“Improved simulation of mixed flow conditions with-in building and local drainage systems”

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Abstract

Building drainage systems, and the local systems that connect buildings and their curtilages to main sewer networks, are often characterised by a large number of small medium diameter pipes, incorporating many junctions and a variety of different pipe lengths and slopes. Although normally designed to operate under free surface conditions, such systems will regularly experience full bore flow events, and may hence be defined as mixed flow systems. Whilst there are a number of fully dynamic modelling suites targeted at large scale urban drainage systems, there are no similar models to accurately simulate the full range of flow conditions that can occur within local drainage systems. Similarly, the numerical techniques employed in the existing DRAINET building drainage model mean that it is not particularly suited to the widespread simulation of mixed flow events within complex systems. This paper outlines the development of a new modelling technique to simulate mixed flow conditions within building and local drainage systems. The underlying principle behind the technique is to ensure that, where numerical stability permits, the appropriate set of governing equations are applied to the relevant flow regimes. To achieve this, a combination of shock capturing and shock fitting techniques is employed, and a new Time Varying Preissmann Slot (TVPS) is introduced.

Keywords

Mixed flow; local; building; drainage; Connections

Introduction-

Piped drainage systems form the backbone of urban drainage infrastructure, both in terms of foul and surface water drainage. This paper concentrates on piped systems at the upstream end of urban drainage networks, namely those installed within buildings and those “local” systems that connect buildings and their curtilages to the main sewer network; examples of local systems range from those serving a single residential property to those draining large retail parks. Whilst internal building drainage normally only carries foul flows from appliances, the local systems they feed into may also convey storm water flows, in either a separate or a combined system. As both building and local systems are located in the upper reaches of urban drainage networks, where unsteady inflows have yet to attenuate to any significant degree, they can experience similar flow conditions. Both types of system are often characterised by a large number of small-medium diameter pipes (typically up to 200mm in diameter), incorporating many junctions and a variety of different pipe lengths and slopes. Although normally designed to operate under free surface conditions, almost all such systems will regularly experience full bore flow events, and may hence be defined as mixed flow systems. For example, systems conveying surface water may become surcharged during intense rainfall events1 , whilst building drainage systems may experience temporary full bore conditions upstream of pipe junctions or following the simultaneous operation of a number of appliances2 . As conditions within building and local systems are normally supercritical, full bore flow tends to occur via a hydraulic jump; where pipe slopes are shallower, the normally subcritical flow develops to pressurised conditions via a more gradual increase in flow depth. Evidently, the onset and propagation of full bore conditions can have significant consequences for system performance. Within large scale surface water systems the actual process of regime transition can generate transients of sufficient magnitude to cause infrastructure damage and the ejection of manhole covers1 , whilst the air pressure transients generated by the formation of full bore conditions within building and local systems can enter appliance venting systems and destroy protective trap seals2 . Once full bore conditions have been established, there is clearly an increased risk of system surcharging and flooding of surrounding areas. In addition, the change in regime can result in an increase in wave celerity of 2 to 3 orders of magnitude, an accompanying increase in the magnitude of pressure waves, and a change in overall system characteristics, i.e. supercritical free surface flow is independent of downstream conditions whilst full bore conditions are inextricably linked to those at downstream boundaries3 .

2 Current approaches-

The relatively large spatial scale of drainage systems, and the need for time varying simulation over extended periods, means that most simulation methods are based on 1-D principles. If conceptual “black box” type models are disregarded, the 1-D physical modelling of mixed flow systems can generally be divided into three categories, namely: steady state, partially dynamic and fully dynamic approaches. In recognising the inherently unsteady nature of drainage system inflows, only fully dynamic models can accurately simulate the governing physical processes. Within this field, three fundamental techniques have emerged, namely: rigid column techniques1 , shock fitting techniques4 and shock capturing techniques5 . Each of these different numerical approaches has its own advantages and disadvantages; For example, rigid column and shock fitting techniques preserve the “integrity” of regime interfaces but require considerable computational effort to track and calculate each interface, whilst shock capturing techniques can be considerably more computationally efficient at the cost of introducing errors into the solution. Within academia, the fully dynamic techniques discussed have been used as the basis for many different models, each of which tends to be tailored to a specific application. The majority of these models concentrate on water flow conditions within elements of large scale urban drainage systems, though some also incorporate limited air phase pressurisation effects; examples include a rigid column approach to the modelling of severe transients within storm sewers1 , a shock fitting approach to the simulation of mixed transient flows in storm sewers4 and the use of a two component shock capturing technique for rapidly filling sewer systems6 . In terms of building drainage, fully dynamic finite difference models have been developed for both internal and siphonic roof drainage applications (DRAINET2 and SIPHONET7), although the numerical techniques employed mean that neither model is particularly suited to the widespread simulation of mixed flow events within complex systems. Similarly, a shock capturing finite volume model has been applied to the simulation of unsteady flows within individual building drainage pipes8 . The majority of commercial modelling suites use some form of shock capturing approach, and are targeted at large scale urban drainage systems (e.g. Info Works CS from HR Wallingford). Such models commonly employ simplifying assumptions, which improve computational robustness and efficiency, at the cost of introducing numerical errors and instabilities9 . Some commercial models offer the option of partially dynamic solution methods, which can prove useful for long duration simulations or when backwater effects are negligible. Most software packages aimed at building and local drainage systems are based on steady state methodologies, but may include more advanced techniques to check for failure modes (e.g. WinDes form Micro drainage). Although such approaches are commonly employed for the design of small developments schemes10 and some building drainage applications11, they tend to treat individual pipes as single entities under one hydraulic state at any given time, rather than physical elements along which conditions may vary both spatially and temporally; consequently they are not strictly applicable to the simulation of mixed flows in individual pipes.

