Euler-Lagrange model for local scour and grain size variation around a spur dyke

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ABSTRACT

This paper presents a three-dimensional Euler-Lagrange two-phase flow model. The fluid phase is simulated by solving the unsteady Reynolds-averaged Navier-Stokes equations with a $k-\epsilon$ turbulence closure on an unstructured Eulerian grid, and a Lagrangian model integrating the grain trajectory and momentum equations is employed to predict the granular phase in motion. Considering the deterministic nature of the movement of individual grains and the stochastic nature of the behaviour of grain groups, the grain-bed exchanges in terms of the grain entrainment and deposition are modelled with a stochastic approach. The vertical bed sorting and armouring processes are simulated by introducing a layering scheme for static grains in the bed. The numerical model is applied to predict the bed deformation around a spur dyke in a uniform and a non-uniform sediment beds. It is found that both the predicted local scour geometry and the grain size distribution are reasonably consistent with those of the experiments. According to the results, local scour in a non-uniform bed is smaller than that in a uniform one. The non-uniform bed around the spur dyke is coarsened, but sand ribbons occur in the upper part of the scour hole and at the downstream of the spur dyke.

Key Words: Spur dyke, Euler-Lagrange coupling, stochastic model, local scour, grain sorting

1.Introduction

In the proximity of in-stream hydraulic structures such as spur dykes constructed along rivers, the alluvial beds adjust their morphological features and substrate compositions spatially and temporally. This phenomenon has profound implications for the structure safety, channel stability and habitat quality. Therefore, it is quite important to develop numerical models capable of accurately predicting the associated mechanisms and underlying processes. Numerical modeling of bed deformation around hydraulic structures requires descriptions of the complex local turbulent flow, the entrainment, movement and deposition of sediment particles, as well as the flow-sediment-bed interactions. Over the past decade, there have been significant advances in the turbulent flow modeling around in-stream hydraulic structures. Three-dimensional numerical models based on RANS (Reynolds-Averaged Navier-Stokes equations), DES (Detached Eddy Simulation) or LES (Large Eddy Simulation) have been widely reported in the literature (Chrisoholdes et al., 2003; Salaheldin et al., 2004; Nagata et al., 2005; Koken and Constantinescu, 2008; Zhang et al., 2009; Paik et al., 2010; Koken, 2011 and Nakagawa et al., 2013). Using the latest numerical model, not only the complex patterns of the mean flow but also the dynamics of the coherent structure of the turbulence can be resolved. Unfortunately, numerical models on the sediment transport are still far lagged compared with those of the turbulent flow. As a result, the overall accuracy of morphological modeling is insufficient in the state-of-the-art. Most of the existing models are empirically or semi-empirically formulated for the sediment transport by simply incorporating conventional formulae such as those proposed by Meyer-Peter and Muler (1948), Ashida and Michiue (1972) or van Rijn (1984). As those formulae were obtained based on steady unidirectional flows and equilibrium sediment transport conditions, their applicability to sediment transport around local hydraulic structures is questionable (Zhang et al., 2006; Onda et al., 2007; Zhang and Nakagawa, 2009; Bihs and Olsen, 2011; Khosronejad et al., 2012 and Karami et al., 2014). To overcome the inherent deficiency in sediment transport modeling, a clear understanding and description, preferably in a mathematic form, of the fundamental physics during the transport of sediment particles is required.

The Euler-Lagrange coupling approach is emerging as a promising method to simulate the grain motion in fluids (Fukuoka et al., 2013). With this method, the sediment particles are treated as an independent phase in a Lagrangian frame and are simultaneously coupled with the fluid phase in an Eulerian frame. As the detailed movement of individual particles are exactly tracked, this kind of two-phase flow models are capable of resolving more physics and are expected to be more general and accurate. Chang and Scotti (2003) investigated the sediment entrainment in ripple-dominated bedforms with a Euler-Lagrange model. Steady LES was used to simulate the turbulent flow, while the motion of individual particles was calculated in a Lagrangian framework considering the effects of drag, lift and added mass,

neglecting both particle-particle interaction and the effect of the suspended sediments on the flow. Zamankhan (2009) developed a four-way coupling model to simulate the marine pipeline scour in dense particle-fluid flows. In the model, the fluid phase was simulated using 3D LES on a staggered Cartesian grid, and the grain phase was captured by solving the momentum equations of each grain. The simulation results for a mono-dispersed sand bed were in qualitative agreement with the experimental observations, while a bi-dispersed system and its mono-dispersed counterpart exhibit different scour behaviours at submarine pipelines. Yeganeh-Bakhtiary et al. (2009) proposed a model to simulate the small-scale hydrodynamics of bedload transport. In their model, a steady logarithmic velocity distribution with turbulence intensities over the flow depth is considered to represent the fluid motion, and the grain motion is simulated using DEM (Distinct Element Method). Later, the model was improved by introducing a 2D RANS model with a $k-\epsilon$ turbulence closure to simulate the fluid phase (Yeganeh-Bakhtiary et al., 2013). It was found that the model could capture the key features of bedload transport and reasonably reproduce the local scour around a marine pipeline. Escauriaza and Sotiropoulos (2011) proposed an Euler-Lagrange model to investigate the mechanisms of bedload transport in turbulent junction flows. They coupled a 3D DES model for the fluid and a Lagrangian particle model based on the particle momentum equations. In their model, the bed-particle and particle-fluid interactions were considered while the particle-particle interactions were neglected. The model was able to reproduce reasonably the sediment dynamics observed in multiple experiments performed under similar conditions. Unfortunately, there is almost no existing practical Lagrangian model for the simulation of local bed deformation around spur dykes although several models provide, to some extent, the fundamental insights into the grain motion and bedload flux in local scales. It is due to a combination of many factors, for example, the high demand for computational time and resources, the computational representation of the grain bed conditions, the physical interpretation of coefficients involved in the particle collision modeling and the efficient approach to link the micro-mechanics of individual grains with the macro-change in the bed.

