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The performance characteristics of multi-outlet siphonic roof drainage systems

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Siphonic roof drainage systems have been in existence for approximately 30 years, and are becoming an increasingly common element of urban drainage infrastructure. In that time, the construction sector in most developed countries have been gradually persuaded of the benefits that these systems offer when compared to conventional roof drainage technologies. The work reported herein details an ongoing UK government-funded research programme to investigate the performance characteristics of multi-outlet siphonic roof drainage systems. The experimental aims, apparatus and procedures are described, and results are illustrated. In addition, 'real' data obtained from three installed siphonic roof drainage systems are discussed. Conclusions are drawn regarding the performance characteristics of multi-outlet systems, and plans for future work are outlined.

1 Introduction

1.1 Conventional roof drainage systems

Conventional roof drainage systems generally consist of a network of collection gutters connected, via open outlets, to vertical downpipes. The system components are sized to ensure annular flow through the downpipes with a continuous central air path, and system pressures therefore remain close to atmospheric.[1] Consequently, the driving head for flow within conventional roof drainage systems is limited to the gutter flow depths, which results in relatively low flow velocities within the system. This inefficient use of pipework necessitates many, relatively large diameter, downpipes (typically 150 mm) each of which must be connected into a suitable underground drainage network. Furthermore, the dimensions/gradients of the gutters and the underground drainage network must be designed to ensure sufficient capacity and self-cleansing flow velocities.

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1.2 Siphonic roof drainage systems

In contrast to conventional systems, the siphonic approach to roof drainage aims to restrict the ingress of air into the system, and hence induce the full-bore flow conditions necessary for siphonic action. This is achieved by utilizing specially designed gutter outlets, such as those shown in Figure 1, in conjunction with smaller diameter pipework. Once all of the air has been purged from the system, siphonic action occurs and the system is said to have primed. Although siphonic gutter outlets normally incorporate vortex-reducing elements, the turbulent gutter flow conditions will invariably result in small quantities of entrained air entering the system (up to 10%[2]), even when the outlets are fully submerged.

At its specific design condition, the driving head within a siphonic roof drainage system can be equal to the gutter flow depths *plus* the full vertical height between the outlets and the point of discharge. This yields significantly higher flow velocities than is possible in conventional

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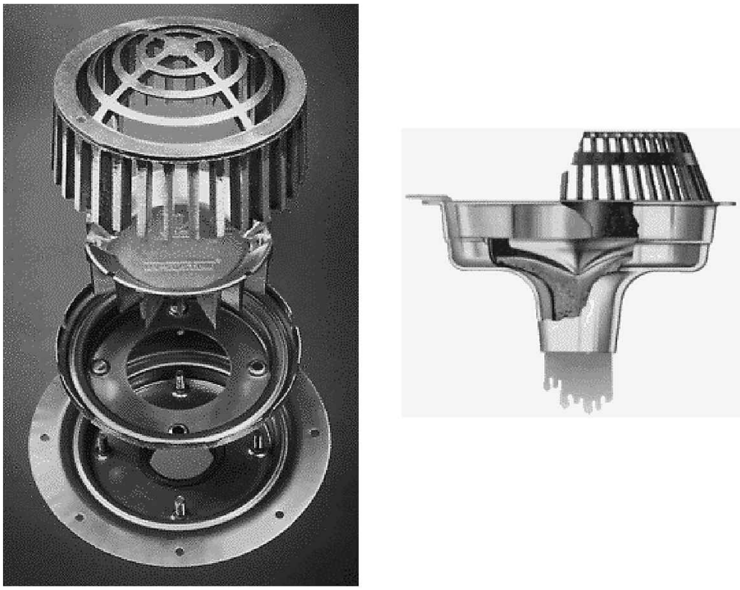

Figure 1 Typical siphonic gutter outlets (reproduced with permission)

systems, which means that attaining self-cleansing velocities is rarely a problem and more than one outlet can be connected to a single downpipe. As the flow is full-bore and depressurized, there is considerably more flexibility in pipe routing, allowing most of the horizontal collection pipework to be located just below roof level, and reducing the extent of costly underground drainage networks. In addition to these operational benefits, the small diameter pipework employed in siphonic roof drainage systems can have less of an architectural impact than conventional systems, and may even be incorporated within the building itself.

A siphonic roof drainage system will only operate efficiently at its design condition, e.g., a 1 in 30 year rainfall event; that is, only one rainfall event matches any particular system. (The situation is slightly different where 'secondary' systems have been installed. Typically, the 'primary' system will drain rainfall events up to a predetermined notational return period. Beyond that level, runoff passes over weirs in the gutter and enters a 'secondary' system[3]). Consequently, a siphonic system will rarely, if ever, operate at its design condition. If a siphonic system is exposed to a rainfall event which exceeds the design criteria, flooding may occur and the system may fail due to gutter overtopping. The more likely scenario is that a system will be exposed to a rainfall event below the design criteria. When this occurs, the flow conditions will differ from those in a fully primed system, their exact nature depending on the specific characteristics of the rainfall event. Similar conditions can occur if the flow distribution between gutter outlets is not as per design, possibly as a result of poorly installed roof surfaces/gutters or wind-driven rainfall. Another disadvantage of siphonic roof drainage systems is that the restrictive outlets and small diameter pipework are relatively easily blocked by detritus in the flow, e.g. leaves. If a regular maintenance programme is not adhered to, this can lead to operational problems and system failure.[4]

2 Current state of siphonic roof drainage technology

Since their development in Scandinavia in the late 1960s, siphonic roof drainage systems have gradually become accepted by the construction sector in most developed countries. Their high capacities and low architectural impact have made them particularly popular for large, prestigious developments such as airports and major sporting stadia, e.g., Chep Lap Kok Airport (Hong Kong) and The Olympic Stadium (Sydney, Australia). Despite this, siphonic roof drainage systems are virtually unheard of in the USA, with the authors knowing of only one such installation.[5] The lack of acceptance of such technology in the USA may be due to a lack of understanding of the underlying principles of siphonic systems and problems involved in changing the necessary regulatory codes. Interestingly, there is no specific European standard for siphonic roof drainage systems.

