3D NUMERICAL MODEL OF SEDIMENT TRANSPORT CONSIDERING TRANSITION FROM BED-LOAD MOTION TO SUSPENSION —APPLICATION TO A SCOUR UPSTREAM OF A CROSS-RIVER STRUCTURE—

Kazuyuki OTA¹, Takahiro SATO² and Hajime NAKAGAWA³

¹Member of JSCE, Central Research Institute of Electric Power Industry
(1646 Abiko, Abiko-shi, Chiba 270-1194, Japan)
E-mail: k-ota@criepi.denken.or.jp

²Member of JSCE, Central Research Institute of Electric Power Industry
(1646 Abiko, Abiko-shi, Chiba 270-1194, Japan)
E-mail: t-sato@criepi.denken.or.jp

³Member of JSCE, Disaster Prevention Research Institute, Kyoto University
(Shimomisu, Yoko-oji, Fushimi-ku, Kyoto 612-8235, Japan)
E-mail: nakagawa@uh31.dpri.kyoto-u.ac.jp

This study suggests a novel 3D numerical model for simulating the flow and bed deformation around hydraulic structures, considering the transition process from bed-load motion to suspension. The numerical analysis of the fluid is carried out by solving the Reynolds-averaged Navier-Stokes (RANS) equations coupled with the Volume of Fluid (VOF) method. The temporal change in bed topography is calculated by coupling a stochastic model of sediment pickup, deposition, and transition and a momentum equation of sediment particles to account for the effect of non-equilibrium and transition from bed load to suspension. The numerical model was applied to an experimental scour phenomenon upstream of a slit weir, in which the initial bed elevation was lower than the crest elevation of the slit (i.e., all eroded particles experienced the transition process from bed load to suspension around the slit). A comparison between the numerical results and experimental data indicated that the model could reproduce the scour geometry around the slit weir with sufficient accuracy.

Key Words: *scour, numerical simulation, transition, non-equilibrium sediment transport, OpenFOAM*

1. INTRODUCTION

In the vicinity of a cross-river structure with an opening (e.g., check dam or dam with a gate), three-dimensional vortices are formed, causing local scour upstream of the opening. In a check dam, the scour hole influences the trapping and controlling of sediment discharge at the dam. In a hydropower dam facing a problem of sedimentation around its water intakes, the dam gate can release sediments by causing the scour around the gate to lower the risk of burying the water intakes. Therefore, for effective sediment management utilizing a cross-river structure, it is very important to evaluate and predict the scour shape upstream of the structure.

In recent years, 3D numerical models for local scour have been developed in many studies. These

models can be roughly classified into two types based on the method used. One treats sediment as continuous media and calculates bed deformation using functions of sediment transport^{1), 2), 3), 4)}, while the other calculates the particle motion individually using a discrete element method⁵⁾. Currently, the former is more practical in terms of computational cost. Roulund et al. (2005)²⁾ successfully reproduced the scour around a circular pile by a 3D model using the bed-load formula. Dixen et al. (2013)⁴⁾ improved this model by introducing the effect of externally generated turbulence on the bed load. In order to consider the effect of non-equilibrium on bed-load transport, Nagata et al. (2005)¹⁾ incorporated the momentum equation of bed-load particles into the stochastic model of pickup and deposition and applied this model to the scour around hydraulic

structures. Liu and García (2008)³⁾ used the Volume of Fluid (VOF) method to consider the effect of water surface variation on scour and calculated the bed deformation considering both the bed load and suspended load.

In the upstream region near a cross-river structure with an opening, bed-load movement in the longitudinal direction is intercepted by the structure. Instead, bed-load particles are entrained into suspension and flow into the opening of the cross-river structure because of the rapid upward flow caused by the contracted flow at the opening⁶⁾. Thus, the entrained particles experience a transition from bed-load motion to suspension. Ashida et al. (1982)⁷⁾ showed that, when the bed consists of well-sorted particles, all particles transition as “no motion - bed load - suspension” and no particles transit directly from no motion to suspension. Furthermore, Nakagawa et al. (1990)⁸⁾ introduced the stochastic model for the transition from bed-load motion to suspension by modeling the orbital motion of saltating particles. In spite of these insights into the transition process, most existing 3D simulation models of sediment transport treat sediment entrainment as “no motion - suspension” for simplification and do not consider the transition from bed load motion to suspension (e.g., Liu and García, 2008³⁾; Baykal et al., 2015⁹⁾). Thus, the applicability of existing models to scour phenomena upstream of cross-river structures becomes questionable, because the scour is mainly caused by the transition from bed load to suspension.

