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Experimental analysis of wave deformation and bottom flow under wave-current interaction in the river mouth

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ABSTRACT

A river mouth is a physically dynamic area. In this study, we analyze the hydrodynamic characteristics of this area by performing hydraulic experiments to investigate wave-current interaction by building a river mouth model in a 3-D wave basin. Using the results of these hydraulic experiments, we analyze the hydrodynamic characteristics of the region in which wave-current coexist in the river channel and the vicinity of the river mouth. We observe that, in a river channel, the turbulence flow field develops more rapidly when both waves and current are present as opposed to a situation where no current exists. This contributes to the wave energy loss, resulting in wave attenuation. This phenomenon is more obvious when the ratio between the current velocity and wave celerity, V_c/C_i increases. From the wave reflection measurements, we observe that the reflection coefficient increases as V_c/C_i increases. This causes wave attenuation in the wave-current interaction. We observe the changes in the wave heights, bottom flow, and horizontal velocity distributions in the areas where wave-current coexist in the river mouth. In particular, the measured horizontal velocity distribution shows the influence of the flow field on the combined effects of the wave and current velocity components. We observe that there is a close relationship between the wave-current interaction and sediment transport near the river mouth.

1. Introduction

A river mouth refers the area where the freshwater from a river joins the saltwater of the ocean. It is a dynamic area, where the ocean waves interact with the river currents, and its range of fluctuation greatly varies according to the location and time. Because of its unique and physically complicated characteristics, it is very difficult to understand the hydrodynamic characteristics of the river mouth. In this context, the interaction mechanism between the ocean waves and river currents should be analyzed for a better understanding.

Studies on the wave-current interaction based on the potential theory (Zhao and Faltinsen, 1988; Baddour and Song, 1990; Isaasson and Cheung, 1993; Lin and Hsiao, 1994) report that the wave height continuously increases with wave propagation due to the wave-current interaction. As a result, the wave energy decreases because of wave breaking. However, results from the hydraulic model test (Iwasaki and Sato, 1971; Kemp and Simons, 1983; Sakai and Saeki, 1984; Umeyama, 2005; Lee et al., 2006) indicate that the wave height decreases due to the wave-current interaction.

Among the representative experimental studies, Iwasaki and Sato (1971) directly measured the reduced height of waves in the wave-current coexisting field. Kemp and Simons (1983) suggested that the reduced height was larger when the wave and current had opposite directions. The advanced measuring instruments used in later studies enabled a more precise measurement of physical quantities using hydraulic model tests. Umeyama (2005) studied the vertical distribution of flow velocity and turbulence structure under wave-current interaction in a 2-D hydraulic model experiment. Recently, Lee et al. (2006) conducted hydraulic model experiments to analyze the vertical flow velocity and wave height using a 3-D river mouth topography. Umeyama (2010) measured and analyzed the flow velocity and trace of water particles by combining them with the particle image velocimetry (PIV) and particle tracking velocimetry (PTV) when the wave and current have the same direction. Chen et al. (2012) studied the trace of water particles using the electronic hydrometer when the wave and current have opposite directions. However, none of the experimental studies conducted so far describe the wave deformation phenomenon and the mechanism of energy decrease clearly. The abovementioned studies focus on the motion of water particles from the wave-current interaction instead of the characteristics of wave deformation.

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Fernando et al. (2011) discussed the topographic change resulting from the wave-current crossing angle, and the characteristics of local and vertical distribution of flow velocity. However, it is difficult to extend this study to analyze the effect of the hydraulic pattern. Lim and Madsen (2016) analyzed the vertical flow velocity structure and shear velocity for wave-current crossing angles of 30°, 60°, and 90° for conditions of smooth and uniform beds of fixed roughness. The results show that the fluid motion effects some topographic changes depending upon the wave-current crossing angle.

The wave reflection caused by the current in the wave-current interaction is not strong. Longuet-Higgins and Stewart (1961) built the theoretical model for the wave reflection by current. This has been extended by many researchers (Dingemans, 1997), but the final model does not provide a comprehensive definition of the reflective characteristics of the wave-current interaction. Lee et al. (2006) did not discuss wave reflection, although a partial standing wave field was formed by the wave-current interactions in their experiments. Rey et al. (2014) measured wave reflection using a 3D experiment basin in which the wave and current coexist, using the incidence and reflected wave separation method proposed by Drevard et al. (2009). However, an underwater structure was installed in this experiment, so the net wave reflection due to the wave and current cannot be known.

Recently, Liu et al. (2016) applied the homotopy analysis method (HAM) to the analysis of wave-current interaction to identify the utility and show the potential of solving the issue of strong wave-current interaction. Lee et al. (2017) analyzed the effect of turbulence on the reduced wave height using the 3-D Navier-Stokes solver. They calculated the coefficient of wave reflection due to the current in the partial standing wave field measured in the numerical wave basin. Despite using the 3-D numerical model, this study only discussed the cross-sectional 2-D hydraulic characteristics. It is difficult to extend this to analyze the hydrodynamic characteristics of the wave-current interaction in the almost-real 3-D river mouth.

