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LOCAL SCOUR AND SEDIMENT SORTING AROUND A SERIES OF GROYNES

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Abstract

Groynes are widely constructed along alluvial rivers for disaster mitigation and environment restoration in the world. Understanding the local scour and the sediment sorting is important to maximize the benefits and to mitigate potential disasters associated with groynes. In this paper, an experimental study has been presented on the properties of the bed deformation around a series of groynes in non-uniform sediment beds with both bedload and suspended load transport. The experiments are conducted for a group of impermeable groynes under both emerged and submerged conditions. The results indicate that groynes significantly enhance the bed diversity in terms of promoting scour-deposition morphology and sediment sorting in their neighborhood. The sediment sorting results in different grain size distributions in longitudinal, transverse and vertical directions. Longitudinal coarsening of sediment particles are observed in the mainstream narrowed by the groynes. In the transverse direction in the groyne reach and its downstream, an evidently coarsened zone forms near the centerline of the flume. Groyne bays and groyne wakes are capable of trapping fine sediment particles, but the patterns of fine deposition depend on their locations and submergence conditions. Local scour areas are coarsened and the bottom sediment is coarser than that at the top within the scour hole.

Key Words： Groyne, emerged, submerged, local scour, grain size variation

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1. INTRODUCTION

Groynes as an effective solution for bank protection, navigation enhancement and ecological rehabilitation, are widely constructed in alluvial rivers on our planet. Protruding of groynes into a river course results in changes in the local bed configurations and the substrate types (Zhang et al., 2011). The former, mainly in terms of local scour, is a crucial concern for the channel stability and the structure safety. While the latter, largely due to sediment sorting, exerts impacts on the bio-richness and bio-diversity in the riverine aquatic system. Therefore, an insight into the local scour and sediment sorting is important to know the potential benefits and disasters associated with groynes.

Over the past several decades, there have been a huge amount of literature contributing to the hydraulics, morphodynamics and local scour around groynes. Zhang and Nakagawa (2008) conducted a systematic review which covered most of the early and influential works. Recent advances are available from publications by research groups such as Yossef and de Vriend (2010), Koken and Constantinescu (2011), Cai and Tominaga (2012), Henning and Hentschel (2013) and Sukhodolov (2014). Unfortunately, the sediment heterogeneity that is a distinctive feature of alluvial riverbeds has been seldom considered in the existing studies. In the past several years, the authors' group has conducted a lot of fundamental research to clarify the roles of the sediment heterogeneity plays in the bed deformation process around a single groyne installed along a straight channel. The research has revealed the importance of several governing parameters such as the bed sediment non-uniformity (Zhang et al., 2012), the flow overtopping ratio (Mizutani et al., 2012), the type of the groyne (Zhang et al., 2013) and the protruding angle of the groyne (Mizutani et al., 2013). In addition, the detailed three-dimensional flow field and bed deformation properties around a single groyne have been obtained. Many common features were observed between a homogeneous sediment bed and a heterogeneous sediment bed in terms of local flow structures and scour-deposition morphologies around a single groyne. On the other hand, properties unique to a heterogeneous sediment bed were also noted mainly as a consequence of sediment sorting. For more reliable design and management of groynes, it is of great meaning to explore research taking into account the impacts of the heterogeneity of bed sediment. Moreover, as groynes are usually arranged in groups rather than in the form of an individual structure in actual rivers, it is necessary to investigate the local scour and sediment sorting around a series of groynes.

As a first step, the authors' group has investigated the flow structure and bedload transport around a series of groynes in non-uniform sediment beds (Mizutani et al., 2014). The differences in terms of flow structures and bed variations between a single groyne and a group of groynes with various arrangements have been clarified. On the other hand, fine depositions were commonly reported in field surveys around river groynes (Zhang et al., 2011), indicating the importance of suspended sediment transport. In this study, the bed variation characteristics in a non-uniform sediment bed around a series of emerged and submerged groynes were investigated under both bedload and suspended load transport conditions. In particular, the properties of the local scour and the grain size distributions were emphasized.

2. LABORATORY EXPERIMENTS

2. 1 Experiment setup

Two cases of experiments were performed in a glass-sided tilting flume in the Ujigawa Open Laboratory of Kyoto University (Japan). The groynes were kept emerged from the water throughout the experiment in Case1 and were overtopped from the beginning by the water in Case2. The experiment flume was 8 m-long, 40 cm-wide and 30 cm-deep as shown in **Fig. 1**. A 20 cm-thick wooden deck was put on the bottom of the flume to make a fixed flatbed and a 2.5 m-long sediment recess was situated at 4 m downstream from the inlet boundary. The recess was filled with silica sands to form a movable bed. Four impermeable groynes were installed on the movable bed along the right side of the flume. Each of the groyne was 1 cm-thick and 10 cm long. The groynes were perpendicular to the side of the flume and were labelled as groyne A, B, C and D from the upstream to the downstream. The length of the groyne bay between two consecutive groynes was a constant of 20 cm. The flow discharge was the same for both experiments, while the height of the groynes differed from case to case. In the emerged case, i.e. Case1, the height of the groynes was much larger than that of the water level. In the submerged case, i.e. Case2, the height of the groynes was 2.5 cm above the initial sediment bed (**Fig. 1**c).