In order to properly simulate the scour upstream of cross-river structures, this study suggests a 3D model of flow and sediment transport that considers the effect of non-equilibrium bed-load transport and the transition process from bed load to suspension. For validation, the model was applied to a laboratory test of scour upstream of a slit weir.

2. NUMERICAL MODEL

(1) Flow model

The flow model used the interFoam solver, which is one of the standard solvers within the open-source software code OpenFOAM® (OpenCFD Ltd.). The RANS and continuity equations used in the solver are as follows:

$$\nabla \cdot \mathbf{U} = 0 \quad (1)$$

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho \mathbf{U} \mathbf{U}) = -\nabla p^* + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g} + \mathbf{f}_s \quad (2)$$

where ∇ is the three-dimensional gradient operator, $\mathbf{U}$ is the flow velocity vector, ρ is the fluid density, p^*

is the excess pressure, $\boldsymbol{\tau}$ is the viscous stress tensor, $\mathbf{g}$ is the gravitational acceleration vector, and $\mathbf{f}_s$ is the body force equivalent of the surface tension. In the solver, the VOF method is used to model the free surface. In order to solve the velocity-pressure coupling, the PISO (pressure implicit with splitting of operator) approach was adopted. The finite volume method (FVM) was used for discretization, the second-order central difference method for spatial discretization, and the first-order implicit method for temporal discretization. Further information on the implementation of the model can be found in Jasak (1996)¹⁰⁾.

The $k-\omega$ SST (shear stress transport) model¹¹⁾, which is often applied to boundary layer flow under inverse pressure gradient, was used to model the closure turbulence. As the local scour phenomenon is mainly caused by the inverse pressure gradient around hydraulic structures, the $k-\omega$ SST model has often been applied to simulate local scour^{2), 15)}.

(2) Bed-deformation model

In the presence of the obstacle and the associated scour hole, the near-bed flow and bed slope, which have significant influence on sediment movement, vary rapidly around the structure; therefore, the assumption of equilibrium sediment transport becomes questionable. In this study, the framework for a non-equilibrium sediment transport model, as suggested by Nagata et al. (2005)¹⁾, has been introduced, with the addition of the transition process from bed-load motion to suspension. The present model calculates: (1) the volume of sediment pickup, (2) the trajectory of sediment motion, (3) the volume of sediment deposition, and (4) the volume of sediment transition from bed-load motion to suspension. The sediment pickup, deposition, and transition are obtained by employing a stochastic model of sediment motion, whereas the sediment movement is calculated by a momentum equation of sediment particles. From sediment pickup, deposition, and transition, the temporal change in bed elevation is obtained.

a) Pickup volume

The volume of sediment pickup per unit time from a numerical mesh on the bed surface, V_p , is given by:

$$V_p = \frac{A_3 d}{A_2} p_s S_p \quad (3)$$

where p_s is the pickup rate; d is the diameter of the sediment particle; A_2 ($= \pi/4$) and A_3 ($= \pi/6$) are the two- and three-dimensional shape coefficients of the sand grain, respectively; and S_p is the area of the bed-surface mesh.