Current design practice assumes that, for the specified design criteria, a siphonic system fills and primes rapidly with 100% water. This assumption allows siphonic roof drainage systems to be designed utilizing steady state hydraulic theory. The steady flow energy equation is normally employed,[2,6] with the elevation difference between the outlets and the point of discharge being equated to the head losses in the system. Although this design approach neglects the small quantities of entrained air that always enter a siphonic roof drainage system, it has been reported to yield operational characteristics similar to those observed in laboratory test rigs at the fully primed state.[2,7] However, steady state design methods are not applicable when a siphonic system is exposed to a rainfall event below the design criteria, when the flow may contain substantial quantities of air, or an event with time-varying rainfall intensity. As such events are the norm, it is clear that current design methods may not be suitable for determining the day-to-day performance characteristics of siphonic roof drainage systems. This is a major disadvantage, as it is during these events that the majority of operational problems tend to occur, e.g., noise, vibration and flooding.

In addition to these considerations, a number of more serious problems have occurred with specific siphonic roof drainage installations. These include a UK manufacturing plant, where the site layout necessitated the use of a ‘U-bend’ arrangement to connect the siphonic roof drainage system under an existing road, and into the surface water sewer network. Following installation, the gutters were observed regularly to overtop during insubstantial rainfall events. Inspection of the system indicated that this was due to the large air pocket that formed in the upward leg of the ‘U-bend’ arrangement, i.e., the gutters overtopped before the system pressures had built up to the levels necessary to purge the system of this air. It is considered unlikely that current design methods would be capable of predicting this type of system failure. Another interesting example of the failure of a siphonic roof drainage system occurred at a storage depot in southern England. In this case, the siphonic system was subjected to a rainfall event which, although substantial, was less than the total system capacity (design capacity plus emergency provision). The resulting system pressures dropped below approximately -8 mH_20, causing the pipes to implode. This resulted in a reduction in system capacity, which led to overtopping of the gutters, flooding of the facility and an insured loss of several million pounds. Failures such as this illustrate the importance of considering system pressures, as well as total system capacity, during the design process.

It should be noted that, although the siphonic roof drainage industry and its clients are understandably reticent in publicizing problems, it is considered that the number of system failures is only a tiny percentage of the large number of systems installed throughout the world. Furthermore, there is no evidence to suggest that siphonic systems are more prone to failure than conventional systems. Blockages remain the most common cause of operational problems and system failures, and these can be avoided with a regular maintenance programme.

3 Previous relevant research

Although siphonic roof drainage systems have been in existence for approximately 30 years, it has only been since the mid-1990s that substantial research has been reported.[7] In terms of the priming of single outlet siphonic roof drainage systems, previous laboratory-based research at Heriot-Watt University, Edinburgh, has identified a number of distinct phases, including the formation of full-bore flow conditions and the movement of trapped air pockets.[7] The results of this work have been used as the basis of a numerical model capable of simulating the priming of single-outlet siphonic systems.[8]

Further laboratory experimental work has confirmed that, at rainfall intensities less than 40% of the fully primed system capacity, single-outlet siphonic systems act in a similar manner to conventional roof drainage systems.[7] This work also confirmed the unsteady nature of the flow conditions within siphonic systems at rainfall intensities above 40% of the fully primed system capacity. Such conditions were shown to be characterized by cyclical variations in gutter water levels and system pressures, and were observed to result in large quantities of air being drawn into the system, leading to noise generation and structural vibration.

4 Description of research programme

The main aim of the research detailed in this paper is to extend the existing numerical model to enable the simulation of multi-outlet siphonic roof drainage systems. In this context, the term multi-outlet siphonic roof drainage system refers to a system where more than one gutter outlet is connected to the same downpipe. In order to achieve this aim, it was first necessary to gain a better understanding of the conditions occurring within such systems, with particular reference to priming and the effect of different gutter inflow combinations. This was accomplished through laboratory experimental work and field observations.

5 Laboratory investigation

5.1 Overview

Experimental work was undertaken using the laboratory test rig detailed in Figure 2. To ensure realistic flow conditions, each gutter was fed via a rear supply trough and a simulated sloping roof. Pressure transducers were installed in the base of the gutters to measure flow depths, and in the crown of the connected horizontal pipework to measure system pressures. In addition, magnetic induction flowmeters were used to measure the gutter inflow rates. The transducers and flowmeters were connected to a PC-based data acquisition system, capable of sampling data at frequencies of up to 30 kHz. All the pipework was transparent, allowing direct observations and high-speed video capture to assist identification of relevant flow conditions.

Using the equipment detailed above, laboratory experiments were undertaken to determine the flow conditions arising as a result of the following realistic scenarios:

- design criteria rainfall events (fully primed system) – constant gutter inflows;
- rainfall events below the design criteria;
- design criteria rainfall events (fully primed system) – varying gutter inflows;
- rainfall events above the design criteria;
- total blockage of one of the outlets.

