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Dam-break generated flow from an infinite reservoir into a positively inclined channel of limited width

Gustaaf Adriaan Kikkert *, Thiruni Liyanage, Chii Shang

Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

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Abstract

To investigate the feasibility of suspending sediments in storm-drains in coastal cities using tidal energy, numerical and physical experiments are carried out to understand the behaviour of a dam-break generated flow from an infinite reservoir (the sea) into a positively inclined channel of limited width (the storm-drain). The numerical results are obtained using LES as these yield the most accurate predictions of the results from the physical experiments. The hydrodynamics of the flow inside the channel are controlled by the large volume of water in the reservoir and cross waves are generated in the channel due to its limited width. On relatively steep slopes, the bed shear stress results indicate that sediment suspension is likely to occur under the leading edge of the flow while on mild slopes suspension of sediments may occur over a great distance into the channel and for a long duration after the initial dam-break.

Keywords: Dam break; Infinite reservoir; Numerical simulation; Physical experiments; Storm-drain

1. Introduction

Rapid urbanization in South-East Asia has resulted in a significant increase in the number of urban centres with more than one million inhabitants. For urban expansion, coastal cities often consider reclaiming land from the sea (in Hong Kong 6.7 km^2 or 6% of the land is reclaimed). Reclaimed land is flat and hence ideal for construction, however drainage of storm water is an issue. Large storm drains (cross-sections of 3 m by 3 m) have been constructed to transport water from the original coast line underneath the reclaimed land to the new coast line and therefore have shallow slopes (down to 1:2000). Sediments transported with the storm water and sewage from run-off, illegal discharges or misconnections settle in the storm-drain and it is inundated with seawater during high-tide. This combination results in an anaerobic environment in the sediment phase in which sulphate reducing bacteria use the sulphate from the seawater and organic carbon from the sewage to reproduce. As a by-product, hydrogen sulphide (H_2S) is generated, creating a nuisance for local people because of the very low detection threshold (Firer et al., 2008). To control the formation of H_2S, chemicals such as hydrogen peroxide, nitrate and ferric salt (Firer et al., 2008; Zhang et al., 2008) are used, but in storm-drains would require continuous or intermittent dosing which is costly and impractical. In our project a sustainable solution is investigated (Sun et al., 2013b) that uses the natural redox cycle of iron–sulphur. Iron particles added to the sediments oxidize H_2S to odourless substances. When their capacity is exhausted it is recovered by rapidly mixing the sediment and iron particles with seawater. To achieve this mixing inside the storm-drain, tidal energy is used by placing a gate at the entrance of the storm-drain that is closed during low-tide and opened rapidly during high-tide. This generates a dam-break flow that travels into the storm-drain disturbing the layer of sediment so that oxygen-rich seawater can come into contact with the iron particles. The current paper investigates the

* Corresponding author. Tel.: +852 2358 8190.
E-mail addresses: kikkert@ust.hk (G.A. Kikkert), tull@connect.ust.hk (T. Liyanage), cechii@ust.hk (C. Shang).

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hydrodynamics of the dam-break generated flow into the storm-drain and its potential to suspend the sediment and iron particles.

