**Bed morphology and grain size characteristics around a spur dyke**

**Abstract**

This paper presents an experimental study on the local bed morphology and grain size characteristics around an impermeable spur dyke. A series of experiments are conducted with different types of sediment beds. It is found that the heterogeneity of the sediment exerts an influence on detailed bed topographies around the spur dyke, but does not influence the typical features of scour-deposition morphologies. The mean grain size and the geometric standard deviation of the bed sediment are two important and practical parameters in characterizing the changes of the bed morphologies and the bed compositions around the spur dyke. The sediment sorting process plays a crucial role in the grain size distribution, and the process occurs longitudinally, laterally and vertically. In the proximity of the spur dyke, the bed is generally coarsened from upstream to downstream and sand ribbons consisting of fine particles are observed. Within the scour hole, the bottom sediment is coarser than that at the top.

**Key Words:** Spur dyke, Non-uniform sediment, Local scour, Grain size distribution, Sand ribbon







1 Dr. of Eng., Assistant Prof., Disaster Prevention Research Institute, Kyoto University, Japan, Corresponding author, E-mail: [zhang@uh31.dpri.kyoto-u.ac.jp](mailto:zhang@uh31.dpri.kyoto-u.ac.jp)

2 Dr. of Eng., Prof., Disaster Prevention Research Institute, Kyoto University, Japan, E-mail: [nakagawa@uh31.dpri.kyoto-u.ac.jp](mailto:nakagawa@uh31.dpri.kyoto-u.ac.jp)

3 Doctoral student, Department of Civil and Earth Resources Engineering, Kyoto University, Japan,

E-mail: [mizutani@uh31.dpri.kyoto-u.ac.jp](mailto:mizutani@uh31.dpri.kyoto-u.ac.jp)

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# Methodologies

* 1. Experimental setup

A series of experiments were performed in a straight tilting flume at the Ujigawa Open Laboratory, Disaster Prevention Research Institute, Kyoto University (Japan). The flume is 8m in length, 40cm in width and 40cm in depth, with a 1.5m-long inlet tank attached upstream (Fig. 1). The flume contains a re-circulating water supply system. A soft and permeable pad is installed near the junction of the inlet tank and the flume to inhibit flow concentrations and to minimize the wavy surface. A sediment recess is located 4m downstream from the inlet tank. It is 1.7m long and is covered with a 20cm-thick layer of model sediment: silica sand, forming a movable bed. The upstream and downstream sections of the sediment recess are fixed with 20cm-thick wooden boards. A 50cm-long sediment trap is fixed at the end of the flume, followed by a tailgate.

An impermeable spur dyke, 10cm long and 1cm thick, is installed on the right side of the flume in the movable bed area as shown in Fig. 1. The spur dyke is perpendicular to the flume side and remains non-submerged throughout the experiments.





**Fig. 1** Experiment setup (Unit: cm)

* 1. Experiment conditions

The hydraulic conditions before the installation of the spur dyke are shown in Table 1. Two series of experiments are conducted, consisting of 9 cases in total. The first series is composed of 4 cases and tests the effects of the mean grain size on the bed topography around the spur dyke using uniform sediment particles (hereafter referred to as the U-series experiments); the remaining 5 cases belong to the second series and test the impact of the non-uniformity, in particular the grain size distribution of sediment on the bed topography and bed-material composition around the spur dyke using sediment mixtures of various size distributions (hereafter referred to as the M-series experiments). The sieve analysis results of sediment particles at the initial bed for each case are shown in Fig. 2, and the characterizing parameters are shown in Table 2. In the experiments, 6 types of silica sediment of relatively uniform size distributions are used to prepare the uniform and non-uniform sediment beds: No. 2 (*D*=2.38mm), No. 3 (*D*=1.70mm), No. 4 (*D*=1.03mm), No. 5 (*D*=0.48mm), No. 6 (*D*=0.31mm) and No. 7 (*D*=0.16mm).



