TRANSPORT OF SOLIDS IN DEFECTIVE BUILDING DRAINAGE SYSTEMS

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Abstract

The transport of waste solids in building drainage systems is dependent upon the characteristics of the appliance discharge, the position of the discharged solids within the appliance flush profile, the action of other appliances contributing flow to the network and the physical parameters of the system itself. These system parameters naturally include pipe slope, diameter, roughness and the choice and location of the pipe junction. Many of these dependencies have been investigated and previous research has allowed the development of time dependent numerical analysis models capable of describing both the unsteady flow conditions within the network and the transport of solids within such flows.

However, all previous work has concentrated upon "perfect" systems in that all the constituent pipes are assumed to be laid to a constant slope and no pipe coupling interference is allowed to disrupt the flow at pipe junctions. This paper will present a laboratory validated extension to the method of characteristics numerical model that predicts the effect on solid transport of localised changes in pipe slope, including backfall, and pipe coupling effects. Localised variation in the flow depth caused by these discontinuities will be incorporated within the mathematical model and the subsequent solid retardation predicted. The likelihood of an increased deposition probability will be predicted. In addition to laboratory validation, site investigations aimed at identifying the occurrence of defective drainage systems will be presented.

Keywords: Solid velocity, Defect-free, Slope defect, Obstruction, Solid transport, Drainage

1 HISTORICAL BACKGROUND

1.1 The development of waste solid modelling techniques

The earliest systematic work on solid transport was conducted at the National Bureau of Standards, Washington (Wyly, 1964). However, this work was not concerned primarily with solid transport performance and therefore did not introduce the experimental and instrumentation techniques required to monitor variations in solid velocity along the pipe system.