3 Description of research

3.1 Aim-

The main aim of the research reported herein was to improve the simulation of mixed flow conditions within building and local drainage systems. It was anticipated that this will help provide the integrated tools necessary to radically improve the design and operation of building and local drainage systems, under current and future loading conditions.

3.2 Objectives-

In order to achieve the overall project aims, the primary objectives of the project were as follows:

- Develop a novel numerical technique for the simulation of mixed flow conditions within small-medium diameter piped drainage.
- Develop the necessary boundary conditions to represent system elements within building and local drainage systems.
- Develop 1-D finite difference models for the simulation of mixed flow conditions within building and local drainage systems under all realistic loading conditions.

4 Model development-

The underlying principle behind the model methodology presented herein is to ensure that, where numerical stability permits, the appropriate set of governing equations are applied to the relevant flow regimes, i.e. free surface equations are used in regions of free surface flow and full bore equations are used in regions of full bore flow. As the governing equations of both free surface and full bore flow are nonlinear hyperbolic partial differential equations which cannot be solved directly, recourse must be made to some form of numerical solution technique. As such one of three different solution techniques are employed.

1. Purely free surface flow conditions are simulated using a TVD MacCormack12 solution of the governing equations of free surface flow.
2. Mixed flow conditions within the same pipe are simulated using the same TVD MacCormack solution of the governing equations of free surface flow, in conjunction with a Preissmann slot8 .
3. Purely full bore flow conditions are simulated using the Method Of Characteristics3 (MOC) solution of the governing equations of full bore flow.

The governing equations of 1-D free surface flow (continuity and momentum equations) may be written in conservative form as:

(1)

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

(2)

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left[\frac{Q^2}{A} + gAI_1\right] = gA(S_0 - S_f)$$

(3)

$$\rho c^2 \frac{\partial V}{\partial x} + V\rho g\left[\frac{\partial H}{\partial x} + S_0\right] + \rho g \frac{\partial H}{\partial t} = 0$$

(4)

$$V\frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} + g\frac{\partial H}{\partial x} = g(S_0 - S_f)$$

Where: A is flow area, c is wave celerity, g is acceleration due to gravity, H is pressure head, I1 is the first moment of the area A about the free surface, Q is flow rate, S_0 is pipe slope, S_f is friction slope, t is time, x is distance along pipe, V is flow velocity, ρ is fluid density.

4.2 Mixed flow conditions-

Mixed flow conditions are simulated using the same TVD MacCormack solution of Equations (1) and (2), in conjunction with a modified Preissmann slot. Whilst the use of a Preissmann slot enables the same set of equations for regions of both free surface and full bore flow, it does introduce errors into the solution. The scale and nature of these errors are directly linked to the size and geometry of the slot. For example, narrow slots can result in terminal numerical instabilities, particularly when the water level is close to the pipe crown, whilst wide slots can lead to significant continuity errors and unrealistically low full bore celerities14. This latter point can be appreciated by noting that full bore wave celerity is a function of pipe and fluid charcteristics3, and is generally of the order of 1200m/s, whilst free surface wave celerity is inversely proportional to flow surface width T $\left(c = \sqrt{gA/T}\right)$, and is generally less than10m/s; hence, unless the flow surface width (slot width) is insignificant compared to flow area, the calculated wave celerity will be significantly lower than its true full bore value. To minimise numerical instabilities, it is common practice to use some form of pipe-slot "transition", whereby the slot width gradually decreases with height. One such transition is given by15:

(15)

$$T/D = 0.05423.\exp\left(-\left(H/D\right)\right)$$

Where T is slot width, D is pipe diameter and H is pressure head. Whilst the pipe-slot transition described by Equation(15) can help reduce numerical instabilities, it can still lead to unrealistically low full bore wave celerities; for example, within a 100mm diameter pipe the full bore celerity at a 150mm pressure head would only be ~9m/s as opposed to its true value of ~1200m/s. In addition to underestimating transient pressures and overestimating transient travel times, the use of unrealistically low wave celerities also makes the transition to the third numerical solution approach (purely full bore conditions described using MOC) inherently unstable, as the disparity between the Preissmann slot and true full bore celerities is too great to allow a smooth numerical solution. To overcome this, and bring wave celerities up to comparable values for full bore flow conditions, a new Time Varying Preissmann Slot(TVPS) is introduced. This is achieved by introducing a time dependent power (F) into the pipe-slot transition relationship, thus:

4.3 Full bore conditions-

Once the conditions within a complete pipe reach have become full bore, and the wave celerities within the TVPS have attained values comparable to their true values, the solution technique switches from MacCormack TVD to the classical MOC solution of the governing equations of full bore flow. Whilst switching to a third solution technique adds additional computational complexity, it removes the inaccuracies inherent in utilising the free surface equations for full bore conditions and enables sub-atmospheric pressure waves to be accurately simulated. The form of the equations used, and the precise solution procedure, for the MOC technique can be found in any reputable text book dealing with fluid tranisents3.

