EXPERIMENTS AND ANALYSES ON THE DEFORMATION OF THE BED PROTECTIVE WORKS DOWNSTREAM OF A WEIR

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Abstract

Bed protective works are installed on the bed downstream of a weir to prevent failure and collapse of the structure due to bed scouring. Because failures of bed protective works expose the main structure in danger, it is important for river technology and management to maintain the safety of the bed protective works. So, it is required to establish the method for evaluating the hydrodynamic forces acting on the bed protective blocks and estimating the deformation range of the structure. In this paper, we measure the hydrodynamic forces acting on the last row elements in the threshold of block movement and developed the threshold model of block movement. The model of a vertical two-dimensional analysis for the flow with complex boundary shape of the blocks is presented, in order to evaluate hydrodynamic forces acting on the blocks. Then, we developed the numerical model for deformation of the bed protective works downstream of a weir using the threshold model. It is clarified through the comparison between measured and computed results that the model can explain the experimental deformation process.

Keywords: bed protective work, threshold of block movement, hydrodynamic force, deformation and failure mechanism, last row elements, vertical two-dimensional model

1. INTRODUCTION

Bed protective works are installed on the bed downstream of a weir to prevent failures and collapses of the structure due to bed scouring. Because failures of bed protective works endanger the main structure, it is important for designing a weir to maintain a safety of the bed protective works downstream of the structure.

In general, the bed downstream of bed protective works is eroded. So, many researchers have been concerned with the local scour downstream of the bed protective works. For example, Kanda et al. (1993) and Revelli et al. (2001) investigated the scour downstream of a bed protective works. Hoffimans and R. Booij (1993) presented the two-dimensional analysis for the local scour. On the contrary, the bed protective blocks should have enough weight against flood flow (Fukuoka et al. (1988)). We indicated the drag force acting on the last row elements of the bed protective works are greater than that of any other elements (Uchida and Fukuoka, (2001)). This indicates that the downstream end of the structure is a weak point due to not only bed scouring but also large hydrodynamic forces and the completely protection of the last low block of the bed protective works is difficult. So, it is required to establish the method for evaluating the stability of the bed protective blocks and estimating the deformation range of the structure.

In this paper, we present the deformation process of the bed protective blocks and the hydrodynamic forces acting on the last row elements in the threshold of block movement. And we developed the threshold model of block movement. The model of a vertical two-dimensional analysis for the flow with bed protective blocks is presented to evaluate hydrodynamic forces acting on the blocks. Then, we developed the model for deformation of the bed protective works downstream of a weir using the threshold model. It is clarified through the comparison between measured and computed results that the model can explain the experimental deformation process.

2. EXPERIMENTS ON THE DEFORMATION OF THE BED PROTECTIVE WORKS AND THRESHOLD MODEL OF A BLOCK MOVEMENT

The experimental channel is 10m long, 0.45m wide, has a slope of 1/500. The bed protective blocks are installed downstream of a groundsill of 0.24m height, as shown in Fig.1. We examined the deformation process of the bed protective blocks, degrading the water level downstream of the structure h_b for the condition of a constant discharge. Table 1 shows the experimental condition. The blocks deformation breaks out downstream end of the blocks on which the large hydrodynamic forces were acted. Then the deformation goes to upstream direction by the degradation of water level downstream of the structure, as shown in Fig. 9 (a). To design the bed protective works, whether the blocks survive is important rather than the motion of the blocks. The threshold model of block movement is discussed below before the evaluation of drag forces and the development of the deformation model of the blocks.

First, we assume that the block got into rotating motion at the outset. To formulate the threshold of a block movement, we should consider the moment equilibrium of a block overlapping between the blocks. The threshold of a circular object shown in Fig.1 is written by Eq. (1).

$$\gamma = \frac{\left(1+\dfrac{\alpha_x}{cos\,\phi}\right)\cdot D_x + tan\,\phi\left(1-\dfrac{\alpha_z}{sin\,\phi}\right)\cdot D_z}{\left(tan\,\phi\cdot cos\,\theta - sin\,\theta\right)\cdot W_W} \tag{1}$$

In which, (D_x, D_z)=x,z direction drag forces, (α_x, α_z)= shift coefficients of point of action by velocity distribution, ϕ=limit incline for a block stability.

