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Modeling Flows over Gravel Beds by a Body Force Method

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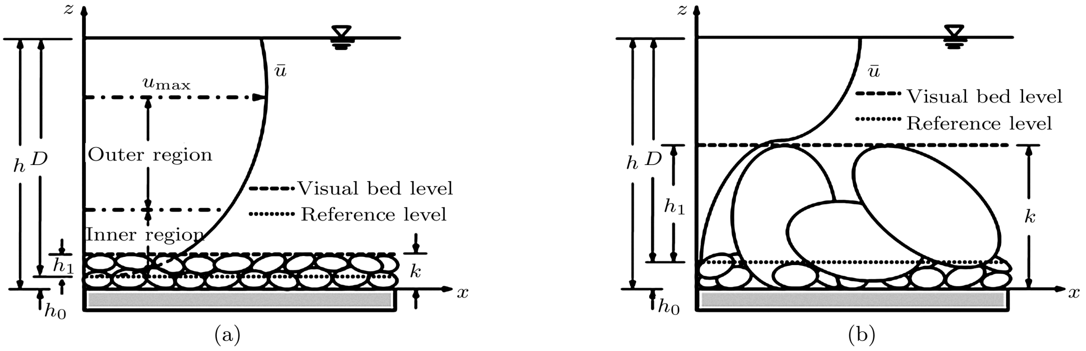
Abstract A Reynolds-averaged Navier-stokes equations (RANS) model using the body force method (BFM) has been developed to simulate open-channel flows over gravel beds. The momentum equation is modified by introducing the form drag as an extra body force term to represent the gravel-bed resistance. By applying the body force within the roughness layer of the flow over small-scale roughness, it is found that the body force coefficient f_{rk} varies inversely with the roughness length scale k_s. The method is robust, not sensitive to mesh resolution and is easily extended to deal with large scale roughness.

Key words: open-channel flows, RANS modeling, turbulent flows, gravel beds, body force method

INTRODUCTION

The roughness elements on gravel-bed open-channel flows vary in size and shape from site to site. Depending on the ratio D/d_{50}, where D is water depth and d_{50} is diameter of gravels for which 50 percent are finer, the bed surface condition can be subdivided into two categories. One is small-scale roughness for which D is much larger than d_{50} and the other is large-scale roughness for which D is of the same order as d_{50}. For the condition of small-scale roughness, it is conventional to consider the flow as a perturbed boundary layer flow. As shown in Figure 1(a), two different flow regions can be identified in the vertical direction: the inner (or near-wall) region and the outer (or near-water-surface) region. In the inner region, the logarithmic velocity distribution is valid [1]. For the condition of large-scale roughness, if d_{50} is comparable to D (say $D/d_{50} < 2.0$), the flow can be assumed to be a mixing layer flow [2]. The flow velocity profile may be S-shaped (Figure 1(b)) with near-surface velocities much larger than near-bed velocities [3]. The criterion differentiating the small-scale and large-scale roughness is not clear-cut, and depends on the shape, concentration and arrangement of the roughness elements.



(a) (b)

Figure 1: Velocity distribution over (a) small-scale roughness (b) large-scale roughness

The present paper describes the use of a body force method to represent the roughness effect induced by the complex surface topography of gravel bed in open-channel flows. The study is originated from the similarity between the velocity profiles over large-scale roughness and those over vegetation. Although the body force method is commonly used to simulate the resisting effect induced by vegetation, its application in gravel-bed open-channel flows has not been widely reported. In the present study, the body force method is implemented to predict the velocity profiles of open-channel flows over small-scale roughness. Its performance will be evaluated by comparing to that of the conventional wall function approach (WFA).

NUMERICAL MODELLING

The momentum equation for 1D incompressible, uniform open-channel flow is

$$\frac{\partial \bar{u}}{\partial t} = \frac{\partial}{\partial z}\left[(\nu_m + \nu_t)\frac{\partial \bar{u}}{\partial z}\right] + g_x - \frac{1}{\rho}F_x \tag{1}$$

where x is streamwise ordinate; z is vertical ordinate with datum set at h_1 below the roughness element surface; $\bar{u}$ is time-averaged streamwise velocity component; t is time; ρ is density; ν_m is molecular viscosity; ν_t is eddy viscosity; F_x is streamwise resistance force per unit volume induced by roughness elements; $g_x = gS_0$ is streamwise component of the gravitational acceleration and S_0 is bed slope.

