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THREE-DIMENSIONAL FLOW AROUND BANDAL-LIKE STRUCTURES

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Using Bandal-like structure in a recurrent way is a promising method for the management of large alluvial rivers. Unfortunately, scientific knowledge on Bandal-like structures is still very poor despite of their historied applications in the Indian subcontinent. In this paper, the fundamental characteristics of the three-dimensional flow around Bandal-like structures are investigated with field survey, laboratory experiment and numerical simulation methods. The field survey was made with a velocity profiler in the Brahmaputra-Jamuna River in Bangladesh. The experiment was conducted under live-bed scour condition with a pair of simplified Bandal-like structures in the Ujigawa Open Laboratory, Kyoto University. A three-dimensional numerical model was developed and used to simulate the flow field under the same conditions as those of the laboratory experiment. It is found that the numerical results are reasonably consistent with those of the experimental measurements. Based on the analysis and comparison of the results from different research methods, the complex flow structure is clarified and characterized.

Key Words : *Bandal, flow structure, field survey, laboratory experiment, numerical simulation*

1. INTRODUCTION

Management of alluvial rivers is one of the most challenging problems in both engineering practices and scientific researches. The problem is even more challenging in developing countries where most of the rivers are untrained. For example, the frequent migration of the Brahmaputra-Jamuna River in Bangladesh consumes large areas of floodplain, makes thousands of people homeless and destroys lots of infrastructures. Effective management of this river is crucial and urgent to reduce water-related disasters and to eliminate the country's poverty.

The Brahmaputra-Jamuna River originates from the Himalayas and flows across China, India and Bangladesh. It meets with some major rivers in its lower part: the Teesta, the Ganges and the Meghna and supplies sediment into one of the world's largest deltas before finally entering the Bay of Bengal. The Brahmaputra-Jamuna River ranks in the top group of the earth's large rivers in terms of both water and sediment discharges. The averaged annual flow discharge is about 20,200m^3/s and sediment transported through the river is around 590 million tons per year at the Bahadurabad gauging station[1)]. The river is braided and geomorphologically active, characterized by numerous shifting channels and rapid bank erosion. In the past several decades, a lot of researches have been conducted to understand the dynamism of the river and to seek countermeasures against erosion[2-9)]. Based on research findings as well as engineering experiences and consultants' recommendations, some river training methods have been implemented, e.g. BRE (Brahmaputra Right Embankment), groynes, revetments and recurrent dredging. Those measures did have positive impact on channel bank protection although they were much expensive and many of them experienced damages[10), 11)]. In recent years, the efficiency, affordability and environmental suitability of those measures have been criticized[11), 12), 13)] and the importance of adopting methods/techniques which are both cost-effective and eco-friendly has been addressed. It is most desirable that the methods and techniques should combine the updated insight in the river engineering with indigenous materials, experiences and knowledge. Bandal-like structures have a potential to satisfy all those requirements [12].