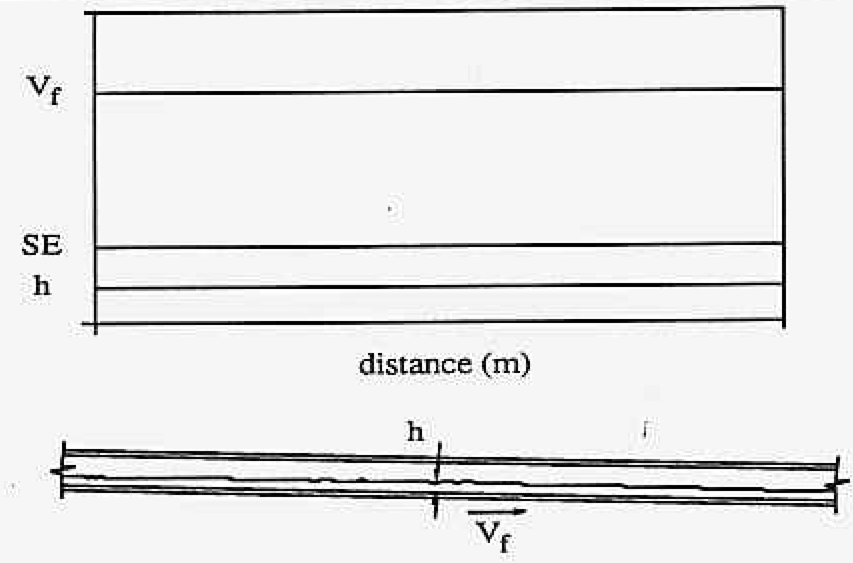

Figure 1 A defect-free pipe : h and V_f constant, SE (= h + $V^2/2g$) constant

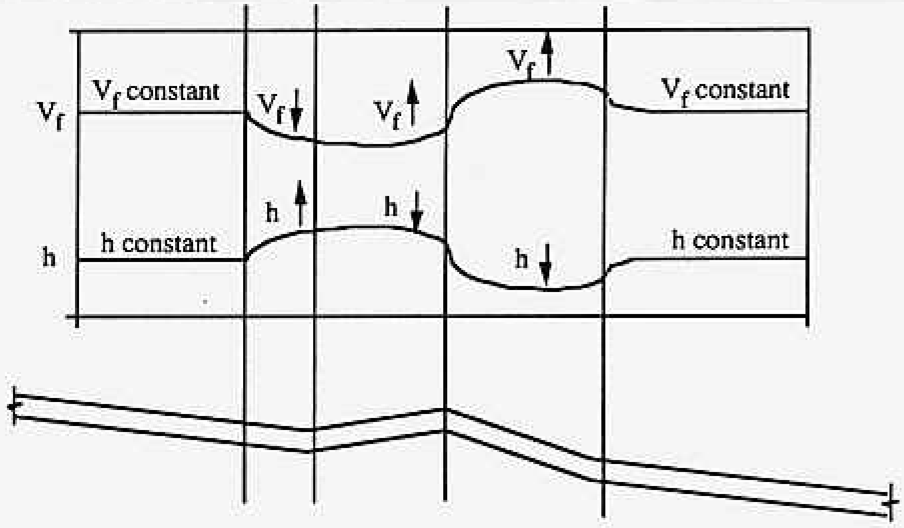

Figure 2 Change in slope defect : effect on V_f and h

The need for the study of solid transport in building drainage probably arose in the UK due to the problems experienced when blockages occurred in many the long, low-pitch drainage systems installed in many large hospitals constructed in the 1960s. Increasing concern with water conservation further stimulated study in this area, which is now a subject of research at several centres in the UK, Europe and the USA.

A methodical study of the transport of waste solids was initiated in the UK in 1974 at Brunel University (Swaffield and Galowin, 1992). These studies developed the necessary instrumentation techniques and established the mechanisms of solid transport in both the laboratory and in installed hospital drainage systems.

1.2 The choice of representative solid

The use of "live" solid waste in experimental work for solid transport studies involves obvious problems that are difficult to overcome. Therefore, the development of a suitable artificial solid was inevitable.

The faeces of the average healthy adult in the USA vary in size from 100mm to 205mm in length with a diameter of between 15mm and 40mm, the weight lying between 100g and 200g (Kira, 1976). Due to the large water content the specific gravity is close to unity.

The following substitutes for solids in experimental work have been studied (Bokor, 1982):

Flour putty - didn't maintain consistent shape and form under test
Fakazell (a German synthetic faeces simulant) - had the same failing as flour putty
Potter's clay - tended to fracture and could not be re-used
Polyvinylalcohol powder - was too rigid
Polyvinylalcohol sponge - was too buoyant
Sanitary protection products - deformed when saturated

A further range of artificial solids supplied by the Stevens Institute was tested at Heriot-Watt University (Campbell, 1991). The solids tested and Campbell's comments on them were:

Water-filled latex cylinder - the performance depended on surface condition; cleaning before use was essential; it tended to come to an abrupt stop
Large natural sponge - gave an unrealistic performance, perhaps because it always dammed the pipe
'Siris' cosmetic natural sponge - gave a repeatable performance
Rectangular synthetic sponge - gave a repeatable performance
17mm diameter polypropylene ball - no comment

In addition to the Stevens Institute solids, Campbell also tested boiled rolled oats, which was found to give more repeatable data than the latex cylinder, but would only tolerate 3 or 4 circuits of the rig

The National Bureau of Standards (NBS) developed a range of hollow plastic cylinders 38mm to 80mm in length and 10mm to 38mm diameter.

The specific gravity can be altered by partial filling of the cylinders with water. Although the range of lengths of the cylinders differs from that of "live" waste, the factor most affecting solid transport is the diameter of the solid and not its length (Bokor, 1982). The solids used in the laboratory experiments described in this paper are NBS cylinders 80mm long and 38mm diameter with a specific gravity of 1.05, this type of solid agreeing with Bokor's site observations.

1.3 The flow specific energy vs solid velocity model

Fok (1990) describes a simple model for determination of the solid velocity that is dependent on the relationship between the solid velocity, V_s, to mean flow velocity, V_f, ratio and the flow specific energy, SE. SE is defined by the relationship $SE = h + V_f^2 / 2g$. The model is of the form

$$V_s / V_f = K (SE - SE_0)^n \tag{1}$$

where the constants K and n depend on the shape, size and mass of the solid and on the diameter and slope of the pipe. The term SE_0 is the flow specific energy necessary to produce motion from rest.

1.4 The solid velocity / flow velocity decrement model

Swaffield and Galowin (1992) suggest that the solid velocity can be calculated from the local flow depth, this being described as a velocity decrement approach because the local flow velocity is linked to flow depth.

However, whilst the model described appears capable of accurately predicting solid velocities in defect-free drainage systems, it fails to model those in defective systems properly.

The solid velocity decrement model must be based on local flow velocity as both are vector quantities. A depth-only model would suggest that solid velocity increases with depth, as it would in steady uniform flow. However, in the non-uniform flows caused by the presence of junctions, obstructions and defects, increasing flow depth can also be associated with decreasing flow velocity. Similarly, reversed flow around junctions may result in reversed solid movement direction and this can only be simulated by a velocity-based model. Figures 1 to 3 illustrate some of these constraints.