The pickup rate p_s is obtained from the following

equation proposed by Nakagawa et al. (1986)¹²⁾, which includes the effect of the local bed slope on sediment motion:

$$p_s \sqrt{\frac{d}{(\sigma/\rho-1)g}} = F_0 G_* \tau_* \left(1 - \frac{k_p \phi \tau_{*c}}{\tau_*} \right)^{m_p} \quad (4)$$

$$G_* = \frac{\cos \psi + k_L \mu_s}{1 + k_L \mu_s} \quad (5)$$

$$\phi = \frac{\mu_s \cos \theta_b - \sin \theta_b \cos \alpha}{\cos \psi + k_L \mu_s} \frac{1 + k_L \mu_s}{\mu_s} \quad (6)$$

where σ is the density of sediment; τ_* and τ_{*c} are the dimensionless shear stress and dimensionless critical shear stress for sediments, respectively; and F_0 ($= 0.03$), k_p ($= 0.7$), and m_p ($= 3.0$) are constants, as suggested by Nakagawa et al. (1986)¹²⁾. G_* is the coefficient that accounts for the direction deviation between the near-bed velocity and sediment movement, ψ is the angle between the near-bed velocity and sediment movement, and ϕ is the coefficient that accounts for the local bed slope and the direction deviation between the maximum local bed slope and sediment movement. μ_s ($= 0.7$) is the static friction factor, k_L ($= 0.85$) is the ratio of lift force to drag force, θ_b is the local bed slope, and α is the angle between the maximum local bed slope and sediment movement.

b) Deposition and transition volumes

During the transport of sediment particles, some of the particles continue moving, whereas others are deposited on the bed surface at a certain place. The amount of sediment deposition on the bed along the sediment transport trajectory is estimated using the probability density function of the step length:

$$V_d^{(n)} = V_p F_s^{(n)} (1 - F_t^{(n)}) \quad (7)$$

where the superscript (n) represents the n th step after sediment pickup, $V_d^{(n)}$ is the deposition volume of the sediment, $F_s^{(n)}$ is the deposition probability of the bed-load particle, and $F_t^{(n)}$ is the transition probability of the bed-load particle from bed-load motion to suspension. The deposition probability $F_s^{(n)}$ is written as follows:

$$F_s^{(n)} = f_s(s^{(n)}) \Delta s \quad (8)$$

with

$$f_s(s^{(n)}) = \frac{1}{\lambda} \exp\left(-\frac{s^{(n)}}{\lambda}\right), \quad s^{(n)} = \sum \mathbf{u}_{sed} \Delta t \quad (9)$$

where $f_s(s^{(n)})$ is the probability density function of the step length; $s^{(n)}$ is the distance that the sediment par-

ticle moves from the pickup point; and λ is the average step length of the sediment particle, which is estimated using the formula given by Einstein (1942)¹³⁾; and u_{sed} is the bed-load velocity calculated from the momentum equation of the bed load motion, which is mentioned later.

In order to evaluate the transition probability $F_t^{(n)}$, a probability density function with Poisson distribution is introduced, taking into account that the transition event occurs only once per time Δt . The transition probability $F_t^{(n)}$ is written as follows:

$$F_t^{(n)} = \sum f_t(t^{(n)}) \Delta t \quad (10)$$

with

$$f_t(t^{(n)}) = p_t \exp(-p_t t^{(n)}) \quad (11)$$

where $f_t(t^{(n)})$ is the probability density function of transition from bed-load motion to suspension at the n th step after sediment pickup; and p_t is the transition rate, which represents the expected value of the frequency of transition. The transition rate p_t is calculated using the formula introduced by Nakagawa et al. (1990)⁸⁾ through theoretical and experimental investigation of the transition phenomenon:

$$p_t \sqrt{\frac{d}{(\sigma/\rho-1)g}} = F_{0t} \left(\frac{u_*}{w_0} \right)^n \left[1 - \frac{(u_*/w_0)_c}{(u_*/w_0)} \right]^m \quad (12)$$

where F_{0t} ($= 0.0175$), n ($= 0.4$), and m ($= 1.10$) are constants; (u_*/w_0) is the dimensionless shear stress for suspension; and $(u_*/w_0)_c$ is the dimensionless critical shear stress for suspension, estimated using the suggestion of van Rijn (1984)¹⁴⁾:

$$\left(\frac{u_*}{w_0} \right)_c = \begin{cases} \frac{4}{d_*} & \text{for } 1 < d_* \leq 10 \\ 0.4 & \text{for } d_* > 10 \end{cases} \quad (13)$$

where u_* is the frictional shear velocity, w_0 is the settling velocity of the particle, and $d_* = [(\sigma/\rho-1)gd^3/\nu^2]^{1/3}$ is the dimensionless particle diameter.