The eddy viscosity ν_t is specified by the Spalart-Allmaras (S-A) turbulence model which involves the solution of a new eddy viscosity variable ν. The S-A model is a one-equation model which is simpler than the commonly used k-ε or k-ω model and it has been successfully applied in the modeling of open-channel flows through vegetation (e.g. [4]).

The modeling of resistance force induced by a gravel bed is based on the quadratic friction law. The average force per unit volume within the roughness layer can be obtained by

$$F = \frac{1}{2}\rho C_d b_s N \bar{u}_1^{\,2} = \frac{1}{2}\rho\, f_{rk} \bar{u}_1^{\,2} \tag{2}$$

where N is number density (number of gravels per unit area, in 1/m^2), b_s is effective projected width of the roughness element and f_{rk} $(= C_d b_s N)$ is body force parameter reflecting the effects of shape and size of the gravels, $\bar{u}_1$ is average velocity within the roughness layer. The thickness of the region in which F is introduced is set equal to h_1 (Figure 1(a)). Previous experiments by others show that $h_1 \sim 0.2k_s$, where k_s is roughness length scale. The velocity profile can be approximated by the following logarithmic law

$$\frac{\bar{u}}{u^*} = \frac{1}{\kappa}\ln\left(\frac{z}{k_s}\right) + 8.5 \tag{3}$$

where $\kappa = 0.41$. Within the roughness layer of thickness $0.2k_s$ the above equation indicates that the ratio $\bar{u}_1/u^*$ will be approximately a constant. A simple force balance analysis shows that

$$f_{rk}k_s = 5 f_{rk}h_1 = 10\left(\frac{u^*}{\bar{u}_1}\right)^2 \sim \text{const.} \tag{4}$$

For natural rivers k_s is generally determined from field measurements and f_{rk} can then be found.

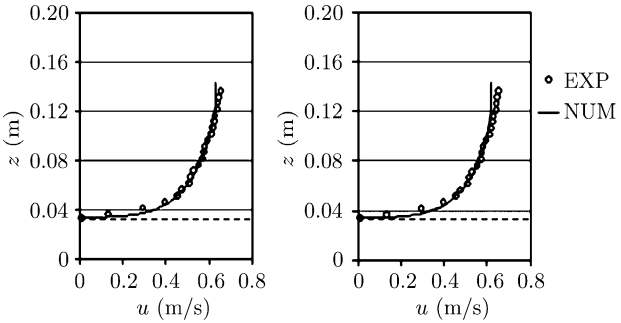
OPEN-CHANNEL FLOWS OVER SMALL-SCALE ROUGHNESS

The experimental data used herein to test the body force method for small-scale roughness were collected in a rectangular tilting flume under uniform flow condition. Quasi-uniform real gravels were used to roughen the bed. The thickness of the gravel bed was about 35 mm and the median and standard deviation values of the gravel size are given by $d_{50} = 23 \pm 3.2$ mm. The gravel bed was considered fixed as no motion of the gravels was observed throughout the experiments. A total of 25 flow cases with different bed slopes or flow rates were conducted. More details about the experiments can be found in Zeng and Li [5].

The computational domain extends from the reference level to the water surface (see Figure 1(a)). The reference level is also called the "hypothetical bed" (i.e., the level where the mean velocity is assumed to be zero). The body force term is added within the roughness layer (from reference level to the visual bed level). A rectilinear grid with refinement at the near wall region is used in the simulation. In order to evaluate the sensitivity of this method to mesh resolution, a fine mesh with 60 grid cells and a coarse mesh with 30 grid cells were used in the simulation under the same flow condition.