This paper intends to present a new and practical Euler-Lagrange model, which is able to simulate the local bed deformation in terms of both bed configuration and composition around in-stream hydraulic structures. The rationale behind the model formulation is as follows. Considering the cost-effectiveness, the fluid phase is simulated through a 3D RANS model with a $k-\epsilon$ turbulence closure on an unstructured Eulerian grid. The granular phase, however, is a bit complicated. Keep it in mind that the transport of sediment grains of different sizes is a phenomenon of both deterministic and stochastic nature. For an individual sediment grain, its movement must follow the basic mechanical law. On the other hand, when a group of sediment grains are concerned, the problem turns into a stochastic one in which the turbulent flows, the bed conditions and the grain properties all involve uncertainties. In this study, the motion of grains is considered as a three-stage process: the entrainment from the bed, the transportation near the bed and the deposition onto the bed. The near-bed transport process is

governed by the Newton's laws and is simulated with a Lagrangian model incorporating grain trajectory and momentum equations. While the other two processes which are closely related to the grain-bed exchanges, are considered and modeled as stochastic problems. With the resolved fluid flow and granular motion, the information of the grains in the Lagrangian frame are transformed into the Eulerian grid, and the change of the bed configuration and composition are simulated by introducing a layering scheme for static grains in the bed. For verification, the numerical model is applied to predict the local bed deformation around a spur dyke in a uniform and a non-uniform sediment beds in an experiment flume.

2. Numerical model

2.1 Module for the fluid phase

To simulate the turbulent flow fields in geometrically complex domains, Zhang (2005) has developed a 3D numerical model based on the unsteady RANS with the widely-used k - ε equations for the turbulence closure. In dilute flows, the effect of sediment grains on the fluid flow is negligible. The governing equations for the fluid phase written in the tensor form with the convention of Einstein summation are Eq. (1) and Eq. (2) as follows.

$$\frac{\partial u_j}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = g_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{1}{\rho} \frac{\tau_{ij}}{\partial x_j} \quad (2)$$

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G - \varepsilon \quad (3)$$

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + (C_{1\varepsilon} G - C_{2\varepsilon} \varepsilon) \frac{\varepsilon}{k} \quad (4)$$

in Eq. (1) and Eq. (2), u_i , u_j = velocity components of the fluid flow; x_i , x_j = Cartesian coordinate components; t = the time; ρ = the density of the fluid; g_i = components of the body force; p = the pressure field; ν = the molecular kinematic viscosity of the fluid; τ_{ij} = Reynolds stresses. Due to the existence of the Reynolds stress terms, equation system Eq. (1) and Eq. (2) is not closed. In a k - ε model, the Reynolds stresses are evaluated from the information of the mean flow after introducing a concept of eddy viscosity ν_t and constructing two transport equations, i.e. Eq. (3) and Eq. (4), for the turbulence kinetic energy k and its dissipation rate ε . Then the Reynolds stress terms are estimated from the following expression.

$$\tau_{ij} = -\rho \overline{u_i' u_j'} = 2\rho \nu_t S_{ij} - \frac{2}{3} \rho k \delta_{ij} \quad (5)$$

where

$$\nu_t = C_\mu \frac{k}{\varepsilon} \quad S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad \delta_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$$

in which u_i' , u_j' = the fluctuating velocity component in i , j direction, respectively; ν_t = the eddy viscosity; S_{ij} = the strain-rate tensor, δ_{ij} = the Kronecker delta and C_μ = a coefficient, being usually set as a constant 0.09. In the transport equations for k and ε , G = the rate of turbulence production and is defined as

$$G = -\overline{u_i' u_j'} \frac{\partial u_i}{\partial x_j} \quad (6)$$

The model parameters in Eq. (3) and Eq. (4) generally take the following values for practical uses.

$$\sigma_k = 1.0 \quad \sigma_\varepsilon = 1.3 \quad C_{1\varepsilon} = 1.44 \quad C_{2\varepsilon} = 1.92 \quad (7)$$

The above governing PDEs (Partial differential equations) are integrated over a series of control volumes covering the fluid domain with an FVM (Finite volume method). Then, the conserved equations are discretized on a collocated unstructured grid. The power law scheme is adopted during the spatial discretization. The surface fluxes are calculated from the Rhie-Chow momentum interpolation method in order to avoid the so-called checkerboard phenomenon. For the temporal integral, the second order implicit Crank-Nicolson scheme is employed. The widely used SIMPLE (Semi-implicit method for pressure-linked equations) procedure is included in the model for the coupling of the pressure and the velocity. The final algebraic equations resulted from the discretization process are solved with a preconditioned GMRES (Generalized minimal residual method) incorporated with an ILUTP (Incomplete LU factorization with threshold and pivoting) preconditioner (Zhang, 2005).

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2.2 Module for the granular phase

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For individual grains in motion, the governing equations are the grain trajectory and momentum equations, which read in tensor form as follows.

$$\frac{ds_i}{dt} = v_i \quad (8)$$

$$\sigma V \frac{dv_i}{dt} = f_i \quad (9)$$

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where s_i , v_i = the component of the grain position and the velocity vector, respectively; V = the volume of the grain and f_i = the component of the total force acting on the grain. In general, the total force may contain the contributions from various sources such as the added mass, gravity, buoyancy, drag, lift, Coulomb friction, particle-particle collision and Basset history effect. For the time being, however, only the dominant forces in typical dilute flows such as the submerged particle weight, the fluid drag and the bed friction are considered. Moreover, the grains are assumed to be spherical and the motion of which is assumed to follow the local bed plane. With these assumptions, the momentum equation can be simplified. If two unit vectors are defined paralleling to the local bed surface: $\mathbf{p}_{b1}$ on xz -plane and $\mathbf{p}_{b2}$ on yz -plane, the momentum equation of a grain in i direction is written as below.

$$\frac{\pi}{6}\rho\left(\frac{\sigma}{\rho}+C_m\right)d^3\frac{dv_i}{dt}=D_i+W_i-F_i \quad (i = \mathbf{p}_{b1}, \mathbf{p}_{b2}) \quad (10)$$

in which v_i = the grain velocity in i direction; C_m = the coefficient of added mass (=0.5); D_i = the component of the drag force in i direction; W_i = the component of the submerged grain weight in i direction; F_i = the component of the friction force between the grain and the bed in i direction. The magnitude of the drag force, the submerged grain weight and the friction force are obtained as below.

$$D = \frac{\pi C_D \rho}{8} v_r^2 c_e d^2 \quad W = \frac{\pi}{6} (\sigma - \rho) g d^3 \quad F = \mu_k \left(W \frac{\cos \theta_{bx} \cos \theta_{by}}{\sin \theta_p} - k_L D \right) \quad (11)$$

where D = the drag force on the grain; W = the submerged weight of the grain; F = the friction force between the bed and the grain; v_r = the relative fluid-to-particle velocity; C_D = the drag coefficient; c_e = the coefficient accounting for the effective application area of the drag force; θ_{bx}, θ_{by} = the angle of the local bed inclination in x and y direction, respectively; and θ_p = the angle between $\mathbf{p}_{b1}$ and $\mathbf{p}_{b2}$. With Eq. (8) and Eq. (10), the velocity and the trajectory of a sediment grain at any time after being dislodged from the bed is known. Thus, the grains in motion are captured in an explicit way.