c) Sediment trajectory

By disregarding inter-particle collisions, the movement velocity vector $\mathbf{u}_{sed}$ of a sediment particle is calculated using its motion equation. Two unit vectors parallel to the local bed surface are defined as $\mathbf{e}_{b1}$ on the x - z plane and $\mathbf{e}_{b2}$ on the y - z plane. Then, the motion equation of the sediment particle in the $\mathbf{e}_{bj}$ ($j = 1, 2$) direction is written as follows:

$$m_{sed} \frac{\partial \mathbf{u}_{sed,j}}{\partial t} = \mathbf{D}_j + \mathbf{W}_j - \mathbf{F}_j \quad (14)$$

with

$$m_{sed} = \rho \left(\frac{\sigma}{\rho} + C_M \right) A_3 d^3 \quad (15)$$

where m_{sed} is the submerged weight of the sediment particle; $\mathbf{u}_{sed,j}$ is the velocity component of bed-load motion in the j direction; $\mathbf{D}_j$, $\mathbf{W}_j$, and $\mathbf{F}_j$ are the j -direction components of the drag force on the particle, submerged weight of the sediment particle, and friction force between the sediment particle and bed, respectively; and C_M ($= 0.5$) is the coefficient of added mass. The magnitudes of the drag force, submerged weight, and friction force of the sediments are obtained as follows:

$$\mathbf{D}_j = \frac{C_D \rho}{2} |\mathbf{u}_{r,j}| \mathbf{u}_{r,j} c_e A_2 d^2 \quad (16)$$

$$\mathbf{W}_j = \begin{cases} -W \left(\frac{\sin \theta_{bx} \cos^2 \theta_{by}}{\sin^2 \theta_p} \right) & \text{for } j = 1 \\ -W \left(\frac{\sin \theta_{by} \cos^2 \theta_{bx}}{\sin^2 \theta_p} \right) & \text{for } j = 2 \end{cases} \quad (17)$$

$$\mathbf{F}_j = \mu_k \left(W \frac{\cos \theta_{bx} \cos \theta_{by}}{\sin \theta_p} \mathbf{e}_{b,j} - k_L \mathbf{D}_j \right) \quad (18)$$

where u_{bj} is the velocity component of the near-bed flow in the j direction; C_D ($= 0.4$) is the drag coefficient; c_e is the coefficient accounting for the effective application area of the drag force ($c_e = 1.0$ for moving particles and $c_e = 0.4$ for static particles); μ_k ($= 0.35$) is the coefficient of kinetic friction of the sediment particles; θ_{bx} and θ_{by} are the angles of the local bed inclination in the x and y directions, respectively; and θ_p is the angle between $\mathbf{e}_{b1}$ and $\mathbf{e}_{b2}$.

d) Sliding sediment volume

When local scour occurs because of the presence of a hydraulic structure, the local bed slope in the scour hole becomes steep. When the local bed slope θ_b exceeds a critical value θ_{bc} , sliding of bed materials occurs around the structure. Thus, assuming that the sliding event takes place instantly, the sliding sediment volume required to keep the bed slope at its critical value θ_{bc} is calculated when θ_b exceeds the critical value θ_{bc} , which is assumed to be the angle of repose in water. The volume of sliding sediment is then added to the pickup volume at the mesh region where the sliding event takes place.

e) Temporal variation in bed elevation

Using the volumes of sediment pickup and sediment deposition, which are calculated as previously described, the temporal variation in bed elevation is expressed as follows:

$$\frac{\partial z_b}{\partial t} = \frac{A_1 A_2}{A_3} \frac{\sum_{n=1}^N V_d^{(n)} - V_p}{S_d} \quad (19)$$

where z_b is the bed elevation; A_1 ($= 1.0$) is the shape coefficient of the sediment particles; the summation of $V_d^{(n)}$ represents the total volume of deposited sediments in each computational cell at each time step; and S_d is the projected area of the computational cell in which the sediment is deposited.

In the present scheme, the position at which the deposition volumes were obtained did not necessarily coincide with the numerical grid points. Therefore, the mesh region with the location of the moving sediment particle was found at each time step, and the deposition volume was distributed proportionally to each grid point based on the relative location of the particle.