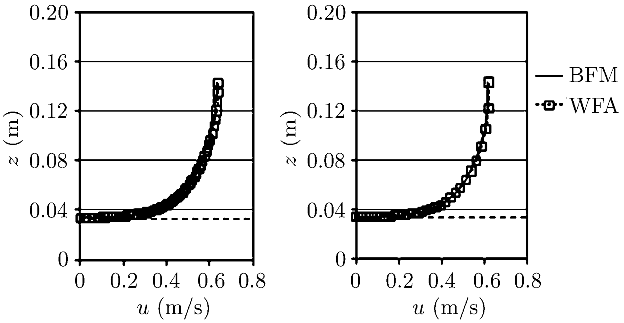
Figure 2(a) and 2(b) shows the comparison between the numerical results and the experimental data for the case with relative submergence $D/k_s = 16.97$. It can be found that the calculated velocity profiles from both mesh systems fit the logarithmic law well in the inner region. Only a slight difference occurs for the velocities at the near-water-surface region as shown in Figure 2(b), where the number of grid cells has been significantly reduced. Figure 3 shows the comparison between the calculated velocity profiles using the body force method and the wall function approach with the same mesh. Excellent agreement is obtained between these two methods for both mesh systems. The variation of f_{rk} against k_s for the fine mesh is shown in Figure 4 and the equations of the regression lines for the two cases are $f_{rk} = 0.890\,8k_s^{-1.013}$ for fine mesh and $f_{rk} = 1.005k_s^{-0.953}$ for coarse mesh. The results indicate that f_{rk} is not sensitive to the change in mesh size and support the claim that $f_{rk}k_s$ ∼constant. The constant is approximately 0.94.

The roughness length scale, k_s is an essential parameter in the quantification of the bed roughness effects. It is generally assumed to be directly proportional to a characteristic grain diameter, eg. $k_s = Cd_{50}$. From our flume experiments the coefficient C is dependent on the bed slope as shown in Figure 5. Once k_s is estimated, f_{rk} and h_1 can then be specified. Thus the body force method is feasible and easy to implement.



(a) Fine mesh (b) Coarse mesh

Figure 2: Measured and calculated velocity profiles (The dash line denotes the reference level)



(a) Fine mesh (b) Coarse mesh

Figure 3: Calculated velocity profiles using body force method and wall function approach

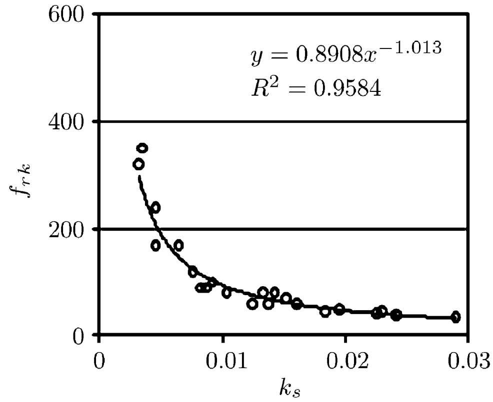


Figure 4: Variation of f_{rk} with different roughness length scale k_s (fine mesh)

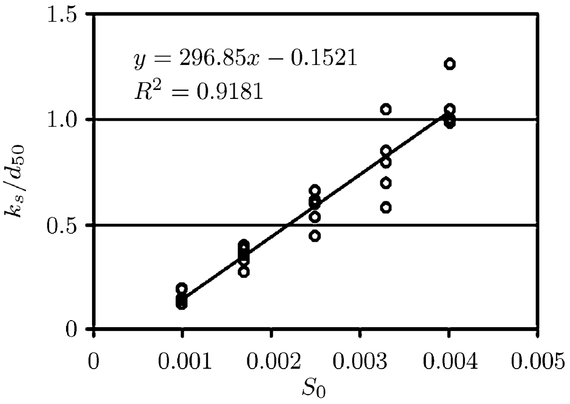


Figure 5: Variation of k_s/d_{50} against S_0

CONCLUSION

A RANS model using the body force method has been developed and validated for the simulation of flows over small-scale roughness. The method requires the field determination of only one parameter, k_s, and compares favorably with the wall function approach. The major advantage of the method is that it can be easily extended to deal with large-scale roughness and the general case of a mix of small-scale and large-scale roughness.

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