Bandal is a locally developed structure for the improvement of channel navigability in the Indian subcontinent. It may be simply described as a vertical screen mounted on a frame. The main construction materials are bamboo mats with a bundle of bamboo sticks. Bandal works are quite cheap since bamboos are locally available and inexpensive labors are easily employable on site without special training. When the sediment-laden flow approaches the Bandal, flow separation occurs: low sediment-concentrated flow at the upper layer is diverted to the main channel and is accelerated, resulting in bed degradation in the main channel, while high sediment-concentrated flow at the lower layer passes through the Bandal and deposits behind it due to velocity reduction there. A structure, having the similar functions as described above, is named a Bandal-like structure herein despite its construction materials, shape and layout. Although the effectiveness of Bandal-like structures was recognized and the structures were successfully applied in some alluvial rivers a long time ago[12), 13)], there were no guidelines on the design of these structures. During analyzing the field data in major Bangladeshi rivers, Rahman et al. (2003) found that the performances of existing Bandals were not always as good as desired [14]. These facts demonstrate that there is still extremely poor understanding on the hydraulic and morphological consequences of this kind of structure. Sharmin et al. (2007) reported that Bandal structures were more suitable than dredging works in terms of both economic and hydrological aspects with quantitative evidences from several field studies of the Brahmaputra-Jamuna River. They also mentioned that Bandal was particularly effective for non-tidal rivers with fine bed materials and it was better to place the Bandal with an angle of 40^{o} to the current [15]. Das et al. (2007) suggested based on clear-water scour experiments that a funnel-shaped arrangement of a group of Bandals with an interval of 1.5b (b is the projected Bandal length normal to the flow) and an extension tail should work best to enhance the navigational channel [16]. Rahman et al. (2004) carried out a series of laboratory experiments to investigate the hydraulic functions of impermeable groynes, pile dykes and Bandal-like structures in clear-water scour conditions[12]. Based on their experiments, empirical formulae to predict the local scour depth and main channel degradation were developed. The formulae were preliminarily verified with field data collected from Bangladesh. It was concluded from their research that Bandal-like structures were able to take full advantages of impermeable groynes and pile dykes. Unfortunately, researches up to date are too few in amount and are of much qualitative nature, most of the important underlying processes are unknown yet.

It has to be mentioned that a Bandal-like structure may be physically considered as a combination of a groyne and a pile dyke. As is known, the latter two structures have been widely applied in Japan and many other countries. These structures are usually designed to have a long working life and may be considered as permanent structures. On the other hand, for large rivers like the Brahmaputra-Jamuna River with a mean width over 10km, permanent structures designed using extrapolation methods based on experiences of small rivers in other places are not favorable since these structures will be very huge in both size and cost as well as they may exert great disturbances on the river dynamism and environment system. In view of these, Bandal-like structures should be basically used as temporary structures in a recurrent way to cope with changing conditions adaptively. The total cost will include initial investments and timely maintenances. A systematic research is needed for the using of Bandal-like structures. As the first step, the characteristics of the flow around Bandal-like structures are investigated herein with field surveys, laboratory experiments and numerical simulations.

2. FIELD SURVEYS

The field site was chosen at the Betil/Enayetpur spurs located 25km south of Sirajganj Town of Bangladesh. Both spurs consist of a 150m-long RCC (Reinforced Cement Concrete) dyke and a huge earthen shank. The RCC part is supported by a number of piles. The Betil and Enayetpur Bazar areas are historically well known for their handloom textile production and are high priority areas to be protected designated by the government. The RCC part of the upstream one (i.e. the Betil spur) blocks the flow at the upper part and allows it to pass in-between the piles at the bottom, working as a Bandal-like structure. It is focused on in this paper. Field measurements of the flow velocity were conducted on July15, 2008 with an ADCP (Acoustic Doppler Current Profiler). The bathymetry of the riverbed 4-days after the measurements is shown in Fig.1, collected from the Sirajganj branch of BWDB (Bangladesh Water Development Board). It is very clear that there is a local scour concentrated at the toe of the structure. Downstream of the structure, sediment deposits and sandbar forms there. Satellite image suggests that this sandbar is formed after the construction of the structure [8]. In the upstream area away from the bank, there are also large sandbars due to active sediment transport in this huge river.

