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Resistance of Overland Flow on Complex Microrelief

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Abstract Resistance problem of the overland flow on complex microrelief is intricated. The difficulty in evaluating the resistance mainly comes from the variety of flow status and the complex composition of the resistance. Finding out the correlation between resistance components and influence factors is believed valuable to this problem. Because experimental data in which the resistance components could be distinguished is dramatically short, the numerical Monte-Carlo method is employed. After several representative complex microrelief, surfaces are generated randomly with Monte-Carlo method. Series of detailed numerical simulations is carried out to discuss the resistance composition of the overland flow. Numerical experiments with different flow discharges and slopes are carried out on the generated surfaces. The resistance constitution regularity shown in these simulation results is discussed. Statistics of correlation between resistance component and its influence factors are obtained.

Key words: resistance, overland flow, microrelief, inundated rate, wet area

INTRODUCTION

Overland flow is a common natural flow on hillslopes in rainfall events. Its dynamic process is a key factor of the runoff model for small basin. The main driving forces of the overland flow are the gravity and the raindrop splash, while its resistance composition is sensitive due to the complexity of its influence factors. Resistance expression on the analogy of the open channel flow is widely used. However this analogy would result incorrect resistance prediction in many situation. For example, Dunkerley [1,2] observed an unconventional increase of resistance on f–Re diagram in two experimental studies. As pointed out by Dunkerley, one key reason leading to these unusual results is the pretermission of the microrelief effects. The resistance expression of the open channel flow is based on generalized model in which velocity is two-dimensional and uniform along the depth. But the overland flow is much shallower comparing with the open channel flow. The microrelief fluctuation even could not been completely inundated by the overland flow, thus the assumption of the velocity mentioned above is not valid anymore. Thus the factor of microrelief would dominate the flow in many situations, and contributes a lot to the total resistance. Actually the mechanism in this phenomenon is still unclear and no effective physical resistance model dealing with various inundation conditions on microrelief is obtained till now. So discussing the role which microrelief plays and the mechanism in it are necessary for ingoing knowledge of the overland flow.

THEORETICAL ANALYSIS

The difficulty in evaluating the resistance mainly comes from the variety of flow status and the complex composition of the resistance. Finding out the correlation between resistance components and influence factors is believed valuable to this problem. In fact the resistance problem of overland flow is similar to it of aircraft and ship instead of open channel flow, especially when the microrelief factor dominates the flow. Thus the resistance of overland flow can be decomposed by analogy with ship drag. On complex microrelief, the resistance of overland flow may be divided into roughness drag, pressure drag and shock wave drag. The roughness drag is induced by the non-uniform velocity profile along the depth which in turn depends on local roughness height. The pressure drag comes from the asymmetry of the flow which could be induced by either flow separation or irregular relief form of the free surface. The shock wave drag is generated by water head loss in hydraulic jump around large scale landform fluctuation.

Actually because of the complexity of the microrelief and variety of the flow regime, attempt of setting up one unified and universal resistance expression would be in vain. A practical choose is to find out which influence factor contributes to each particular drag. And then with the experimental data, experiential expression could be obtained in specific situation. The local Reynolds number Re, roughness height k, local flow depth h, wet area A_{w}, microrelief shape coefficient χ, inundation area A_{ind} and the local Froude number Fr are believed correlated with the resistance. Thus we have

$$f_{\mathrm{total}} = f_{\mathrm{rough}} + f_{\mathrm{pres}} + f_{\mathrm{wav}} = f_{\mathrm{rough}}\left(Re, \frac{k}{h}, A_{\mathrm{w}}\right) + f_{\mathrm{pres}}\left(Re, \frac{k}{h}, \chi, A_{\mathrm{ind}}\right) + f_{\mathrm{wav}}(Fr, \chi, A_{\mathrm{ind}}) \tag{1}$$

in which f_{total} is the total drag, which is assumed to related to local Reynolds number Re, relative roughness height k/h and wet area A_{w}; f_{pres} is the pressure drag, which is assumed to related to Re, k/h, the microrelief shape coefficient χ and the inundation area A_{ind}; f_{wav} is the shock wave drag, which is assumed to related to Froude number Fr, χ and A_{ind}.

Because experimental data in which the resistance components could be distinguished is dramatically short, the numerical Monte-Carlo method is employed later. Our numerical Monte-Carlo procedure includes: the generation of the random microrelief following the statistics law, the validation of the numerical method, systematic numerical experiments dealing various factors, and the statistics analysis trying to find out close correlations.

NUMERICAL METHOD

1. Numerical model The commercial software Fluent is employed in numerical simulation. The incompressible N-S equation is solved with the SIMPLE algorithm. The volume of fluid (VOF) model for multiphase flow is used to deal with free surface, and the surface tension is also considered. The dealing of viscous is more difficult, as the overland flow, of which the Re is commonly in the range of 300–10 000, is far from the well-known "fully developed turbulence". Considering the conventional k-ε and k-ω model might not provide correct resistance prediction, the large eddy simulation (LES) method and the low-Re k-ε model are tested and employed.