**Table 1** Details of the hydraulic conditions

|  |  |  |  |
| --- | --- | --- | --- |
| Flow discharge *Q* (l s-1) |  | Sediment density *o* (g cm-3) |  |
| Channel slope *I* |  | Friction velocity *u\** (cm s-1) |  |
| Flow depth *h* (cm) |  | Reynolds number *Re* |  |
| Flow velocity *U* (cm s-1) |  | Froude number *Fr* |  |

**Fig. 2** Sieve analyses results of sediment samples at initial stage

In the U-series experiments, silica sand Nos. 6, 4, 3 and 2 are used for Cases U1, U2, U3 and U4, respectively. Correspondingly, the shear velocity ratios *u\*/u\*c*, indicating the particle mobility, are 1.18, 0.83, 0.62 and 0.49, respectively, where *u\** is the friction velocity in the approach flow area and *u\*c* is the

critical friction velocity for sediment entrainment. The friction velocity is calculated from *u*\*  *gRI* ,

where *g* is the gravitational acceleration, *R* is the hydraulic radius, and *I* is the channel slope. The critical friction velocity is estimated with Iwagaki’s formula (Iwagaki, 1956).

**Table 2** Sediment properties and bed topographic features

where unit for the location (*x, y*) is (cm, cm).

In the M-series experiments, the mean grain size *D* of each case is constructed in a manner similar to Case U2, while the geometric standard deviation *og* varies from case to case. Case U2 is also referred to as Case M0 in the analysis, due to the fact that it possesses a smaller value of *og* compared with other M-series cases. Moreover, both Cases M3 and M5 adopt gap-graded sediment consisting of particles with two clearly distinguishable size fractions, a coarse one and a fine one. In Case M3, sediment Nos. 3 and 6 are mixed, while in Case M5 the coarsest sediment, No. 2, and the finest sediment, No. 7, are mixed together. The grain size distribution curves of Cases M1 and M4 are made relatively smooth as shown in Fig. 2, and the sediment particles are considered to be relatively well graded. Sediment Nos. 3, 4, 5 and 6 are mixed in Case M1, while all sediment sizes available (from No. 2 to 7) are mixed in Case M4. In order to understand this phenomenon more visually, colored sands are utilized in Case M2. Relatively uniform silica sand particles which are black, blue or red in color are fully mixed for the preparation of the non-uniform sediment bed. The black particles possess grain sizes ranging from 1.40 to 2.36mm, with a mean size similar to that in Case U3; the blue sand particles range from 0.50 to 1.40mm and are similar to Case U2; and the red sand particles range from 0.125 to 0.50mm, and are similar to Case U1. As for *u\*/u\*c*, the blue portion falls in the vicinity of unity, the black portion is much less than 1, and the red portion is much larger than 1. Moreover, all the experiments are conducted under clear water scour conditions, with the exception of Case U1.



* 1. Experiment procedure

Sediment is filled in the sediment recess to form the movable bed. Before each run of the experiment, the sediment bed surface is levelled with a scraper blade attached to a sliding metal carriage positioned on the rails over both sides of the flume. Then, the flume is slowly filled with water from the downstream using a plastic hose with a valve mounted on it to adjust discharge. When the desired water depth is achieved by adjusting the height of the tailgate at the end of the flume, the pump is activated and set to the desired discharge. In general, each experiment is carried out for 3 hours. At this stage, sediment transport becomes inactive, the variation of the bed topography is insignificant and the changing process of the bed surface composition is almost undetectable to the naked eye.

After the completion of each experiment, the flume is drained out and the bed configuration is measured with a high-resolution laser displacement meter (Model LK-500, Keyence, Co., Ltd.). For cases of non-uniform sediment, changes of the bed materials composition at the surface layer are measured by taking samples in the proximity of the spur dyke with a special sampling spoon. The sampling depth is approximately 2.86mm, corresponding to the *D90* of the coarsest silica sand No. 2 used in the experiments. After being completely dried, the sediment samples are analyzed with a nested column of sieves, along

with a high-resolution balance scale (UW220H, Shimadzu, Co., Ltd.). Since the local scour and deposition patterns in all the experiments are quite similar, the flow field is measured for one case only,

i.e. Case U2 (M0). Before the measurements of the flow field are taken, the deformed bed is moulded with instant cement after the flume has been completely drained. Afterwards, water is pumped into the flume and the same flow discharge is applied to the channel. The water level is then surveyed with a servo-type gauge. PVC (Polyvinyl chloride) tracers are distributed in the flume and videos are recorded for PIV (Particle image velocimetry) analysis of the surface velocity. In the water column, velocity fields in several transverse and longitudinal sections are recorded with an EMV (Electromagnetic velocimetry, Model ACM250-A, JFE Alec Co., Ltd.). Moreover, a series of pictures are taken for Case U2 (M0) and Case M2 at regular intervals to capture the expansion process of the scour and bed deformation around the spur dyke with two DSLR (Digital single-lens reflex) cameras (Nikon D5000 and Nikon D40X).

