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Negative surges and unsteady turbulent mixing induced by rapid gate opening in a channel

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ABSTRACT

A negative surge is an unsteady open channel flow characterised by a drop in water surface elevation. In this study, a negative surge generated by the rapid gate opening was investigated experimentally with three types of bed roughness. Both instantaneous free-surface and velocity measurements were performed and the results were ensemble-averaged. The experimental data showed a rapid flow acceleration beneath the negative surge, and large and rapid fluctuations in all instantaneous velocity components were observed during the passage of the negative surge leading edge. The Reynolds stress data showed large ensemble-average and fluctuation levels, significantly larger than in the initially steady flow, occurring slightly after the passage of the surge leading edge. The time difference between the maximum Reynolds stress and surge leading edge was observed to increase with increasing distance from the gate, and it was comparable to the time delay for the occurrence of maximum free-surface fluctuations. The findings suggested that the unsteady flow properties were little affected by the bed roughness, despite the broad range of equivalent sand roughness heights tested herein.

1. Introduction

In an open channel, the operation of a regulation structure (e.g. gate) is typically associated with a lowering of the water level on one side and the rise in water elevation on the other side. These unsteady processes are called respectively negative surge and positive surge. They are commonly observed in water supply channels during the operation of regulations gates (Fig. 1). Although there is an extensive literature dealing with their steady flow operation [19,11,22], limited information is available on the transient operation of gates. Fig. 2 illustrates the generation of negative surges caused by gate operation.

Negative surges may be analysed using the Saint-Venant equations and the method of characteristics in channels of relatively simple geometry. The Saint-Venant equations are one-dimensional unsteady open channel flow equations characterising the variations in space and time of the water depth d and flow velocity V:

$$B \times \frac{\partial d}{\partial t} + A \times \frac{\partial V}{\partial x} + B \times V \times \frac{\partial d}{\partial x} + V \times \left(\frac{\partial A}{\partial x}\right)_{d=\text{constant}} = 0 \quad (1)$$

$$\frac{\partial V}{\partial t} + V \times \frac{\partial V}{\partial x} = -g \times \frac{\partial d}{\partial x} + g \times (S_o - S_f) \quad (2)$$

where x is the longitudinal co-ordinate positive downstream, A is the flow cross-section area, B is the free-surface width, g is the gravity acceleration, S_o is the bed slope and S_f is the friction slope [20,3]. Several textbooks presented the complete solutions of negative surges propagating in prismatic rectangular channels [11,23,29]. Experimental studies included the free-surface measurements of [7], and the unsteady velocity data of [26]. Numerical studies of negative surges are more numerous [27,30], albeit restricted by the limited amount of detailed validation data sets.

In this contribution, a physical study is presented with a focus on the unsteady turbulent mixing during a negative surge propagating upstream following a rapid gate opening. Detailed measurements were performed in a relatively large facility with three types of bottom roughness. Both instantaneous free-surface and velocity measurements were conducted and the results were ensemble-averaged. It is the purpose of this contribution to study thoroughly the upstream surge propagation and associated turbulent mixing, including the impact of bed roughness.

2. Physical modelling of negative surges and instrumentation

2.1. Presentation

Physical models are commonly used in hydraulic engineering to optimise a structure. In a laboratory model, the flow conditions

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Fig. 1. Fully-opened radial gates along the Toyohashi-Tahara aqueduct, Toyohashi City (Japan) on 26 November 1998.

must be similar to those in the prototype: that is, geometric, kinematic and dynamic similarities must be fulfilled. In a dimensional analysis, the relevant parameters include the fluid properties and physical constants, the channel geometry and initial flow conditions, and the unsteady flow properties. Considering the simple case of a negative surge propagating in a rectangular, horizontal channel after a sudden and complete gate opening, a dimensional analysis yields:

$$\frac{d}{d_o}, \frac{P}{\rho \times g \times d_o}, \frac{V_x}{V_o}, \frac{V_y}{V_o}, \frac{V_z}{V_o} = F\left(\frac{x}{d_o}, \frac{y}{d_o}, \frac{z}{d_o}, t \times \sqrt{\frac{g}{d_o}}, \frac{V_o}{\sqrt{g \times d_o}}, \rho \times \frac{V_o \times d_o}{\mu}, \frac{g \times \mu^4}{\rho \times \sigma^3}, \frac{B}{d_o}, \frac{k_s}{d_o}, \ldots\right) \quad (3)$$

