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Study of bedload transport in backwater flow*

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Abstract: This paper studies the flow structure and the bedload transport regime in backwater flows, to provide a theoretical support for solving the sediment transport and bed scour problems in rivers or reservoirs with backwater. The bedload transport rates under different conditions are analyzed first on the basis of theoretical analysis, measurement comparison and flume experiment, and it is pointed out that the existing formulas for the bedload transport rate are not applicable for the bedload transport rate in backwater flows. Next, the flow structure in a non-uniform flow is observed by flume experiments, and by introducing the backwater degree index, the quantitative relation between the relative bed shear stress and the backwater degree is obtained. Finally, the formula for the bedload transport rate applicable for the reservoir channel segment with backwater flows is obtained through measurements and flume experiments.

Key words: backwater flow, bedload transport, flume experiment, formula for bedload transport rate

Introduction

A number of studies were conducted in the past few years concerning the bedload transport rate, generally based on flume experiments under steady flow conditions or observations of natural rivers close to a uniform flow. In natural streams, backwater flows are frequently observed, which are not fully understood because of their complicated nature. The backwater flows are a crucial issue in the studies of the bedload transport. The flow structure and the sediment transport in backwater flows (also known as decelerating flows) are different from those in uniform flows. This is typically the case for channel reservoirs where, under the same flow condition, the water depth gradually increases from the reservoir tail to the dam, leading to non-uniformity.

The backwater flow is a kind of non-uniform flows. Several studies examined the turbulence characteristics of non-uniform flows. Afzalimehr and Anctil[1] studied the behavior of the bed shear stress in the presence of a decelerating flow. Their study revealed that the velocity distribution can be described by a parabolic law in the outer region and by a logarithmic law in the inner region of the boundary layer. Song and Chiew[2] obtained the velocity profiles, the turbulence intensities and the Reynolds stress distribution for both decelerating and accelerating flows and found that the maximum velocity occurs at the water surface for decelerating flows and the Reynolds stress and the turbulence intensity distributions for decelerating flows are convex. Balachandar et al.[3] studied the velocity distributions in a decelerating open channel flow over rough and smooth surfaces. The study shows that for the boundary layer generated in a decelerating open channel flow, the power laws can adequately describe the mean velocity profile. Dey and Lambert[4] and Yang et al.[5] studied the Reynolds stress and velocity distributions in non-uniform flows analytically. The analytical results of Yang et al. show that the non-zero vertical velocity in non-uniform flows introduces an additional momentum to the flow that causes the Reynolds stress distribution to have a convex form in decelerating flows and a concave form

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in accelerating flows. Based on the above observations, Yang[6] made preliminary studies about the velocity distribution of gradually decelerating flows, but the pictures of variations of the velocity and the sediment transport under the backwater condition are not clear. Zhang et al.[7] used a mathematical model to investigate the shear velocity under decelerating non-uniform flow conditions. It is shown that under a backwater condition, the friction velocity decreases with the increase of the water depth when the flow rate and the bottom slope are fixed and they proposed a convenient calculation formula for the friction velocity, based on the numerical results.

In recent years, many researchers investigated the influence of the flow non-uniformity on the initiation of the sediment motion. Afzalimhr et al.[8] studied the incipient motion of gravel bed steams in steady-decelerating flows. Their results show that the Reynolds stress distribution over fixed and mobile beds has a convex form. Moreover, the critical Shields parameter value for their decelerating flow expeiments is less than the published results obtained in uniform flow experiments. Emadzadeh et al.[9] studied the effect of the flow acceleration and deceleration on the velocity, the Von Karman constant, the Reynolds and normal stress distributions under the incipient motion using eight positive and negative bed slopes. It is shown that the shear and normal Reynolds stresses in the decelerating flow are greater than those in the accelerating flow, and the acceleration and the deceleration along with the slope variation are the key factors governing the incipient motion in non-uniform flows. Hoan[10] experimentally studied the relation between the flow intensity and the gravel transport intensity parameters by increasing the flume width along the way and producing a retarded flow, and it is discovered that the correlation between the Shields flow intensity parameter Ψ and the transport intensity parameter Φ is merely 0.18, while that between the turbulence intensity flow parameters Ψ_{WL}, Ψ_{Lm} and the transport intensity parameter is at least 0.77. He suggested that the near bed turbulence intensity should be included in the calculation under the gravel starting conditions in non-uniform flows. Khorram and Ergil[11] selected some key parameters associated with the reservoir bedload movement for a sensitivity analysis, and obtained a sediment transport relation for the sand, the gravel and the mixed sand by the artificial neural network (ANN) method. Afzalimhr et al.[12] studied the effects of accelerating and decelerating flows on the flow structure in an flume with vegetated banks and gravel beds. It is shown that a significant dip phenomenon can be observed in the velocity profiles in the decelerating flow and the velocity defect law is not suitable due to the effect of vegetated banks.

In spite of the importance of the flow structure and the sediment transport under backwater flows, no systematical study has been reported to describe the effect of the backwater on the bedload transport regime. The studies of the bedload discharge under backwater flow conditions will enable hydraulic engineers to better understand the sediment transport in rivers or reservoirs with backwater flows. The paper is to study the motion of the bedload transport under backwater flow conditions, by means of flume experiments.

1. Examination of existing formulas for bedload transport rate in backwater flow

The bedload transport rate variations in a backwater flow and the results obtained by the existing formulas will be discussed with the case of the Wanxian Station as an example.

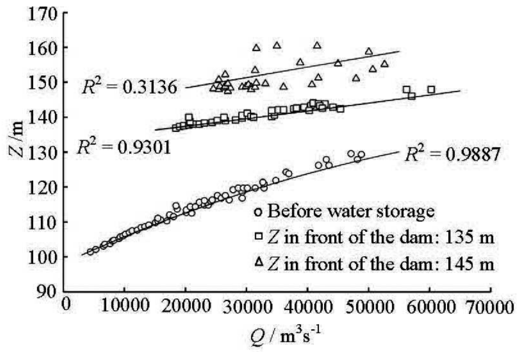

Fig.1 Water level-discharge relation during different periods at Wanxian Station

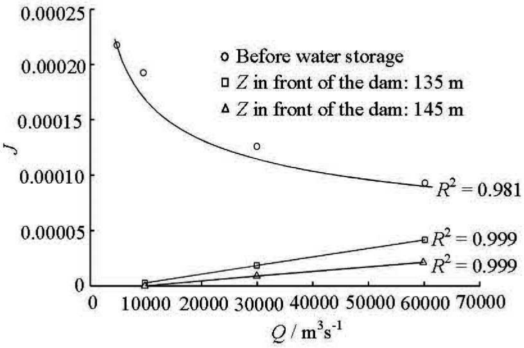

Fig.2 Water surface gradient-discharge relation during different periods at Wanxian Station

The Wanxian Station is located in the Three Gorges Reservoir permanent backwater area and is about 300 km away from the dam. Under the natural condition, the depth of the river is 12 m-30 m, its width is 400 m-600 m, and the water surface slope is about 0.09%. When the level in front of the dam is 135 m, under the same discharge, the water depth would rise about 15 m-25 m during the flood season,