# Results and discussions

* 1. Bed morphology

The bed contours at the final stage are plotted in Fig. 3. For clarity, a sketch of the dimension of the local scour hole is shown in Fig. 3(e) and key parameters representing the topographic features of the bed are listed in Table 2. In this table, *em* and *dm* are the maximum scour depth and the maximum deposition height from the initial flatbed, respectively; *em* (*x, y*) and *dm* (*x, y*) are the *x* and *y* components of the locations of the maximum scour and the maximum deposition, respectively, and *Vs* is the volume of the scour hole. Other variables are defined in detail in Fig. 3(e).

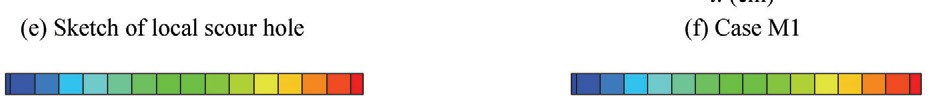
1. Uniform beds

In uniform sediment beds, it is evident from Fig. 3 that the mean grain size, and hence *u\*/u\*c* plays an important role. Figs. 3(a) to 3(d) indicate that the deformed area, especially the local scour area, decreases with a decrease of *u\*/u\*c*. The values of *a/L, b/L, c/L* and *d/L* in Table 2, expressing the expanding area of the scour hole, offer more quantitative evidence. In addition to the extension area, the maximum scour depth and the scour volume decrease with a decrease of *u\*/u\*c* as well (see Table 2). It is understood that the entrainment of coarse particles requires more flow energy and hence these coarse particles are not easily removed from the bed. A plot of the dimensionless maximum scour depth against *u\*/u\*c* is shown in Fig. 4. In the figure, the clear water peak is drawn for reference. The relationship cannot be considered as a monotonic function, although the scour depth becomes larger with an increase of *u\*/u\*c* under the current experiment conditions. The maximum scour depth shows a positive relation to *u\*/u\*c* in the clear water scour range. If *u\*/u\*c* exceeds the clear water peak, the development of bed forms will influence the scour process. This is why the scour depth in Case U1 shows a slightly different trend from the other cases. It should be noted that the graph is very similar to that reported by researchers from the University of Auckland such as Chiew (1984) and Dongol (1994), who conducted a series of pier and abutment scour experiments. Moreover, it demonstrates the possibility of using prediction formulae proposed by the Auckland research group to roughly estimate the maximum scour depth around spur dykes, e.g. the K-factor formula suggested by Melville (1997). Since the sediment size *D* is relatively small compared to the spur dyke length *L* in the current study (*L*/*D*>25), the potential scour depth will be a simple function of the shear velocity ratio, the spur dyke length and the water depth, according to Melville (1997).



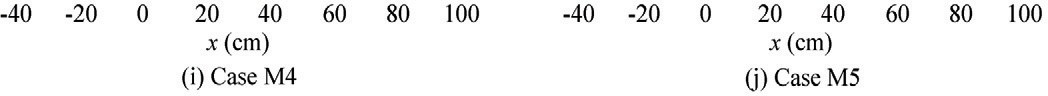
The location of the deepest point of the scour hole also exhibits some interesting trends. The deepest point is located at the toe of the spur dyke when *u\*/u\*c* is small (Case U4), and gradually shifts to the side of the flume with an increase of *u\*/u\*c* (from Case U3 to U1). This phenomenon is surely related to the applied forces on the bed particles and is governed by the flow structure and the geometry of the scour hole. It is known that the local scour initiates at the toe of the spur dyke and the expanding process is highly dependent on the bed degradation in the toe area at the early stage. However, the influence of the toe area becomes weak when the scour hole is suitably large. Comparing the vicinity of the toe with the upstream of the spur dyke where the maximum scour depth is possibly located, it should be noted that the latter also has potential to pose great impact on the former. The vicinity of the toe area is an important passage for sediment eroded from the upstream scour area to the downstream of the channel. Therefore, the bed elevation at the toe not only depends on the local flow field, it is also affected by the changes in

the upstream flow, sediment and bed conditions. On the other hand, there is almost no sediment supply in the upstream area of the spur dyke, except for that caused by possible sliding of the local slope. Consequently, the upstream of the spur dyke suffers from almost continuous scouring if the shear stress is great enough. As a result, the maximum scour does not necessarily appear at the toe of the spur dyke.







