after a comprehensive comparison with other materials. Water level and bed elevation were measured at typical transverse sections. The water level was measured with an ultrasonic level system and the bed elevation was obtained through a sand-surface profiler. The flow structure on the free surface in the restoration stretch was investigated with the PIV (Particle Image Velocimetry) method.

A 2D morphological model was developed [2)]. The model simulates the flow field by solving the unsteady shallow water equations with the k-ε model for the turbulence closure. The channel evolution process is obtained through the sediment continuity equation with an empirical formula for bedload transport rate. Effects of secondary flows on both the flow and sediment transport have been taken into account by introducing a dimensionless diffusivity coefficient in the k-ε transport equations and considering the deviation of the near-bed flow from the mean flow [4)]. The model is formulated with FVM (Finite Volume Method) on unstructured meshes, capable of resolving complex geometries.

3. RESULTS AND DISCUSSIONS

(1) Experimental and computational conditions

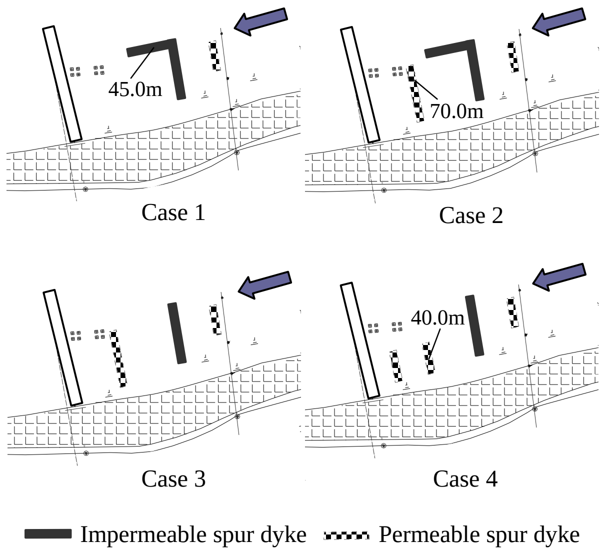


Fig.2 Alternatives for improvement

Four alternatives as shown in **Fig.2** are proposed to improve the effectiveness of the project based on previous study results [2)]. In order to investigate the flood impacts on the channel morphologies around the restoration project, the bed deformation patterns are compared with each other under the same flow and sediment scenarios in a typical flood event. The flood discharge corresponds to the maximum annual discharge (2000m^3/s) of the river and lasts 8 hours.

The numerical simulations are based on the experimental scale. But all the results appeared in this paper are transformed to prototype scale for the clarity of explanation. In the simulations, the flood plain area is considered as fixed bed, coinciding with the treatment in the experiments. Impermeable spur dykes are accurately resolved during the mesh generation. While permeable spur dykes are treated as roughness elements for computational efficiency. Relatively larger roughness coefficients are assigned to the corresponding meshes. Boundary conditions in the simulations are specified as follows. At the upstream inlet, the mean velocity u is obtained according to the given discharge. Sediment supply rate is the same as that calibrated by preliminary experiments. 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 by specifying a viscosity ratio of around 20. At the downstream outlet, a zero gradient boundary is assumed there. The wall function approach is adopted near the bank and non-submerged hydraulic structures.

(2) Bed contours before/after the flood

The bed levels in the restoration stretch before and after the flood are shown from **Fig.3** to **Fig.14**.

In all cases, the spur dykes are submerged. It is evident that the flood has significant effects on the local channel morphologies. The riverbed becomes more irregular after the flood in the experiments compared with that in the simulations. These are probably due to the development of bed forms. The bed forms, mainly in terms of ripples, have been observed in the experiments under flood conditions. However, these micro-scale morphological features are not accurately accounted for in the simulation for reasons of model practicability. Instead, a comprehensive and relatively rough estimation, i.e. the Manning's roughness coefficient has been used for the time being. Due to ripples, the local bed level may fluctuate, but it will not essentially affect the analyses and conclusions on the characteristics of the morphological evolution process of engineering interest. It is also noted that the trends and patterns of sediment deposition and erosion predicted by the numerical model are reasonably consistent with those of the experimental measurements.