To consider the shift of fulcrum point of rotating motion of a block by protrusion of the blocks, we represented ϕ by Eq.(2) using a protrusion coefficient C.

$$cos\,\phi = 1 - C\frac{k_0}{k} \tag{2}$$

In which, k_0= length of a block, k_0= overlapping length between blocks.

We established measurement method of threshold drag forces of a block to discuss the adequacy of the threshold model of block movement. Fig.2 shows the instrument of threshold drag forces of a bed protective block. In which F_x and F_z are output forces of X and Z direction, respectively. We put a block for measuring the drag force on blocks connected to the force measure. The block for measuring the drag force is not fixed with the under blocks and we call it movable block. Fig.3 shows the change of F_x and F_y by time included the movement period of a movable block. F_x and F_z include the hydrodynamic force acting on the movable block when a movable block is on the under fixed blocks. However, if the movable block leaved the fixed blocks, F_x and F_z will change by the force acting on the movable block ΔF_x, ΔF_z. From principle of action and reaction, the force acting on the movable block D_x and D_z are derived by Eq.(3).

$$D_x = -\Delta F_x,\ \ D_z = W - \Delta F_z \tag{3}$$

To obtain the adequate force, we checked the movement period of the movable block and extracted the maximum and minimum forces from the output in the period. ΔF_x and ΔF_z are computed by the difference between the maximum and minimum forces. To check on the accuracy of this method, we calculate a weight W and fined that the error of this method is 5 %.

In here, we do not discuss D_z but D_x, because D_z is quite a little compared with D_x and W in this experiment condition. Fig.4 shows the relationship between non-dimensional overlapping length between blocks k/k_0 and the ratio of D_x to W. D_x/W increase with increasing k/k_0. Because, increasing k/k_0 rise the fulcrum point of the block rotating motion to the action point of D_x. A line on Fig.4 is computed D_x/W by Eq.(1) with assumptions of neglecting D_z and α_x, using C=1.6 that was obtained by Eq.(2) using measured limit incline for a block stability ϕ. Although some measured D_x/W have varied, the entire measured D_x/W are fit on the computation line.

In above discussion, we can determine if blocks can move by the threshold model of Eq.(1) if hydrodynamic forces are given.

3. HYDRODYNAMIC MODEL

A flow with complex boundary shape as bed protective blocks can be computed in principle, if all the boundary shapes are taken into the flow model. Hirt (1992) factored the proportion of fluid part in control volume and its faces into the computation to compute the flow with the complex boundary shape. However, the computation method in which all the shape and arrange of the blocks are taken into account will be not suitable for practical use, because the blocks are randomly arranged and the protrusion scales of the blocks are considerably small compared with water depth of the typical scale of flood flow. In this case, we know that it is better to add the resistance terms to the momentum equations of flow (e.g. Uchida et al., 2001). However, for using this method, we should clarify how individual hydrodynamic force acting on a bed protective block is taken into the flow model to estimate the stability of bed protective block.

3.1 GOVERNING EQUATIONS FOR FLOW WITH BED PROTECTIVE WORKS

Fig.6 is a control volume including n blocks. In this paper, Δy is the channel width in order to develop the two-dimensional model. A drag force of x direction acting on a block D_x is divided the components of the form drag of a block D_x' and the other (volume drag). We define D_x' in Eq.(4) using a drag coefficient C_D.

$$D_x' = \frac{1}{2} C_D \rho \overline{u_x} U k^2 \tag{4}$$

In which, ρ = fluid density, $\overline{u_x}$ = averaged x-direction fluid velocity for a control volume, $U = \sqrt{\overline{u_i}^2}\ \ (i = 1,2)$. The sum of D_x in a control volume is represented by Eq.(5).

$$nD_x = \left|\overline{p} \cdot \Delta y \Delta z (1 - A'_x)\right|_x^{x+\Delta x} - \Delta x \Delta y \Delta z (1 - V') \frac{\partial \overline{p}}{\partial x} + nD_x' \tag{5}$$

In which, $\overline{p}$ = averaged pressure intensity for a control volume (D'_x is drag force due to the deviation pressure distribution from $\overline{p}$), A'_x, V'= proportion of fluid part in x-section and the control volume. z-direction force is derived in a similar way. Applying a law of conservation of momentum for a control volume including *n* blocks (Fig. 5) with Eq.(5), we can obtain the averaged flow equations for a control volume as below.

