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NUMERICAL SIMULATION ON SPATIAL DEVELOPMENT PROCESSES OF ROLL WAVES IN A STEEP CHANNEL

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ABSTRACT

Although roll waves have been well studied as a basic unsteady open flow in a steep channel, there are still unresolved problems. In this paper, we dealt with the formation mechanism of a dominant wave length in roll wave trains by means of numerical simulation. Judging from the previous and present experiments, it can be pointed out that roll waves consists of waves with various wave lengths scattered around a dominant wave length. To clarify the formation processes of the wave composition, the numerical simulation was conducted under the two upstream boundary conditions with and without periodic disturbances of discharge. It was pointed out that when the period of disturbances increases, the waves in the upstream region are broken up into a few waves with short wave lengths and the wave lengths of simulated results without disturbances exist in the range of the short wave lengths after breakup. It was also pointed out that further investigation is required to identify the dominant wave length of waves after breakup theoretically.

1. INTRODUCTION

This paper describes the spatial developments of roll waves in a steep open channel by means of numerical simulation. Although roll waves are one of the typical unsteady flow phenomena which we observe frequently in steep open channels, and have been well studied theoretically and experimentally for many years [Vedernikov (1945,1946), Dressler (1949), Craya (1952), Iwagaki & Iwasa (1955), Brock (1969), Needham & Merkin (1984), Merkin & Needham (1986), Ng & Mei (1994)], there are still unresolved problems on the formation processes of fully developed roll wave patterns.

Dressler (1949) showed the mathematical method to determine the depth distribution of roll waves propagating without changing the wave profile. But, the theory also indicated that the wave form can’t be determined uniquely without designating one wave parameter such as wave celerity or wave length. Based on the hydraulic experiments, we indicated that small random waves generated in the upstream part of a steep channel develop in the downstream direction through merging, breakup and interaction processes between different waves, but one unique wave pattern, which Dressler dealt with, is not realized in the downstream of a channel. It was also pointed out through

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the spectrum analysis that there is a peak in the frequency spectrum of roll waves in the downstream region, although roll waves with various wave lengths are observed.

In this study, in order to clarify the generation mechanism of this average wave pattern we conducted the numerical simulation on the development of roll waves giving the periodic disturbances at the inlet of a channel. The period and wave length of simulated roll waves in the downstream area were analysed with increasing the period of disturbances given at the inlet of a channel and were discussed in comparison with the simulated results without disturbances at the inlet.

2. HYDRAULIC EXPERIMENTS

Based on the hydraulic experiments using the flume (Figure 1) with 30m in length, 0.1m in width and 0.096 in slope, it was pointed out that small random waves generated in the upstream part of a steep channel develop in the downstream direction through merging, breakup and interaction processes between different waves.