In addition to the above, experimental work was also undertaken to determine the effect, upon system performance, of different types of system terminations. This was considered an essential element of the investigation, as it is this section which provides the interface between the siphonic roof drainage system and the connecting drainage network.

With reference to Figure 2 and the experimental data detailed herein, *branch 1* refers to the pipework connecting *gutter 1* to the branch junction, *branch 2* refers to the pipework connecting *gutter 2* to the branch junction and *common pipe* refers to the pipework downstream of the branch junction. It should also be noted that, unless otherwise stated, the gutter inflow rates

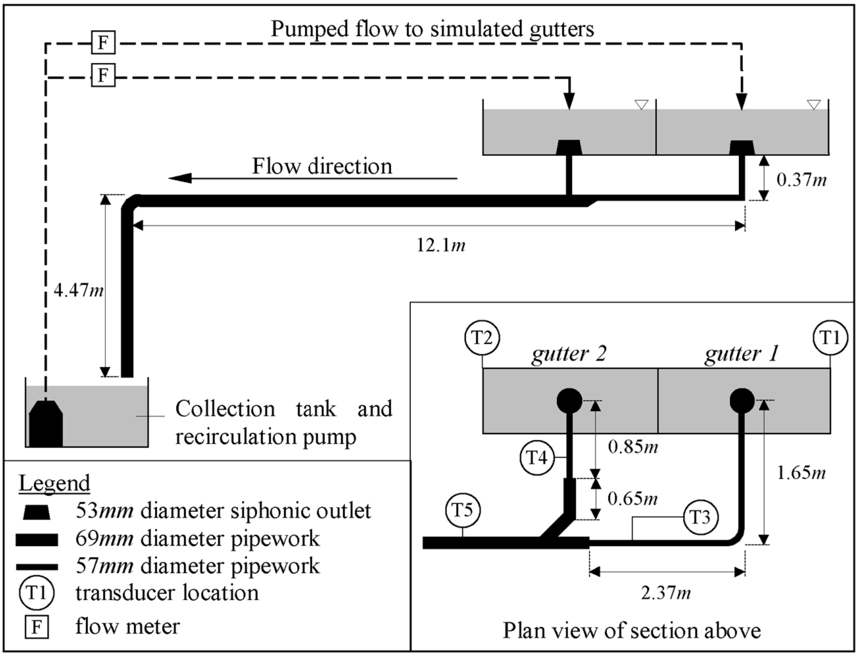

Figure 2 Schematic view of the siphonic roof drainage test rig. The capacity of the system is the same as 75 mm/h falling on a 665 m^2 roof – all drained via a 69-mm diameter pipe.

were constant throughout the testing periods, i.e., the simulated rainfall events were assumed 'instantaneously' to reach a constant intensity.

5.2 Design criteria rainfall event (fully primed system) – constant gutter inflows

Priming of the laboratory siphonic test rig was observed to occur when the inflow to gutter 1 was set to 5.85 l/s and the inflow to gutter 2 was set to 7.78 l/s. As the two gutters were located at the same elevation above the point of discharge, the difference in inflows required for siphonic conditions was due solely to the different branch configurations. This is highlighted by inspection of Figure 2, which indicates that the head losses associated with the branch 2 configuration would be significantly less than those associated with the branch 1 configuration. The priming procedure of the siphonic test rig was generally observed to occur as follows:

1) *Initial gutter inflow:* At the start of the simulated rainfall event, the gutter water levels and the system inflows were relatively low, leading to free surface, subcritical flow within the horizontal pipework and annular flow within the vertical pipework.
2) *Formation and movement of hydraulic jumps:* As the gutter water levels increased, so the system inflows increased, leading to supercritical flow at the upstream end of the branches and the formation of hydraulic jumps immediately upstream of the branch junction (refer to Figure 3a). As the system inflows increased further, the hydraulic jump in branch 1 moved upstream and its height increased. Similar observations were made with respect to the flow conditions in branch 2, although the upstream movement of the hydraulic jump was less marked.
3) *Formation and propagation of full-bore flow:* Eventually the downstream depth of the hydraulic jump in branch 1 became equal to that of the pipe diameter, and full-bore flow developed (refer to Figure 3b). Once full-

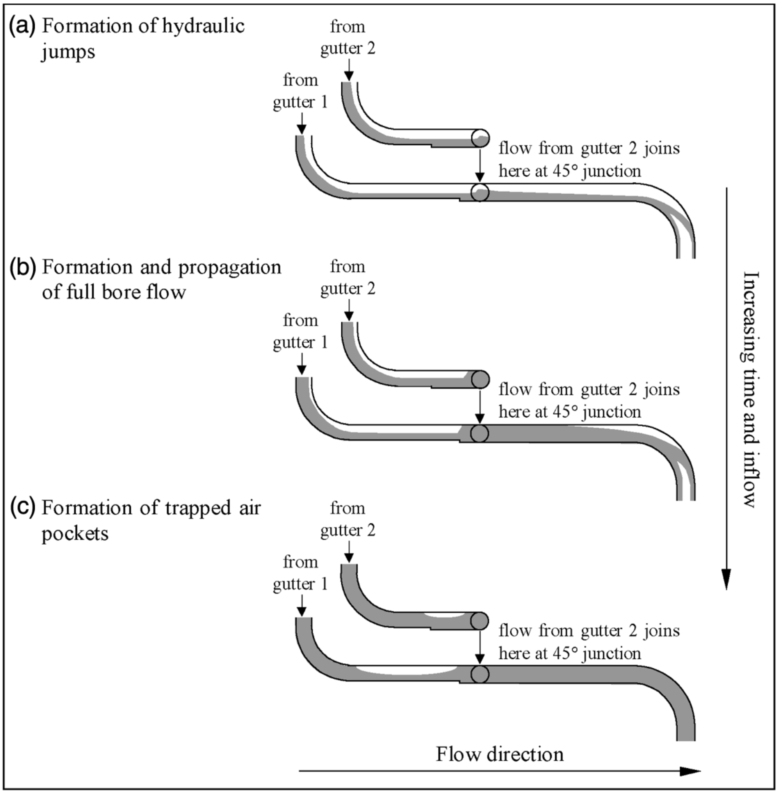

Figure 3 Priming process of the siphonic roof drainage test rig

bore flow conditions formed, they were seen to propagate downstream into the common pipe and, to a lesser extent, further upstream into branch 1. Similar observations were made with respect to the flow conditions in branch 2, although the propagation of full-bore flow was less marked.