The movable bed was prepared by mixing two types of uniform silica sands with a ratio of 2:3 (coarse: fine). The mean diameters of the two

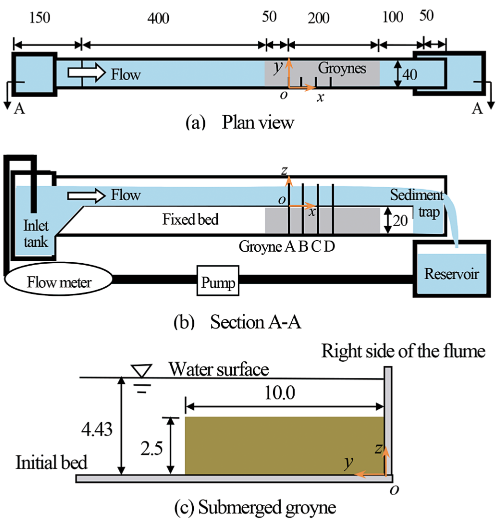

Fig. 1 Experiment setup (unit: cm, not to scale)

types of sediment were 2.43 mm and 0.09 mm, respectively. The sieve analysis result of the initial sediment bed materials was shown in **Fig. 2**. According to the figure, the mean grain size of the initial sediment bed was 1.03 mm.

The hydraulic conditions applied in the experiments were tabulated in **Table 1**. It was evident that the friction velocity in the approach flow area was much smaller than the critical friction velocity of the coarse fraction and much larger than that of the fine fraction. Moreover, the ratio of the friction velocity in the approach flow to the settling velocity of the fine fraction was calculated as 2.93, which was larger than the critical values for sediment

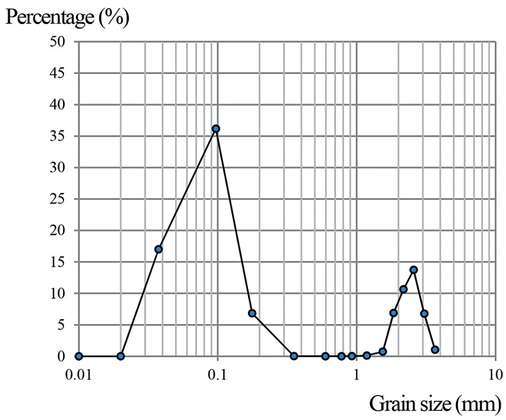

Fig. 2 Sediment sieve analysis results

Table 1 Details of the hydraulic conditions

Flow discharge Q (l/s)	5.70
Channel slope I	1/1,280
Approach flow depth h (cm)	4.43
Approach flow velocity U (cm/s)	32.17
Sediment density σ (g/cm^3)	2.65
Sediment mean diameter D (mm)	1.03
Friction velocity u^* (cm/s)	1.67
Critical friction velocity (coarse fraction) u^*_c (cm/s)	5.85
Critical friction velocity (fine fraction) u^*_c (cm/s)	1.29
Settling velocity (coarse fraction) w_f (cm/s)	15.88
Settling velocity (fine fraction) w_f (cm/s)	0.57
Reynolds number Re	10,894
Froude number Fr	0.49

suspension proposed by most of the researchers (Chanson, 2004). Therefore, both bedload and suspended load would be observed in the experiments.

2. 2 Experiment measurements

Both experiments started from a flatbed and lasted 3 hours when a quasi-equilibrium condition was achieved. The quasi-equilibrium condition was defined as a condition that the bed configurations in the proximity of the groynes exhibited insignificant changes. In the experiments, no sediment was supplied from the upstream of the flume. The final bed levels were measured with a laser displacement meter (LK-500, Keyence co., Ltd) after the beds were completely drained out. The bed materials of the surface layer at several representative locations were taken with a special sampling spoon. The sampling depth was approximately 2.86 mm, corresponding to D_{90} of the coarse fraction of the sediment. Finally, the dry sediment samples were analyzed with a nested column of sieves, together with a high-resolution balance scale (UW220H, Shimadzu co., Ltd).

3. RESULTS AND DISCUSSIONS

3. 1 Local scour and bed deposition

Local scour is one of the most important concerns in the design and implementation of groynes. Excessive scour may result in the undermining of the groyne structures, which should be avoided from the perspective of disaster mitigation. On the other hand, the pool habitat created by local scour has a potential to improve the river ecology, which should be promoted from the viewpoint of environment restoration. Moreover, local scour is generally followed by immediately downstream sediment deposition. Therefore, an insight into the scour-deposition morphology is a key to understand the performance of groynes.