4.4. Boundary conditions-

When using any of the techniques detailed above, it is necessary to supply information to the solution at pipe boundaries in the form of Boundary Conditions (BCs). Such conditions normally comprise of a set of equations, including steady flow relationships, conservation equations(continuity, momentum and energy) and available characteristic equations. Within building drainage networks, BCs have been developed previously to represent commonly occurring appliance discharges and pipe junctions within the DRAINET building drainage model2. Whilst these existing BCs can be readily utilised in conjunction with the new model methodology detailed herein, a number of new BCs are required to fully represent local drainage systems.

6 Conclusions and recommendations for future work-

The simulation or purely free surface or purely full bore flow conditions within drainage systems is relatively straightforward, but the accurate determination of mixed flow conditions is significantly more complex. Consequently, whilst there are a number of fully dynamic modelling suites targeted at large scale urban drainage systems, there are no similar models to accurately simulate mixed flow conditions within building and local drainage systems. In response, a new numerical modelling technique has been developed to accurately simulate the full range of flow conditions that may occur within building and local drainage systems under all realistic scenarios. This technique employs a variety of different solution methods, including the introduction of a novel Time Varying Preissmann Slot (TVPS) to minimise continuity errors and ensure full bore comparable wave celerities. Experimental work is now underway to further validate the developed modelling technique. Once validation is completed, the technique will be incorporated into the existing DRAINET building drainage model and a new 1-D finite difference numerical model for the simulation of flow conditions within local drainage systems. In tandem, work is also continuing on developing the necessary additional BCs and on further minimising the numerical errors associated with the TVPS.

References-

1. Li J. and McCorquodale A. (1999). Modelling mixed flow in storm sewers. Journal of Hydraulic Engineering. Vol. 25, No. 11.
2. Wise A.F.E. and Swaffield J.A. (2002). Water, sanitary and waste services for buildings. Butterworth.
3. Fox J.A. (1977). Hydraulic analysis of unsteady flow in pipe networks. Macmillian.
4. Cardle J.A. and Song C.C.S (1988). Mathematical modelling of unsteady flow in storm sewers. International Journal of Engineering Fluid Mechanics. Vol. 1, No. 4, pp 495-518.
5. Toro E. (2000). Shock capturing methods for free surface shallow flows. Wiley.
6. Vasconcelos J.G., Wright S.J. and Roe P.L. (2006). Improved simulation of flow regime transition in sewers: two-component pressure approach. Journal of Hydraulic Engineering. Vol. 132, No. 6.
7. Wright G.B., Swaffield J.A and Arthur S. (2006). Numerical simulation of the dynamic operation of siphonic roof drainage systems. Building and Environment. Vol. 41, No.
9, pp 1279-1290.
8. Capart H., Sillen X. and Zech Y. (1997). Numerical and experimental water transients in sewer pipes. Journal of Hydraulic Research. Vol. 35, No. 5, pp 659-672.
9. Djordjevic S., Prodanovic D. and Walters G.A. (2004). Simulation of transcritical flow in pipe/channel networks. Journal of Hydraulic Engineering. Vol. 130, No. 12, pp 1167-1178.
10. BSI (1998). Drain and sewer systems outside buildings. Hydraulic design and environmental considerations. BS EN 752-4:1998.
11. BSI (2000). Gravity drainage systems inside buildings - Part 2: Sanitary pipework, layout and calculation. BS EN 12056-2:2000.
12. MacCormack R.W. (1971) Numerical solution of the interaction of a shock wave with a laminar boundary layer. Proceedings of second international conference on numerical methods in fluid dynamics. Berlin.
13. Liang D., Falconer R.A. and Lin B. (2006). Comparison between TVD-MacCormack and ADI-type solvers of the shallow water equations. Advances in Water Resources. Vol29, No 12, pp. 1833-1845.
14. Leon A.S., Ghidaoui M.S., Schmidt A.R., Garcia M.H. (2006). Godunov-type solutions for transient flows in sewers. Journal of Hydraulic Engineering. Vol 132, No 8, pp 800-813.
15. Sjoberg A. (1982). Sewer Network Models DAGVL-A and DAGVt-Dim. Urban Stormwater Hydraulics and Hydrology. (B. C. Yen, Ed.). Water Resources Publications. Littleton, Colorado. pp 127-136.