4) *Depressurization of flow:* When full-bore flow conditions reached the vertical section of the common pipe, the mass of water collecting in the vertical pipework caused depressurization of the system, which resulted in an increase in the system inflows. This led to the development of full-bore flow conditions at the upstream ends of both branches. In turn, this trapped volumes of air between the hydraulic jumps and the upstream end of the branches (refer to Figure 3c). The volume of air trapped in branch 2 was significantly less than that trapped in branch 1.
5) *Partial repressurization of flow:* As the system inflows continued to increase, the air-pocket trapped in branch 1 moved downstream at the local velocity of the flow. When this air pocket passed into the vertical pipework it caused a partial repressurization of the entire system. The smaller airpocket in branch 2 also moved downstream, although it appeared to become mixed with the water at the branch junction, forming a 'bubbly flow' that did not have such a significant effect on system pressures.
6) *Fully primed system:* Once all of the initial air pockets had left the downstream end of the vertical downpipe, the pressures decreased and remained relatively constant. The system was then fully primed, although

it was observed that small quantities of entrained air continued to enter with the water inflows.

The gutter depths and system pressures recorded during the priming of the siphonic test rig are shown in Figure 4. The time lag between pressure peaks clearly illustrates that the repressurization wave was generated at the downstream end of the common pipe, and propagated upstream. The 0.04 s time lag shown between transducers 3 and 5, which were 2.3 m apart, yields a wave propagation velocity of 57.5 m/s. Noting that the laboratory pipework was not restrained against radial or longitudinal movement, an iterative solution of the appropriate wave speed equation[9] yields an air content of 5.4% for a wave propagation velocity of 57.5 m/s. Although this can only be considered to be an approximation of the actual air content within the flow, it is of a similar magnitude to that previously estimated for single-outlet systems.[7]

Employing a design program used by industry, it was predicted that siphonic conditions would occur at the measured gutter inflow rates if the internal roughness of the pipework was 0.028 mm. Although such a roughness value is considered to be reasonable for the type of pipework employed in the laboratory test rig, the system pressures predicted by the design program were up to ~40% lower than those actually measured in the laboratory. These discrepancies were considered to be due to inaccuracies in the predicted head losses across fittings and the simplifying assumptions employed within the program.

The recorded data and observations confirm that the priming process for a multi-outlet siphonic system is similar to that which occurs with a single-outlet siphonic system.[7] The only significant difference is that the increased complexity of the multi-outlet system results in more complex flow conditions, particularly with respect to the formation and movement of trapped air within the system. This is evidenced by the variable nature of the pressure traces prior to the priming of the system. This was also con-

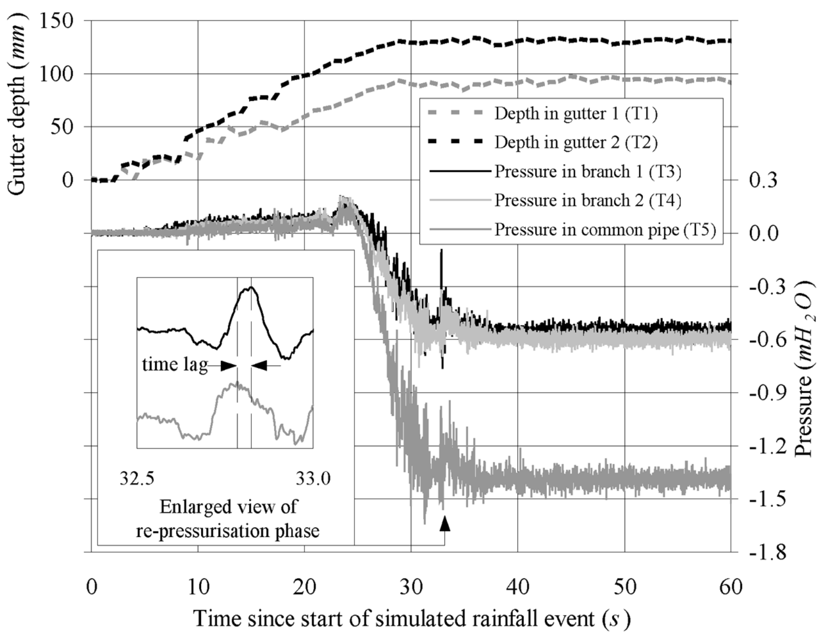

Figure 4 Measured gutter depths and system pressures for the design criteria rainfall event (gutter 1) inflow = 5.85 l/s, gutter 2 inflow = 7.78 l/s. These data illustrates that even when fully primed (40–60 s) the pressures are not truly 'steady'.

firmed during the experimental work, where it was observed that the movement of the air pocket from branch 2 occasionally varied from the general case outlined previously. High-speed video footage indicated that the air pocket from branch 2 would move downstream as a single entity if it reached the branch junction at the same time as the air pocket from branch 1. If it reached the junction after the air pocket from branch 1, the full-bore flow conditions at the junction represented such a restriction that the air pocket could not move downstream as a single entity. Instead, the turbulent conditions in this region led to the formation and downstream movement of a section of 'bubbly flow' (air and water mixture).