The variations of the channel morphologies due to flood and their impacts on river restoration are discussed hereafter. In Case1 (**Fig.3** to **Fig.5**), an L-head is added to the existing impermeable spur dyke, expecting to change the flow approaching the Nagare Bridge and to prevent the low flow channel from shifting to the left and colonizing the river terrace. However, the effect is not very evident. The bed morphology around the L-head is significantly changed, but the channel thalweg still maintains. Possibly, a beach, as an important target of this project, will form just downstream of the bridge due to sediment deposition there. Unfortunately, this beach is disconnected from the left-side river terrace by the channel thalweg. These observations indicate that the existing spur dykes are located too far from the bridge and that modifications on the spur dykes themselves will not result in influential impacts on the area close to the bridge. In order to re-distribute sediment in the desired area, a permeable spur dyke is introduced in-between the bridge and the existing impermeable spur dyke, i.e., Case2 (**Fig.6** to **Fig.8**).

Compared with Case1, the bed contour in Case2 is quite encouraging. The newly introduced permeable spur dyke has changed the flow velocity and sediment transport pattern in its neighborhood. Deposition is observed in the vicinity of the bridge, covering most of the area from the left-side river terrace to the tower foundations. The accessibility of the possible beach (i.e., deposition area) is improved due to the change of the river thalweg. From the results of Case1 and Case2, it is believed that the L-head will introduce a huge amount of *ad hoc* investments while contribute few to the project benefits. Hence, the L-head seems not so necessary.

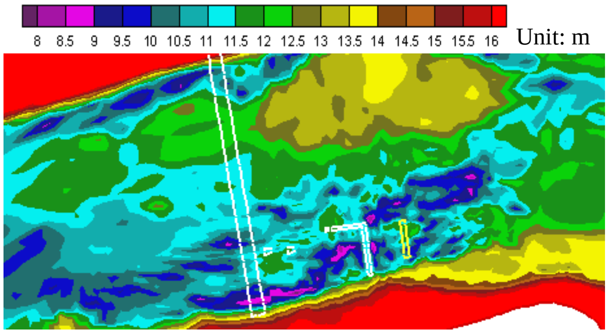


Fig.3 Bed contour before flood (Case1)

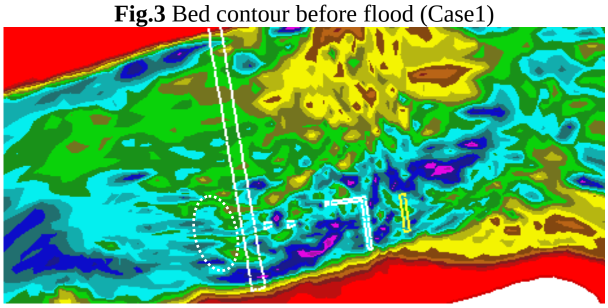


Fig.4 Bed contour after flood (Case1, Experiment)

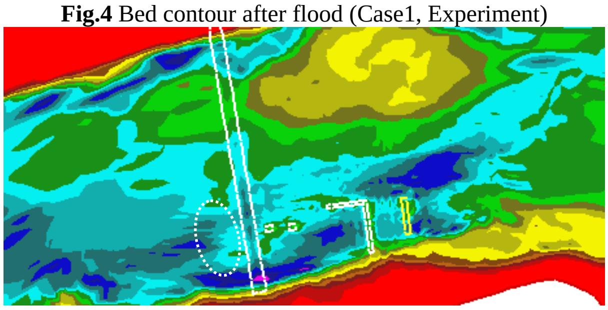


Fig.5 Bed contour after flood (Case1, Simulation)

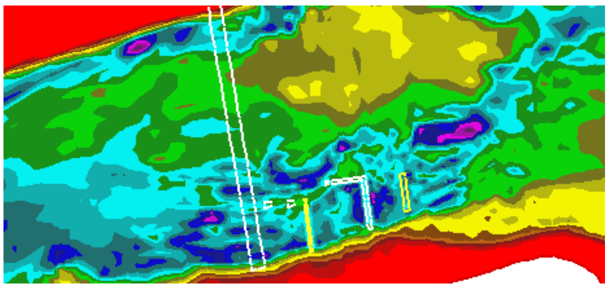


Fig.6 Bed contour before flood (Case2)

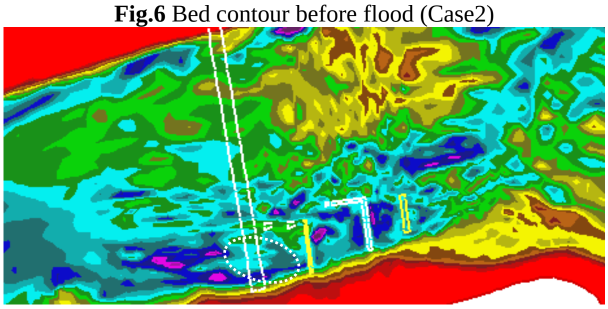


Fig.7 Bed contour after flood (Case2, Experiment)