The differences of the elevation between the final bed and the initial flatbed are plotted in **Fig. 3** and several characterizing parameters are extracted from the figure as listed in **Table 2**. For reference, the photos of the bed surface taken at the final stage are presented in **Fig. 4**. It is evident

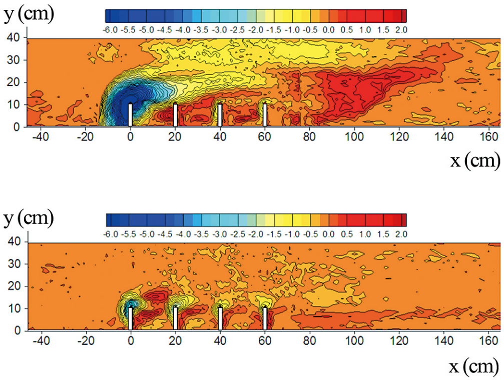

Fig. 3 Bed deformation from the initial flatbed (unit: cm, Top: Case1; Bottom: Case2)

Table 2 Local scour depth and bed deposition depth (unit: cm)

Parameter/Case	Case1	Case2
Max. scour depth	7.96	3.65
Max. deposition depth in bay AB	1.39	0.89
Max. deposition depth in bay BC	0.62	0.70
Max. deposition depth in bay CD	0.80	0.51
Max. deposition depth behind groyne D	1.17	0.76

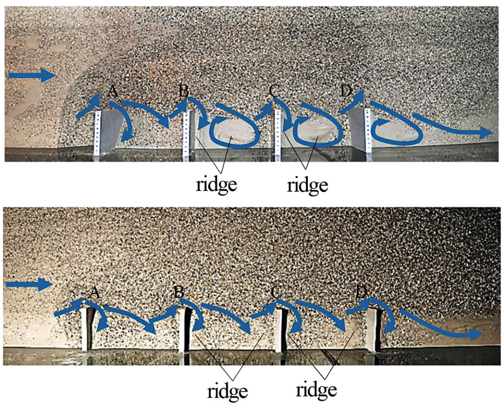

Fig. 4 Bed surface conditions at the final stage (Top: Case1; Bottom: Case2)

that the bed morphologies in Case1 and Case2 are similar to some extent but differ a lot in terms of detailed scour-deposition patterns.

In the approach flow zone, the bed shows insignificant changes due to the formation of an armor layer which prevents the bed from continuous degradation. On the other hand, ripples consisting of fine sediment are observed in some places especially in the proximity of the right side of the flume as shown in **Fig. 4**. The mainstream area is slightly degraded due to the flow acceleration caused by the local narrowing of the channel width. Compared with that in Case2, the bed degradation in Case1 is more drastic, indicating the different constriction effect of groynes in different cases. In the wake zone behind the most downstream groyne, i.e. groyne D, a relatively long distance of deposition with ripples of fine sediment is observed in both cases although the deposition pattern is slightly different. The bed morphology in the proximity of the groynes is characterized by local scour and corresponding deposition in both cases. In Case1, severe local scour up to 7.96 cm takes place at the most upstream groyne, i.e. groyne A, and a large area of sediment deposition forms behind it. The scour-deposition pattern in general is similar to that around a single groyne which is mainly controlled by the local vortex system (Zhang et al., 2012 and Zhang et al., 2015). The local scour at groyne A exerts great impacts on the bed deformation around the downstream groynes. Although local scour holes and deposition areas are also observed around groynes downstream, they are basically superimposed on the wake deposition induced by groyne A. In Case2, the maximum scour is found at the toe of groyne A which is similar to that of Case1, but the scour depth is only 46% of that in Case1. Moreover, the influence of the wake deposition due to groyne A on the bed morphology around downstream groynes is much less compared with that in Case1. The deposition patterns in the groyne bays are different in different cases. The first groyne bay, i.e. bay AB is influenced a lot by the local scour around groyne A. Due to the large scour hole, sediment carried by the horse-shoe vortex is transported to the foreside of groyne B and deposits there in Case1. On the other hand, the deposition in bay AB of Case2 locates along the leeside of groyne A due to the small scour and the flow overtopping the groyne. The deposition patterns in bays BC and CD are somewhat similar. In either of the groyne bay, there are two ridges in the deposition area. One is located along the leeside of the upstream groynes, and another is near the center of the bays in Case1 and near the foreside of the downstream groynes in Case2. The maximum deposition depth and the deposition area in Case 1 are generally larger than those in Case2 as shown in **Fig. 3** and **Table 2**, corresponding to the differences in the local scour volume and the degree of the mainstream bed degradation.

3. 2 Grain size variation

Sediment sorting is a common phenomenon in alluvial rivers. Sediment sorting affects both the bed topography and the bed materials composition. Hereafter, the distributions of the dimensionless mean grain size along typical longitudinal and transverse cross-sections are investigated. The dimensionless mean grain size is defined as the ratio between the mean grain size at the final stage D to that on the initial bed D_0. The bed is coarsened if the value is larger than 1.0. On the other hand, a value less than 1.0 indicates an increase of the fine fraction.