**Fig. 3** Local scour and bed contour (Unit: cm)

**Fig. 4** Local scour vs. shear velocity ratio

The geometry of the scour holes shows some common features despite the differences in *u\*/u\*c*. Due to the existence of two different scour engines (i.e. the horse-shoe vortex at the toe and the wake vortex behind the spur dyke, as pointed out by Zhang et al., 2009) and their interaction with the movable bed, the geometry of the degraded area in the upstream differs substantially from that in the downstream. The slope of the scour hole in the downstream is much milder compared with that in the upstream, as shown in Table 2. The representative slopes of the scour hole also show some relation with *u\*/u\*c*. If different cases are concerned, the local slope generally becomes steeper when *u\*/u\*c* becomes smaller. As for the maximum deposition depths and their locations, it is clear from Table 2 and Fig. 3 that the highest deposition point is located closer to the spur dyke in smaller *u\*/u\*c* cases. Moreover, there is a trend that the maximum deposition depth is larger in smaller *u\*/u\*c* cases, except for Case U1; in this particular case, development of bed forms is observed since *u\*/u\*c* is over unity. The superimposition of the bed forms on the deposition caused by the existence of the spur dyke may have some influence.



1. Non-uniform beds

Although Fig. 3 offers that the sediment heterogeneity does not exert much impact on the general scour-deposition pattern in the bed topography around the spur dyke, the differences in the grain size distribution do have a substantial influence on the detailed dimensions of the scour hole and the deposition pattern. In the non-uniform sediment experiments, the mean grain size, and hence *u\*/u\*c*, has been made similar by adjusting the mixing ratios. Consequently, the impacts of the grain size distribution may be isolated.

The extent of the scour hole exhibits a strong relationship with *og* or *D*90 according to the bed contours in Fig. 3 (b, f-j) and the values of *a/L, b/L, c/L i d/L* in Table 2. The extent area of the scour hole decreases with an increase of *og* despite the curvature of the grain size distribution curve, i.e. it does not make the essential differentiation between whether the mixture is well-graded or gap-graded. Table 2 also indicates that the maximum scour depth and the scour volume show a clear trend of decreasing with an increase of *og* irrespective of the shape of the grain size analysis curve. Plotting the dimensionless maximum scour depth against *og* in Fig. 5, it is found that the maximum scour depth monotonically decreases with an increase of the *og*, and the relationship between the two is almost linear. If the scour depth in a uniform bed, *e* is known or predictable from empirical formulae such as that proposed by Melville (1997), the scour depth in a non-uniform bed *es* may be simply estimated from the equation below:

However, the applicability of this equation to other situations is unknown. It is noted that there are also other formulae for the prediction of scour depth in non-uniform sediment beds. For example, Raudkivi and Ettema (1983) found that there was a relationship between *es/e* and *og*, and this relationship could be expressed by a diagram in case of a bridge pier. Moreover, the widely used K-factor formula proposed by Melville also included the effect of sediment non-uniformity by relating the armouring conditions to *og*

and the maximum grain size of sediment mixtures *D*90 (Melville and Sutherland, 1988; Melville, 1997). Unfortunately, it is found that the results of the current study cannot be accurately predicted using these formulae. This demonstrates that the local scour in a non-uniform bed may not be reasonably predicted with a simple empirical equation. Relations accounting for more details of the local flow and the bed sediment properties or advanced numerical models capable of resolving the complex flow and sediment transport are required. In the authors’ research group, a 3D numerical model is currently in development and some of the results have been reported by Zhang and Nakagawa (2009) and Mizutani et al. (2010).

**Fig. 5** Local scour vs. ˰*g*



Since a larger *og* implies a larger portion of coarse fractions in sediment mixtures, it is not difficult to understand the results of less scour depths in the non-uniform cases, according to the conclusions drawn from Fig. 4. The deepest point of the scour hole in non-uniform cases is much closer to the toe of the spur dyke compared with that in a uniform bed, but the location does not show a direct relationship with *og*, it indicates that the location of the maximum scour depth is directly related to the scour geometry, rather than to the bed composition. These observations suggest that the local scour will be the most severe in a uniform sediment bed if the shear velocity ratio remains constant. Therefore, scour prediction formulae based on uniform sediment studies will overestimate the maximum scour depths and in practice will generally result in conservative scour countermeasures. The formation of an armour layer at the bottom of the scour hole is responsible for the smaller scour in non-uniform sediment beds. During the scour process, relatively fine particles are eroded and the bed is gradually coarsened, preventing the bed from further degradation. The coarse portion in the bed affects not only the geometry of the scour hole, but also the deposition pattern behind the spur dyke. With an increase of *og*, the location of the highest deposition point becomes closer to the spur dyke (Table 2), and the deposition area becomes narrower (Fig. 3). The deposition height does not show any clear relationship with any specific parameter related to bed sediment properties. The wake zone of the spur dyke is a relatively stagnant area, and the sediment transport there is relatively inactive. Therefore, the deposition is mainly a result of the accumulation of sediment particles carried by the horse-shoe vortex. Since the downstream part of the scour becomes smaller and the horse-shoe vortex becomes weaker with an increase of *og*, it is easier to set down particles at a greater og.