2.3 Module for the grain-bed exchanges

The equations of trajectory and momentum are theoretically applicable for any grain either in the water column or on the channel bed, which is the method adopted in most of the existing literature. However, a huge amount of computational resources is needed to account for all grains in the computational domain. In this study, the equations are only applied to mobile grains in the water column for computational efficiency and to avoid the complex treatment in the grain-bed exchanges and bed deformation processes. The exchanges between the mobile grains in the fluid and the static grains in the bed are very complex. In general, the exchanges take place in terms of grain entrainment into the water and grain deposition onto

the bed. Both processes are closely related to the near-bed turbulent flows, the bed conditions and sediment grain properties. It is quite difficult, if not impossible, to properly capture the near-bed behavior of each grain. Instead, developing a stochastic model becomes an alternative, which estimates the pick-up and depositional probabilities of grains while avoiding to go into the details of the micro-processes of individual grains and grain-bed interactions.

Nakagawa et al. (1986) established a formula to determine the pick-up rate of sediment grains on a steep side slope, which was favorable for the simulation of local scour problems. If the grains can be categorized into several fractions according to their representative grain sizes, the formula reads as follow for each size fraction k .

$$p_{sk} \sqrt{\frac{d_k}{(\sigma/\rho - 1)g}} = 0.03 G_* \tau_{*k} \left(1 - \frac{0.7 \Phi \tau_{*ck}}{\tau_{*k}} \right)^3 \quad (12)$$

in which

$$G_* = \frac{\cos \psi + k_L \mu_s}{1 + k_L \mu_s} \quad \tau_{*k} = \frac{u_*^2}{(\sigma/\rho - 1)gd_k} \quad \Phi = \frac{1 + k_L \mu_s}{\mu_s} \frac{\mu_s \cos \theta_b - \sin \theta_b \cos \alpha}{\cos \psi + k_L \mu_s}$$

where p_{sk} = the pick-up rate for grain size fraction k ; d_k = the diameter of grain size fraction k ; σ = the density of the sediment grain; G_* = the coefficient accounting for the direction deviation between the near bed velocity and the sediment movement direction; ψ = the angle between the near bed velocity and the sediment movement direction; τ_{*k} = the dimensionless shear stress for grain size fraction k ; u_* = the near-bed friction velocity; τ_{*ck} = the dimensionless critical shear stress for grain size fraction k ; Φ = the coefficient accounting for local bed slope; μ_s = the static friction factor (=0.7); k_L = the ratio of lift force to drag force (=0.85); θ_b = the local bed slope; α = the angle between the maximum local bed slope and the sediment movement direction. It is noted that this formula does not allow an accurate consideration of the hiding and exposure effects in sediment mixtures, which is a topic to be explored in the near future. As is known, the hiding and exposure effects generally result in a smaller pick-up rate for fine grains and a larger pick-up rate for coarse grains. With the pick-up rate, the number of sediment grains being dislodged from a specific computational grid per unit time is obtainable. While being picked up, the grains move near the bed. The velocities and trajectories of the grains are then calculated with the Lagrangian model as described in the module for the granular phase. It is noted that it is not necessary to compute the velocity and trajectory of each grain in dilute flow conditions. As the interactions among grains are negligible, one only needs to capture the movement of a representative grain in each size fraction. It will save a huge amount of computational memory and time compared with conventional particle-based methods which have to track the movement of each grain. During the movement, some of the grains may keep moving following their own trajectories,

while some of them may settle down and deposit onto the bed at a certain place. The number of the grains deposited onto the bed along a transport trajectory starting from a specified grid is estimated with the aid of the probability density function for the step length, i.e.

$$N_{d(k,n)} = N_{pk} f_s(s_{(k,n)}) \Delta t |\mathbf{v}_{(k,n)}| \quad (13)$$

where Δt = the time step for the calculation of sediment trajectory; $\mathbf{v}_{(k,n)}$ = the grain velocity of size fraction k at the n th time step; $N_{d(k,n)}$ = the number of grains of size fraction k deposited onto the bed after the n th time step; N_{pk} = the number of grains of size fraction k being picked up from the bed; $s_{(k,n)}$ = the movement distance of a grain of size fraction k after the n th time step; $f_s(s_{(k,n)})$ = the probability density function of the step length, and is estimated as follows according to Nakagawa et al. (1982).

$$f_s(s_{(k,n)}) = \frac{1}{\lambda_k} \exp\left(-\frac{s_{(k,n)}}{\lambda_k}\right) \quad (14)$$

where λ_k = the average step length of grains of size fraction k , which is estimated following Einstein's suggestion as below (Einstein, 1942).

$$\lambda_k = 100d_k \int_{-0.156/\tau_{*k}-1/\eta_0}^{0.156/\tau_{*k}-1/\eta_0} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{r^2}{2}\right) dr \quad (15)$$

in which η_0 = the coefficient of the variation of the lift force, being equal to 0.5 in this study.

2.4 Module for bed deformation

With the methods introduced above, the detailed information on the motion of the grains is obtained along their moving trajectories. In general, these trajectories do not coincide with the computational grid. In order to simulate the bed deformation process, the information at the center of any computational grid must be acquired based on that along the sediment moving trajectories. The change of the bed level is hence calculated in the following procedure: The number of grains of size fraction k being picked up from grid i is calculated with the aid of Eq. (12). Then the position of each sediment grain after the n th time step is estimated with Eq. (8) and Eq. (10). The corresponding number of grains deposited along the trajectory is estimated from Eq. (13) and the grid where each deposited grain locates is specified. The calculated number of deposited grains is then distributed to the center of the grid and that of its neighbors. For each grid, the number of deposited grains is a summation of distributed numbers of grains deposited within the grid itself and from its neighbors. As a result, the estimation of the change of the bed level at each grid becomes possible, i.e.

$$\frac{\partial z_b}{\partial t} = \frac{\pi}{6} \frac{1}{1-\phi} \frac{\sum_k N_{dk} d_k^3 - \sum_k N_{pk} d_k^3}{A_b} \quad (16)$$

where z_b = the bed level at the center of a grid; N_{dk} = the number of deposited grains of size fraction k ; N_{pk} = the number of grains of size fraction k being picked up; ϕ = the porosity of the bed materials; and A_b = the projected area of the calculated grid onto the horizontal plane