2 SOLID VELOCITIES IN DEFECT-FREE DRAINAGE SYSTEMS

All laboratory measurements were carried out on the drainage test rig installed at Heriot-Watt University. The rig consists of 75mm, 100mm and 150mm nominal diameter glass pipes (actual internal diameters 78mm, 105mm and 155mm respectively) each in a single horizontal run 14 metres long, suspended from a scaffolding framework by threaded steel hangers. The pipes can be set to any desired slope by adjusting the hangers, levelling being done using a laser level with an accuracy of ±1.5mm.

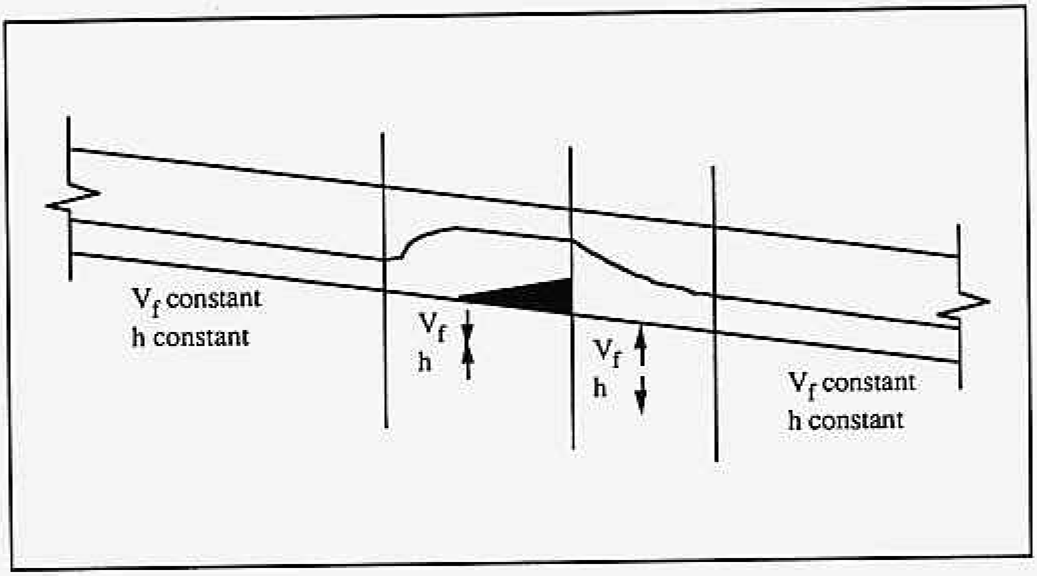

Figure 3 Obstruction defect : effect on V_f and h

Although the laser level is very accurate, it is not possible to set up a perfect system with no slope defects. Setting a one-metre pipe length to a theoretical slope of 0.01 using the laser level would result in the actual slope lying somewhere between 0.007 and 0.013, a variation of ±30%. This maximum percentage variation is in inverse proportion to the pipe length and theoretical pipe slope. From now on, a pipe set to a slope within these limits will be called "defect-free".

A measured steady flow of water may be fed down any of the pipes using a battery of two large and one small rotameters.

Velocity measurements were obtained using a series of lamp / photocell pairs (16 per pipe) connected to a microcomputer serving as a data logger. Solids passed down the pipes interrupt the light passing from each lamp in turn to its corresponding photocell, the times of the interruptions being recorded and saved to a file for later processing. The velocities were calculated from the times at which the solid passes adjacent photocells and from the distances between those photocells.

2.1 The flow velocity vs solid velocity model

Figure 4 shows the laboratory measured velocities obtained, for a series of flow rates ranging from 0.3 litres / second to 2.0 litres / second, on a "perfect" 75mm diameter pipe at a slope of 1:100 (i.e., 0.01) plotted against the distance along the pipe.

Average solid velocities were calculated over the full pipe length for each flow rate, and are shown plotted against the flow rate in