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial A'_j \overline{u_i}\,\overline{u_j}}{V' \partial x_j} = -g\delta_{2i} - \frac{F_i}{\rho V'} - \frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial A'_j \overline{u'_i u_j'}}{V' \partial x_j} \tag{6}$$

$$\frac{\partial A'_j \overline{u_j}}{\partial x_j} = 0 \tag{7}$$

In which,

$$F_i = \frac{nD_i'}{\Delta x \Delta y \Delta z} = \frac{C_D \rho \overline{u_i} U}{2k}\left(\frac{\theta_b}{\theta_{bo}}\right),$$

$\theta_b = 1 - V'$, $\theta_{bo} = V_{bo} / k^3$, $x_1, x_2 = x, z$, $\overline{u_i}$ = averaged x_i-direction fluid velocity distribution for a control volume, δ_{ij} = Kronecker delta, u'_i = the deviation of x_i-direction fluid velocity from $\overline{u_i}$.

In this study, fluid mixing terms in Eq.(6) are represented by Eq.(8), using averaged strain rate of fluid and kinematic eddy viscosity ν_t. And, ν_t is represented based on Smagorinsky model to take into the account the flow mixing by the blocks resistance.

$$\overline{u'_i u'_j} = \nu_t \frac{\partial \overline{u_i}}{\partial x_j} = 2\nu_t S_{ij}, \quad \nu_t = (\Delta \cdot Cs)^2 \sqrt{2|S_{ij}|^2 + \frac{\overline{u_i} F_i}{\rho V' \nu_t}} \tag{8}$$

In which, $\Delta = \sqrt{\Delta x \Delta z}$, $Cs = 0.3$.

Eq.(6) and Eq.(7) are solved in σ coordinate system (Uchida et al., 2004) to take into account water surface profiles downstream of a weir.

3.2 EVALUATION OF DRAG FORCE AND DEFORMATION MODEL

In this section, we discuss the evaluation method of drag force acting on a block. In Eq.(5), the drag force is represented only the form drag component of second term in Eq.(5), if we introduce an assumption of a uniform volume density. This means that, in the model, the drag force acting on a block is not computed directly because the model regard drag forces due to averaged pressure gradient as the internal stress of the blocks. So, in order to evaluate drag force acting on a block, we should separate the target block from the other blocks. In other words, we should evaluate the drag force by Eq.(5) without the first term of right side. In this case, we can obtain D_i/W that is the ratio of drag force acting on a block D_i to its weight in water W_w by Eq. (5) as below.

$$\frac{D_i}{W_w} = \iiint_{k\,k\,k} f_{*i} dxdydz = \frac{1}{sg\theta_{bo}} \iiint_{k\,k\,k} \left(-\frac{\theta_{bo}}{\rho}\frac{\partial p}{\partial x_i} + \frac{C_D u_i}{2k}|U| \right) dxdydz \tag{13}$$

We can determine the threshold of block movement by the computation, using Eq.(1) and Eq.(13). The deformation model is the simple model, in which only the threshold model of block movement is used. In the model, as shown in Fig. 7, criterion of start and stop are

γ_1 and γ_2. And a criterion of finishing washout is γ_3. Because γ_1 means the threshold of block movement, $\gamma_1 = 1.0$. However, γ_2 and γ_3 should be smaller than one if we use Eq.(1), because γ_2 and γ_3 have a strong relationship to speed reduction and acceleration respectively. So, in this study, $\gamma_2 = \gamma_3 = 1.0$ is taken in the deformation analysis.