5.3 Rainfall events below the design criteria

Experimental work has indicated that, at flow rates up to approximately 15% of the design criteria inflows, the laboratory test rig behaved as a conventional roof drainage system; that is, the flow conditions remained free surface/annular throughout. At all other flow rates below the design criteria inflows, the system conditions were observed to be unsteady. With reference to Figure 5, it was determined that the flow would exhibit one of the following sets of characteristics:

1) *Regime 1 – system inflows between 15% and 40% of the design criteria inflows:* These levels of inflow resulted in highly unsteady conditions, characterized by cyclical periods of positive and negative pressures. Such conditions were caused by low gutter flow depths, which meant that siphonic action could only be sustained for short periods, i.e., once initiated, siphonic action would quickly drain one or both of the gutters, creating an airpath to the atmosphere and hence breaking the siphon.
2) *Regime 2 – system inflows between 40% and 60% of the design criteria inflows:* These levels of inflow resulted in oscillating, constantly negative system pressures that were above those associated with the fully primed system. Such conditions were caused by intermediate gutter flow depths, which were sufficiently high to ensure a continuous siphonic action but were not high enough to 'swamp' the vortices that occurred around the gutter outlets. These vortices led to large amounts of air being entrained into the water flows, which in turn resulted in lower flow rates and higher pressures than those associated with the fully primed system (95–100% water).
3) *Regime 3 – system inflows above 60% of the design criteria inflows:* At these levels of inflow, the system pressures initially mirrored those occurring in a fully primed system, although they shortly returned to the type of higher, oscillatory pressures associated with Regime 2. Such conditions arose as the gutter flow depths were only sufficient to sustain full siphonic action for a short period. After this, the gutter depths decreased to levels that enabled large quantities of air to become entrained with the water inflows.

In general, it was determined that, with the inflow to one of the gutters fixed at a constant rate, increasing the inflow into the remaining gutter resulted in steadier and lower system pressures. This was as expected, as an increase in total system inflow leads to a decrease in the volume of air being drawn into the system together with an increase in energy losses. It was also apparent that, for the same total system inflow, overtopping became less likely as the ratio of the gutter inflows ($Q_{\text{gutter 1}}$:$Q_{\text{gutter 2}}$) approached that of the fully primed system (7.78:5.85 $\approx$ 1.33:1). This was again as expected, a more even gutter flow distribution increasing the probability of siphonic operation.

The disparity between the transition from free surface/annular to unsteady/siphonic conditions in the multi-outlet system and the single-outlet system[7] mentioned previously is considered to be due to the smaller pipe diameters employed and the flow distorting effect of the branch junction in the multi-outlet system.

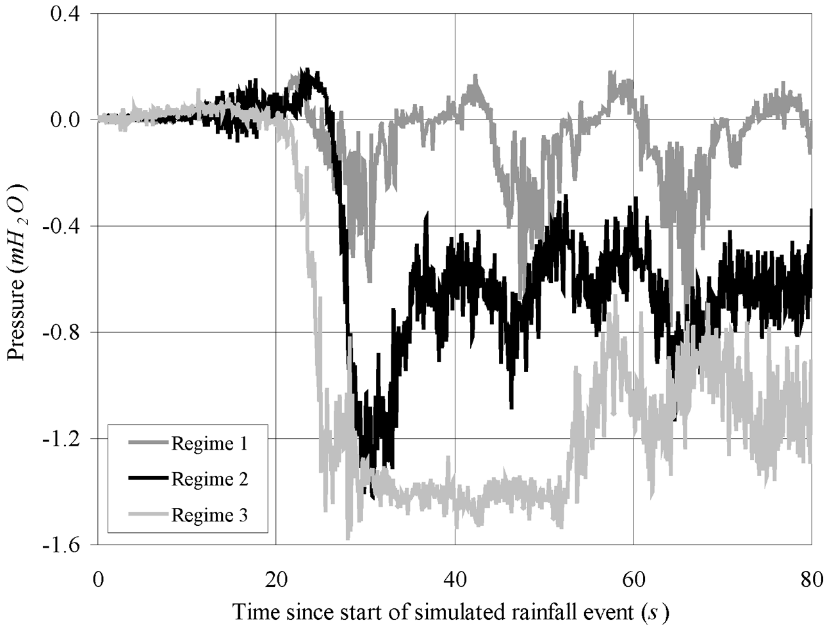

Figure 5 Measured common pipe pressure (T5) for three rainfall events below the design criteria. These data illustrate the flow regimes which can result in vibration and noise generation.

5.4 Design criteria rainfall event (fully primed system) – varying gutter inflows

As many real rainfall events progressively build in intensity, experimental work was undertaken to assess the effect of gradually increasing the gutter inflows up to design criteria levels. The only significant difference between these results and those obtained with constant gutter inflows was that it took longer for the system pressures and gutter flow depths to build up to the those necessary purge the air from the system, and initiate siphonic action

Additional experimental work was also undertaken to determine the effect of staggering the gutter inflow start times, which would represent systems incorporating widely varying roof geometries, e.g., one gutter outlet serving a steeply pitched roof and one gutter outlet serving a shallower pitched roof. As may be appreciated, the resulting flow conditions were very complicated, exhibiting two or three of the unsteady flow regimes identified previously. However, it was apparent from the data collected that, after a short period at the design criteria inflows, the gutter flow depths and system pressures mirrored those obtained with synchronized inflow start times (refer to Figure 4).