As for the geometry details of the scour hole, the local slope of the scour hole in the downstream is much milder than that in the upstream, which is similar to the uniform cases. Unfortunately, there is no clear trend in the changes of the local slope of the scour hole corresponding to the changes in *og*, and there may also be other parameters playing roles in the bed variation process. Moreover, it is noted that the value of *og* provides information on the initial state of coarse particles in the sediment mixtures, but it cannot express the critical size of armouring around the spur dyke. It is evident that this critical size is a function of the shear velocity which varies both spatially and temporally. Therefore, the bed variation should be more accurately predicted with numerical models rather than empirical formulae.

* 1. Grain size distribution

The sediment heterogeneity affects not only the bed configuration but also the bed composition, and there is no doubt that the two aspects interact with one another.

In the experiments, the bed surface in the proximity of the spur dyke generally shows a trend of down-valley coarsening. An overlay of fine sediment strips on relatively coarse sediment textures, termed as sand ribbons in this study, is observed at the downstream of the spur dyke. During the experiments, the locations of fine sediment strips which are evidently distinguishable with the naked eye are memorized for analysis. Moreover, the local scour area, although physically small, exhibits significant changes in grain size distributions and differs significantly from those in the other areas.

The dimensionless grain size distributions are plotted in Fig. 6 for the M-series experiment cases. In this figure, the scatters represent the ratios of the mean grain sizes of the scoured bed (*Ds*) to the initial bed (*Di*) based on regular sampling points. The belt area shows the ratios of the mean grain sizes of the scoured bed (*Ds*) to the initial bed (*Di*) in sand ribbons according to *add hoc* sampling points. For reference, the bed elevations are also plotted in lines as background images. Furthermore, a sketch showing the proximity of the spur dyke is shown in Fig. 7.





**Fig. 6** Grain size distribution *Ds*/*Di* (scatters: sampling points, belts: sand ribbons, curves: bed contours)

1. Upstream zone

In the upstream approach flow area, the bed surface is slightly coarsened, except for in Case M5 where the mean sizes of the sediment particles at several points are finer than the mean grain size. Since the bed shear stress in this area is greater than the critical shear stress of some of the fractions consisting of the sediment mixtures, the bed coarsening phenomenon, which is a result of the longitudinal sediment sorting process, is understandable. On the other hand, only the coarsest and finest particles are mixed in Case M5. In essence, the fine portion on the bed surface will be washed away after the activation of the pump.

However, the voids between coarse particles easily trap fine sediment, and this trapped fine sediment may not be easily exposed to the flow. As a result, the ratio of the fine sediment decreases in some locations while it increases in some particular locations.





**Fig. 7** Proximity of the spur dyke

1. Local scour zone

Grain size becomes finer from the bottom to the top of the scour hole. The coarsest particles are found at the toe of the spur dyke. In Cases M1 and M2, the sizes of the sediment particles at the upper part of the upstream scour hole are even smaller than the mean grain size. The vortex system within the scour hole, as has been well reported by previous researchers (e.g. Koken and Constantinescu, 2008; Zhang et al., 2009), is responsible for this phenomenon. The vortex system promotes sediment sorting along the surface of the scour hole. On the other hand, the fine sediment may be trapped by the vortex and remain in the scour hole, forming a fine sediment belt. In the experiments with coloured sands (i.e. Case M2), the distribution of differently sized particles may be visually confirmed. The surface colour of the scour hole evidently changes from black to blue and then to red with an increase in the bed elevation.



