学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

Bedrock incision due to the interaction between flow and sediment transport in uniformly curved channels
(一様湾曲水路における流れと土砂輸送の相互作用によって生じる基盤岩穿入プロセス)

This study aims to investigate the bedrock incision in uniformly curved channels. Compared to the straight channels, the flow dynamics and the mass transfer in curved channels are more complex due to the inherent spiral flow. The spiral flow is the combination of the primary/streamwise and secondary/transverse flow in the channel. Due to this particular flow feature in curved channels, the sediment is deposited along the inner wall. This complexity, however, raises concerns about potential effects on the erosion of the channels' bed.

Analytical and experimental methods are mainly used to conduct the actual study. The flow characteristics in curved channels are analytically derived, as well as the deposition morphology - transverse slope bed profile, and the experiments are conducted to investigate the bedrock incision in uniformly curved channels. The flow conditions necessary to produce the spiral flow are presumed to be met, however bedload transport of sediment predominates with minor suspended sediment. Moreover, it is assumed that the main erosion of the channel bedrock occurs by incision, i.e. by physical interaction between bedrock surface and the sediment grains displacement, such as grain saltation or sliding.

The three-dimensional Reynolds-averaged Navier-Stokes equations and the continuity equation are used to derive the flow velocities in uniformly curved channels. For simplicity and symmetricity, the channel is subdivided into two equal domains, the lower half and the upper half domain. The wall effect is neglected. After the normalization, the equations are expressed as function of the parameter ϵ - the ratio of the channel width for the curvature radius. The primary/streamwise flow velocity is obtained as the solution of normalized equation for straight channels. The secondary flow velocity, however, is obtained by doing the asymptotic expansion on ϵ. The velocities are obtained separately from the predefined domains but satisfying the continuity at the center of the channel. The flow velocities are expressed as function of the boundary roughness z_0. The transverse bed profile is then obtained using the lateral sediment transport equation with the previous flow velocities, in the equilibrium state.

It is found that the flow velocities distribution along the vertical is generally symmetrical, due to the assumption that the top ceiling and the bottom would have the same roughness. Indeed, the boundary roughness influences greatly on the shape of the flow velocity distribution: the water column flows more uniformly and there is less secondary flow at smoother boundaries. Additionally, the transverse slope become steeper with the boundary roughness and with the depth-average velocity.

On the other hand, the experiments in an annular flume aim to simulate the bedrock incision. Two cases - Case 1 and Case 2 are carried out, each with different rotation speeds of the top ceiling, 40 and 48 RPM respectively. Both cases use plaster as the bedrock and same amount of sediment - grain size 0.45 mm, density 2.61 g/cm^3 - as the abrasive tools. In both cases, sediment motion is kept as bedload transport. It is found that the sediment deposition and the moving bedforms along the inner wall differ for each case. A uniform transverse slope is observed for a rotation speed of 48 RPM and wavy bedforms are found for a rotation speed of 40 RPM. The bedrock incision results in the development of the inner channel along the base of the transverse slope. This inner channel grows more quickly and toward the inner wall under the wavy bedforms than under the uniform transverse slope. These findings suggest that in the case of bedload transport of the sediment, the bedrock erosion would depend mainly on the bed morphology, and that the bedform influences more on the bedrock incision than flow speed.

Nevertheless, the comparison between the analytical results with the experimental data shows suitable agreements. Such results are obtained under the following conditions: the depth-averaged flow velocity is estimated to be 60 - 70 % of the top ceiling speed, and the boundary roughness becomes a 'bedform roughness' for wavy bedforms and a 'grain roughness' for uniform transverse slope.

The thesis includes five chapters. Chapter 1 introduces the background, literature review, objectives, and organization of this study. Chapter 2 introduces the theoretical model to evaluate the secondary flow in uniformly curved closed channels with the use of the mixing length turbulent model, one of the simplest turbulent closure models, and demonstrates their solutions of main flow and secondary flow. In addition, the shape of sediment deposition in the riverbed is derived from the velocity profiles in the uniformly curved channel obtained in the analysis. Chapter 3 describes laboratory experiments using a uniformly curved closed channel. Chapter 4 provides the detailed description of the results of the experiments. Chapter 4 compares the experimental and analytical results and discusses the physical implications of the results. Finally, Chapter 5 summarizes the conclusions of this study and gives several recommendations for future studies.