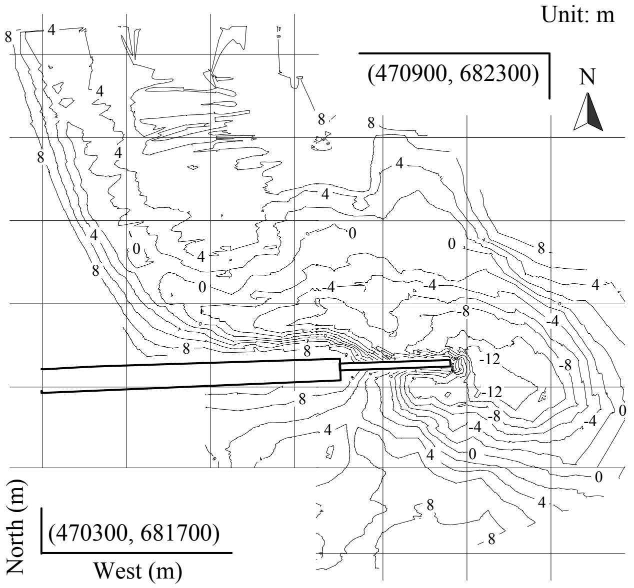


Fig.1 Bed bathymetry around Betil spur (July19, 2008).

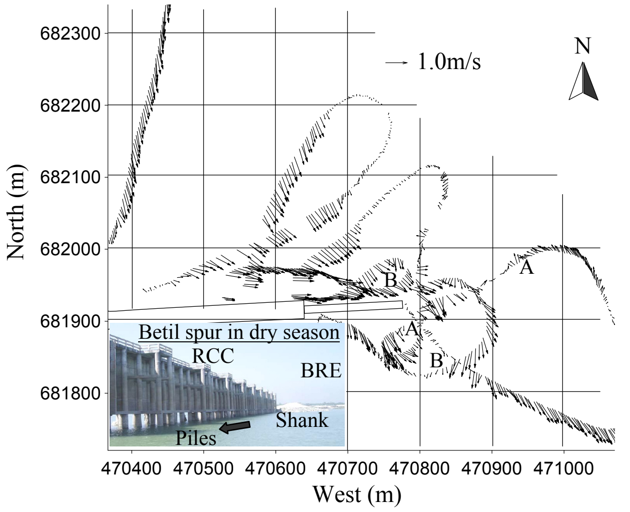


Fig.2 Flow velocity (u, v) near water surface.

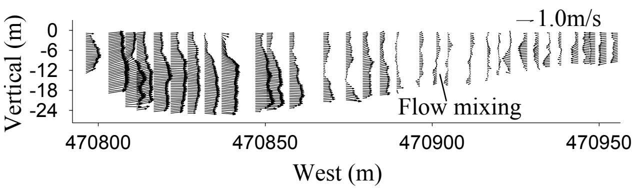


Fig.3 Flow velocity (v, w) in vertical plane A-A.

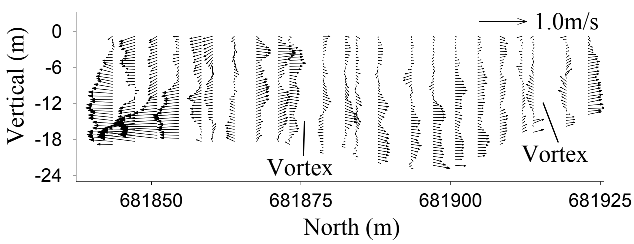


Fig.4 Flow velocity (u, w) in vertical plane B-B.

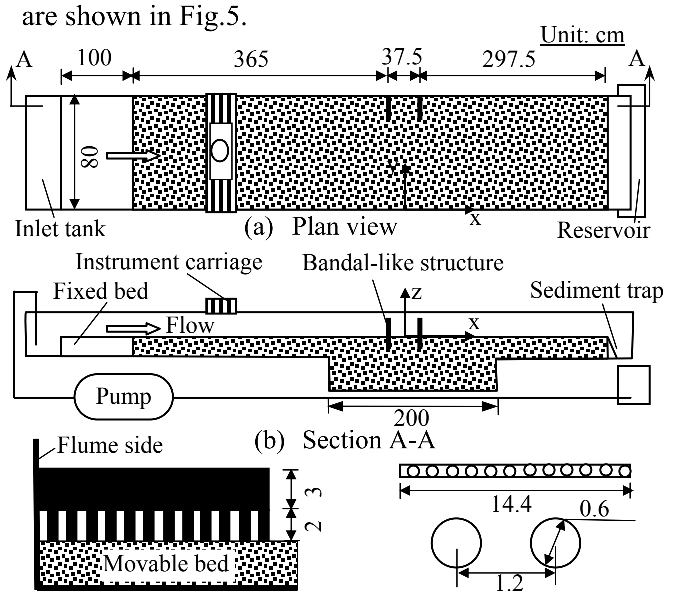
*Vertical Coordinate: Distance from the water surface