Comparing the dimensionless sediment sizes at the toe of the spur dyke (Fig. 6), it is found that the mean sizes in Cases M4 and M5 are similar but are clearly larger than those in Cases M1, M2 and M3. This may be explained with the fact that the coarsest sediment particles, i.e. sediment No. 2, are mixed in Cases M4 and M5 but are excluded in the other M-series cases. It is also evident from Table 2 that the *D90* in Cases M4 and M5 are much larger than those in Cases M1, M2 and M3. Since coarse fraction forms an armour layer at the toe of the spur dyke, the mean size there is strongly dependent on the properties of the coarse particles. The sieve analysis results of the sediment mixtures at the toe of the spur dyke for all the M-series experiments are shown in Fig. 8. It is evident that on the final bed the percentage of the fine materials dramatically decreases, and that of the coarse particles significantly increases.



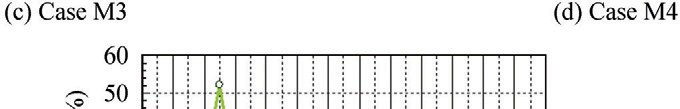
1. Downstream zone

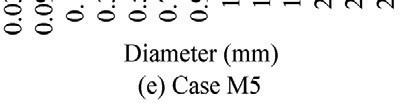
In addition to the scour zone, the downstream area of the spur dyke also experiences significant changes in the bed surface composition. In the mainstream, the downstream section is generally coarser than the upstream section due to the velocity acceleration in the downstream. On the other hand, the alternating distributions of fine and coarse particles, i.e. sand ribbons, are observed in the downstream of the spur dyke and are sketched in Fig. 6. There are basically two sand ribbons in each case, one is located between the mainstream zone and the wake zone and the other is located between the wake zone and the side of the flume. In Case M5, the ribbon between the mainstream zone and the wake zone disappears due to the unfavourable bed geometry and flow conditions there.

The sand ribbons are somewhat parallel to the side of the flume in the longitudinal direction. As is known, sand ribbons in alluvial channels are generally caused by lateral sediment sorting and have been documented to exhibit a strong relation with secondary currents (McLean, 1981; Tsujimoto, 1989; Colombili, 1993). In the experiments of this study, it should be noted that the ribbons begin from where the scour geometry and the flow structure show dramatic changes. Therefore, the complex bed geometry and the corresponding flow field in the neighbourhood of the spur dyke are mainly responsible for the formation of these ribbons. It is noted from Fig. 6 that the locations of possible sand ribbons are roughly determinable if the scour geometry is known. It must be mentioned that the fine sediment in the ribbons is not readily defined by a specific grain size. In this study, if the particles are clearly finer than the

surrounding ones, they are termed fine sediment. Moreover, it is found in the experiments that particles in sand ribbons are not necessarily uniform and that bed forms such as ripples may form if the ribbons are thick and wide enough. The sand ribbons are also visually confirmed in the colour sand experiment.







**Fig. 8** Sieve analysis result of the sediment particles at the toe of the spur dyke (Initial: lines, Final: bars)

* 1. Flow structures

The results on the bed changes in terms of both morphology and sediment composition reveal that the two aspects are highly dependent on each other and are both strongly related to the bed properties as well as the flow field. The flow field in the proximity of a spur dyke, especially in the scour hole, has been investigated by many researchers, e.g. Koken and Constantinescu (2008). However, the existing information seems insubstantial for the understanding of some of the phenomena, in particular the sediment sorting process in the proximity of the spur dyke and its morphological implications. In this section, additional information on the velocity field is supplemented and the roles it plays in the bed variations are discussed. Since the bed geometry in each case is similar in nature, the measurements are based on Case U2 (M0) and the conclusions drawn from this case are easily extended to others.

1. Velocity field near the bed

The flow field near the bed provides important information regarding the movement of sediment particles. The longitudinal and lateral velocity components located 1.5cm away from the initial flatbed and the final scoured bed are measured and are plotted in Fig. 9, normalized by the approach flow velocity. The flow field does not show any clear differences in the approach flow zone where the bed elevation shows little change from the initial stage to the final one. However, significant differences are observed in other locations, indicating the strong interaction between the flow and the bed. The presence of the spur dyke results in flow accelerations in the main stream, flow reductions in its wake zone, flow separations at its head and several vortex systems around it. The flow acceleration in the mainstream is a crucial impact of the spur dyke, promoting longitudinal sediment sorting processes and dramatic bed coarsening. With the degradation of the mainstream and the expansion of the local scour, the flow velocity in the mainstream decreases and the flow around the spur dyke becomes much more complex. As will be discussed below, the flow structure evidently becomes three-dimensional after adapting to the deformed bed geometry, particularly in the extent of the local scour hole. In the downstream of the spur dyke, alternating distributions of high and low velocity zones are observed on the scoured bed. The low velocity zone is triggered by the bed geometry induced by the spur dyke and is crucial for the formation of sand ribbons. In the local scour area, the velocity components are small in the lower and upper sections of the scour where the vertical velocity is dominant.