3. 2. 1 Grain size variation along longitudinal cross-sections

The changes of the grain size along typical longitudinal cross-sections are plotted in **Fig. 5**. In the figure, Sections y=20 cm and y=30 cm are

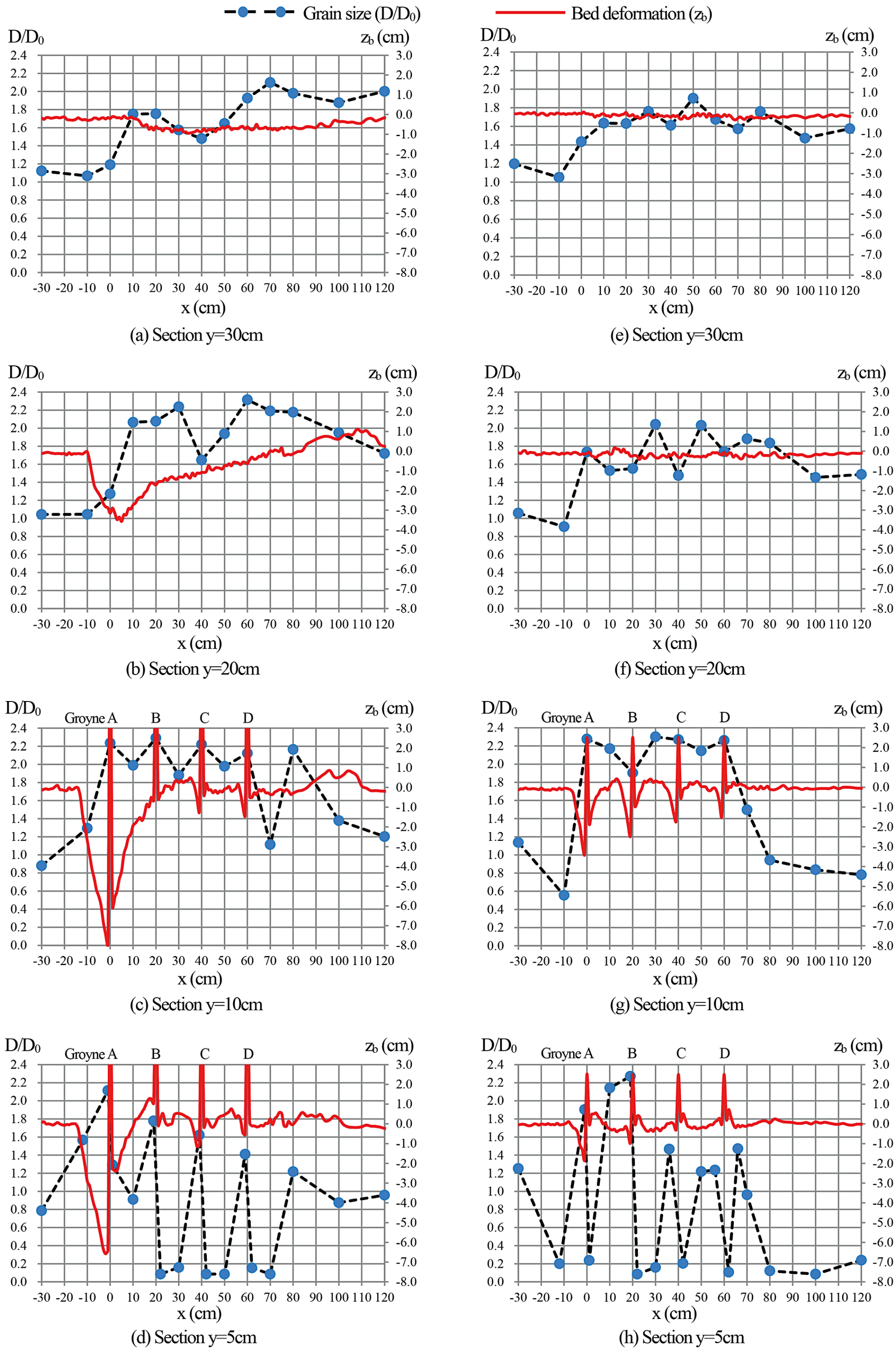

Fig. 5 Grain size variation along typical longitudinal cross-sections (Left: Case1; Right: Case2)

sections in the mainstream, Section y=10 cm is the section connecting the heads of all groynes and Section y=5 cm passes the geometric center of the groyne bays. For reference, the bed level change with respect to the initial flatbed of each section, denoted by z_b, is also plotted in the figure with the secondary vertical axis.

Fig. 5(a) and **Fig. 5**(b) draw a clear image on the longitudinal bed variation in the mainstream in Case1. In the approach flow zone (x<0 cm), the bed level almost maintains and the bed materials are slightly coarsened. This phenomenon is caused by the transport of fine sediment and the formation of an armor layer. In the reach narrowed by the groynes (0 cm<x<60 cm), bed degradation is obvious due to the flow acceleration, especially in the area near to the groynes (Section y=20 cm). In this reach, the bed materials are significantly coarser than those on the initial bed. The coarsest grains are found in the proximity of the end of the groyne reach (x=60 cm-70 cm), where the grain size is more than twice of that on the initial bed. In the downstream of the groyne reach (x>60 cm), coarse sediment is still dominant for a long distance. Unfortunately, the experimental data availableness does not allow a quantitative estimation of the influence range. Similar trends are observed on the bed variation in Case2 according to **Fig. 5**(e) and **Fig. 5**(f). However, the changes of both the bed level and the bed composition in Case2 are much milder than those in Case1. It is also interesting to note that the grain size in the groyne reach does not monotonically increase in the groyne reach. The grain size at x=40 cm is relatively smaller compared with other areas in both cases. It is probably due to the boundary on the left side of the flume which exerts influences on the flow separated from the heads of the groynes, particularly the most upstream groynes.