*Velocity components: u: West, v: North and w: Vertical

The flow velocity near the water surface is shown in Fig.2. In the upstream and downstream of the Betil spur, the flow direction follows the thalweg of the channel and the magnitude of the velocity shows some positive relation with the water depth. But in the neighborhood of the RCC part, the flow field turns very complex and the impact of the structure is significant. The flow velocities in two selected vertical planes are plotted in Fig.3 and Fig.4. The flow separation is evident at the head of the RCC part and the velocity reduction behind the structure is also clear. It is seen in Fig.3 that the flow diverted from the head of the structure mixes in the scour area with the flow detached from the sandbar. Along the B-B section in Fig.4, at least two circulating cells are recognized. The locations of them indicate that they are closely related to the geometry of the local scour hole. Similar circulations of different scales were also found in the scour hole around an impermeable groyne [17]. The flow is strongly 3D if one takes into account all the velocity vectors.

3. LABORATORY EXPERIMENTS

In order to understand the flow structure more precisely, laboratory experiments are conducted in the Ujigawa Open Laboratory, Kyoto University. In the experiment, powdered anthracite is used as model sediment, which has a mean size of 0.835mm and a specific gravity of 1.41. A pair of Bandal-like structures is set perpendicular to the left side of a flume. The flume is 10m-long and 80cm-wide and has a slope of 1/800. Each Bandal-like structure is made of 12 brass cylindrical piles, having a vertical steel plate mounted at the upper part. The details of the Bandal-like structure and the experiment setup are shown in Fig.5.



(c) Bandal-like structure: side view, top view and piles details

Fig.5 Experiment setup.

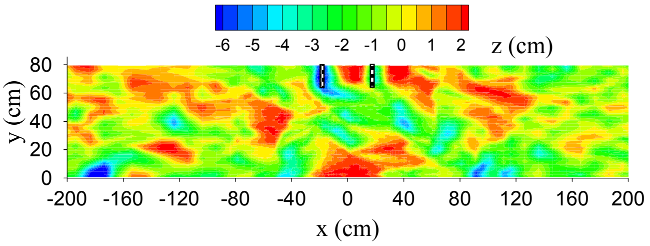


Fig.6 Final bed configuration in the experiment.

Table 1 Hydraulic condition in the experiment.

u_* : friction velocity, u_{*c} : critical friction velocity

Flow discharge	7.76 l/s
Mean velocity	24.25 cm/s
Approach flow depth	4.0 cm
u_*/u_{*c}	1.91 (live-bed scour)
Reynolds number	7,460
Froude number	0.387

The experiment is carried out under live-bed scour condition, i.e. the approach flow velocity is larger than the critical flow velocity for sediment entrainment. As a result, bed forms develop in the whole movable bed area. The hydraulic parameters in the experiment are shown in Tab.1.

The experiment starts from a flat bed and continuous sediment supply is ensured from the upstream of the flume. The total amount of sediment supplied is the same as that collected from the downstream, which is determined by some trial experiments. After 6 hours, a dynamic equilibrium condition is reached. The pump was then stopped. When the bed is drained out, a laser displacement meter is then used to measure the bed deformation. The measured bed configuration is shown in Fig.6. In the deformed bed, large areas of sandbars occur due to sediment movement in the whole movable bed domain. Local scour takes place at the toes and along the bodies of the Bandal-like structures, particularly the upstream one. Moreover, sediment deposition is observed in the wake zones behind both structures. Compared with experiments under clear-water scour regime[12], the morphology resulted from the current experiment is more similar to that formed in actual rivers such as that in Fig.2.