In this study, the numerical model was applied only to the early stages of scouring, during which the suspended particles did not settle on the scour hole again because of the very high shear stresses on the scour hole. Thus, it should be noted that, for simplification, it was assumed that the suspended load did not transition back to bed load.

3. VALIDATION IN THE SCOUR EXPERIMENT

The present numerical model was applied to a scour experiment around a slit weir. In the experiment, bed load could not pass through the weir because the initial bed elevation was lower than the crest elevation of the slit. Therefore, all eroded sediments experienced the transition process from bed load to suspension. Thus, this experiment was used to validate the proposed numerical model that included the transition process.

(1) Experimental setup

A scour experiment was conducted at the Central Research Institute of Electric Power Industry (CRIEPI) in a circulating flume that was 10.5 m long, 0.50 m wide, and 0.35 m deep. As shown in **Fig. 1**, a slit weir made of Plexiglas was placed in the flume, and a sediment bed was positioned upstream of the slit weir. The bed elevation was leveled at 10 mm below the crest elevation of the slit. Laser displacement sensors (IL-600, Keyence Co., Ltd.) were used to scan the sediment surface at a resolution of 1 mm and 4 mm in the longitudinal and lateral directions, respectively. Further details of the experimental apparatus can be found in Ota and Sato (2013)⁶.

The scour experiment was carried out under the

clear scour condition, as this study was focused on the bed deformation caused by the local flow around the slit weir. The flow rate was $4.0 \times 10^{-3} \text{ m}^3/\text{s}$, and at 0.5 m upstream of the slit weir, the approaching flow depth was 72.7 mm, the approaching flow velocity was 0.11 m/s, and the Froude and Reynolds numbers for approaching flow were 0.13 and 8.2×10^3 , respectively. It should be noted that these hydraulic parameters did not vary with time while the bed was scoured in the experiment.

First, the slit was closed with a plate that had the same shape as the slit (50 mm height, 100 mm width, and 15 mm thickness), and the flume was filled gradually until the water overflowed the wing. The slit was then opened, and the experiment was initiated. After a given time had passed, the slit was closed, and the bed topography was measured. After the bed topography measurement, the experiment was resumed. The bed topography measurements were carried out at 40 s, 80 s, 160 s, 320 s, and 640 s after the start of the experiment.

Additional rigid-bed experiment for velocity

measurement was conducted using the bathymetry data, which has been taken at 320 s after the scour experiment started. The topography of scour hole was reproduced using the 3D printing technique. The bed particle was pasted on the surface of the rigid scoured bed in order to adjust the roughness. Velocity measurement was conducted using Profiling ADV (vctrino 2, Nortek, Inc), which allows for taking an instantaneous velocity profile for 3 cm length with 1 mm interval. The velocity measurement was conducted under the condition of 20 Hz of sampling frequency, 240 s of measurement time.

(2) Numerical condition

The numerical conditions used in the simulation were similar to the experimental conditions. The cross-section at 0.5 m upstream of the slit weir was taken as the inlet boundary. The computational cells consisted of cubes, and their total number was 478,520. At the initial condition, the edge length was set to 5.0 mm, but a finer edge length was applied in the near-bed region in geometric progression. The

Fig. 1 Schematic of the slit weir (unit: mm).

Fig. 2 Streamlines near the bed and variation of transition rate p_r .

mesh points moved in the vertical direction when the bed deformed, and the non-slip condition was imposed at the bed and the wall boundary. The bed shear stress used in sediment transport model was evaluated by conventional wall function using log-law. In the present calculation method for bed deformation, it was necessary to keep track of the exact location and speed of every sediment particle that leaves each numerical grid point on the bed surface. This made it impractical to calculate the sediment pickup volume at all time steps because of computational memory limitations. To overcome this difficulty, the calculation of bed deformation was carried out only every 0.01 s (20 times the interval of flow calculation). Furthermore, parallel computation with domain decomposition was used to accelerate the simulation. As OpenFOAM comes with

parallel-computing support, the present model easily used these modules to implement both the flow-field solver and the sediment-transport solver simultaneously. The computations were done on the supercomputer SGI ICE X at the CRIEPI.