Fig. 5(c) shows the grain size distribution in the transition zone between the mainstream and the groyne bays in Case1. In the approach flow zone, sediment becomes finer than the original one due to the formation of a thin layer of fine sediment ripples. In the groyne reach, bed sediment is greatly coarsened. The sediment at the bottoms of scour holes is extremely coarsened and is around 2.2 times of the original one, which indicates that the bottoms almost completely consist of coarse sands. In the downstream of the groyne reach, sediment is coarser than that on the initial bed. Moreover, the sediment becomes coarser and coarser with the elevation on the foreside and finer and finer on the leeside of the deposition hill. In Case2 as shown in **Fig. 5**(g), surface armoring and ripples are distinguishable in the approach flow zone. Sediment coarsening is also evident in the groyne reach, but the coarsest grains are not always found at the bottoms of the local scour holes. This phenomenon is closely related to the local flow field. According to previous research of the authors' group, the horse-shoe vortex within the scour hole which is the main engine for the local scour development contributes dominantly to the bottom coarsening in emerged conditions (Zhang et al., 2012). On the other hand, the overtopping flow plays an important role in case of submerged groynes (Mizutani et al., 2012). The mixing of the two flow patterns in the transition zone is responsible for the differences in the bed variations. Downstream of the groyne reach, the bed level is slightly aggraded and the bed materials gradually turns finer with the reduction of the flow velocity. Different from that in Case1, the deposited sediment is finer than that on the initial bed after a certain distance from groyne D.

In **Fig. 5**(d) and **Fig.5**(h), the bed properties in the approach flow zone are similar to those in **Fig. 5**(c) and **Fig. 5**(g). Nevertheless, the characteristics of the grain size distributions in other areas are quite different. The grain size in bay AB is a little complex and is largely influenced by the local flow around groyne A. The bed materials are mostly coarser than those on the initial bed except a small area along the leeside of groyne A in Case2. In bays BC and CD, the grain size distributions show a close relation with the local bed topography. In general, fine sediment accumulates at high elevations and coarse sediment is dominant at low elevations. In either bay BC or bay CD, two deposition ridges as mentioned before are evidently confirmed in the figures. However, as shown in **Fig. 4**, the thickness of the fine deposition in Case1 is much larger than that in Case2. In both cases, the grain size on the foreside of the groyne is much larger than that on the leeside. In the wake zone of groyne D in either of the case, two regions of fine sediment are observed. The two fine deposition areas are closely related to the scale of the horseshoe vortex and the wake vortex around groyne D. The area of the fine deposition immediately behind groyne D in Case1 is larger than that in Case2. But the situation changes when the fine deposition far from groyne D is concerned. Compared with those in Case1, the area is larger and the mean grain size is smaller in Case2.

3. 2. 2 Grain size variation along transverse cross-sections

The changes of the grain size along typical transverse cross-sections are plotted in **Fig. 6** and **Fig. 7** for Case1 and Case2, respectively. In the figure, Sections x=−30 cm and x=−10 cm are sections in the approach flow zone, Sections x=0 cm, x=20 cm, x=40 cm and x=60 cm are sections passing the normal centers of groynes, Sections x=10 cm, x=30 cm, x=50 cm are sections passing the geometric centers of groyne bays, and Sections x=70 cm, x=80 cm and x=120 cm are representative sections in the downstream of the groyne reach. Along the sections passing the normal centers of the groynes, samples are taken from both the foreside and the leeside of each groyne, and it is found that the grain size of the former is larger than that of the latter in all sections. In both cases, the grain size distributions in the approach flow zone, the groyne reach and the downstream area of the groyne reach exhibit quite different characteristics in the transverse direction.

In the approach flow zone (x<0 cm), the bed is generally coarsened, but the locations of fine sediment ripples and the geometry of the local scour hole influence the mean grain size of the samples. Along Section x=−30 cm, sediment near the right side of the flume is finer than the initial bed materials and gradually turns coarse towards the left side in Case1 as shown in **Fig. 6**(a), while in Case2, the bed is coarsened everywhere especially near the sides of the flume according to **Fig. 7**(a). Along Section x=−10 cm, the distribution patterns change a lot. In Case1, the local scour extends to this cross-section and the sediment materials at the bottom of the scour are coarser than those on the upper layer. Outside of the scour, the grain size is slightly coarser than that on the initial bed as shown in **Fig. 6**(b). On the other hand, sediment near the right side of the flume almost consists of only fine sediment due to the development of ripples and the mean grain size gradually turns coarse towards the left side of the flume in Case2 as shown in **Fig. 7**(b).