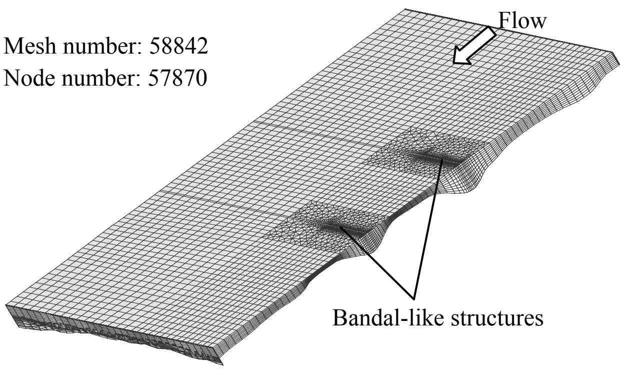


Fig.7 Computational mesh around Bandal-like structures.

Instant cement is sprayed to the bed surface and the deformed bed becomes fixed. Water is then pumped to the flume again. The velocity on the water surface is obtained with PIV (Particle Image Velocimetry) and two electromagnetic velocimetries are used to measure the 3D velocity in the water column. Water level is recorded with a point gauge.

4. NUMERICAL SIMULATIONS

Since the flow around a Bandal-like structure is highly 3D, the details of the flow cannot be resolved without a 3D model. Moreover, a Bandal-like structure is generally sophisticated in shape and the boundary of an actual river is commonly irregular. Hence, the numerical model should be capable of resolving complex geometries as well. The authors have developed a numerical model satisfying the above requirements [18]. In the numerical model, the complex flow field is obtained based on the RANS (Reynolds-averaged Navier-Stokes) equations with the k- ε model for the turbulence closure. In the near-wall domain, the wall-function approach is applied and the resistance of the wall can be easily accounted for. The widely used FVM (Finite Volume Method) is adopted in the formulation of the numerical model and the governing equations are discretized based on an unstructured mesh.

The flow field on the deformed bed in the laboratory experiment is investigated with the proposed numerical model. The measured water stage and bed level are used in the mesh generation. In order to reproduce the details of the Bandal-like structures, a hybrid mesh consisting of different types of polyhedra is employed. The computational mesh in the proximity of the Bandal-like structures is depicted in Fig.7. At the inlet boundary, all flow variables are known and are prescribed according to the mean velocity. At the outlet boundary, zero diffusion flux is assumed for all flow variables. The free surface is considered as a rigid lid and is unchangeable during the computation. Near the wall boundaries such as the channel bed, the Bandal-like structure and the side of the flume, the flow velocity is assumed to be parallel to the walls.

5. RESULTS AND DISCUSSIONS

Flow velocities resulted from both experiments and simulations are plotted in Fig.8-12. Already, it has been found that the model under-estimates the deflection angles around protruding structures[18]. On the other hand, the current PIV over-estimates those angles due to an over-accumulation of tracers there. The actual deflection angles should be in-between the results of the PIV analysis and the simulation.

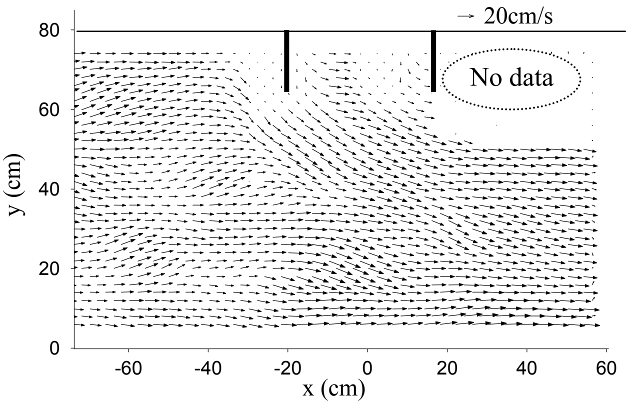


Fig.8a Flow velocity (u, v) on water surface (PIV).