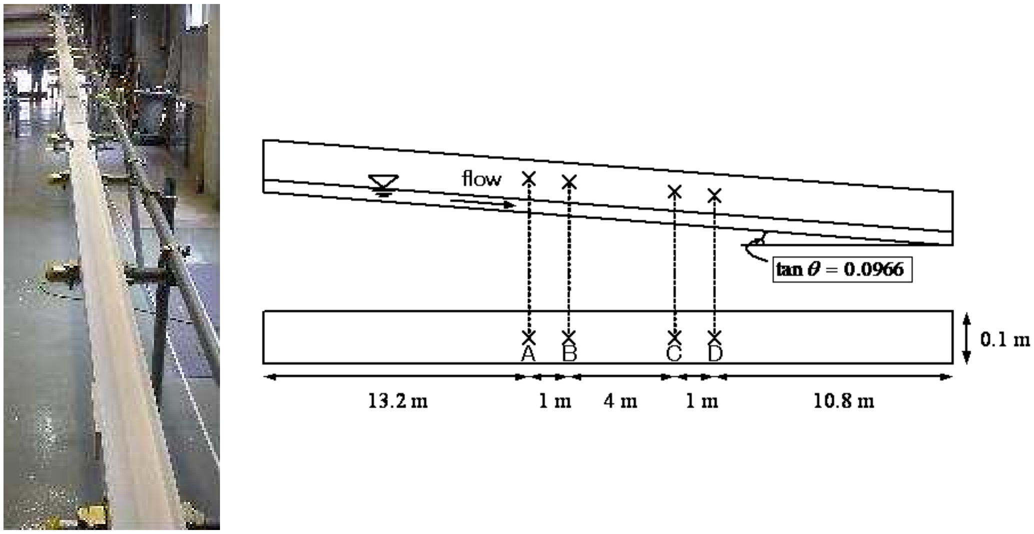

Figure 1 Experimental Flume

Figure 2 shows the temporal change of depth measured at 14m (point A) and 19m (point D) downstream from the upstream end. The averaged wave lengths are 1.01m at A and 1.30m at D. The increase of wave length indicates that the roll waves still develop in the downstream in the flume. The circles colored blue and red show the propagation of the same portion of waves.

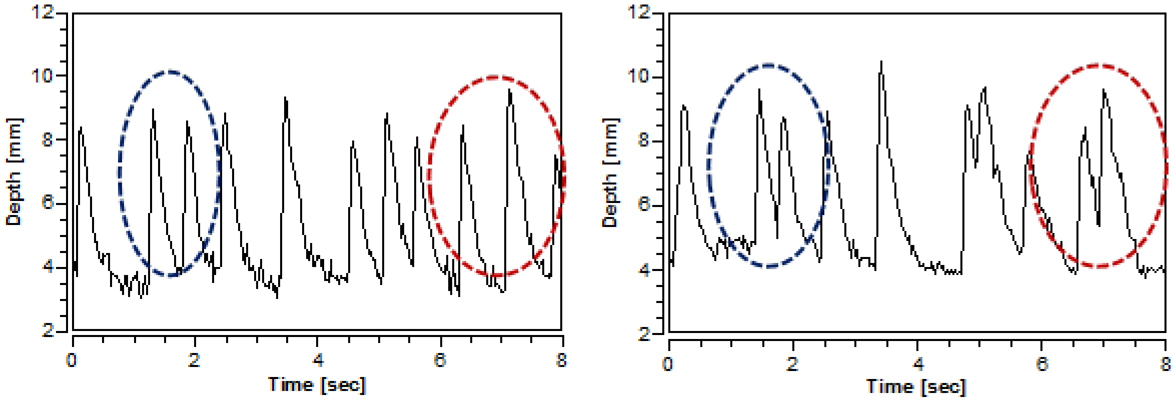

Figure 2 Temporal variations of depth at points A and D

3. OUTLINE OF NUMERICAL SIMULATION

In order to investigate the spatial development of roll waves with various wave lengths generated in the upstream region of the flume, the numerical simulation was conducted. Basic equation consist of 1-D continuity equation and momentum equation denoted in Eq.(1) and (2).

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial uQ}{\partial x}+gA\frac{\partial h}{\partial x}=gA\sin\theta-gA\frac{\tau_{bx}}{\rho gR} \tag{2}$$

where x is spatial coordinate, t is time, A is cross-sectional area, Q is discharge, u is cross-sectional averaged velocity, h is depth, R is hydraulic radius, τ_{bx} is bottom shear stress vector in x-direction, ρ is density of water and g is gravitational acceleration.

We applied Finite Volume Method which is one of the common methods to compute Eq.(1) and (2) numerically (Kimura & Hosoda (1997), Nagata & Hosoda (2000)). The staggered allocation is used as the definition points of hydraulic variables A and Q. TVD scheme with minmod-limiter function was applied to the convective term in Eq.(2) to prevent numerical oscillation keeping 2nd order accuracy (Pinilla et al. (2010)) .

Numerical simulation was conducted under the experimental conditions as shown in Figure 1, but the flume length for the simulation was set to be 1,000m which is much longer than the experimental flume. The discharge Q_0 given at the inlet is 5.435×10^{-4} (m^3/sec) and the spatial grid size is $\Delta x=0.02(m)$.

For Run 1, the constant discharge Q_0 was given at the inlet without disturbances. For Run 2-4, the periodic disturbances given by Eq.(3) were added to Q_0.

$$Q_{up}=Q_0+\alpha\cdot Q_0\sin\left(\frac{2\pi t}{T}\right),\quad \alpha=0.02Q_0 \tag{3}$$

0.6 *sec* for Run 2,1.2 *sec* for Run 3 and 6 *sec* for Run 4 were given as the periods of disturbances.