5.5 Rainfall events above the design criteria

Laboratory experiments undertaken with rainfall events above the design criteria indicated that the system pressures were almost identical to those obtained at the design condition. However, the additional system inflows above the design criteria levels resulted in continuously increasing gutter depths, which would have eventually lead to overtopping of the gutter(s). If the slight variations in driving head associated with higher gutter depths are disregarded, these observations confirm that the system pressures occurring once a siphonic system has become primed are the minimum possible, and the capacity is the maximum possible, for that particular system.

5.6 Total blockage of one of the outlets

An example of the data obtained from laboratory experiments undertaken with one of the out-

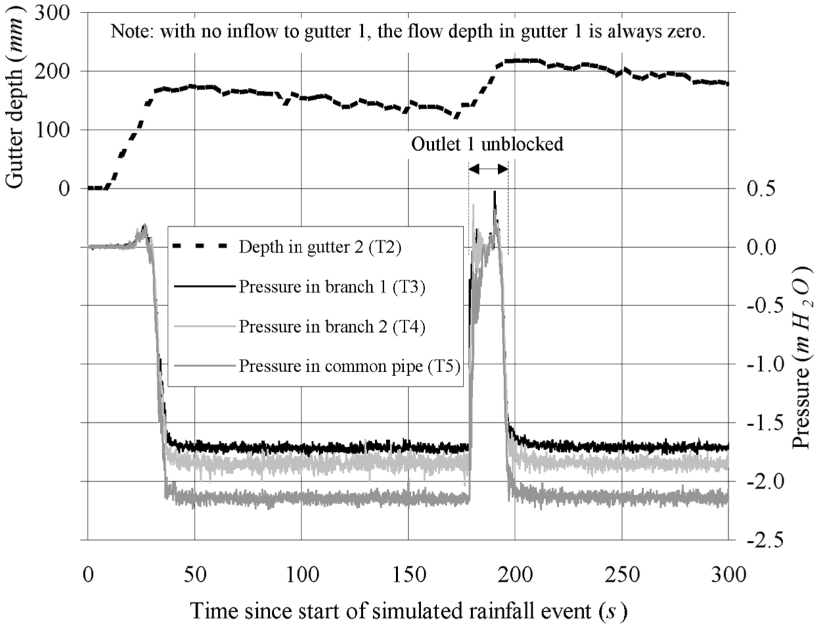

Figure 6 Measured gutter depths and system pressures with the outlet in gutter 1 blocked/unblocked/blocked (gutter 1 inflow = 0 l/s, gutter 2 inflow = 11.3 l/s).

lets blocked is shown in Figure 6. This scenario seeks to represent the sudden blockage of an outlet caused by detritus in the flow. It can be seen that, whilst the outlet in gutter 1 (outlet 1) was completely blocked (0–178 s), the laboratory test rig acted as a single-outlet siphonic system, with the pressures stabilized at the relevant fully primed levels and the flow depth in gutter 2 approaching a steady state. Table 1 summarizes the salient system conditions pertaining to Figure 6, when outlet 1 was blocked, and Figure 4, when both outlets were open. As shown, although the total system capacity was lower with outlet 1 blocked, the capacity of the open outlet in gutter 2 was actually higher than was the case in an unblocked system. The data in Table 1 also highlight that system pressures were considerably lower when outlet 1 was blocked. This would indicate that, if a system were designed to operate at pressures below approximately −7 mH_2O, a complete blockage of one of the outlets might result in the onset of cavitation and/or failure of the system by pipe deformation.

Figure 6 also indicates that, when outlet 1 was unblocked (178–197 s), the system quickly reverted to a multi-outlet mode of operation. As experimental restrictions meant that there could be no inflow into gutter 1, an airpath to the atmosphere was created, leading to the cessation of siphonic action, an increase in system press-

Table 1 Measured system conditions with outlet 1 unblocked and blocked

Outlet blocked	Fully primed capacity (l/s)	Capacity of outlet in gutter 2 (l/s)	Minimum measured pressure (mH_2O)		
			Transducer 1	Transducer 2	Transducer 3
None	13.63	7.78	−0.552	−0.595	−1.388
Outlet 1	11.30	11.30	−1.719	−1.846	−2.147

ures and a decrease in system flow rates. This resulted in a very rapid increase in the water level within gutter 2, and would have led to overtopping of this gutter if outlet 1 was not re-blocked (after 197 s). In real situations, the water collected in a gutter whose outlet is blocked would prevent such dramatic pressure changes occurring when the outlet became unblocked. However, these data do indicate the operational problems that could occur in a multi-outlet siphonic system if one of the outlets is not submerged and is allowing large quantities of air to enter the system.

5.7 Effect of different system termination configurations

To ensure the efficient operation of a siphonic roof drainage system, it is essential that full-bore flow conditions are broken before any connection to the surface water sewer network. If not, the flows within the siphonic system and the sewer network may interact, leading to unpredictable conditions and potential problems. Breaking of full-bore flow conditions can only be guaranteed by ensuring that the flow exits the siphonic system above the highest water level in the surface water sewer. However, as surface water sewers are normally designed to a lower level of risk than roof drainage systems, it is clear that a rainfall event which causes the priming of a siphonic roof drainage system may also cause surcharging of the downstream surface water sewer, a scenario that could lead to the type of flow interactions discussed above. Therefore, experimental work was undertaken to determine the effect of terminating a siphonic roof drainage system under water. In addition, data was also collected to determine the effect of a right-angled termination, which often proves necessary due to the site layout. The four different system terminations that were investigated are shown in Figure 7. It should be noted that, due to space restrictions, the length of the vertical downpipe in these configurations was reduced to 4.07 m.