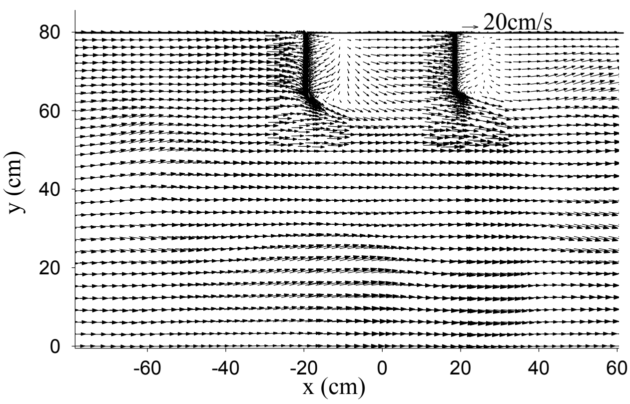


Fig.8b Flow velocity (u, v) on water surface (Sim.).

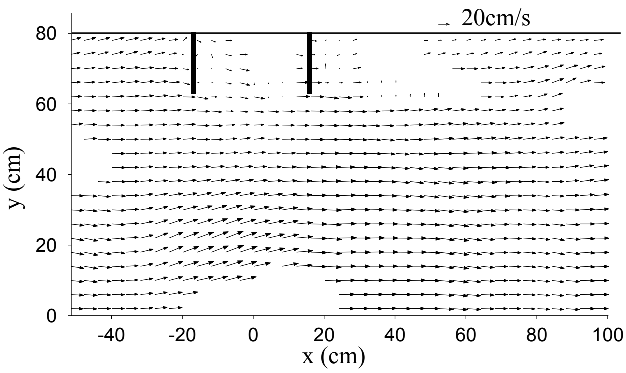


Fig.9a Flow velocity (u, v) at 2cm from initial bed (Exp.).

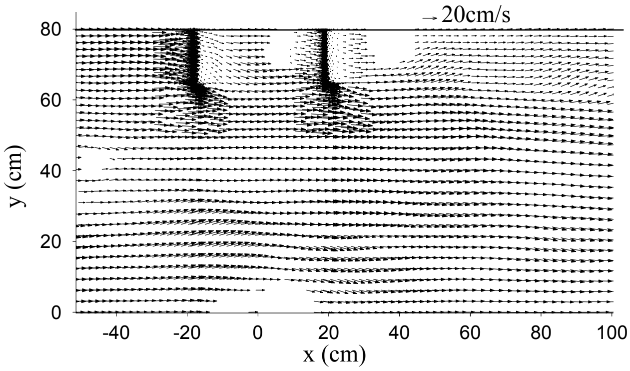


Fig.9b Flow velocity (u, v) at 2cm from initial bed (Sim.).

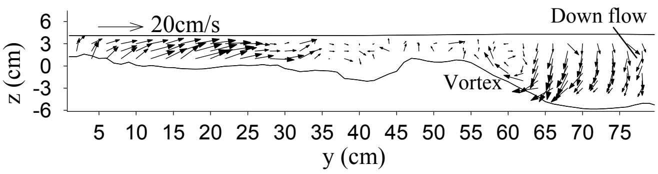


Fig.10a Flow velocity (v, w) at x=-22cm (Exp.).

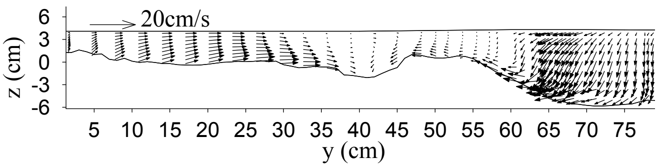


Fig.10b Flow velocity (v, w) at x=-22cm (Sim.).