2. Validation Two sets of experiments data are used for the model validation. The velocity profile measured by Lu et. al. [3] in a sheet flow experiment is used to verify the validity of the multiphase model and the turbulence model. This experiment measured velocity profile using FLDV of a 10 mm-depth sheet flow on a very mild smooth slope. The simulation matches the experimental data well as shown in Figure 1. Another validation is based on the experiments by Dunkerley [1]. Overland flow on complex microrelief is numerically simulated to test the method validation dealing with microrelief. Good agreement is observed (as space is limited the figure is not included).

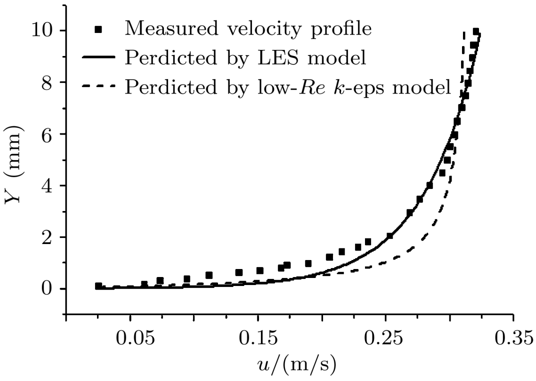


Figure 1: Comparing of the velocity profile between the calculated and the experimental data by Lu et. al. [3]

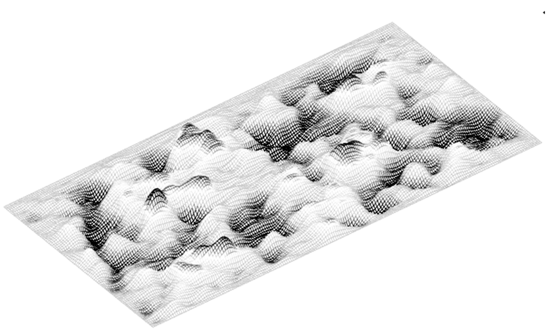


Figure 2: Microrelief generated with Monte-Carlo Method

NUMERICAL EXPERIMENTS

1. Microrelief generation Microrelief in numerical experiments is generated with a Monte-Carlo method base on height distribution generalized from a fine measurement by Brunton [2]. The microrelief is constructed by superimposing a series of single heaves of which the size follows normal distribution as observed in experiments by Brunton [2].

And each heave is assumed to have the shape of normal distribution. Then we could obtain various random microrelief (Figure 2) following the statistics.

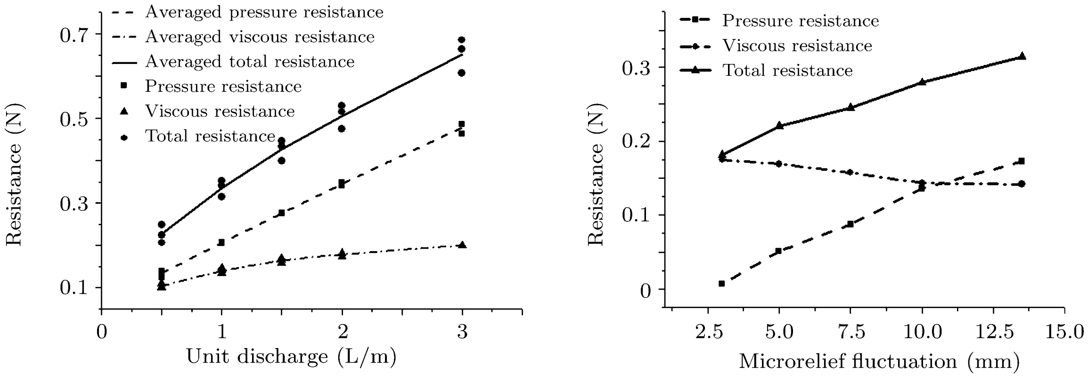
2. Systematic experiments A series of numerical experiments with different microrelief, flow discharge, slope and roughness height are carried out. The constitutions of resistance and correlation between variables are analyzed. The parameters involved in the experiments are list in Table 1.

Table 1. The parameters in the systematic experiments

Item	Microrelief height/(mm)	Slope angle/(°)	Unit discharge/(m^2/s)	Roughness height/(mm)
Value	3, 5, 7.5, 10, 13.5	5, 10, 20, 30	0.5, 1, 1.5, 2, 3	0, 0.2, 0.5, 0.8, 1.2

DISCUSSING

Complicated relationship between resistance and influence factors is observed from numerical result. When the slope is mild, the constitution rate of pressure resistance would not change a lot along with the increase of flow discharge. While for the steep slope cases, the proportion of friction resistance keeps increasing. The correlation coefficient between the friction resistance and wet area is found to be very high, especially when the water depth is small comparing with microrelief fluctuation. The viscous resistance dominates the flow when microrelief is negligible which is similar to classical open channel model. While when the microrelief character-height is larger than water depth, pretermission of the pressure resistance would cause severe underestimate of the total resistance which may be the key reason to the unconventional increase of resistance on *f–Re* diagram observed by Dunkerley [1]. For lack of space, more regularity between resistance components and factors could not be included.



(a) Resistance relationship with the unit discharge

(b) Relationship between resistance and microrelief fluctuation

Figure 3: The relationship between resistance and influence factors

CONCLUDING REMARKS

Numerical Monte-Carlo method is employed to study the resistance constitution problem. This procedure works well and provides unwonted detailed information on resistance problem of overland flow. The conceptual expression of the resistance components is partly validated and thus provides a possible foundation for further experimental studies.

Acknowledgements

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