The distribution of the grain size in the groyne reach (0 cm<x<60 cm) is significantly influenced by the existence of the groynes. In the extent of the scour hole, for example, Figs.6(b)-(e) in Case1 and Figs.7(c), (e), (g) and (i) in Case2, the sediment becomes coarser and coarser with the decreasing of the channel bed elevation. It demonstrates that the local scour not only alters the local bed configuration but also leads to the vertical coarsening of bed materials within the scour hole. In general, the change of the grain size in the groyne reach follows such a pattern of fine-coarse-fine from the groyne bay toward the mainstream. Here, the

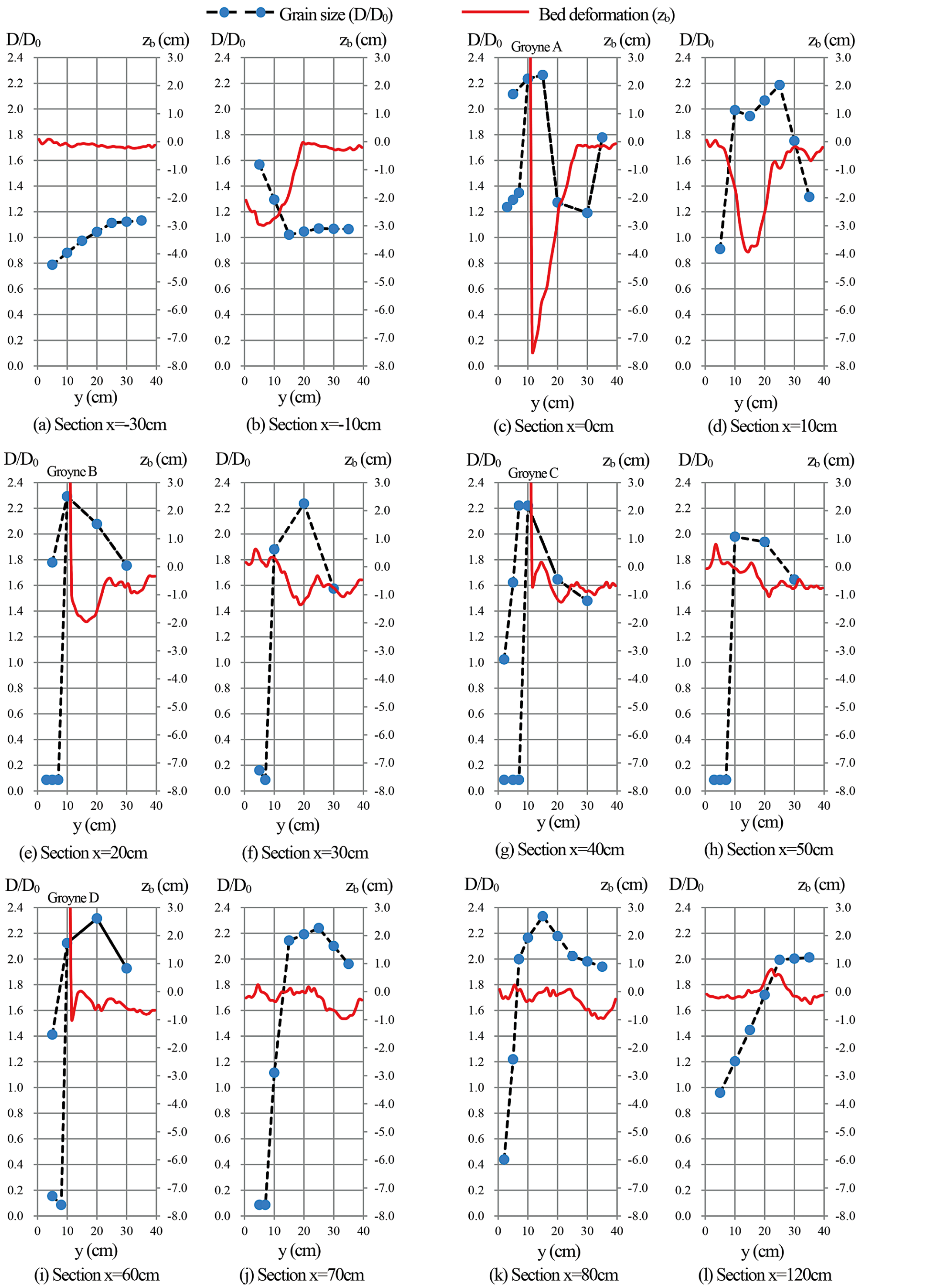

Fig. 6 Grain size variation along typical transverse cross-sections (Case1)