Apart from the bed level, the bed composition also plays an important role in the sediment transport modeling. To consider the grain size variation, the bed is vertically divided into an active layer (or termed as mixing layer), a transition layer and a series of depositional layers. The active layer changes its elevation and grain size distribution with the transport of bedload but keeps a constant thickness. The change of the bed level is expressed by the changing of the thickness of the transition layer and the number of the depositional layers (Liu, 1991 and Zhang, 2005). With this layering scheme, the percentage of each size fraction in the bed surface is estimated as follows.

$$\frac{\partial p_{bk}}{\partial t} + \frac{1}{E_a(1-\phi)} \frac{\pi}{6} \left(\frac{\sum_k N_{dk} d_k^3 - \sum_k N_{pk} d_k^3}{A_d} \right) + \frac{1}{E_a} \frac{\partial z_b}{\partial t} [\eta p_{bk} + (1-\eta) p_{bk0}] = 0 \quad (17)$$

where p_{pk} = the percentage of grain size fraction k in the active layer; E_a = the thickness of the active layer; p_{pk0} = the percentage of grain size fraction k below the active layer and

$$\eta = \begin{cases} 1 & \partial z_b / \partial t \geq 0 \\ 0 & \partial z_b / \partial t < 0 \end{cases}$$

This method allows the interaction of erosion and deposition within a discrete layer without affecting undisturbed sediments below and provides a simple way to modelling the armouring process.

In general, there is a critical value for the angle of the local bed slope during the development of the scour hole. This critical angle is assumed to be the angle of sediment repose for computational simplicity. In the calculation, the unrealistic steep slope larger than the angle of repose hence should be avoided. A sediment sliding model considering the mass conservation is introduced in this study, which is detailed in Zhang et al. (2006). However, the corresponding change of the bed composition due to the sliding process is neglected in the model for the time being.

3. Laboratory experiments

In the past several years, the authors have conducted a series of fundamental experiments on the local bed deformation around spur dykes at the Ujigawa Open Laboratory, Kyoto University (Mizutani, 2011 and Zhang et al., 2012). In this study, two laboratory experiment cases are selected to test the performance of the proposed numerical model.

The experiment flume is 8m-long, 40cm-wide and 40cm-deep, with a 1.5m-long inlet tank upstream (Fig.1). A working area locates 4m downstream from the inlet tank. It is 1.7m long and is covered with 20cm-thick silica sand. In this area, an impermeable spur dyke is set perpendicular to the right side of the flume with a protruding length of 10cm. The spur dyke is 1cm thick and is kept non-submerged throughout the experiments. In Case1, the bed consists of uniform sediment with a grain size of 1.03mm and a corresponding critical friction velocity for entrainment of 2.38cm/s. In Case2, the bed is non-uniform and is made by mixing two kinds of uniform sediment. The grain sizes are 0.31mm and 1.70mm, respectively and they are mixed at a mixing ratio of 1:1. As a result, the mean grain size of the non-uniform bed in Case2 is 1.00mm, which is quite similar to that of the uniform bed in Case1. The critical friction velocities for entrainment are 1.68cm/s and 3.18cm/s for the fine fraction and the coarse fraction, respectively. The sieve analyses results of the bed materials at the initial stage are shown in Fig.2.

The hydraulic conditions of the experiments are listed in Table1. The experiments start from a flat bed and last 3hours when the change of the bed surface becomes insignificant and a quasi-equilibrium condition is reached. The experiments are conducted under clear-water scour conditions and no sediment is fed in the upstream area. The bed configurations at the final stage are measured with a high resolution Laser displacement meter and the bed materials at several representative locations in the bed surface are sampled and are analyzed with a column of sieves.

4. Computational conditions

The computational domain covers a 2.4m-long reach of the experiment flume with a fixed bed of 0.7m and a movable area of 1.7m. Unstructured grid is used in the simulation. The plan view of the computational grid in the vicinity of the spur dyke is shown in Fig.3. The grid is hybrid, consisting of both hexahedra and prisms. The total grid number is 6,344 and the total node number is 4,030. The grid is automatically adjustable in its vertical direction according to the change of the bed topography.

The water surface is considered as a rigid lid and the wall function approach is employed in the near-wall area. The initial thicknesses of the active layer, the transition layer and each depositional layer in the bed are the same and are assumed to be 2.5mm considering the maximum grain size used in the experiments. For computational efficiency, different time steps are employed in the simulations of the fluid flow and sediment transport. The time steps are 0.1s for the fluid flow, 0.2s for the sediment entrainment and 0.005s for the sediment trajectory, respectively. Moreover, parallel computation using OpenMP is implemented to speed up the simulation. It is found that the computation time is possibly reduced by up to 54% compared with normal computing methods, according to test computation experiments (Mizutani et al., 2010). As the performance of the turbulent flow modeling has already been

confirmed in the authors' previous research (e.g. Zhang, 2005; Zhang et al., 2006; Zhang and Nakagawa, 2009 and Mizutani, 2011), this paper concentrates on the results of the variation of the local bed configuration and composition.

5. Results and discussions

5.1 Local scour and bed topographic change

The bed configurations at the final stage are shown in Fig.4 and Fig.5 for Case1 and Case2, respectively. Both experimental and numerical results are plotted in the figures. It is found that the numerical model is able to predict most of the topographic features observed in the experiments such as the mainstream degradation, the local scour hole and the corresponding wake deposition in the proximity of the spur dyke. Both the experimental and the numerical results indicate that larger scour hole forms in the vicinity of the toe of the spur dyke in relatively uniform bed (i.e. Case1) while higher deposition depth appears in the wake zone of the spur dyke in non-uniform bed (i.e. Case2). These phenomena are resulted from the different transport mechanisms of uniform and non-uniform sediment grains. In the non-uniform grain bed, the coarse fraction forms an armour layer and prevents the bed from continuous degradation, which is mainly responsible for the deceleration of local scour development. On the other hand, the coarse particles in non-uniform bed eroded mainly by the horse-shoe vortex may settle down immediately at the wake zone of the spur dyke, which are hardly transported further downstream as they require much flow energy. Consequently, the coarse particles in non-uniform bed are easily accumulated behind the spur dyke and form a deposition belt which is higher in elevation and closer to the spur dyke compared with the uniform case. In general, the simulated local scour holes are more rounded in their upstream part than those in the experiments. The difference might originate from the error in the prediction of the maximum scour location. In the simulations, the maximum scour is located at the toe of the spur dyke in either case. While in the experiments, they shift more or less towards the right side of the flume as will be detailed later.