4. RESULTS OF SIMULATION AND CONSIDERATIONS

Figure 3 shows the spatial distribution of depth for Run 1 without disturbances. The spatial instability of flow is detected at 60 *m* downstream of the inlet, and then the waves grow into the fully developed roll waves which can be observed in more than 150 *m* downstream region from the inlet. The typical wave pattern of roll waves can be seen in Figure 4.

Figure 5 shows the spatial distributions of wave lengths for Run 1. The wave length of fully developed roll waves is not unique but ranges from 2 *m* to 5 *m*. Figure 6 shows the frequency spectrum of temporal depth variations at $x = 250m$. This figure also indicates that the roll waves have not unique wave length but ranges widely around the average.

Figure 7 to 9 show the results of Run 2 with periodic disturbances (T=*0.6* sec). The waves observed in the downstream region are also periodic, and the period is the same as one of the disturbances at the inlet. The distance for run-up to fully develop waves is shorter than the distance in Run 1 without disturbances.

Figure 10 and 11 show the temporal and spatial depth distributions with disturbances of Run 3 (T=1.2 *sec*) and Run 4 (T=6.0 *sec*). The results in Run 4 are notably different from the results of Run 2 and Run3. The period of waves observed in the downstream region in Run 4 is much shorter than the period of disturbances due to the breakup of waves generated near the inlet. Figure 12 indicates that the waves generated near the inlet by the forced oscillation are broken up into three small waves with the wave lengths of 2 *m*, 3 *m* and 5 *m*. It should be noted that these three wave lengths range between wave lengths shown in Figure 5 (Run 1). This indicates that the waves with long wave length cannot be maintained due to break up. It can be pointed out that the wave amplitude in Run1 is almost same as one in Run4.

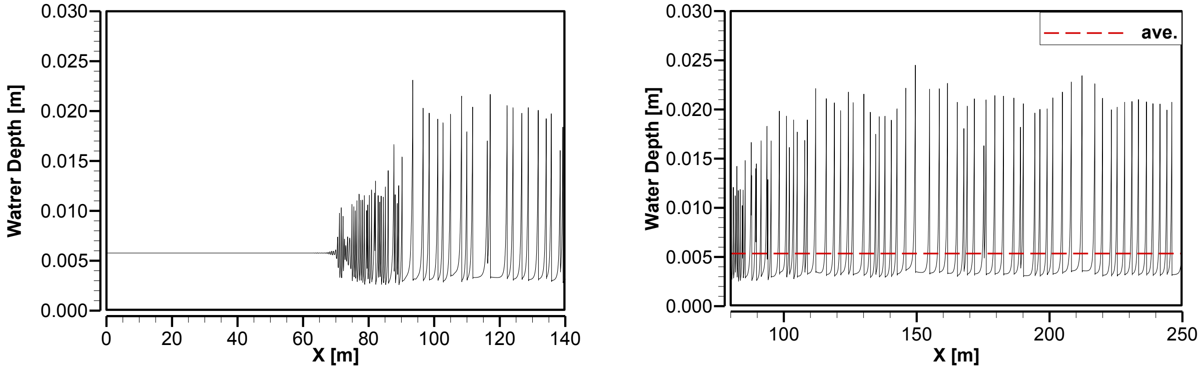

Figure 3 Spatial distributions of depth without disturbances (Run 1)

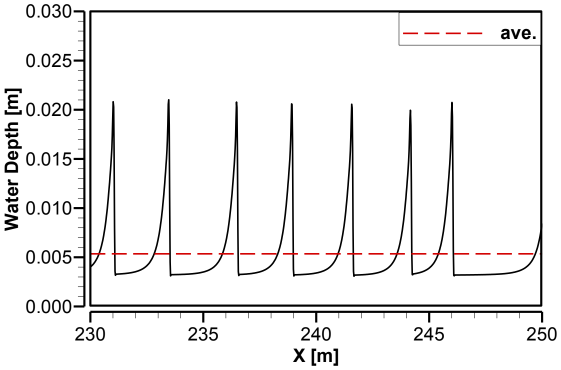

Figure 4 Enlargement of depth distributions (Run 1)