4. COMPARISONS BETWEEN MEASURED AND COMPUTED RESULTS

Fig.8 shows comparisons of (a) water surface profiles and (b) velocity distributions between measured and computed results. In the computation, we use C_D=7.4 that is obtained by the experiment. There is scarcely a flow between the blocks except in the thin upper layer, in which the momentum of the flow is exchanged between the flow between the blocks and the flow over the blocks. We can see that the flow over the blocks is supper critical in Fig.8(b). The kinetic energy of the supper critical flow is attenuated downstream of the blocks, producing the wave jump flow. Although the water surface of two-dimensional analysis has a pronounced tendency of the wave jump than that of measurement, we also examined the wave jump occurred by the experiment. As a general rule, the flow will change to submerged jet flow from wave jump flow by the degradation of water level downstream of a weir. But, we can not look see the submerged jet flow downstream of the blocks in both of the experiment and the computation. Because, the more the water level downstream of the blocks degrades, the more water flows into the void of blocks, in which the flow energy is burned. The computed results cannot fit in the measured results just downstream of the weir. The model formulated by simplifies the shape and the resistance of blocks is not fit to express the complex flow field as the flow impinging on the blocks. On the other hand, the model can explain the characteristics of the flow field downstream part of the blocks which controls the pattern of the blocks deformation.

Fig.9 shows comparisons of the blocks deformation processes between measured and computed results. The blocks profile by computed results deforms from the downstream-end, and then the blocks deformation goes upstream by the degradation of water level downstream of the blocks, as in the similar way of the experiment. Because the motions of the blocks are not computed in the model, the blocks profiles of moved blocks (downstream part of the blocks) are different between measured and computed results. However, the computed profiles of the blocks by surviving blocks (upstream part of the blocks) are similar to that of the experiment.

5. CONCLUSIONS

1) We established measurement method of threshold drag forces of a block and developed the threshold model of block movement.
2) The model of a vertical two-dimensional analysis for the flow with bed protective blocks is presented to evaluate hydrodynamic forces acting on the blocks. And we developed the model for deformation of the bed protective works downstream of a weir using the threshold model.
3) The model can explain the measured results of the flow with bed protective works.
4) The computed profiles of the blocks by surviving blocks (upstream part of the blocks) are similar to that of the experiment.

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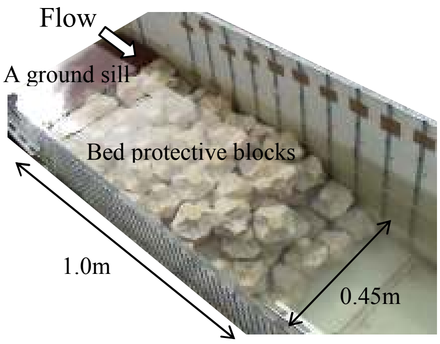


Fig.1 Bed protective blocks downstream of a groundsill

Table 1 Experimental conditions

Discharge	7.5×10^{-2} (m^2/s)
Channel wide	0.45 (m)
Channel length	10.0 (m)
Characteristics length of the block k	9.1×10^{-2} (m)
Volume of the block V_{bo}	2.4×10^{-3} (m^3)
Specific gravity of a block	2.3