To acquire more details on the local scour properties, the typical local scour dimension is sketched in Fig.6 and several key parameters representing the bed topographic features are listed in Table2. In the table, e_m and d_m are the maximum scour depth and deposition depth, respectively. And $e_m(x,y)$ and $d_m(x,y)$ are the locations of the maximum scour depth and the deposition depth, respectively. The maximum local scour depths are 11.60cm and 9.45cm for Case1 and Case2 in the experiments, respectively, indicating that the scour hole is reduced by 19% from a uniform bed to a non-uniform bed due to the armouring effect. The simulated local scour depths are 10.45cm and 8.64cm, corresponding to 90% and 91% of those observed in the experiments, respectively. In the past several years, the authors have made a lot of efforts to simulate local scour phenomena with traditional transport formulae approaches. It is

found that the numerical model could predict, to the best, 73% of the scour depth accompanying with a much smaller scour area in similar experimental conditions (Zhang and Nakagawa, 2009). Therefore, the agreement obtained from the current model is quite good. It should be attributed to the explicit tracking of the non-equilibrium sediment transport around local in-stream structures, which are almost impossible with traditional transport formulae models. Unfortunately, the locations of the deepest scour holes are not well predicted as also observed in Fig.4 and Fig.5. Experimental results show that the deepest scour occurs near the side of the flume in Case1 and near the middle part of the spur dyke in Case2, while the simulated maximum scour locates at the toe of the spur dyke in either case. The difference might be resulted from the insufficient resolution of the detailed turbulent structure within the scour hole and the gravity-induced sediment sliding process along the scour hole surface. On the other hand, the maximum deposition depth in the experiment of Case2 is 15% larger than that in Case1, consistent with the qualitative observations in Fig.4 and Fig.5. The numerical model slightly under-estimates the maximum deposition depths, particularly in Case1. In both cases, the locations of the highest deposition points are a little bit closer in the simulations compared with those in the experiments. The reason is not well clarified. But it is noted from Fig.4 and Fig.5 that several patches of high deposition areas are found in the wake deposition zone in the simulations which are not observed in the experiments. It is hence believed that although the general deposition patterns are reasonably predicted, the isolation of those patches exerts impact on the local flow and bed topography.

Table2 also gives interesting information on the extension area and the local slope of the scour holes. Compared with Case1, the scour area in Case2 is slightly smaller in the upstream domain and is significantly smaller in the downstream reach. Moreover, the local bed slopes in Case2 are much steeper in the downstream and are generally milder in the other areas within the scour holes compared with those in Case1. As has been mentioned before, the transport properties of the coarse fraction in the non-uniform sediment bed plays an important role in shaping these kinds of bed topographical features. As the cone-shaped scour hole is elongated in its downstream part, the slope of the scour hole in the downstream is much milder than that in the upstream in either case. It is noted that all these features can be extracted from the tabulated information of either the experimental or the numerical results. In summary, the numerical model predicts the extension area of the scour hole quite well, however, slightly under-estimates the local bed slopes in most of the designated directions. A straightforward result of this phenomenon is an under-estimation of the maximum scour depth.

5.2 Grain size variation

Field investigations and laboratory experiments indicate that spur dykes promote not only bed topographic changes but also bed composition variations. The bed in the vicinity of a spur

dyke is generally coarsened and sand ribbons consisting of relatively fine particles may occur as a consequence of sediment sorting (Zhang et al., 2011 and Zhang et al., 2012). Therefore, the grain sizes commonly show complex distributions around a spur dyke in a non-uniform bed. For easy understanding, the dimensionless mean grain size distributions along several representative longitudinal and transverse cross-sections are plotted in Fig.7 and Fig.8. In the figures, the primary vertical axis stands for the ratio between the mean grain size at the final stage and that at the initial bed. If the value is larger than 1.0, the bed is coarsened. If the value is less than 1.0, the percentage of the fine fraction is increased. Moreover, the bed level is plotted as well with the secondary vertical axis for reference. According to the comparisons between the experimental and numerical results, both the bed level and the bed composition are reasonably simulated with the proposed numerical model. At several locations, the numerical model seems to over-estimate or under-estimate the mean grain sizes. However, the trends of sediment coarsening and fining are almost the same as those of the experiments. Therefore, the detailed information obtained from the numerical simulations can be used, together with the experimental data available at limited sampling points, to understand the local grain sorting phenomenon and the spatial variation of the mean grain sizes around the spur dyke.

5.2.1 Longitudinal variation of grain sizes

The results of the mean grain sizes at four typical longitudinal cross-sections are plotted in Fig.7 which are located at $y=5\text{cm}$ (representing the spur dyke field), $y=15\text{cm}$ (representing the transition zone from the spur dyke field to the mainstream), $y=25\text{cm}$ (representing the mainstream) and $y=35\text{cm}$ (representing the area near to the opposite side).

Along the section passing the spur dyke field, i.e. Fig.7 (a), both the bed level and bed composition show profound longitudinal changes. In the approach flow area, the bed level is almost maintains but bed materials are slightly coarsened. It is due to the selective transport of sediment particles in this region, where the near-bed shear stress is enough to transport fine particles exposed in the bed surface but is not enough to remove the coarse fraction. It is also noted that some of the fine particles locate beneath the coarse ones and are not directly exposed to the flow. Consequently, although some fine particles are removed from the bed, the bed level does not exhibit significant changes. Severe local scour occurs in the neighborhood of the spur dyke, and the depth of which is reduced almost half from the upstream side to the downstream side. In the scour hole upstream of the spur dyke, the sediment is coarse at the bottom and fine at the upper part although the entire scour surface is generally turned coarser from the initial bed. In the wake zone, however, the sediment at the upper part of the scour hole is generally coarser than that at the lower part. This difference originates from the difference in the local bed configuration and the complex vortex systems. The 3D scour geometry and corresponding vortices promote and control the sediment sorting along the surface of the scour hole. Following the scour area, a long distance of deposition is

observed which owns a very gentle slope on its leeside. Along the leeside of the deposition area, the bed materials show a trend of downstream fining. Moreover, the mean grain sizes are much less than those of the original bed after a distance of around $5L$ downstream from the spur dyke. In fact, this area falls in the sand ribbon triggered by transverse sediment sorting along the side of the flume as to be discussed later. It is noted that a sand ribbon stands for a belt region where sediment is clearly finer than its surrounding area. The grains in the sand ribbon are not necessarily uniform or completely composed of fine fractions of a sediment mixture.