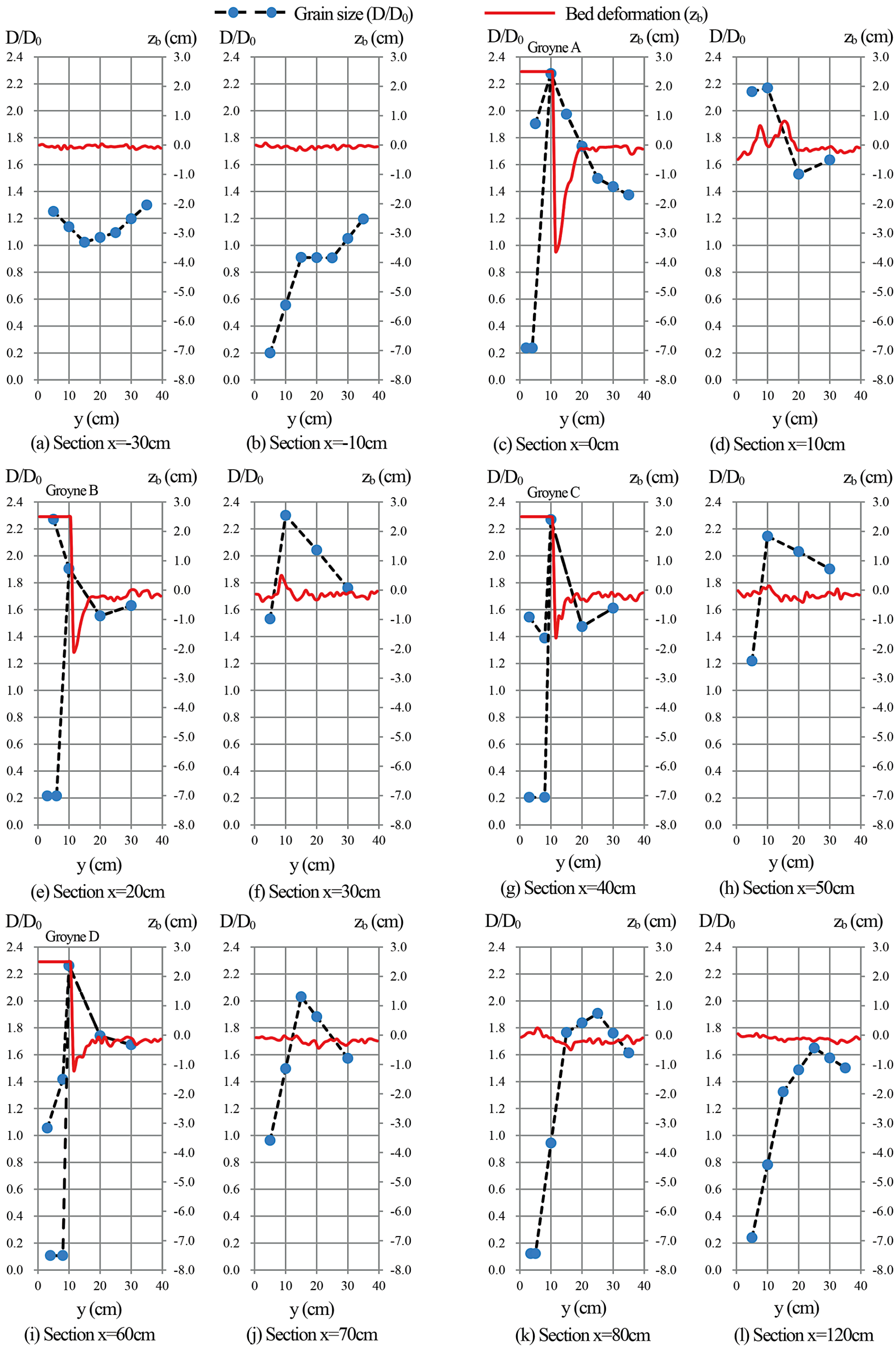

Fig. 7 Grain size variation along typical transverse cross-sections (Case2)

grain size of the fine area is not necessarily finer than that on the initial bed. The coarsest sediment is commonly found in the range of y=10 cm-20 cm, which is more than 2.2 times of that of the sediment on the initial flatbed. An evidently coarsened area is formed in the proximity of Section y=20 cm. In Case1, the grain size at most of the representative points in the bay areas is finer than that on the initial bed, especially in bays BC and CD. On the other hand, only the sample on the leeside of each groyne is finer than the initial bed sediment in Case2. These observations are also visually confirmable from the experiment photos in **Fig. 4**.

In the downstream of the groyne reach, i.e. Sections x=70 cm, 80 cm and 120 cm, the grain size also follows a trend of fine-coarse-fine from the right side to the left side of the flume in both cases. The coarsened region extends to this reach and is located in the proximity of Section y=20 cm as well. Although the percentage of fine sediment varies with locations, the mean grain size in the proximity of the left side of the flume is generally larger, and that in the proximity of the right side of the flume is smaller than the mean grain size of the initial bed materials. The existence of an obviously coarsened region is also observed in case of a single groyne according to the authors' previous research, e.g. Zhang et al. (2012) and Zhang et al. (2015). In those research, two fine sediment ribbons have been observed in the groyne wake and near the coarsened region in different non-uniform sediment beds due to sediment sorting in the transverse direction. However, the latter is not evidently distinguishable as the grain size of the fine fraction adopted in this study is too fine and is mainly transported in suspended load.

