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Mixed free-surface / pressurized flows in sewers

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Introduction

In sewer modelling practice, accurate prediction of surcharging is an important issue. Many simulation models deal with this by some approximate technique. Simplified models can provide reasonably realistic solutions in a number of cases, but may also lead to inaccuracies. In addition to other reasons, erroneous predictions are often the consequence of inadequate treatment of the transition from free-surface flow to surcharged flow or vice versa.

The aim of this paper is to describe selected experimental investigations of mixed flow regimes and to discuss some problems related to numerical simulation of such flows. Phenomena are briefly described and referenced in the paper, whereas a number of photographs of various experiments and animation of their simulation will be presented at the conference, highlighting both the strengths and the weaknesses of simulation models.

Experimental investigations – an overview

The first studies of mixed flow regimes, conducted in the decades before and after WW2, were *hydraulic scale models* that looked at design of particular structures.

These have been followed by *theory-oriented investigations*, which considered issues such as the influence of viscosity and increased air-water friction in the transition zone.

With the early developments in computer modelling, installations have been built since the late seventies that were used for *testing of numerical models*.

Finally, in the past few decades, both large-scale field and laboratory experiments have been done in efforts to verify *network flow* simulation models and urban flood models.

Of course, this classification is not exclusive – many authors tried to establish generally applicable laws while studying particular structures or testing simulation models. Neither has the era of any of these groups ended, e.g. recently some scale models have been built.

Mathematical modelling techniques – an overview

Exact solutions of mixed flow equations exist only for a limited number of schematized conditions, e.g. sudden opening of initially full sealed horizontal pipe (Wilkinson, 1982). As in other domains, the main role of analytical solutions is in testing of numerical models.

Empirical formulae exist that quantify certain phenomena, e.g. air-water friction (Blaszczyk, 1989). These are useful, but they usually solve only a part of the problem.

Shock fitting methods treat pressurized and free-surface sections separately with different numerical procedures. That implies that *interface* between the two regimes is an internal moving boundary condition (BC) and that additional unknowns are introduced, namely the location of the interface and its speed. This is indeed physically sound, but it requires a complicated algorithm to keep track of the existence and location of interfaces across the pipe network, and consequently skip from one solution procedure to another depending on the current local flow regime. Thus, there have been only a few successful applications of this approach (Cardle, 1991) none of which ended up in a commercial hydraulic model.

Rigid water column approach separates surcharging process into *phases*, and treats each of them by a separate set of equations (Li and McCorquodale, 1999). This does enable introduction of some advanced concepts such as the interface instability condition, but again this is impractical to be applied on a network level.

Shock capturing methods are widely used. Commonly they are based on *open slot* concept (Preissmann and Cunge, 1961). It assumes an imaginary opening in the closed conduit cross-section by adding a narrow open slot along the top, aiming at simulation of flow in pressurized sections by the open channel flow equations. This introduces some inevitable errors, but it is very convenient as it discards the need for any consideration of the interface and thus enables efficient network modelling.

Finally, there exist models that are hybrids between some of the mentioned concepts.

Mixed regime related phenomena at *constant* boundary conditions

In open channel flow modelling, effects due to air-water interaction are usually negligible. However, at *nearly full* pipe flow, these may become important.

Various experimental investigations showed that air-water friction can reduce pipe capacity at high relative depths, i.e. that observed discharges are consistently smaller from those predicted by Manning or any other formula. On the other hand, some experiments showed that, in the transition zone, yet only under specific conditions (de Somer, 1982), the pipe capacity could be greater than predicted by either the free-surface formula or the pressurized flow formula. From the modelling point of view, a non-unique depth-flow relation (with two-fold higher than full pipe flow capacities at $0.8<h/D<1.0$) is unpleasant as it tends to induce computational instabilities.

When the relative water-air velocity is high (e.g. when two fluids move in opposite directions), instability of the water surface may occur anywhere in the pipe, which may lead to local pressurization, which in turn induces air trapping and possibly also strong pressure fluctuations. The likelihood of this happening strongly increases with relative depth and is highest at almost full-pipe flow (Hamam and McCorquodale, 1981).

In a sequence of full or nearly full pipes, even at constant boundary conditions at both ends of the profile and with no lateral inflows, a spontaneous set of transitions can occur repeatedly involving formation of vortices at manholes and movement of trapped air bubbles (Huberlant and Zech, 1990).