**Fig. 9** Dimensionless velocity vectors (*u/U, v/U*) and their magnitudes near the bed (Initial: left; Final: right)

1. Velocity field in transverse cross-sections



In order to understand the mechanisms of the bed deformation process and the formation of sand ribbons, the flow velocity components in several transverse cross-sections are measured and the variables normalized by the mean flow velocity are plotted in Figs. 10–14. When the flow approaches the spur dyke, severe flow separation occurs as shown in Figs. 10 and 11. The strong lateral flow component removes sediment particles from the bed and sends them towards the mainstream, resulting in bed degradation there. In the mainstream area, the particles are transported to the downstream by the longitudinal flow component or to the wake of the spur dyke by the horse-shoe vortex. Comparing the final stage with the initial stage, it is evident that the vertical velocity component becomes stronger with the development of the scour hole, and a clear horse-shoe vortex occupies the final local scour area.

**Fig. 10** Dimensionless velocity vectors (*v/U, w/U*) at *x*=-5cm (Initial: left; Final: right)

**Fig. 11** Dimensionless velocity vectors (*v/U, w/U*) at *x*=0 (Initial: left; Final: right)

**Fig. 12** Dimensionless velocity vectors (*v/U, w/U*) at *x*=5cm (Initial: left; Final: right)





**Fig. 13** Dimensionless velocity vectors (*v/U, w/U*) at *x*=15cm (Initial: left; Final: right)

**Fig. 14** Dimensionless velocity vectors (*v/U, w/U*) at final stage in Case U2

At the immediate downstream of the spur dyke, a weak vortex is observed on the initial bed as shown in Fig. 12 (left). With the development of the scour hole, the vortex is strengthened and is clearly separated into two vortices: one occupies the wake zone behind the spur dyke and the other locates within the scour hole close to the mainstream. The vortex in the wake zone attempts to transport sediment to the side of

the flume, while the other one attempts to send sediment to the mainstream. As a result, the sediment bed between the two vortices possesses potential to be degraded. Moreover, this type of vortex may trigger sediment sorting processes in the lateral direction. If one goes further downstream of the spur dyke at *x*=15cm as shown in Fig. 13, there are some other interesting findings. At the initial stage the vortex system is not very clear, but the mixing of the flows in the mainstream and the wake zone are observed, coinciding with the existence of the large-scale horizontal wake vortex as sketched in Fig. 9 (left). At the final stage, two vortices derived from the horse-shoe vortex are visible. Compared with Fig. 12, it is found that the two vortices change substantially in size, strength and location, indicating that the impact of the spur dyke becomes smaller. In addition to these two vortices, there are other two weak circulating flow cells, which are also sketched in Fig. 13 (right). The changes in the bed topography and the water depth are mainly responsible for the two circulating cells. In order to obtain more evidence, information on the transverse sections at the further downstream of the spur dyke are plotted in Fig. 14 along sections *x*=30cm and *x*=50cm. Four flow circulations are evidently observed at the section *x*=30cm, and some of the circulation cells join with each other at the section *x*=50cm. The change of the flow structures provides a clear image on the change of the bed profiles due to the existence of the spur dyke.