3. 3 Discussions

The results above indicate that groynes have significant influences on both the bed configurations and the distribution characteristics of the bed materials. As the approach flow area shows insignificant changes in bed elevations and there is no sediment supply from the upstream inlet boundary, it may be considered that the sediment particles on the initial flatbed are re-distributed by the groynes. To understand the functionality of groynes, it is of meaning to know how the sediment moves after the installation of the groynes.

During the running of the experiments, interval timer shooting on a digital single-lens reflex camera (Model: Nikon D5000) was conducted. Based on the records of the camera and observations during the running of the experiments, sketches are made in **Fig. 4** to draw a picture on the primary sediment transport near the bed in the neighborhood of the groynes. The sketch also provides information on the near-bed mass exchanges between the mainstream and the groyne bays/wakes. As the mainstream is the major source of sediment supply for the groyne bays/wakes, the exchange process plays an important role in the bed deformation properties. The sketch demonstrates why the sediment bed is scoured and coarsened as well as how and where the fine particles accumulate to form the deposition area. Common features and differences between different cases and among different groyne bays are distinguishable from the sketches, which provide important information for the understanding of bed variation mechanisms.

It is no doubt that the movement of sediment particles strongly depends on the flow field and the local bed topography. In particular, the transport of suspended load is directly influenced by the structure of the local flow. Although detailed flow velocities are not measured in this study, the sketch is found to coincide with the findings obtained from previous studies of the authors' group on the three-dimensional flow structure under bedload transport conditions, e.g. Zhang et al. (2012) and Mizutani et al. (2014).

4. CONCLUSIONS

The characteristics of the local scour and grain size distribution around a series of emerged and submerged groynes in a non-uniform sediment bed are presented. It is found that the groynes significantly alter the local bed morphologies and promotes sediment sorting longitudinally, transversely and vertically.

Under the current experimental settings, the bed in the approach flow area generally shows insignificant changes in elevation and is slightly coarsened due to the selective transport of fine particles and the formation of an armor layer in the bed surface. However, ripples consisting of fine particles appear in the right half domain of the flume due to the blockage effect of the groynes.

In the groyne reach, the mainstream area is degraded and local scour holes take place at the toes of groynes. The scour hole around the most upstream groyne is the most severe and exert impacts on the groynes downstream, especially in emerged case. The bed in the mainstream and within the local scour holes are significantly coarsened due to flow accelerations and strong horseshoe vortices, respectively. A belt of evidently coarsened zone is found in the proximity of the longitudinal centerline of the flume. On the other hand, fine deposition is obvious in the second and the third groyne bays where fine sediment deposits at high elevations and coarse sediment is dominant at low elevations. Moreover, there are two ridges in the fine deposition areas. One is near the leeside of the upstream groyne of the bay, and another is in the proximity of the geometric center of the bay in emerged case and near the foreside of the downstream groyne in submerged case. The overtopping flow plays an important role in the submerged case. In the first groyne bay, the bed materials are mostly coarser than those on the initial bed except a small area near the leeside of the upstream groyne in the submerged case.

The belt of the evidently coarsened zone in the mainstream extends to the downstream of the groyne reach. While in the wake of the most downstream groyne, two areas of fine deposition form due to the horse-shoe vortex around and the wake vortex behind the groyne in each case. The scales and the mean grain sizes of the two fine deposition areas are different in emerged and submerged cases corresponding to the differences in the vortex system.

The characteristics of the scour-deposition and grain size distribution above and their implications on potential disasters and benefits should be prudently considered for the design and assessment of groynes. Research with field surveys is ongoing to further the understanding in actual rivers.

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要　旨

河川災害の防止並びに多様な河川環境の創出を目的として，伝統的な河川工法である水制工は，世界中の沖積河川に広く導入されている。水制工が有する防災と環境機能を水工学的に評価するには，水制工周りの局所洗掘と流砂分級現象の解明が重要である。本論文では掃流砂と浮遊砂の卓越した状況での混合砂河床において，水制群周辺の砂礫の分級と河床変動特性に関する水理模型実験結果について考察を行っている。すなわち，不透過型水制群を用いて越流および非越流の場を対象とした実験を行い，水制群周辺の洗掘・堆積地形の形成および流砂の分級特性について検討した。その結果，水制群は河床の多様性を大幅に促進することが確認された。特に，実験水路の縦断，横断および鉛直方向における河床材料の粒度分布は流砂の分級により大きく異なること，水制工で水刎ねされた主流部では，流下方向に平均粒径は大きくなること，水制工設置区間とその直下流域では，帯状の粗粒化領域が水路の中心線付近で見られること，一方，細粒土砂は水制間および水制背後域に堆積し，その堆積形態は場所や水制工の水没状況により異なること，洗掘孔は粗粒化領域で，河床材料は上部よりも底部のほうが粗いこと等が明らかになった。このような成果は水制工を用いて河川の多様な環境を創生するうえで重要な情報を提供するものといえる。