As the driving head for a siphonic roof drainage system is defined as the elevation difference between the gutter outlets and the point of discharge (free discharge case) or the point at which the downpipe enters water (submerged discharge case), it can be deduced from Figure 7 that the driving head for each of the four configurations was different. In addition, it is clear from Figure 7 that the head losses associated with each of the four configurations varied. As a result, the gutter inflows necessary to cause priming of the four different configurations were different. From the data shown in Table 2, it is clear that the use of any configuration other than a freely discharging vertical downpipe will result in a lower system capacity.

Figure 8a and b shows a sample of the experimental data obtained using the four different termination configurations. As shown, the configurations that discharged under water resulted in significantly longer priming times and higher gutter flow depths than those discharging directly to the atmosphere. This was because greater (positive) system pressures were required to purge the initial air pockets.

The experimental data discussed above highlight the importance of the interface between a siphonic roof drainage system and a surface water sewer. For example, consider the conditions within a siphonic roof drainage system during a severe rainfall event. Theoretically, there should be no operational problems if the rainfall intensity is less than the design criteria. However, if the downstream surface water sewer happens to surcharge, and the water level in the manhole rises above that of the siphonic system discharge point, the driving head of the siphonic system will reduce. This could increase the time required to prime the system, and will certainly reduce the total capacity of the system. Such a scenario could lead to failure of the system by gutter overtopping.

6 Field observations

To complement the laboratory investigation, flow conditions have been monitored within three siphonic roof drainage systems installed at the National Archives of Scotland Document

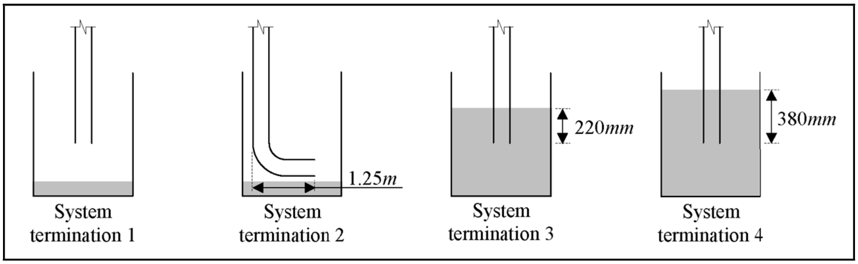

Figure 7 Siphonic system termination configurations investigated

Table 2 Variation in design criteria gutter inflows with termination configuration

System termination type	Fully primed capacity (l/s)		Fully primed capacity (as % of type 1 inflows)	
	Gutter 1	Gutter 2	Gutter 1	Gutter 2
1	7.46	5.71	100	100
2	7.35	5.45	98.5	95.4
3	7.28	5.54	97.6	97.0
4	7.11	5.57	95.3	97.5

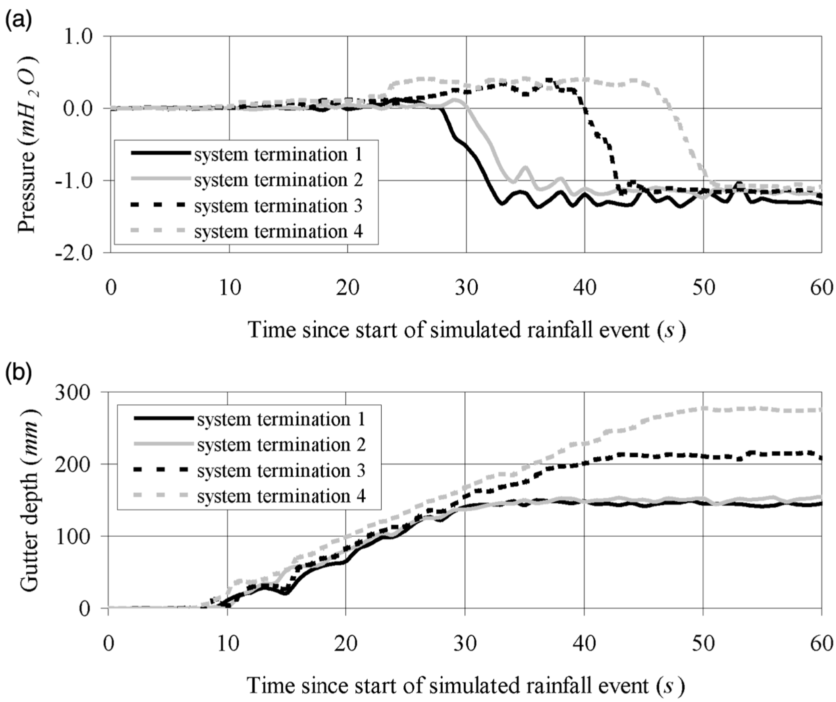

Figure 8 (a) Variation in common pipe pressure (T5) with system termination configuration (fully primed conditions). (b) Variation in gutter 1 flow depth (T1) with system termination configuration (fully primed conditions)

Repository Building, Edinburgh. Whilst a detailed description of the monitoring equipment and protocols is given elsewhere,[10] a schematic of the systems that are being monitored is shown in Figure 9. Since June 2000, system pressures have been recorded when the rainfall intensity exceeds 5 mm/h, and rainfall intensities have been recorded using a tipping-bucket rain gauge. In addition, gutter flow depths have been monitored since September 2001 using modified air pressure transducers.