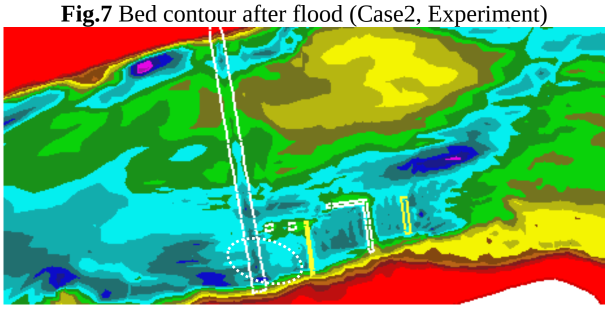
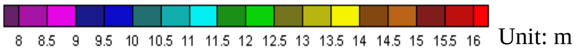


Fig.8 Bed contour after flood (Case2, Simulation)



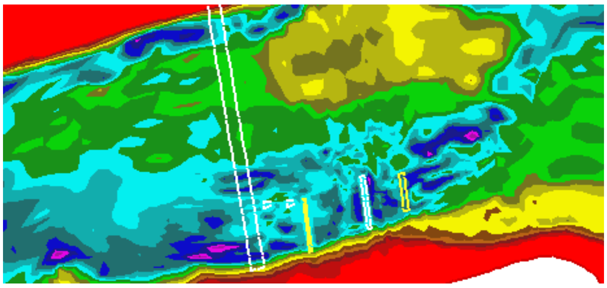


Fig.9 Bed contour before flood (Case3)

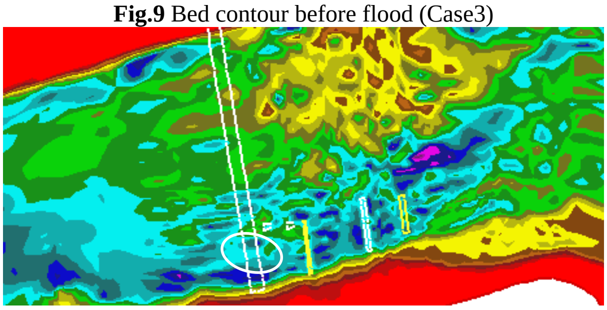


Fig.10 Bed contour after flood (Case3, Experiment)

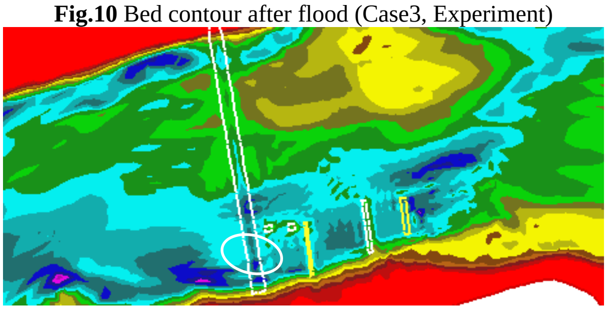


Fig.11 Bed contour after flood (Case3, Simulation)

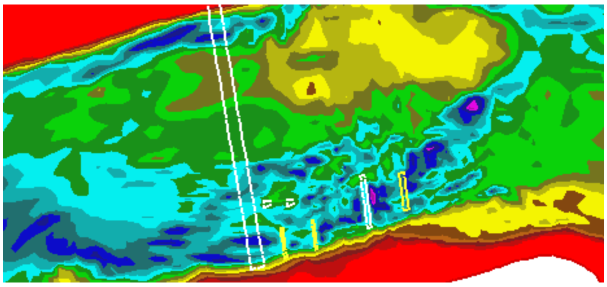


Fig.12 Bed contour before flood (Case4)

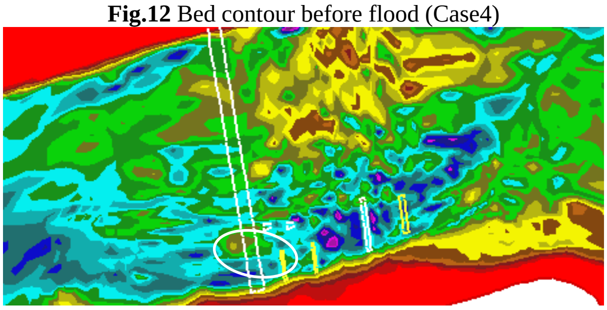


Fig.13 Bed contour after flood (Case4, Experiment)

