学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Formation of Cyclic Steps by Water on Ice Surface
(氷表面上に流れる水によるサイクリックステップの形成)

Cyclic steps are long-wave bedforms that are characterized by hydraulic jumps. On the upstream side of a step, the flow is subcritical, accelerating towards the downstream end to become a supercritical flow. These steps can be observed in various environments, such as rivers, ocean floors, and ice surfaces on Earth, and also on Mars's ice caps. The present study focuses on cyclic steps formed on ice surfaces. Understanding the formation and characteristics of cyclic steps on ice can enhance our knowledge of the cold region environment, such as temperature variations, flow features, and morphologies. In addition, it could help the research of space exploration to provide more options for human beings in the future. Cyclic steps on ice are formed by wind or water by heat transfer. It is difficult to know the normal flow condition of the wind, so we study the formation of cyclic steps formed by flowing water on ice.

In this study, we propose an analytical model to reproduce the formation of cyclic steps created by water on ice. We assume a steady and uniform Froude-supercritical flow over a flat ice surface, which causes the surface to become unstable and results in the spontaneous formation of a series of steps. The formation process involves both mechanical and thermodynamic processes. The water temperature is assumed higher than the ice temperature but lower than the air temperature. The model is governed by four equations: the momentum equation, the continuity equation, the heat transfer equation in water, and the energy balance equation (the Stefan equation).

We use the variables in the normal flow condition without steps as normalization. In addition, we apply the quasi-steady assumption to the governing equations since changes in the ice surface occur so slowly that the flow equations can be approximated as steady. Based on experimental observations, cyclic steps were found that migrate upstream while maintaining their form because of the temperature setting of air, water, and ice. Once this equilibrium state is reached, the average channel slope, wavelength, wave height, and wave migration speed reach constant values. The entire ice surface moves downward since the vertical degradation of ice is more active than the upslope progradation. We introduce a moving coordinate system to describe these features of cyclic steps on the ice.

After further manipulation, the governing equations are reduced to three normalized equations, and we need corresponding boundary conditions to solve them. The flow transitions from a supercritical to a subcritical regime through a hydraulic jump. We thus apply the momentum conservation before and after each hydraulic jump as one boundary condition. Furthermore, we assume the ice elevation and average water temperature are constant before and after hydraulic jumps. However, the problem cannot be closed, and wavelength cannot be determined since these boundary conditions are relationships among variables rather than specific values. We assume the water temper-

ature value at the downstream end of a hydraulic jump to close the problem. During the calculation, we find that the minimum value corresponds to the longest wavelength. We assume it is the most stable when the wavelength is the longest and use it in further analysis.

We solve this two-point boundary value problem using the shooting method with the Newton- Raphson scheme. The calculation is initiated from the vicinity of the Froude critical point (i.e., the point where the Froude number is unity) to avoid singularity and progresses towards upstream and downstream directions. After the calculations, we can generate variations in depth-averaged water temperature, depth-averaged velocity, and bed elevation over one step wavelength. Once we know the variables in the normal flow condition, the actual scale steps and dimensional variables can be obtained. The results calculated by our model are compared with the previous experimental results to validate our model.

The results can explain the formation process of cyclic steps on the ice and suggest relationships among wavelengths and heat transfer capacity of air and water, and the Froude number in the normal flow condition. The calculated steps in the analysis are compared with experimental observations to validate our model.

Cyclic steps formed by water on ice and those formed by long-runout turbidity currents share some similarities. We refer to the previous theory of dividing the currents into two layers to capture the features of long-runout turbidity currents that can run long distances without dissipating. The high-concentrated lower layer is in an equilibrium state and interacts little with the upper layer. This configuration results in the lower layer similar to the open channel flow. We compare these two types of cyclic steps regarding formulations, formation process, and relationships among wavelengths and parameters.