Along the section passing the transition zone, i.e. Fig.7 (b), the bed configuration is characterized by an almost unchanged approaching area, a severely scoured area, a small wake deposition area and an almost unchanged downstream area. The characteristics of the slightly coarsening in the approach flow area and the downstream fining along the leeside of the deposition area are similar to those observed in Fig.7 (a). But there are several new findings in this cross-section. The bed materials of the scour surface in the upstream side of the spur dyke gradually turn coarser and coarser if one goes more and more deeply into the scour hole. Nevertheless, it is obvious to find fine sediment at the upper part of the scour hole which is even much finer than that on the original bed. The fine sediment comes from the finest grains trapped in the vortex system within the scour hole. In the downstream part of the scour hole, the mean grain sizes are 1.5-1.6 times of those on the original bed but show insignificant variations along the slope of the scour hole. It indicates that the flow has been highly intensified in this area. Downstream from the deposition area, the mean grain sizes are larger than those in the initial bed although the bed levels do not show significant differences. It is noted that the numerical model under-estimates the mean grain sizes both in the approach flow area and the downstream of the scour hole in this cross-section irrespective of the good prediction of the bed configuration. The discrepancy might originate from the relatively low resolution of the complex turbulent structures in this transition zone with the current fluid flow model.

In the representative section of the mainstream, i.e. Fig.7 (c), the longitudinal bed change becomes much smaller. The bed level is almost maintains in the approach flow area and the area downstream of the spur dyke. But the extension area of the local scour is still confirmable, i.e. a slightly degraded reach in the vicinity of the spur dyke section. The bed is slightly coarsened in the upstream reach of the spur dyke and becomes quite fine in the spur dyke section. The mechanism of the accumulation of these fine grains is the same as that in Fig.7 (b). Within a short distance downstream of the spur dyke, the bed is greatly coarsened. Then, it gradually turns fine and finally falls into a region of sand ribbon. Along the section near to the left side of the flume, i.e. Fig.7 (d), the bed level maintains in the approach flow area and the area far from the downstream of the spur dyke. And slight bed degradation is observed in the downstream vicinity of the spur dyke section. As to the bed composition, the sediment is coarser than that in the initial bed throughout the longitudinal section. In addition,

the mean grain size is much larger in the degraded area compared with other areas.

5.2.2 Transverse variation of grain sizes

In Fig.8, the dimensionless mean grain sizes at six transverse cross-sections are plotted. The sections are located at the approach flow area ($x=-30\text{cm}$), the upstream part of the local scour ($x=-10\text{cm}$), the spur dyke section ($x=0\text{cm}$), the downstream part of the local scour ($x=10\text{cm}$) and two representative sections at the wake deposition area ($x=30\text{cm}$ and $x=50\text{cm}$).

In the approach flow zone as shown in Fig.8 (a), the bed elevation does not exhibit significant changes. However, the bed materials are slightly coarser than those at the initial bed. The limited experimental data does not show clear trend of grain size changes in the transverse direction. Nevertheless, the numerical model gives such a trend that the bed gradually turns coarser from the right side of the flume to the mainstream and becomes finer at the vicinity of the opposite side. In the scour hole upstream of the spur dyke, the surface of the scour hole is generally coarsened as shown in Fig.8 (b). However, a fine sediment region is observed within the scour area in the proximity of $x=16\text{cm}$, which coincides with the observation in Fig. 7 (b). In the mainstream, the bed is also coarsened but the grain sizes are smaller than those in the scour hole surface. In Fig. 8 (c) showing the section passing the spur dyke, the existence of the greatly coarsened sediment is quite evident at the bottom of the scour hole. The mean grain sizes at the bottom are 1.5-1.6 times of those in the initial bed. In this figure, a region of fine grains are also observed within the scour hole, but the location is shifted to the proximity of $x=25\text{cm}$.

In the downstream part of the local scour, i.e. Fig. 8 (d), two isolated regions of fine grains are evidently observed. One is near the right side of the flume and the other is located in the proximity of $x=29\text{cm}$. The formation of these sand ribbons is the result of sediment sorting which is mainly activated by secondary flows due to local changes in the bed geometry as figured out by Zhang et al. (2012). Fig. 8 (c) also clearly shows that the sediment is the coarsest at the bottom and turns finer and finer with an increase of the elevation within the scour hole. In the deposition area, Fig. 8 (e) and Fig.8 (f) generally show similar variation patterns of the bed configuration and bed composition although the mean grain sizes in Fig.8 (e) are generally larger than those in Fig.8 (f). The highest deposition depth occurs in the shade of the spur dyke. A sand ribbon consisting of a large number of fine grains forms between the right side of the flume and the highest deposition point. Downward from the deposition area to the mainstream, the grain size turns finer and finer till entering the range of another sand ribbon. Compared with that of the sand ribbon near the side of the flume, the mean grain size of this ribbon is much larger.

5.2.3 Overall picture of grain size variations

The mechanism of the formation of sand ribbons and experimental evidences obtained from precise velocity measurements have been reported in Zhang et al. (2012). In this study,

the computed near bed friction velocity at the final stage of Case2 is plotted in Fig.9 to further the understanding of associated processes. Moreover, the spatial distribution of the computed dimensionless mean grain size, i.e. the mean grain size ratio between the final bed and the initial bed, is plotted in Fig.10 for clarity. It is found that the near bed friction velocity shows an obviously diverse nature in the proximity of the spur dyke. The local friction velocities in some areas are significantly larger than that at the approach flow region even at the final quasi-equilibrium conditions. Two high friction velocity zones are evidently shown in the figure. One starts from the toe of the spur dyke and extending both upstream within the local scour hole and downstream to the wake deposition area (termed Zone1 hereafter), and the other is located downstream of the spur dyke section and near the opposite side of the flume (termed Zone2 hereafter). Due to the existence of these two high friction velocity zones, several belt areas of relatively low friction velocities are distinguishable, for example, the area between the right side of the flume and Zone1, the area between Zone1 and Zone2, and the area along the upper part of the local scour hole. It is evident that the locations of these low friction velocity areas show a strong correlation with the fine-grained sand ribbons which are observed in the representative longitudinal and transverse cross-sections in Fig.7 and Fig.8 as well as in Fig.10. Furthermore, since the mean friction velocity in Zone2 is generally larger than that in Zone1, the mean grain size in Zone2 is generally larger than that in Zone1 as obviously shown in Fig.10. Nevertheless, the low velocity zones are not completely consistent with those of the sand ribbons and the high velocity zones do not completely correspond to the coarsening regions. It indicates that the bed morphologies also play an important role in the movement of near-bed sediment grains. If the bed morphologies in Fig.7 and Fig.8 are also taken into account, one may have more comprehensive knowledge on the correlation among the friction velocities, bed variations and grain size distributions. The three aspects interact with each other and adjust themselves on the way to the final equilibrium stage, which is a dynamic process. The current numerical model provides a direct and promising solution to mimic this process.