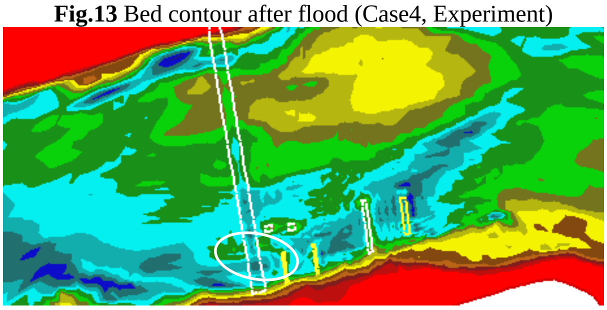


Fig.14 Bed contour after flood (Case4, Simulation)

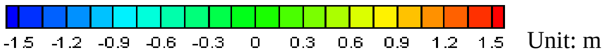
The idea of removing the L-head is crystallized in Case3 (**Fig.9** to **Fig.11**). Compared with Case2, the deposition area in the neighborhood of the bridge almost maintains after the removal of the L-head. This suggests that the current restoration project would be improved simply by constructing a permeable spur dyke in-between the existing impermeable spur dyke and the bridge.

In the final case (Case4), the newly introduced permeable spur dyke in Case3 is replaced with two small ones in a group (**Fig.12** to **Fig.14**). It is expected that the sediment deposition area could be furthermore enlarged, covering both the upstream and the downstream area of the bridge. It is found that this is the most promising solution. The contours indicate that there is a high possibility for the formation of the desired beach. The beach connects the river terrace to the Nagare Bridge, the tower foundations and the two new spur dykes, forming a satisfactory waterfront park. Meanwhile, the habitat diversities of the channel are increased due to the morphological consequences of new spur dykes, which is a good message for the ecosystem.

(3) Characteristics of morphological variations

In this section, the common points and different features of the morphological evolution process among the four cases are discussed. The changes of the bed levels during the flood in all cases are plotted from **Fig. 15** to **Fig. 18**. The erosion and deposition of the sediment materials due to different restoration measures are clearly and quantitatively distinguished in these figures. In the experimental measurements, the absolute values of the bed deformation are larger than those of the numerical simulations. As has been mentioned before, the effects of the bed forms are responsible for these discrepancies. Nevertheless, the locations of sediment erosion and deposition resulted from the numerical model are quite similar to those obtained from the physical model. It demonstrates the applicability of the proposed numerical model.

In the restoration stretch, typical deposition area is labeled with a white circle and erosion area is sketched with a black one. It is very clear that all solutions are possible to promote sediment deposition in the desired beach area except Case1. In Case1, the desired beach area is not aggraded, but severely degraded. It does not mean that the L-head is meaningless. In fact, it has resulted in sediment deposition along the left side of the channel (**Fig. 15**). Furthermore, the possible beach area in **Fig.16** is larger and locates better than that in **Fig.17,** which indicates that introducing both an L-head and a permeable spur dyke, irrespective of cost, is better than introducing a permeable spur dyke only.



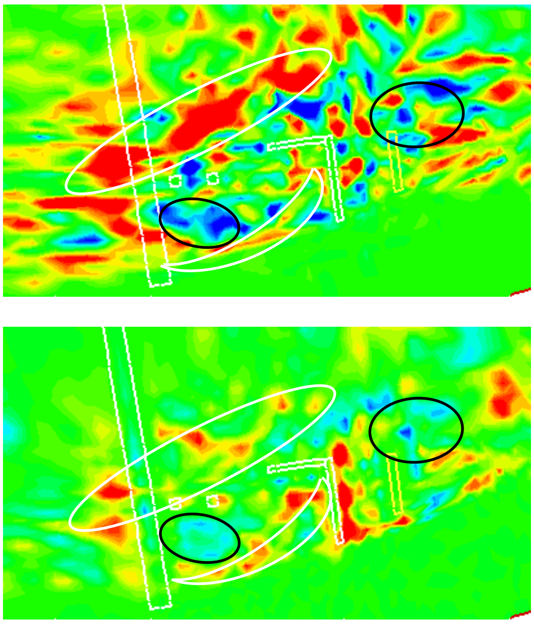


Fig.15 Change of bed level during flood in Case1 (Experiment: Top, Simulation: Bottom)