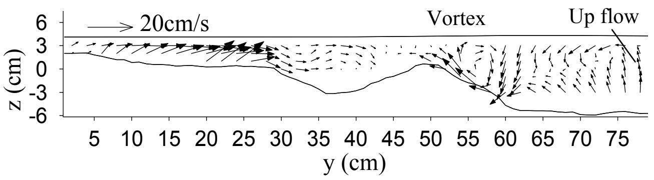


Fig.11a Flow velocity (v, w) at x=-16cm (Exp.).

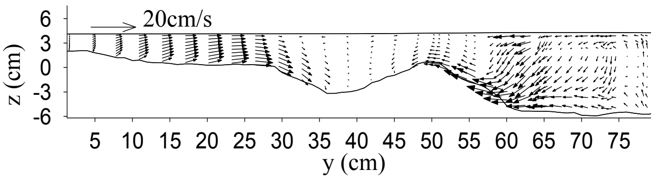


Fig.11b Flow velocity (v, w) at x=-16cm (Sim.).

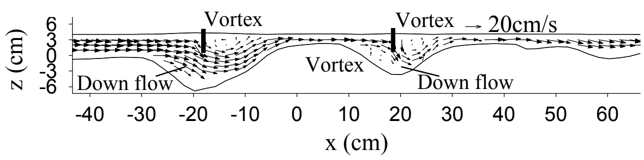


Fig.12a Flow velocity (u, w) at y=72cm (Exp.).

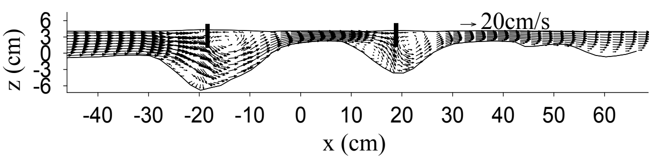


Fig.12b Flow velocity (u, w) at y=72cm (Sim.).

The flow velocity on the water surface is affected significantly by the blockage of the upper part of the Bandal-like structures and 3D vortices in the scour. On the other hand, the flow velocity at the lower layer is closely related to the bed geometries and the existing of the piles of the Bandal-like structures.

3D vortices are obviously confirmed in Fig.10-12, concentrated in the extent of local scours and being similar to those around groynes [17]. These vortices are engines for the scour development. However, there are many properties unique to the Bandal-like structures. Fig.11 and Fig.12 indicate that the wake vortex behind the upstream structure is not well developed. The vortex is very weak and is confined in the shade of the impermeable part of the structure other than inside the scour hole. It is attributed to strong flows which pass the piles of the structure and make great disturbances to the wake zone. It is also found in Fig.12 that there are vortices located in front of and behind the downstream structure. Due to the vortex in front of the structure, flows passing the piles lose their energy and the vortex behind the structure develops more freely and even extends to the inside of the scour hole. The vortex in front of the downstream structure is resulted from the down flow and the relatively small scour depth (hence, a small opening ratio). Similar vortex pair appeared in the field measurements (Fig.4). Furthermore, it is found that flow mixing occurs in both experiments (Fig.10) and field surveys (Fig.3), while a vortex forms in the scour hole in the experiments but not distinguishable in the field surveys. This is probably due to the difference in the direction of the approach flow in the experiments and in the field conditions. These observations provide important supplement information on the physics of the local 3D flow.

6. CONCLUSIONS

The flow velocity around a historied hydraulic structure, i.e. Bandal-like structure is investigated with various methods. As a combined structure of a groyne and a pile dyke, similar functions as them are desirable such as bank protection, navigational channel degradation and scour promotion. On the other hand, the flow around a Bandal-like structure is more complex than either of them despite that they share some common flow characteristics such as the down flow, the up flow and vortex systems. The interaction among the flow velocities in vertical planes plays a crucial role in understanding the flow structure and the latter somewhat depends on the Bandal-like structure itself.

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