Moreover, the flow structure in the transverse sections is also a key to understanding the change of the grain-size distributions in the neighborhood of the spur dyke. Concerning the local scour area, strong near-bed currents in the lateral direction are observed near the toe of the spur dyke in the initial stage. The currents change direction and are completely combined with a vortex system on the final bed. With the development of the local scour, the vertical velocity components and the local slope of the scour hole become more and more important. Both coarse and fine sediment particles are eroded at the beginning if the bed is a non-uniform one. The selective transport of sediment particles occurs along the surface of the scour hole and grain sizes in the scour hole become finer with an increase of the bed elevation. The alternating distributions of fine and coarse sediment downstream of the spur dyke are highly associated with the circulating flows. At the locations where two circulation cells attempt to join with each other near the bed, fine sediment may accumulate, and at the locations where two circulation cells detach from each other at the bottom, the bed may be coarsened. Keeping this in mind, it is concluded from Figs. 13 and 14 that fine sediment strips possibly occurred near *x*=5cm and in the proximity of *y*=25cm if mixed sediment was used. Moreover, the possible meeting points of the circulation cells are generally located near the locations where local bed slopes exhibit significant changes. This coincides with the observations in the M-series experiments and the sketch of the location of the sand ribbons in Fig. 6. Since the magnitude of the flow velocity is closely related to the bed topography, the details of the sand ribbons vary from case to case. In some cases, the ribbon is even connected with the fine sediment belt at the upper part of the local scour hole, e.g. Cases M1 and M2. Only one ribbon is distinguishable in Case M5 along the side of the flume since the change of the bed topography is small and, as a result, the flow circulation is weak. Another reason comes from the bed itself which contains only the finest particles in its fine fraction. It must be mentioned that sand ribbons may form due to the inhomogeneity of turbulence, the gradient in channel geometry, the difference in the bottom roughness, and so on. Investigation of the velocity field here does not allow the separation of those factors. However, experiments without any spur dyke were conducted in flat non-uniform beds prior to the current experiments, and no sand ribbon was observed. Therefore, it is believed that the change of the bed topography is a dominant factor in this study. The complex bed geometry triggers different types of circulating flows and sediment sorting processes. Moreover, the formation of the sand ribbons results in changes in the bottom roughness and flow structures, and also exerts influence on the bed topography. In the M-series experiments, the rapid movement of individual coarse sediment particles on the ribbons is sometimes observed even if the surrounding coarse sediment texture is almost inactive. This is probably due to the fact that the regions of sand ribbons are generally smoother than other locations.



# Conclusions

The bed morphology, grain-size distribution and flow structure around a spur dyke are investigated experimentally, by which means the channel response to the presence of a spur dyke is clarified. By maintaining identical flow conditions and changing the bed sediment compositions in laboratory experiments, the importance of sediment heterogeneity is highlighted.

A spur dyke represents a type of disturbance to a channel, followed by local scour at the toe and

deposition behind it. The sediment heterogeneity exerts impact on the details of the local scour geometry and the deposition amount, but does not alter the basic morphologic features. The grain size, or more precisely, the shear velocity ratio, plays an important role in relatively uniform sediment beds. The local slope of the scour hole and the deposition height in the wake zone increase with a decrease of the shear velocity ratio. On the other hand, the maximum scour depth and the scour area increase with an increase of the shear velocity ratio. The local scour and the corresponding wake deposition in a non-uniform sediment bed are generally smaller compared with those in a uniform bed of similar shear velocity ratio. The maximum scour depth decreases almost linearly with an increase of the geometric standard deviation if the shear velocity ratio remains constant. Empirical scour prediction formulae such as that proposed by Melville (1997) may be used for a rough estimation of the local scour depth, but a three dimensional numerical model is required for a precise prediction.

In alluvial rivers, sediment generally becomes finer in the down-valley direction. Around a dam or a weir, the fine sediment deposits in the upstream and the downstream beds are coarsened. However, in the case of a spur dyke, the situation is much more complex. The sediment sorting process in local scales plays a crucial role in the change of the bed compositions, and this process is strongly dependent on the local bed morphology and the flow structure. The sediment sorting process occurs longitudinally, laterally and vertically, and it is evidently confirmed from the grain size distributions on the scoured bed. Due to the longitudinal sediment sorting processes, the bed materials generally become coarser in the mainstream from the upstream to the downstream. Sand ribbons appear at the downstream of the spur dyke mainly due to lateral sediment sorting processes triggered by secondary flows. The sand ribbons occur at the locations where the bed geometry shows significant changes, and the locations of sand ribbons are roughly predictable if the bed geometry is known. It is noted that sand ribbons around spur dykes are also observed in actual rivers (Zhang et al., 2011). In the local scour hole, the bottom part is substantially coarser than the upper part, indicating the sorting processes in the vertical plane due to the horse-shoe vortex system. The vortex system in the scour hole also possesses potential to trap fine sediment. As a result, the surface of the scour hole is not always coarsened.



The topographic change, the sediment sorting process and the local flow interact with each other and collectively form a strongly coupled system. The results from this study suggest that the mean grain size and the geometric standard deviation are two important and practical parameters in characterizing the changes of the bed morphology and the bed composition around the spur dyke. With the information on the bed morphology, the flow structure and the bed properties, the local scour depth and the general pattern of grain size distributions around the spur dyke are predictable to some extent. However, the quantitative relationships between the grain size distributions and the flow field as well as the bed conditions are very complex and require further investigation. A numerical model capable of resolving the detailed flow and sediment transport is in development and shall be used as a supplement analysis tool in future research.

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