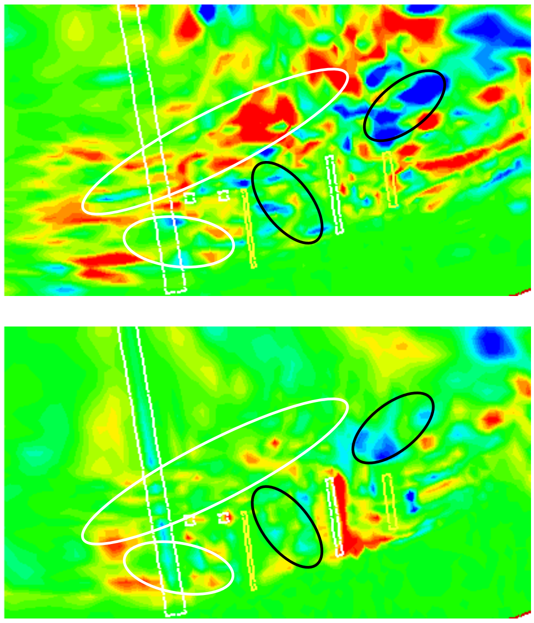


Fig.17 Change of bed level during flood in Case3 (Experiment: Top, Simulation: Bottom)

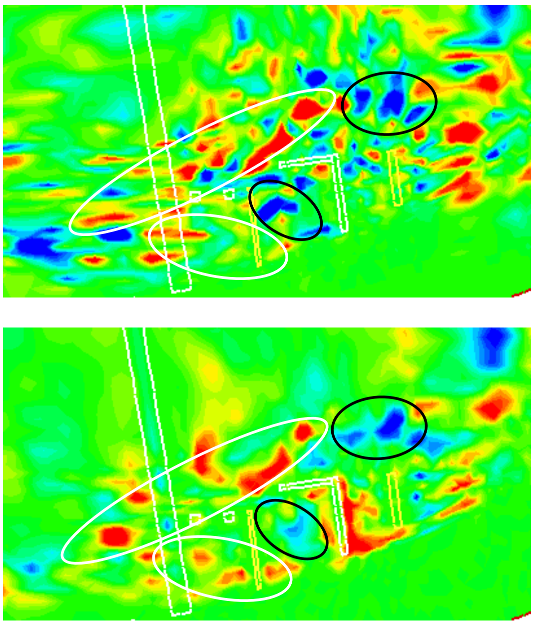


Fig.16 Change of bed level during flood in Case2 (Experiment: Top, Simulation: Bottom)

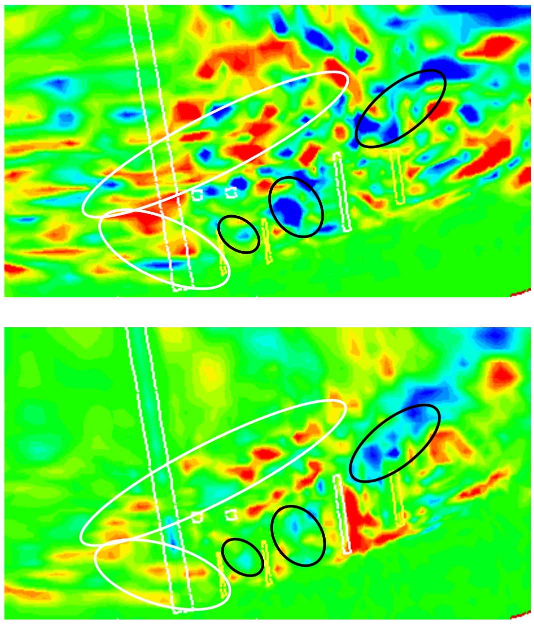


Fig.18 Change of bed level during flood in Case4 (Experiment: Top, Simulation: Bottom)

In order to achieve the objectives of the project, Case1 is not recommended. From Case2 to Case4, the characteristics of the local morphological change in the restoration stretch are generally similar, which may be summarized as an erosion area behind the existing impermeable spur dyke followed by a large area of deposition. In Case4, the erosion area is separated into two small parts by the grouped permeable spur dykes and the deposition around the desired beach area is extended. These observations again suggest that Case4 will provide the best solution for the improvement of the current project.