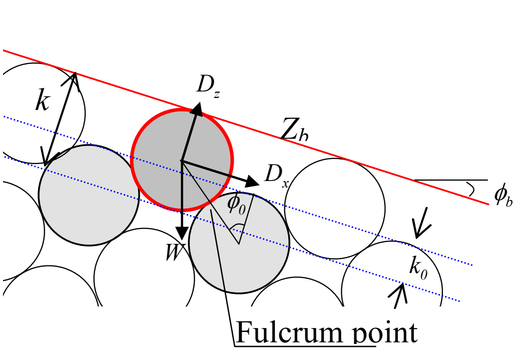


Fig.2 Moment equilibrium of a circular object

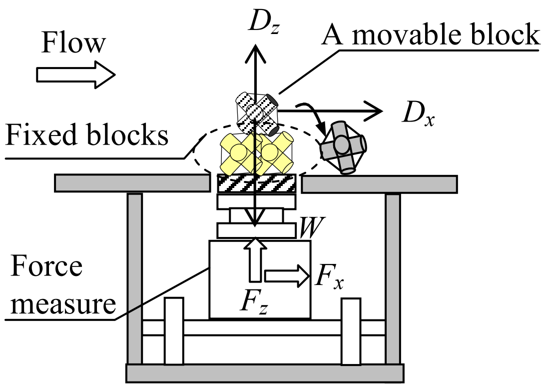


Fig. 3 An instrument of threshold drag force acting on a bed protective block

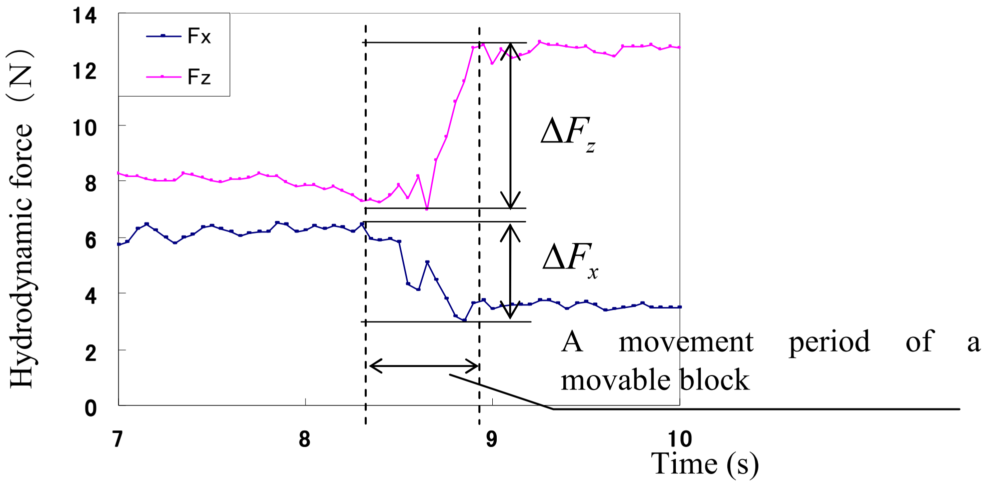


Fig. 4 An example of hydrodynamic changes by time included a movement period of a movable block

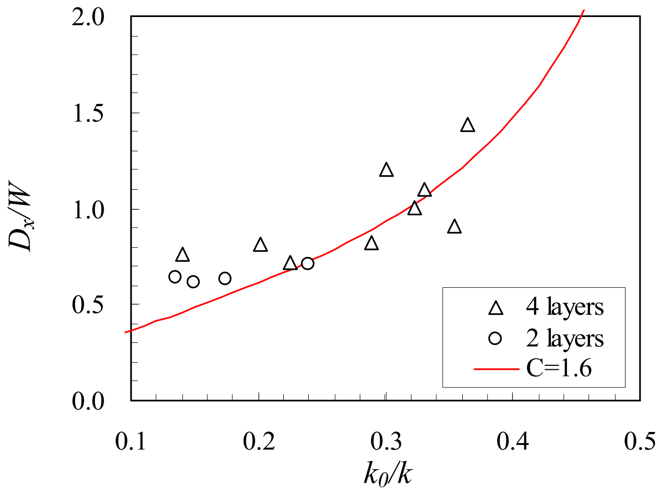


Fig. 5 Relationships between non-dimensional overlapping length k_0/k and x-direction drag forces D_x/W