(3) Results and Discussion

Figure 2 shows a snapshot of the flow and the bed at 160 s after the start of the simulation. The stream-lines were obtained by using tracers from the inlet boundary, which was 10 mm higher than the bed. The bed colors show the variation in the transition rate p_t (i.e., average frequency of transition from bed load to suspension). Vortex flow occurs in the vicinity of the weir, where bed load is entrained into suspension at the maximum rate of 0.3 Hz.

Figure 3 shows a comparison of velocity distribu-

Fig. 3 Comparison of velocity distribution for experiment and simulation at 320s after the scour started: **Fig. 3(a)** shows a velocity field on the horizontal plane at elevation of the slit crest. **Fig. 3(b)-(d)** show streamwise velocity at longitudinal sections, and their lateral location are shown as solid lines b, c, and d. in **Fig. 3(a)**.

Fig. 4 Comparison of contour lines of scour depth between experiment and simulation (unit: mm).

tion for the experiment and simulation at 320s after the scour started. **Figure 3(a)** shows a velocity field on the horizontal plane, and the broken line shows a region where velocity measurement was conducted. The simulation captures well the local flow that bends near the weir and approaches the slit. **Figures 3(b)-3(d)** show comparisons of the streamwise velocity at a longitudinal section, and their lateral locations are shown as solid lines b, c, and d. in **Fig. 3(a)**. Bed elevations in the experiment and simulation are also described in **Figs. 3(b)-3(d)**. Overall, the experiment and the simulation results agree well. However, the streamwise velocity is overestimated near the slit. This is due to the fact that the bed elevation in the simulation is higher than that in the experiment.

Figure 4 compares the contour lines of scour depth obtained from the simulations and the experiment. Both the simulation and experimental results show a crater-shaped scour hole around the slit and an increase in the size of the scour hole with time. In order to validate the simulation quantitatively, the temporal variation in the scour volume was compared with that of the experiment, as shown in **Fig. 5**. It was found that the simulation underestimated the experimental scour volume by up to 30%. A possible reason for this underestimation could be that the initial coefficients of step length and transition rate had been based on the turbulence of uniform flow in an open channel. Therefore, the time scale of the turbulence in the local flow around the slit could have influenced the frequency of transition from bed load to suspension.

Figure 6 shows the horizontal locations of maximum scour depth in the simulation and the experiment. Both results indicate that the bed was most-deeply scoured around the boundary between the slit and the wing. This can be attributed to the fact that the bed particles around this boundary are most likely to be entrained because of the rotational flow

from wing to slit^(6), 15). Thus, the simulation reproduced this feature of the scour quite well. **Figure 7** shows the maximum scour depth in the simulation and the experiment, and it can be seen that the simulation underestimates the maximum scour depth in the experiment, as in the case of scour volume. Furthermore, it was observed that the difference in maximum scour depth between simulation and experiment was larger than the difference in scour volume (see **Fig. 5**). A possible reason for this could be that strong vortex flow appears at the location of the maximum scour depth, thus requiring further investigation of the influence of this vortex flow on the transition rate.

The evaluation of the scour shape upstream of a cross-river structure is important for practical use, and the proposed numerical model was capable of reproducing the scour shape observed in the experiment, although it tended to underestimate the size of the scour hole.

Fig. 6. Comparison of horizontal location of maximum scour depth between experiment and simulation (unit: mm).

Fig. 5. Comparison of temporal variation in scour volume between experiment and simulation.

Fig. 7 Comparison of temporal variation in maximum scour depth between experiment and simulation.

4. CONCLUSIONS

This study suggested a new 3D simulation method of modeling flow and sediment transport, considering the transition process from bed-load motion to suspension. This numerical analysis coupled the RANS equations of the fluid with the VOF method and the $k-\omega$ SST turbulence model using the OpenFOAM library. The temporal change in bed topography was calculated by coupling a stochastic model of sediment pickup, deposition, and transition and a momentum equation of sediment particles to account for the effect of non-equilibrium and transition on sediment transport.