(4) Flow field after flood event

The computed isovels of the mean velocities in the restoration stretch are shown from **Fig. 19** to **Fig. 22**. Since the water depth is much smaller compared with the channel width, the velocity field is very sensitive to the bed configuration. It is evident that the flow velocities are obviously distinguished in the proximity of the restoration structures. In all cases, the flow velocity has been intensified around spur dykes. However, due to the different types and layouts, the contours of the velocities exhibit quite different characteristics.

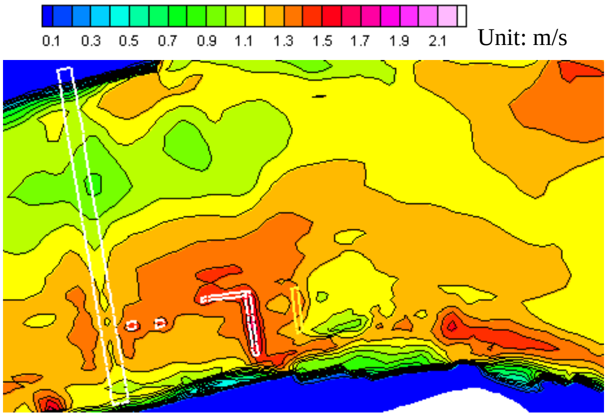


Fig.19 Isovel lines of mean velocity after flood (Case1)

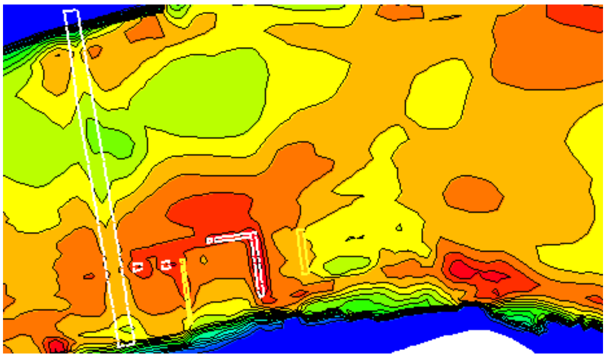


Fig.20 Isovel lines of mean velocity after flood (Case2)

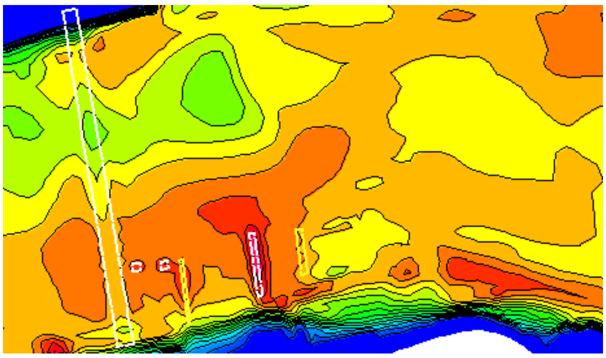


Fig.21 Isovel lines of mean velocity after flood (Case3)

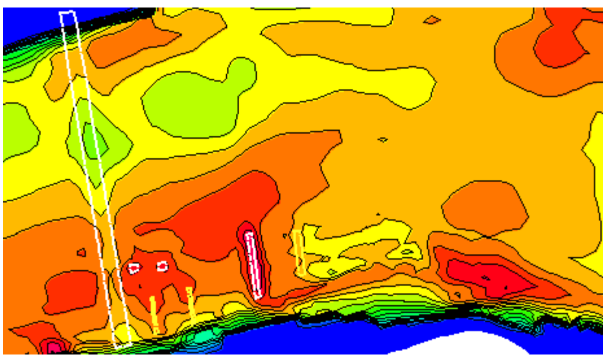


Fig.22 Isovel lines of mean velocity after flood (Case4)

In Case1, the relatively high velocity zone is confined in the area surrounding the L-head and the impermeable spur dyke. It extends almost to the bridge in Case2. After the removal of the L-head in Case3, the high velocity zone is separated into two parts: around the existing impermeable spur dyke and the newly introduced permeable spur dyke, respectively. The two high velocity zones are observed in Case4 as well. But the covering area has expanded much more than that observed in Case3. These findings well coincide with those of the local channel morphologies.

4. CONCLUSIONS

The impacts of a flood event on the channel morphologies around a typical river restoration project have been investigated both experimentally and numerically. The numerical model results are in reasonable agreement with those of the physical model measurements. Morphological consequences of flood are closely related to spur dyke types and layouts, which may be used to restore desired local channel morphologies and riverine environment.

This study not only presents possible solutions for a real river restoration project in Japan but also provides general numerical tools and practical information, which may serve as valuable references for future engineering designs and post-project assessments.

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