where d is the flow depth, P is the instantaneous pressure at a location (x, y, z) and time t, V_x, V_y, V_z are respectively the instantaneous longitudinal, transverse and vertical velocity components, x is the streamwise coordinate in the flow direction, y is the horizontal transverse coordinate measured from the channel centreline, z is the vertical coordinate measured from channel bed, t is the time, d_o and V_o are the initial flow depth and velocity respectively, B is the channel width, k_s is the equivalent sand roughness height of the bed, g is the gravity acceleration, ρ and μ are the water density and dynamic viscosity respectively, and σ is the surface tension between air and water. Eq. (3) describes the dimensionless unsteady turbulent flow properties at a position and time as functions of a number of dimensionless parameters, including the Froude number (5th term), the Reynolds number (6th term) and the Morton number (7th term). Note that the effects of surfactants and biochemicals were neglected in the above development.

Herein a Froude similitude was applied and the experiments were conducted in a large size facility operating at large Reynolds numbers. These conditions may correspond to a 1:10 scale study of the channel shown in Fig. 1, thus ensuring that the extrapolation of the laboratory data to prototype conditions is unlikely to be adversely affected by scale effects.

2.2. Experimental facility and instrumentation

The experiments were conducted in a horizontal rectangular flume. The channel test section was 12 m long 0.5 m wide, made of smooth PVC bed and glass walls. The water was supplied by a constant head tank feeding a 2.1 m long 1.1 m wide 1.1 m deep intake basin, leading to the test section through a bed and sidewall convergent. A tainter gate was located next to the downstream end $x = x_{Gate} = 11.12$ m where x is the distance from the channel test section upstream end. This channel was previously used to study positive surges [5,13].

The water discharge was measured with an orifice meter designed based upon the British Standards [2] and calibrated on site with a V-notch weir. The percentage of error was expected to be less than 2%. In steady flows, the water depths were measured using rail mounted pointer gauges. The unsteady flow depths were recorded with a series of acoustic displacement meters Microsonic™ Mic+25/IU/TC located along and above the channel. The acoustic displacement meters were calibrated against the pointer gauges in steady flows and their accuracy was 0.2 mm. Note herein that the water depths were measured above the top of the rubber mats ($z = 0$) as shown in Fig. 3, in line with studies of d-type roughness [6]. The assumption was supported by visual observations suggesting zero to negligible flow motion through the mats.

The velocity measurements were conducted with an acoustic Doppler velocimeter Nortek™ Vectrino+(Serial No. VNO 0436) equipped with a three-dimensional side-looking head. The velocity range was ±1.0 m/s, the sampling rate was 200 Hz, and the data accuracy was 1% of the velocity range. Both the acoustic displacement meters and acoustic Doppler velocimeter were synchronised within ±1 ms and were sampled simultaneously at 200 Hz. The translation of the ADV probe in the vertical direction was controlled by a fine adjustment travelling mechanism connected to a MitutoyoTM digimatic scale unit. The error on the vertical position of the probe was $\Delta z < 0.025$ mm. The accuracy on the longitudinal position was estimated as $\Delta x < \pm 2$ mm. Herein all the measurements were taken on the channel centreline. Additional information was obtained with some digital still cameras Panasonic™ DMC-FX36 and Pentax™ K-7, and video camera

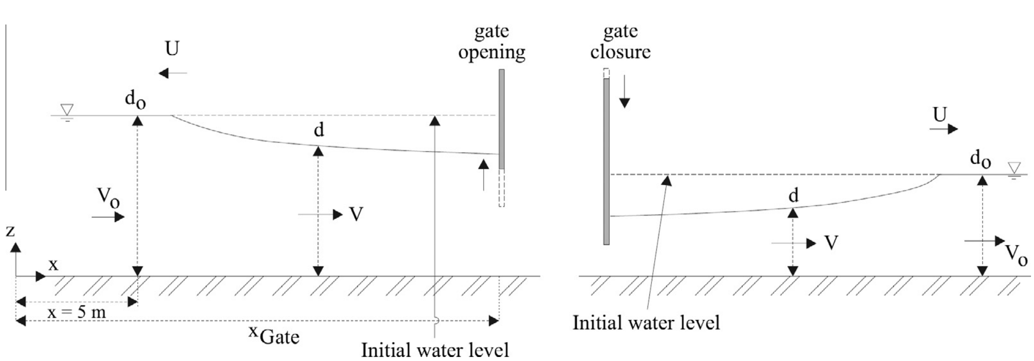

Fig. 2. Definition sketch of negative surges induced by gate operation: upstream surge propagation (left) and downstream surge propagation (right).