For validation of the numerical model, it was applied to the scour experiment around a slit weir, in which the initial bed elevation was lower than the crest elevation of the slit (i.e., all eroded particles experienced the transition process into suspension around the slit). The simulation showed good agreement with the experiment in terms of the scour shape, but underestimated the maximum scour depth. Further research is needed to investigate the effect of transition rate, which is an important parameter in the simulation of the transition process.

ACKNOWLEDGMENT: The authors wish to thank Hideki Tayama and Yoshinori Gotoh (CERES, Inc.) for their help in conducting the experiment.

REFERENCES

- 1) Nagata, N., Hosoda, T., Nakato, T. and Muramoto, Y.: Three-dimensional numerical model for flow and bed deformation around river hydraulic structures, *J. Hydraul. Eng.*, Vol. 131, No. 12, pp. 1074-1087, 2005.
- 2) Roulund, A., Sumer, B. M., Fredsøe, J. and Michelsen, J.: Numerical and experimental investigation of flow and scour around a circular pile, *J. Fluid Mech.*, Vol. 534, pp. 351-401, 2005.
- 3) Liu, X. and García, M. H.: Three-dimensional numerical model with free water surface and mesh deformation for local sediment scour, *J. Waterway, Port, Coastal, and Ocean Eng.*, Vol. 134, No. 4, pp. 203-217, 2008.
- 4) Dixen, M., Sumer, B. M. and Fredsøe, J.: Numerical and experimental investigation of flow and scour around a half-buried sphere, *Coastal Engineering*, Vol. 73, pp. 84-105, 2013.
- 5) Hajivalie, F., Yeganeh-Bakhtiary, A., Houshanghi, H. and Gotoh, H.: Euler-Lagrange model for scour in front of vertical breakwater, *Applied Ocean Research*, Vol. 34, pp. 96-106, 2012.
- 6) Ota, K. and Sato, T.: Temporal evolution of a scour hole upstream of a slit in a vertical wall, *Proc. of 12th Int. Symp. on River Sedimentation*, pp. 913-920, 2013.
- 7) Ashida, K., Okabe, T. and Fujita, M.: Threshold condition of particle suspension and the concentration of suspended sediments at a reference level, *Bull. Disaster Prevention Research Inst., Kyoto Univ.*, Vol. 25B, No. 2, pp. 401-416, 1982.
- 8) Nakagawa, H., Tsujimoto, T., Murakami, S. and Gotoh, H.: Transition mechanism from saltation to suspension in bed-material-load transport, *J. Hydrosci. and Hydraul. Eng.*, Vol. 8, No. 1, pp. 41-54, 1990.
- 9) Baykal, C., Sumer, B. M., Fuhrman, D. R., Jacobsen, N. G. and Fredsøe, J.: Numerical investigation of flow and scour around a vertical circular cylinder, *Phil. Trans. Roy. Soc. A*, Vol. 373, article No. 20140104, 2015.
- 10) Jasak, H.: *Error Analysis and Estimation for the Finite Volume Method with Application to Fluid Flows*, Ph. D. Thesis, Imperial College of Science, Technology and Medicine, London, 1996.
- 11) Menter, F., Ferreira, J. C., Esch, T. and Konno, B.: The SST turbulence model with improved wall treatment for heat transfer predictions in gas turbines, *Proc. the International Gas Turbine Congress - IGTC2003-TS-059*, November, 2003.
- 12) Nakagawa, H., Tsujimoto, T. and Murakami, S.: Non-equilibrium bed load transport alongside slope of an alluvial stream, *Proc. 3rd Int. Symp. on River Sedimentation*, pp. 885-893, 1986.
- 13) Einstein, H. A.: Formulas for the transportation of bed load, *Trans. ASCE*, No. 2140, pp. 561-597, 1942.
- 14) van Rijn, L. C.: Sediment Transport, Part II: Suspended Load Transport, *J. Hydraul. Eng.*, Vol. 110, No. 11, pp. 1613-1641, 1984.
- 15) Ota, K. and Sato, T.: Experimental and numerical study of the local scour caused by sediment releasing through a dam gate, *J. JSCE*, pp. 184-190, 2015.

(Received July 8, 2016)