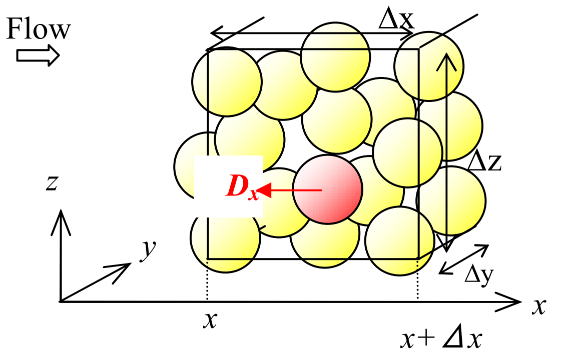


Fig.6 A control volume including n bed protective blocks

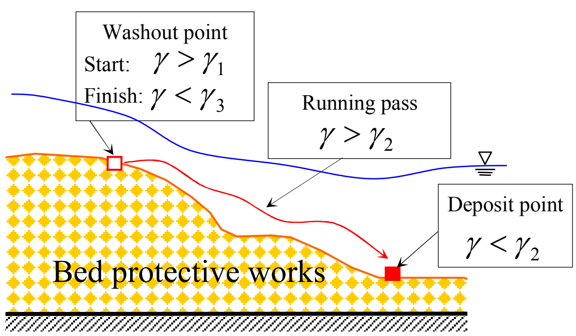
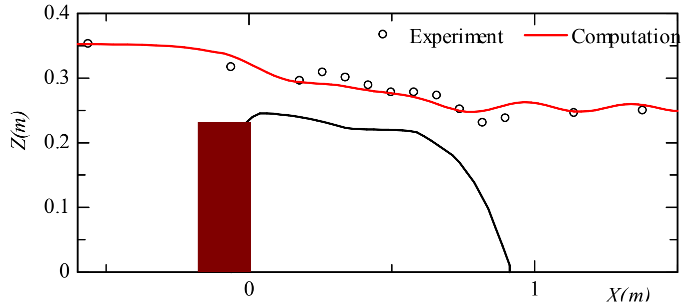
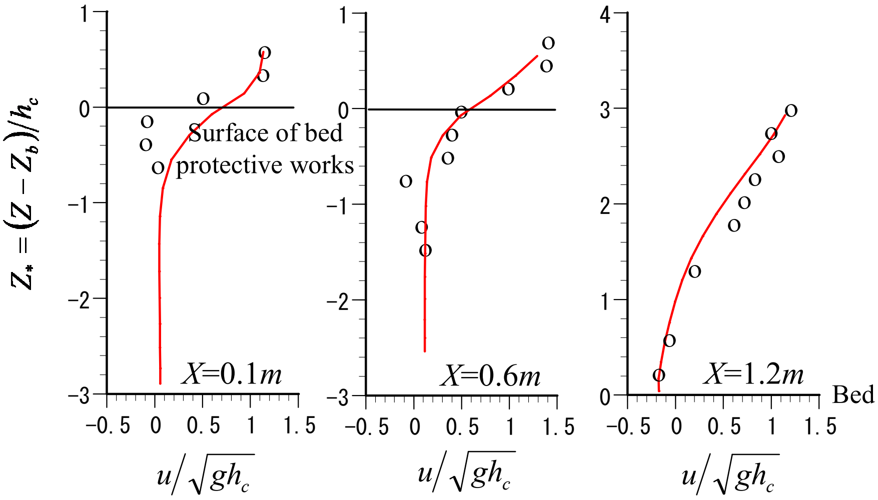


Fig.7 Simple computation method for the bed protective works deformation

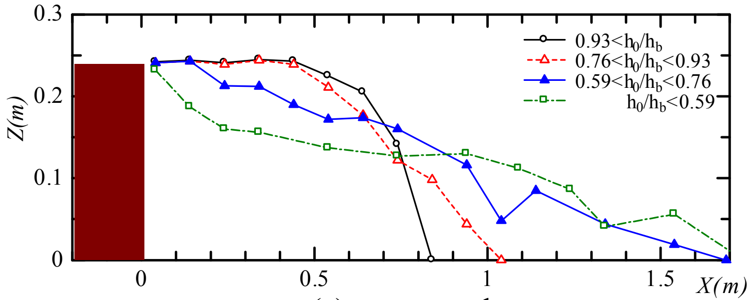


(a) Water surface

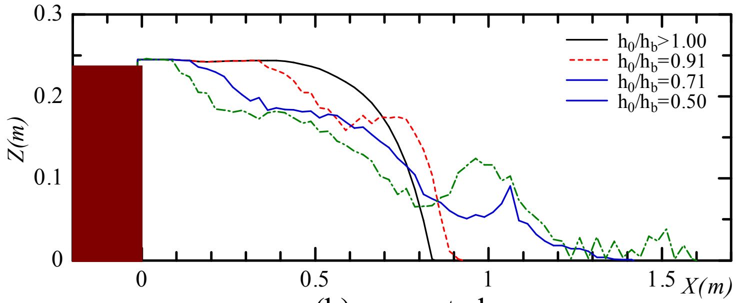


(b) Vertical velocity distributions (h_c: Critical depth (0.083m))

Fig.8 Comparisons of flow fields between measured and computed results



(a) maeasured



(b) computed

Fig. 9 Comparisons of blocks deformation process between measured and computed results