As anticipated, the vast majority of the recorded rainfall events have been below the design criteria of the monitored systems, and much of these data have confirmed the laboratory findings. The data shown in Figure 10 represents the most significant rainfall event, in terms of prolonged siphonic action, that has been recorded to date. This event had a maximum rainfall intensity of 105 mm/h, which equates to a return period of 32 years,[11] and appeared to result in continuous siphonic action for a period of approximately 500 s.

An analysis of the field data collected to date indicates that 7% of recorded events resulted in prolonged siphonic action and 50% of recorded events resulted in significant negative system pressures.

7 Development of the numerical model

As stated previously, the existing numerical model developed at Heriot-Watt University (SIPHONET[12]) is capable of simulating the priming phase of a single-outlet siphonic roof drainage system. This model utilizes a method of characteristics-based solution technique, which has been employed successfully at Heriot-Watt University in the simulation of both free surface and full-bore flow conditions. However, during the development of the model it became clear that the method of characteristics may not be particularly suited to the simulation of moving hydraulic jumps. In addition, numerical stability problems were also encountered with the transition between free surface and full-bore flow conditions. As these deficiencies would become more limiting in the more complex case of multi-outlet systems, it was decided to employ a new modelling approach. This will incorporate the Lax–Wendroff finite difference solution technique.[13]

8 Conclusions and future work

The conclusions of this ongoing research programme may be summarized as follows:

- The priming of a multi-outlet siphonic roof drainage system is similar, although more complex, to that of a single-outlet system.
- Current design programs may yield inaccurate system pressures, which could lead to operational problems and/or system failure.
- At rainfall intensities below the design criteria, the flow conditions within a multi-outlet

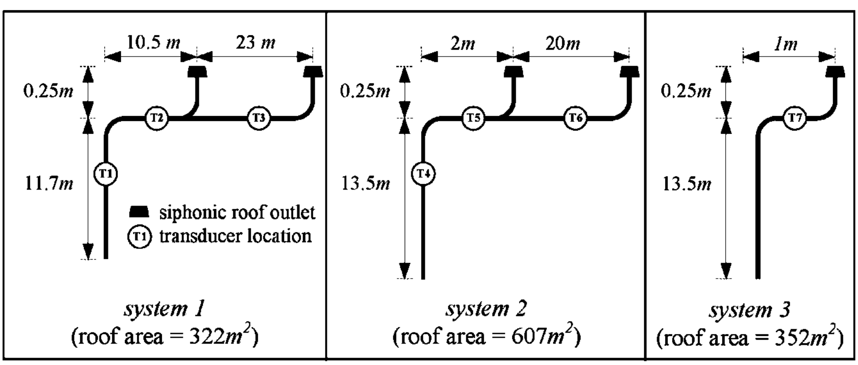

Figure 9 Schematic of the siphonic roof drainage systems being monitored at the National Archives of Scotland Document Repository Building, Edinburgh.

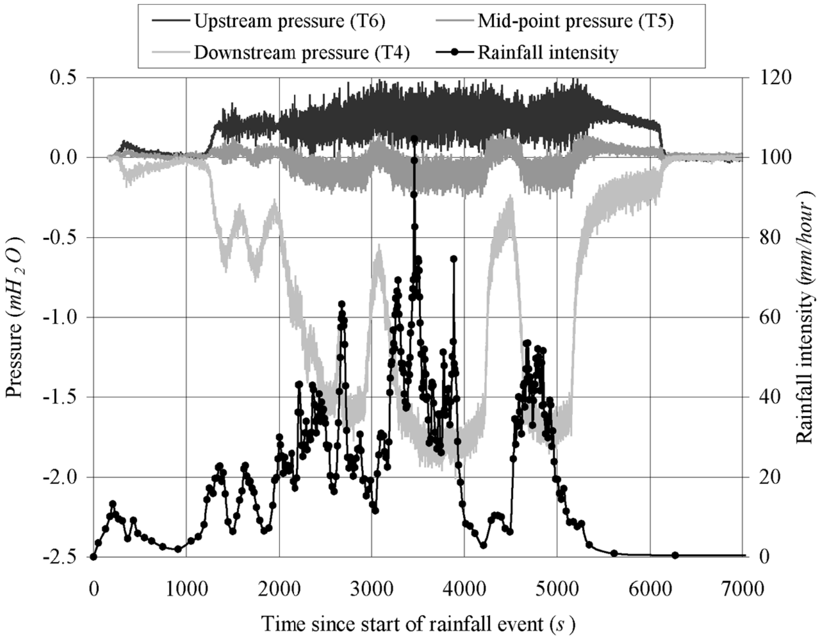

Figure 10 Measured conditions (system 2) on 2 August 2000 (refer to Figure 9 for system and transducer layout). The time-varying nature of this rainfall event is typical, and demonstrates the importance of using rainfall hyetographs to assess system performance fully.

siphonic roof drainage system are unsteady, and may exhibit one of three different flow regimes.

- The complete blockage of one of the outlets in a multi-outlet siphonic roof drainage system may lead to system pressures falling below their design levels, and could result in system failure by cavitation and/or pipe deformation.
- To ensure efficient operation of a siphonic roof drainage system, consideration must be given to its interaction with the downstream surface water sewer network.

The final phase of this current research programme involves the further development of the numerical model. It is intended that the final model will be capable of accurately simulating the flow conditions within multi-outlet siphonic roof drainage systems for all realistic rainfall events. It is anticipated that such a model will be used for diagnostic design purposes and code formulation, which should reduce the occurrence of the type of operational problems and system failures detailed previously.

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