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Fundamental study on mixing layer and horizontal circulation in open-channel flows with rectangular embayment zone*

Michio Sanjou, Iehisa Nezu
Department of Civil and Earth Resources Engineering, Kyoto University, Kyoto, Japan,
E-mail: michio.sanjou@water.kuciv.kyoto-u.ac.jp

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Abstract: A part of mean kinetic energy in a main-channel is used for production of a large-scale horizontal circulation in the side cavity. However, the details of the mechanism such as energy transport are poorly understood. Therefore, we conducted PIV measurements in a laboratory flume and compared space distributions of mean velocity components and Reynolds stress by varying a cavity geometry. In particular, a practical calculation method of Reynolds stress was also developed and its accuracy was examined by comparison with the measured data. Furthermore, contributions of components in an energy transport equation were revealed quantitatively.

Key words: Embayment, open-channel turbulence, mixing layer, Reynolds stress, mean kinetic energy

Introduction

Dead water zones in natural rivers occur in groin fields and embayments. A mixing layer is typically formed in the cavity opening attached to the main channel, and it promotes mass and sediment transportation between the mainstream and the cavity zone. It is well known that nonuniformity of the bed shear stress induces local scour and sedimentation. A large-scale horizontal circulation within the cavity generated by a lateral shear force in the mixing layer often traps pollutants and nutrient salts and results in a sudden drop in the water quality of the dead water zone. Though the development of the mixing layer has a close relation to the shedding vortex along the cavity opening, there are many unresolved issues in understanding the turbulence structure around such an embayment zone.

The mean velocity profile and development of the mixing layer have been studied theoretically by many researchers. Particularly, van Prooijen and Uijttewaal[1] focused on shallow mixing layers in which bed friction stabilizes the coherent structure. They proposed a theoretical model derived from depth-averaged shallow water equations and examined the predicted mean flow field, particularly the streamwise development of the velocity difference between the high- and low-velocity sides, the development of the mixing layer width, and the horizontal distribution of the streamwise velocity component, by comparing these predictions with the measured data. Furthermore, linear stability analysis based on the mean flow field allowed them to determine the spatial evolution of the energy densities and the characteristic length scales.

Local dead water zones in rivers are observed behind isolated spur dikes, within groin fields, and in the embayment attached to the mainstream, and a similar mixing layer due to shear instability should be considered for practical problems concerning sedimentation, mass transport, and water preservation in these locations. Therefore, many previous works have studied these issues from various perspectives.

Ettema and Muste[2] have classified the horizontal flow field around a spur dike into characteristic zones, including flow separation and thalweg alignment, and these length scales and their related hydrodynamic characteristics were investigated in detail. The results imply that single spur dikes produce shedding vortices accompanied by surrounding complex three-dimensional behavior. Duan[3] conducted turbulence measurements around a spur dike model in a gravel bed flume using acoustic Doppler velocimetry

* **Biography:** Michio Sanjou (1975-), Male, Ph. D., Associate Professor

(ADV). After the uncertainty analysis of ADV, three-dimensional distributions of velocity components and Reynolds stress were obtained. The measured data revealed a secondary current structure and the relation between the local scoring and the shear stress. Sharma and Mohapatra[4] measured the velocity components around a spur dike in a meandering trapezoidal flume with a rigid bottom, in their study, the dependence of the separation zone and the streamwise velocity distribution on the dike position was examined. Particularly, characteristic lengths, such as the reattachment distance and the width of the separation layer, may be evaluated quantitatively.

Dead water zones have also been observed in consecutive spur dikes and groin fields. Previous studies have reported that horizontal vortices, related three-dimensional structures, and sediment processes are significantly influenced by cavity geometry and groin rank number. Particle image velocimetry (PIV) measurements by Weitbrecht et al.[5] suggested that the gyre structure within the cavity also depends on the mounting angle on the sidewall of the channel. Some fundamental studies have provided detailed knowledge of mean flow fields, turbulence in the cavity opening, and related mass and sediment transport.

Uijttewaal et al.[6] examined the dependence of the mass transfer coefficient on groin geometry, water depth, groin rank number, and bottom elevation, and the results showed that transfer speed is significantly affected by aspect ratio. In a small gyre field where the aspect ratio is close to 1.0, i.e., a square horizontal shape, the mass transfer is dominated by the mixing layer formed along the cavity opening, whereas in a large groin field, coherent shedding vortices are generated from the tip of the higher ranking groin. The measurement results of a study by Weitbrecht et al.[7] provided the relation between the exchange rate and the bed configuration of the cavity, and they suggested that there is a linear relation between the mass transfer coefficient and the morphometric groin field parameter normalized by water depth, width, and groin length. Yossef and De Vriend[8] conducted experiments by analyzing the time variation of bedform migration using the PIV technique, and these experiments yielded important results. Notably, their results suggested that the mixing layer dynamics induce variation in bedform celerity, and the time series of the instantaneous celerity vector field revealed a sediment transport process toward the cavity zone. Yossef and De Vriend[9] indicated that there are significant differences in the developing processes of the mixing layer and turbulence structures under emerged and submerged conditions.

Some researchers have conducted studies on groin fields in natural rivers. For example, Sukhodolov et al.[10] conducted velocity measurements with ADV in the Elbe River in Germany, and their analysis of the collected data provided mean horizontal velocity vectors, vertical profiles of the mean velocity, turbulent kinetic energy, and spectral properties. It is noteworthy that mean velocity profiles are consistent with the conventional power law, except near the free surface where the effects of wind-induced waves could not be ignored and upwelling occurs. Furthermore, they indicated that the spectral density is consistent with Kolmogorov’s −5/3 power law over the whole depth. Numerical simulations by Ercan and Younis[11] predicted mean velocity components, turbulent kinetic energy, and bed shear stress for the beach of the Sacramento River and calculated the maximum erosion rate of the river bank.

The embayment zone adjacent to the mainstream produces the mixing layer and cavity gyre in the same manner as the groin field. Previous theoretical works have been conducted on two-dimensional simple rectangular cavities. For example, Mizumura and Yamasaka[12] introduced a streamwise function within square- and rectangular-shaped cavities under limited conditions, i.e., two-dimensional assumption, steady flow, ignoring inertia, and rigid free surface assumption. The predicted results agree with the measured data except in the wall region. They deduced that the gap near the wall was caused by neglecting viscidity and three-dimensional behavior. Hill[13] assumed the horizontal gyre in the cavity to be in rigid body circular motion and gave the linear velocity distribution. Considering the shear stress and torque on the cavity opening and three walls, they introduced a rotational velocity profile normalized by the mainstream velocity on the basis of balancing resistance torques acting on the horizontal gyre. Furthermore, they examined the relation between the cavity geometry and the coefficients of friction and moment.

Sedimentation in the side cavity is an irreversibly damaging problem that must be solved as soon as possible. It is necessary to reveal the three-dimensional flow pattern and the related coherent turbulence. Previous studies have noted that the sedimentation and scour processes within the cavity are relevant to not only the horizontal gyre but also the upward and downward currents and the secondary currents with a longitudinal axis. The numerical results proposed by Sanjou et al.[14] provided the time series of cross-sectional secondary currents and a phenomenological three-dimensional model in which the transverse direction of momentum transfer depends on the elevation from the bottom. Measured data obtained by the three-dimensional particle tracking velocimetry (PTV) technique suggested that the rotation axis of the horizontal gyre is tilted by the vertical velocity gradient, which induces outward flow from the embayment near the free surface and inward flow to the embayment near the bottom[15].

Gravity waves and oscillations induced by the