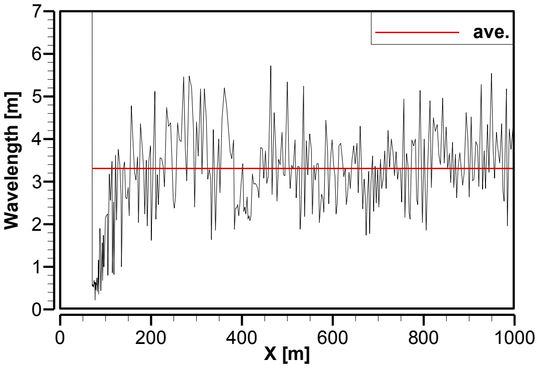

Figure 5 Spatial distributions of wave lengths (Run 1)

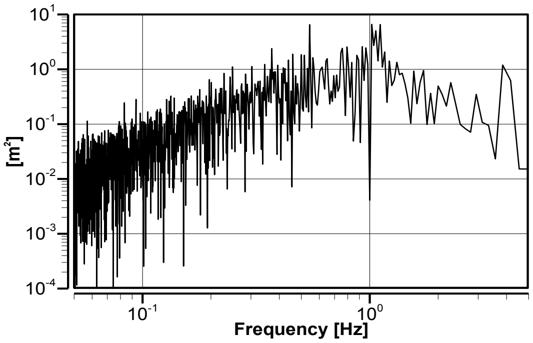

Figure 6 Frequency spectrum of temporal depth variations at x=250(m) (Run 1)

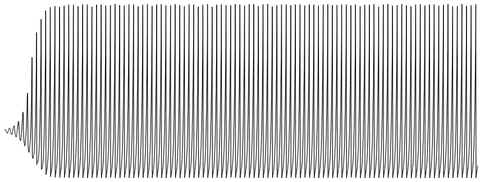

Figure 7 Spatial development of depth distributions with disturbances (Run 2, T=0.6 *sec*)

Figure 8 Temporal and spatial depth distributions with disturbances (Run 2, T=0.6 *sec*)

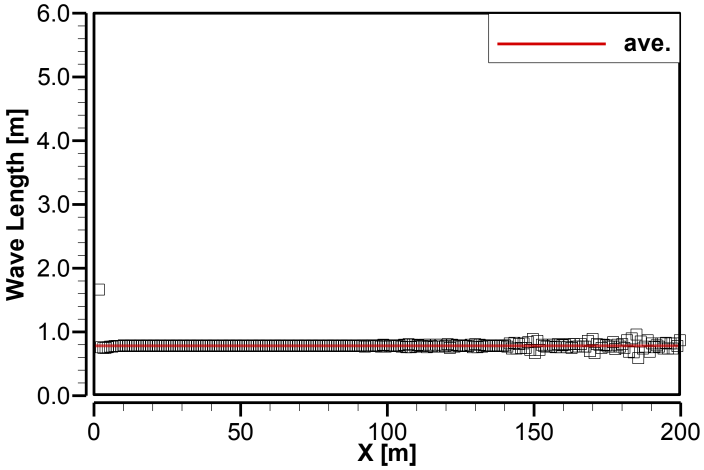

Figure 9 Spatial distributions of wave lengths (Run 2, T=0.6 *sec*)

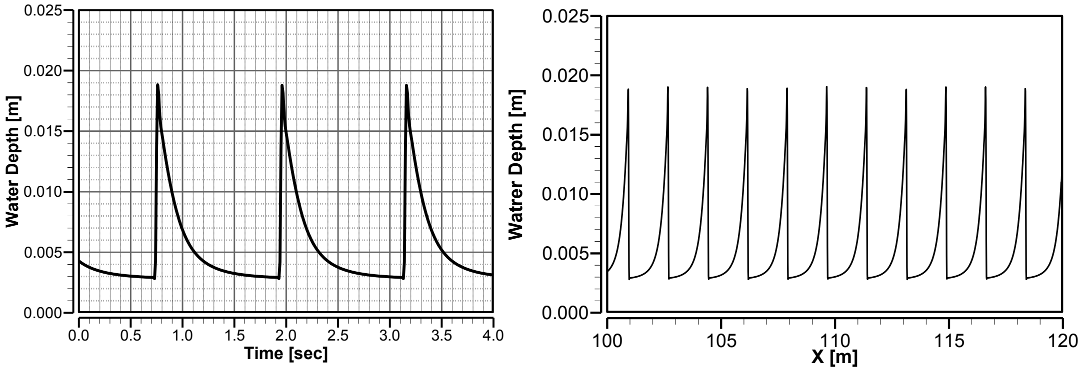

Figure 10 Temporal and spatial depth distributions with disturbances (Run 3, T=1.2 *sec*)