6. Conclusions

In this paper, an Euler-Lagrange two phase flow model was presented to simulate the variation of the local bed configuration and composition around in-stream hydraulic structures. The model simulate the 3D flow with a k- ϵ turbulence model in a Eulerian grid, the grain-bed exchanges with a stochastic approach considering the probabilities of grain pick-up rate and step length, the grain motion with a Lagrangian framework and the bed sorting with a layering scheme. By applying the model to simulate the flow and sediment transport around a spur dyke in an experiment flume, it is found that the simulated local scour and grain size variation are in reasonable agreement with those of the experiments.

According to the research results, the bed variation characteristics around a spur dyke in

different grain beds are revealed in terms of both local scour and bed composition. The local bed configuration around a spur dyke is obviously three-dimensional and is mainly characterized by a local scour and a wake deposition. Local scour in a non-uniform grain bed is smaller than that in a uniform one due to the formation of an armour layer in sediment mixtures, which is expressed by both the maximum scour depth and the local slope of the scour surface. The local grain sorting process in the bed occurs longitudinally, transversely and vertically, which is evidently confirmed from the grain size distributions. The longitudinal grain sorting promotes bed coarsening in most of the areas around the spur dyke due to the flow acceleration and near-bed shear stress increasing, particularly in the mainstream. Two sand ribbons appear at the downstream of the spur dyke due to transverse sediment sorting triggered by secondary flows. In the local scour hole, the bottom part is generally substantially coarser than the upper part, indicating the sorting process in the vertical direction due to the complex vortex system there. The vortex system in the scour hole also possesses a potential to trap fine grains. As a result, sand ribbons also occur in the upper part of the scour hole.

The numerical model is based on an adaptive unstructured grid, being able to solve problems in complex geometries and/or with irregular boundaries. The model takes into account the inherent stochastic and deterministic nature of sediment transport, capable of reproducing more underlying physics compared with conventional transport formulae models. It sheds a light on the formulation of more universal models for sediment transport. Moreover, the model only tracks the trajectories of grains in motion while solves grain-bed exchanges with stochastic approaches, which significantly reduces the computational memories and time required by conventional particle-based models. Therefore, it has a high potential for practical uses in actual rivers. However, the model still needs refinement to account for inter-particle collisions and extension to more densely sediment-laden flows. Moreover, fundamental experiments are also needed to investigate the underlying processes associated with the grain-bed exchanges such as the pick-up and deposition events of non-uniform sediment grains.

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References

Ashida, K., Michiue, M. 1972: Study on hydraulic resistance and bedload transport rate in

- alluvial stream, *Transactions of the Japanese Society of Civil Engineers*, 206: 59-69.
- Bihs, H., Olsen, N.R.B. 2011: Numerical modeling of abutment scour with the focus on the incipient motion on sloping beds, *Journal of Hydraulic Engineering, ASCE*, 137 (10): 1287-1292.
- Chang, Y.S., Scotti, A. 2003: Entrainment and suspension of sediments into a turbulent flow over ripples, *Journal of Turbulence*, DOI:10.1088/1468-5248/4/1/019.
- Chrisoholdes, A., Sotiropoulos, F., Sturm, T.W. 2003: Coherent structures in flat-bed abutment flow: computational fluid dynamics simulations and experiments, *Journal of Hydraulic Engineering, ASCE*, 129 (3): 177-186.
- Karami, H., Bassar, H., Ardeshir, A., Hosseini, S.H. 2014: Verification of numerical study of scour around spur dikes using experimental data, *Water and Environment Journal*, 28 (1): 124-134.
- Koken, M. 2011: Coherent structures around isolated spur dikes at various approach flow angles, *Journal of Hydraulic Research*, 49(6): 736-743.
- Koken, M., Constantinescu, G. 2008: An investigation of the flow and scour mechanisms around isolated spur dikes in a shallow open channel: 2. Conditions corresponding to the final stages of the erosion and deposition process, *Water Resources Research*, 44, W08407, DOI:10.1029/2007WR006491.
- Khosronejad, A., Kang, S., Sotiropoulos, F. 2012: Experimental and computational investigation of local scour around bridge piers, *Advances in Water Resources*, 37: 73-85.
- Escauriaza, C., Sotiropoulos, F. 2011: Lagrangian model of bed-load transport in turbulent junction flows, *Journal of Fluid Mechanics*, 666: 36-76.
- Einstein, H.A. 1942: Formulas for the transportation of bed load, *Transactions of ASCE*, 2140:561-597.
- Fukuoka, S., Nakagawa, H., Sumi, T., Zhang, H. 2013: *Advances in River Sediment Research*, CPC Press/Balkema, Taylor & Francis Group, London, ISBN 978-1-138-00062-9.
- Liu, B.Y. 1991: *Study on Sediment Transport and Bed Evolution in Compound Channels*, Doctoral Dissertation, Kyoto University, 227p.
- Meyer-Peter, E., Muller, R. 1948: Formulas for bed-load transport, *The Second Annual Conference of the International Association for Hydraulic Research*, Stockholm, Sweden: 39-64.
- Mizutani, H., Nakagawa, H., Kawaike, K., Baba, Y., Zhang, H. 2010: Bed deformation around a spur dyke based on non-equilibrium sediment transport model using OpenMP, *The 29th Annual Conference of Japan Society for Natural Disaster Science*, Gifu, September 16-17, 2010: 145-146.
- Mizutani, H. 2011: *Local scour and grain size variation around submerged and non-submerged spur dykes*, Doctoral Dissertation, Kyoto University, Japan.200p.