Free outflow from a pressurized pipe is via a full pipe cross-section only at relatively high flow velocities, otherwise a considerable-size air cavity may intrude into the pipe (Montes, 1997). Simulation models need to take care of this in formulation of BCs.

Mixed flows at *gradually varying* boundary conditions

The distinction between *gradually varying* BCs and *sudden changes* in BCs here refers to the location of the cause of regime change – the former relates to changes of inflow or outflow or water level *outside* a pipe (in which case any change is attenuated by the manhole volume), whereas the latter relates to fast changes inside a pipe or at its ends.

The earliest documented research on mixed flows had described and analyzed *phases* of regime changes in hydro power plant tunnels after turbine manoeuvres and interactions with surge tank filling/emptying (Meyer-Peter and Favre, 1932; Hajdin, 1954). This type of flow can successfully be simulated with the open slot concept. Investigations on the model of Wettingen tunnel in Switzerland later served for quite some time as the benchmark case for testing numerical models.

The first comprehensive field investigation of mixed flows in sewers was done by Jacobsen (1983) on the 2km long Öresund pipeline in Denmark, which is exposed to partial pressurization after activation of the pump at the upstream end. Efforts to simulate these experiments enabled recognition of the importance of various effects, such as increase in energy losses due to presence of tree roots and pressure relaxation in manholes.

Watanabe and Kurihara (1993) experimentally evaluated the influence of pressure relaxation in lateral pipes and in the manholes on the celerity of the pressurization wave in a sewer pipeline. They showed that it is considerable, so that the pressure surge effectively acts rather as a (slow) gravitational wave than as a (fast) acoustic wave. This practical conclusion fits nicely into the open slot concept, as it justifies the use of not-so-narrow slots (which is otherwise desirable to improve the stability of numerical schemes).

Quick filling up of a combined sewer system may lead to odour problems. This has been common in the Vancouver system in Canada where coincidence of high tide with a heavy rainfall often lead to very high air velocities at the ventilation openings (up to 80m/s). A study was conducted that looked at possible reduction of odour (NWC, 1998). Flow in the system was simulated in two steps: standard sewer flow computation and the air flow computation which treated air as a compressible fluid.

Rare field measurements of urban flooding more or less directly recorded surcharging and depressurization processes. Investigations like those of Kolsky (1999) enable analysis of the interaction between the surcharged pipe flow and the street flow where the hydraulic grade line in a pipe is above the surface water level.

Mixed flows after *sudden changes* in boundary conditions

Trajković (1999) experimentally investigated the two-fold mixed flow regime, when both the hydraulic jump and the pressurization interface move in a pipe as a consequence of manoeuvring of the gates at upstream and downstream ends. These experiments also analyzed the effect of ventilation holes on the surcharging process.

Pressure fluctuations mentioned earlier can also occur when the surcharging interface moves fast in the upstream direction. On the other hand, negative pressure may occur during the depressurization. Both of these effects were studied by Cardle et al. (1989).

A number of investigations have looked at trapping of air bubbles on various experimental set-ups (Baines, 1991; Yasukawa et al., 1996; Zhou et al., 2002; and others). Different modes of cavity movement have been recognized.

Hosoda et al. (2002) experimentally and numerically researched the abrupt transients in sewers. They looked at the interaction between overland surface flow and pipe flow and at the air pressure changes.

Transients in rising mains were the subject of a series of field experiments conducted in Sweden (Jönsson, 1989).

None of the phenomena mentioned in this section can be accurately predicted by standard hydraulic simulation models. This is mainly due to two reasons:

- one-to-one relationship between hydraulic head and water level inherent to the open slot concept (which cannot handle negative pressures nor trapped air), and

- simulation parameters whose default values are usually chosen so as to ensure a numerically stable solution (and not the most accurate one).

By careful selection of computational steps and slot width, the reliability of results can be improved, however, in some situations, when the accuracy of mixed flow simulation is essential, more advanced models may be necessary.

Concluding remarks

Mixed free-surface/pressurized flow regimes can occur in sewers during heavy rainfall, after pump manoeuvres, etc. A range of phenomena relating to the transition from one regime to the other has been observed both on laboratory installations and *in situ*. These include different modes of interface movement, air trapping, increased or apparently decreased resistance, various types of flow instabilities, pressure fluctuations, etc.

When a closed conduit experiences a transitional regime, flow conditions are primarily determined by two factors: speed of change (unsteadiness) of boundary conditions and possibilities for ventilation.

Standard hydraulic packages can cope with mixed flows up to a certain extent, though their application is not always justified.

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