In this study, we conduct 3-D hydraulic model experiments for the river mouth topography. We analyze the interaction mechanism based on the wave height distribution, wave reflection, wave transmission, wave energy loss, and turbulent kinetic energy of the region in the wave-current coexist. Furthermore, we study the deformation characteristics of the wave field according to the wave-current crossing angle around the river mouth, the bottom flow, and its distribution, which directly influence the behavior of the seabed.

2. Experimental setup and procedure

The wave entering an actual river mouth is irregular as well as multi-directional. It is very difficult to study wave change deformation and current structure during wave-current interaction if we consider the case of multi-directional irregular waves, and the long-term wave generation is likely to disturb the experiment basin. Hence, in this experiment, we will analyze the hydraulic phenomena only in a region where regular waves and currents coexist. As shown in Fig. 1 and Table 1, the river topography considered in this experiment consists of estuaries of small vertical wall type rivers, and the river mouth model and incidence conditions are established according to Froude's law considering a 1/50 scale.

2.1. Description of the hydraulic model

Fig. 1 shows the setup and arrangement of the river mouth model and experimental equipment in the water basin, with (a) showing the ground plan view and (b) showing the side view at central cross section. The water basin is 28 m long, 11 m wide, and 0.8 m deep, and the water depth is considered to be 0.4 m. The river mouth model is made of 12 mm waterproof plywood and has a water depth of 0.3 m. A wave maker with a non-reflective generation system is used to generate right angle and oblique incident waves using a snake-front piston-type paddle system that has 20 wave-paddles and actuators. Wave absorbers are used to reduce the waves reflected from the side and rear walls of the wave basin. A wave-absorbing beach is used to reduce the wave energy on the shore side. In addition, five submerged pumps are used to generate a current whose velocity is controlled using the valve. In order to generate a stable current, the current is passed through a permeable wave absorber before it goes into the river channel. This wave absorber controls the wave reflection from the upstream end of the river channel. Fig. 2 shows the overview of the wave basin for experiments on the wave-current interaction in the vicinity of a river mouth.

2.2. Experimental conditions and measurement

We conducted experiments on the wave-current interaction in the river mouth for 33 cases. The case studies were created by varying the wave heights (H_i=3, 5, and 7 cm), periods (T_i=1.2, 1.4, and 1.6 s), angles (θ_w=90, 80, and 70°), and current velocity (V_c=0, 10 and 20 cm/s) parameters of the river. The incident wave was established by calibrating the wave maker before installing the river mouth model, while the incidence flow velocity was adjusted by installing the river mouth model and adjusting the valve of the submerged pump as shown Fig. 3. Detailed experimental conditions are listed in Table 2. The length and celerity of the waves are estimated based on the third-order Stokes wave theory. The incident angle of the wave (θ_w) is considered as the angle between the wave direction and the y-axis, while the wave crossing angle (Ψ_{cw}) is the angle between the wave direction and river current.

In all the experimental runs, the wave was generated after the submerged pumps were activated and stable current condition was attained. In addition, all the measurements were conducted after the region in which wave-current coexist stabilized. The water level was measured using 16 capacitive wave height meters; three of them were fixed in front of the river mouth model to synchronize the measurement data, and 13 were used to measure the dynamic water level. The flow velocity was measured using one x-z directional current meter and six x-y directional current meters. All these measurements were made at a frequency of 100 Hz.

In the river channel, the wave height was measured at 39 locations (13×3) in the upstream of the river. A set of 13 wave gauges, placed at 12 cm intervals, covered a distance of 456 cm from the river mouth, and three variations of this set were used. Around the river mouth, the wave height was measured using 13 wave gauges placed 10 cm apart, and 15 such configurations were used. Hence, the value was measured at 195 positions (13×15) in an area of size 144 cm×140 cm. The flow velocity components were measured using six electromagnetic-type current meters, one velocity meter was used to measure the velocity components u and w in the x and z directions, and five velocity meters were used to measure the same in the x and y directions. In the river channel, one velocity-meter and one current meter was installed for measuring the u and v values at a position 250 cm from the river entry (x=0) to study the 3-D flow velocity field. The flow velocity was measured at 20 points in the vertical direction, from 0.5 cm to 19.5 cm, in increments of 1 cm from the bottom. All this data was recorded for 20 wave periods. At the river mouth, six current meters were installed at 12 cm intervals, to record 10 times. A total of 60 (6×10) measuring positions were located in an area of size 50 cm×90 cm.

3. Hydrodynamic characteristics of the river channel

This section considers the cross-sectional 2-D hydraulic characteristics of region in which wave-current coexist. We analyze the wave height and flow velocity data measured at the following positions—in the river, where the parameters are least influenced by the topography of the river mouth; and in an experimental basin, to analyze the