Previous research on dam-break generated flows has focused on the flow from a finite reservoir into an either dry or wet prismatic rectangular horizontal channel with the same width. A gate and a channel with the same width generates an essentially two-dimensional dam-break flow (e.g. Lauber and Hager, 1998a; Shigematsu et al., 2004; Stansby et al., 1998), while a gate with a smaller width generates a flow that initially travels radially outwards (e.g. Aureli et al., 2008; Fraccarollo and Toro, 1995; Soares-Frazão, 2007). The effect of a downwards sloping channel (i.e. negatively inclined) on the dam-break flow was studied by Fraccarollo and Toro (1995) and Lauber and Hager (1998b), while Aureli et al. (2000), O'Donoghue et al. (2010) and Kikkert et al. (2012) allowed the dam-break wave to collapse into a horizontal channel before running up a positively inclined slope. Configurations studied for dam-break flows into a non-prismatic channel include a converging reservoir and diverging channel (Bellos et al., 1992) and a contraction in the downstream channel (Ozmen-Cagatay and Kocaman, 2012), while Feizi Khankandi et al. (2012) investigated the effect of the reservoir shape. Flows from a semi-infinite reservoir, a reservoir with a width that is much larger than that of the channel but with the gate located close to a side wall of the reservoir, into a horizontal rectangular channel with a wide 180° bend and tight 90° bend were investigated by Bell et al. (1992) and Soares Frazão and Zech (2002) respectively. Most experimental studies obtained measurements of the flow depth time-series and profiles, less common were measurements of the wave propagation, free surface velocity, velocity time-series and velocity profiles. Numerical predictions of the dam-break flow have been obtained via the one-dimensional shallow water equations, SWE (e.g. Aureli et al., 2000; Nsom, 2002) and two-dimensional SWE (e.g. Aureli et al., 2008). Alternatively the Reynolds averaged Navier–Stokes equations, RANS, have been solved with a k–ε turbulence model in two-dimensions (e.g. Ozmen-Cagatay and Kocaman, 2010; Shigematsu et al., 2004) or three-dimensions (e.g. Ozmen-Cagatay and Kocaman, 2012). Larocque et al. (2013) compared the results from the 3D RANS with those obtained from Large Eddy Simulations. Results from essentially 2D dam-break experiments have been successfully modelled with either 1D or 2D numerical models (e.g. Aureli et al., 2000; Ozmen-Cagatay and Kocaman, 2010; Stansby et al., 1998). For more complex configurations, it becomes necessary to use a fully 3D numerical model to accurately model the flow behaviour (e.g. Feizi Khankandi et al., 2012; Larocque et al., 2013).

For the application of the current study, the reservoir behind the gate is the sea and therefore has an infinite volume compared to the volume of the channel, which is the storm-drain. The width of the reservoir is also much greater than that of the channel which has a mild positively inclined slope. To investigate the dam-break flow and its potential to suspend the sediment and iron particles, new physical and numerical experiments are carried out. Because of space limitations, the physical channel is scaled-down by a factor of 10 compared to an actual storm-drain and has a slope 1:20. The 3D physical set up is reproduced numerically in CFD software Fluent. The numerical results are compared with the experimental results to determine the most suitable turbulence model before the hydrodynamics of the flow and the sediment suspension potential are investigated in detail. Finally two additional numerical scenarios are investigated to obtain estimates for the suspension potential on a mild slope (1:1000) and in a large-scale storm-drain.

2. Methodology

2.1. Physical experimental set up

The experiments were carried out in the towing tank (15 m long, 2.0 m wide and 1.6 m high) of the Water Resources Laboratory at the Hong Kong University of Science and Technology (Figs. 1 and 2). The channel, made from 5 mm thick PVC panels with equivalent sand roughness of $5*10^{-5}$ m, had an internal cross-section of 0.30 m by 0.30 m, length of 6.6 m and slope of 1:20. The channel was supported by a steel frame that lifted the bottom of the channel at the entrance to a height of 155 mm above the bottom of the tank. Hence a step existed at the entrance to the channel that represented the relatively steep descent at the edge of reclaimed land. A steel gate, constructed in a V-shape to give a waterproof seal and the ability to be lifted rapidly, was installed at the entrance to the channel. To minimize the effect of the gate opening time on the dam break flow, the gate should be opened as quickly as possible. However, good repeatability of the gate opening was also of great importance as the experimental results were obtained by ensemble-averaging using a significant number of individual experiments. The gate was opened manually in approximately 0.30 s which gave good repeatability, but was greater than the time for an instantaneous dam-break of 0.17 s as determined by Vischer and Hager (1998). A barrier across the tank separated the channel from the remainder of the tank which functioned as the (infinitely) large reservoir. The plan view area was 7.5 m by 2.0 m and the water depth in the reservoir before the gate was opened was 350 mm (195 mm above the channel bottom at the entrance). The gate was opened with no water present in the channel, generating a wave travelling initially at about 2 m/s and reaching a maximum runup of 6.5 m. When the water in the channel reached its equilibrium, the water depth in the reservoir had decreased by 6 mm. After each experiment, the gate was closed and the water in the channel pumped back into the reservoir. Time of gate opening is defined as $t = 0$ and the origin of the x–y–z coordinate system is defined at the centre of the gate and bottom of the channel. The positive x-axis is parallel to the channel slope, the y-axis is across the channel and the z-axis is normal to the channel slope. The corresponding velocity components are u, v and w respectively.