- Nagata, N., Hosoda, T., Nakato, T., Muramoto, Y. 2005: Three-dimensional numerical model for flow and bed deformation around river hydraulic structures, *Journal of Hydraulic Engineering, ASCE*, 131(12): 1074-1087.
- Nakagawa, H., Tsujimoto, T. 1979: On generalized stochastic model for bed load transport and sediment dispersion, *Proceedings of JSCE*, 291: 73-83. (in Japanese)
- Nakagawa, H., Tsujimoto, T., Murakami, S. 1986. Non-equilibrium bed load transport along side slope of an alluvial stream, *Proceedings of the 3rd International Symposium on River Sedimentation*, University of Mississippi: 885-893.
- Nakagawa, H., Zhang, H., Baba, Y., Kawaike, K., Teraguchi, H. 2013: Hydraulic characteristics of typical bank protection works along the Brahmaputra/Jumuna River, Bangladesh, *Journal of Flood Risk Management*, 6 (4): 345-359, DOI: 10.1111/jfr3.12021.
- Onda, S., Hosoda, T., Kimura, I., Iwata, M. 2007: Numerical simulation on local scouring around a spur dyke using equilibrium and non-equilibrium sediment transport models, *Annual Journal of Hydraulic Engineering, JSCE*, vol.51: 943-948. (in Japanese)
- Paik, J., Escauriaza, C., Sotiropoulos, F. 2010: Coherent structure dynamics in turbulent flows past in-stream structures: some insights gained via numerical simulation, *Journal of Hydraulic Engineering, ASCE*, 136 (12): 981-993.
- Salaheldin, T.M., Imran, J., Chaudhry, M.H. 2004: Numerical modeling of three-dimensional flow field around circular piers, *Journal of Hydraulic Engineering, ASCE*, 130 (2): 91-100.
- Van Rijn, L.C. 1984: Sediment transport, part1: bed load transport, *Journal of Hydraulic Engineering, ASCE*, 110 (10): 1431-1456.
- Yeganeh-Bakhtiary, A., Zanganeh, M., Kazemi, E. Cheng, L., Abd Wahab, A.K. 2013: Euler-Lagrange two-phase model for simulating live-bed scour beneath marine pipelines, *Journal of Offshore Mechanics and Arctic Engineering*, 135, DOI: 10.1115/1.4023200.
- Yeganeh-Bakhtiary, A., Shabani, B., Gotoh, H., Wang, S.S.Y. 2009: A three-dimensional distinct element model for bed-load transport, *Journal of Hydraulic Research*, 47 (2): 203-212.
- Zamankhan, P. 2009: Analysis of Submarine Pipeline Scour Using Large-Eddy Simulation of Dense Particle-Liquid Flows. *Journal of Offshore Mechanics and Arctic Engineering*, 131 (2), DOI: 10.1115/1.3058705.
- Zhang, H. 2005: *Study on Flow and Bed Evolution in Channels with Spur Dykes*, Doctoral Dissertation, Kyoto University, Japan. 181p.
- Zhang, H., Nakagawa, H., Muto, Y., Baba, Y., Ishigaki, T. 2006: Numerical simulation of flow and local scour around hydraulic structures, *River Flow 2006*, Ferreira, Alves, Leal & Cardoso (Eds.), Taylor & Francis Group, London: 1683-1693, DOI: 10.1201/9781439833865.ch181.
- Zhang, H., Nakagawa, H. 2009: Characteristics of local flow and bed deformation at impermeable and permeable spur dykes, *Annual Journal of Hydraulic Engineering, JSCE*, 53: 145-150, DOI: 10.2208/prohe.53.145.

- Zhang, H., Nakagawa, H., Kawaike, K., Baba, Y. 2009: Experiment and simulation of turbulent flow in local scour around spur dyke. *International Journal of Sediment Research* 24(1):33-45, DOI: 10.1016/S1001-6279(09)60014-7.
- Zhang, H., Zhang, X.H., Nakagawa, H., Xu, W.L., Lin, P.Z., Mizutani, H. 2011: Characteristics of grain size distribution in groin fields and their environmental implications, *Annual of the Disaster Prevention Research Institute, Kyoto University, Japan*, 54B: 511-523.
- Zhang, H., Nakagawa, H., Mizutani, H. 2012: Bed morphology and grain size characteristics around a spur dyke, *International Journal of Sediment Research*, 27(2):141-157, DOI: 10.1016/S1001-6279(12) 60023-7.

Figure Captions:

Figure 1. Experiment setup.

Figure 2. Sediment size distribution.

Figure 3. Plan-view of computational grid.

Figure 4. Final bed configuration in Case1 (Top: Experiment; Bottom: Simulation)

Figure 5. Final bed configuration in Case2 (Top: Experiment; Bottom: Simulation)

Figure 6. Sketch of scour dimension

Figure 7. Grain size variation in typical longitudinal sections in Case2

Figure 8. Grain size variation in typical transverse cross-sections in Case2

Figure 9. Computed near-bed friction velocity in Case2

Figure 10. Computed spatial distribution of mean grain size ratio in Case2

Table1 Hydraulic conditions

Flow discharge (l/s)	5.70
Channel slope	1/1000
Channel width (cm)	40.0
Flow depth (cm)	5.0
Flow velocity (cm/s)	29.0
Frictional velocity (cm/s)	1.98
Sediment density (g/cm ³)	2.65
Spur dyke length (cm)	10.0
Spur dyke thickness (cm)	1.0
Reynolds number	14, 250
Froude number	0.41

Table 2 Local scour and bed topographic features

Case	Case1 (Exp.)	Case1 (Sim.)	Case2 (Exp.)	Case2 (Sim.)
e_m (cm)	11.60	10.45	9.45	8.64
e_m (x,y)	(-2,1.5)	(-1.8,9.8)	(-1,6.5)	(-1.8,9.8)
d_m (cm)	2.37	1.71	2.72	2.22
d_m (x,y)	(51,6.5)	(25,2.3)	(43,5.5)	(27.8,3.5)
a/L	2.1	1.9	1.9	1.8
b/L	2.9	2.9	2.9	2.8
c/L	4.0	3.9	2.3	2.3
d/L	1.4	1.0	0.4	0.4
θ_1	26°	27°	26°	24°
θ_2	31°	29°	26°	24°
θ_3	16°	14°	19°	16°

Figure 1. Experiment setup.

Figure 2. Sediment size distribution

Figure3. Plan-view of computational grid.

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Figure 4. Final bed configuration in Case1 (Top: Experiment; Bottom: Simulation)

Figure 5. Final bed configuration in Case2 (Top: Experiment; Bottom: Simulation)

Figure 6. Sketch of scour dimension

Figure 7. Grain size variation in typical longitudinal sections in Case2

850
851

++++ Simulation (Grain size ratio) ● Experiment (Grain size ratio)
— Simulation (Bed level) Experiment (Bed level)

(a) Section $x=-30\text{cm}$

(b) Section $x=-10\text{cm}$

(c) Section $x=0\text{cm}$

(d) Section $x=10\text{cm}$

(e) Section $x=30\text{cm}$

(f) Section $x=50\text{cm}$

Figure 8. Grain size variation in typical transverse cross-sections in Case2

Figure 9. Computed near-bed friction velocity in Case2

Figure 10. Computed spatial distribution of mean grain size ratio in Case2