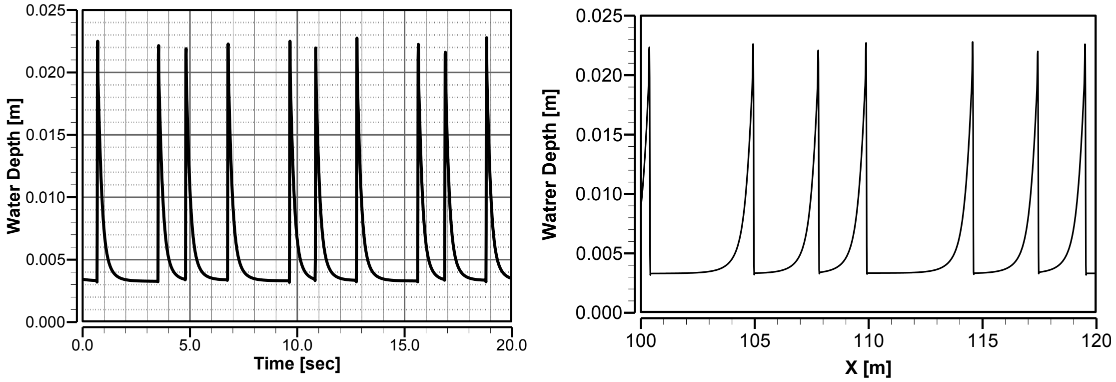

Figure 11 Temporal and spatial depth distributions with disturbances (Run 4, T=6.0 *sec*)

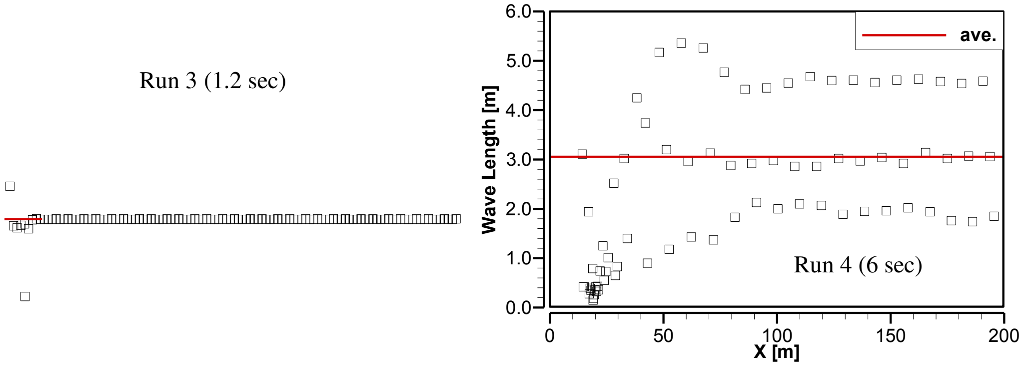

Figure 12 Spatial distributions of wave lengths
(Left: Run 3, T=1.2 *sec*, Right: Run 4, T=6.0 *sec*)

With increasing the period of disturbances the wave amplitude increases, and then approaches to the equilibrium amplitude. So, the waves with short wave length may be merged into waves with longer wave length and large amplitude so that there are no waves with wave lengths shorter than 2 *m* in Figure 5 (Run 1).

4. CONCLUSIONS

In this study, in order to clarify the generation mechanism of roll waves with the range of wave lengths around the average we conducted the numerical simulation on the development of roll waves giving the periodic disturbances at the inlet of a channel. It was pointed out that the long waves generated near the inlet by the forced oscillation are broken up into a few small waves. This indicates that the waves with long wave length cannot be maintained due to break up. The average wave length of fully developed roll waves exists between these small waves due to breakup. It was also pointed out that the waves with short wave length may be merged into waves with longer wave length and large amplitude so that there are no waves with wave lengths shorter than certain length.

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