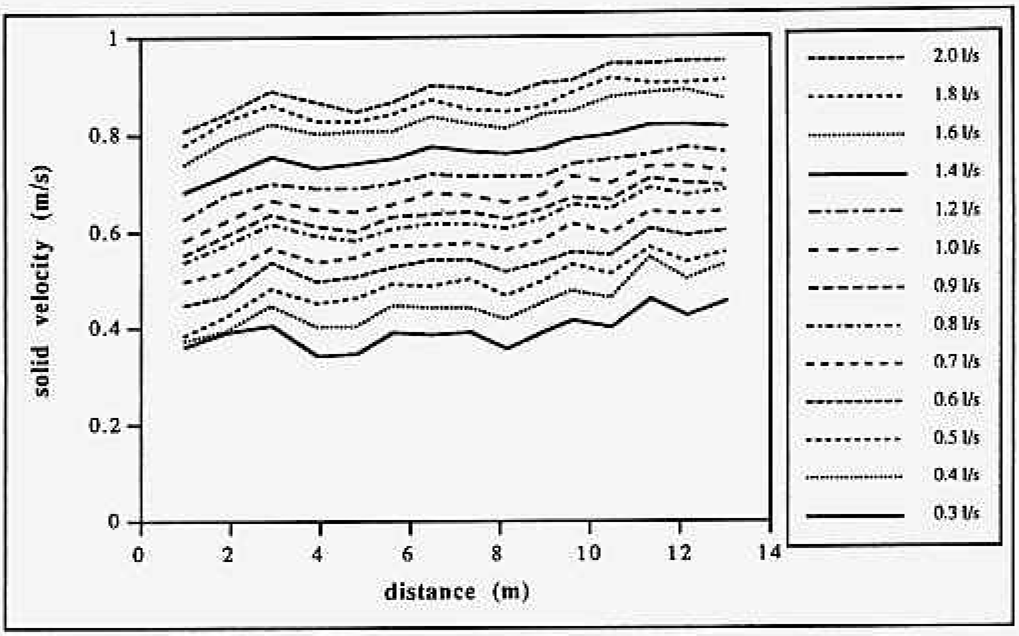

Figure 4 Solid velocities recorded on a defect-free pipe

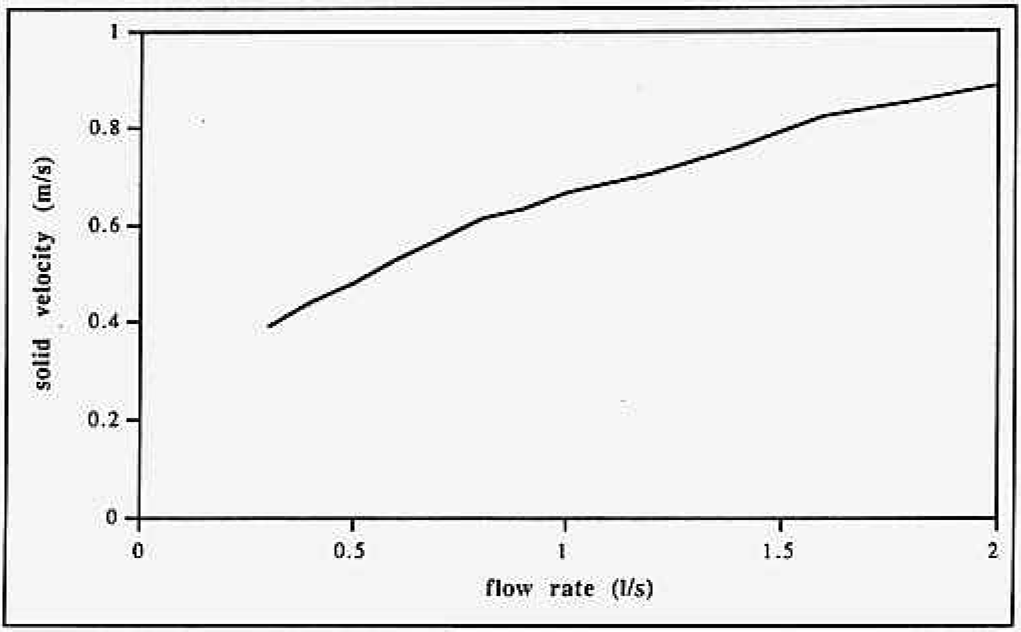

Figure 5 Average solid velocity against flow rate

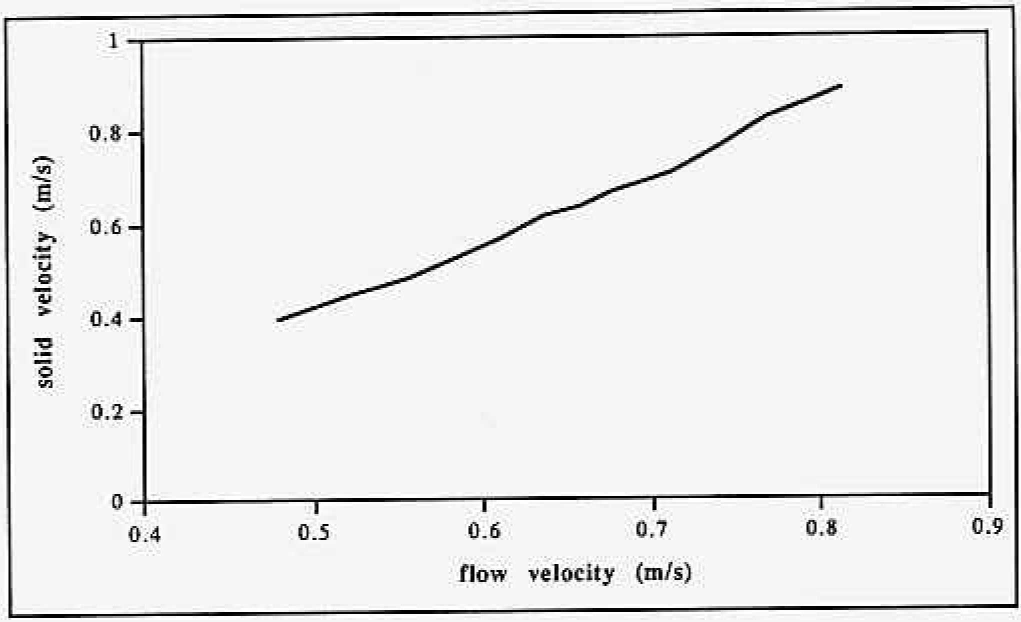

Figure 6 Average solid velocity against flow velocity

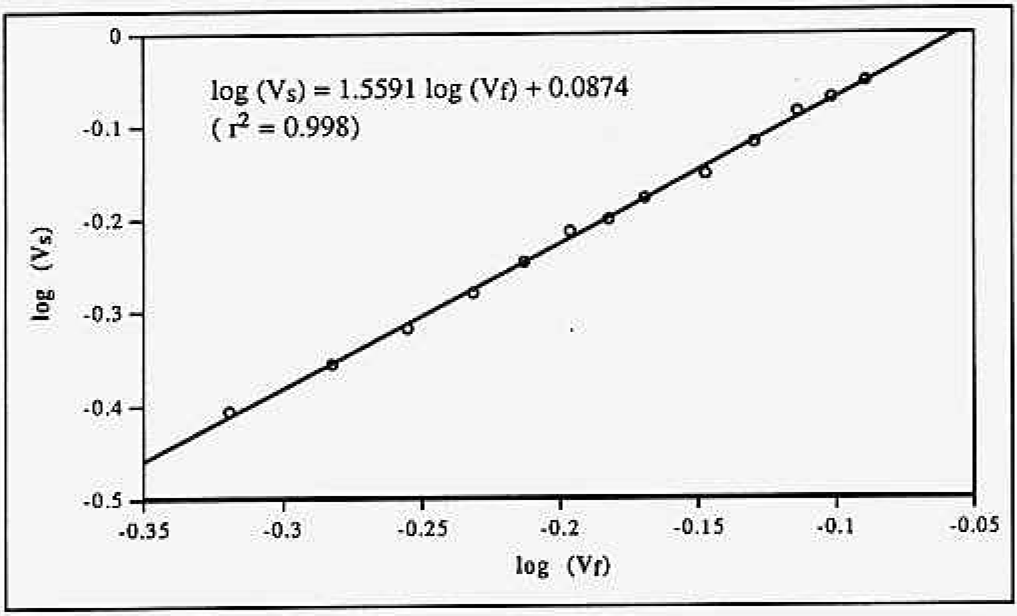

Figure 7 Log-log (base 10) curve fit of average solid velocity against flow velocity

Figure 5 and against the calculated flow velocities for the corresponding flow rate in Figure 6.

The same average solid velocities are shown plotted against the calculated flow velocities using logarithmic scales in Figure 7. The straight line fit, which corresponds to a power regression curve fit, gives the following relationship:

$$\log(V_f) = 1.5591 \log(V_s) + 0.0874 \qquad (2)$$

From equation (2) the following direct relationship between solid velocity and flow velocity can be derived:

$$V_s = 1.223\, V_f^{1.559} \qquad (3)$$

Whilst this relationship was derived from data obtained under steady flow conditions, the conditions found in building drainage systems are unsteady. However, equation (3) can be applied to situations where unsteady flow is being modelled by breaking down both time and distance into small discrete steps and assuming that the conditions operating at each node at a given point in time are steady.

3 THE EFFECTS OF DEFECTS ON SOLID VELOCITIES

3.1 Slope defects

To simulate slope defects, the central 2 metre section of the pipe was constructed from two 1 metre pipe lengths. With the pipe set to a slope of 0.01, the joint at the middle of the central section was then raised above its "normal" level by 5mm, 10mm and 15mm respectively, as shown in Figure 8.

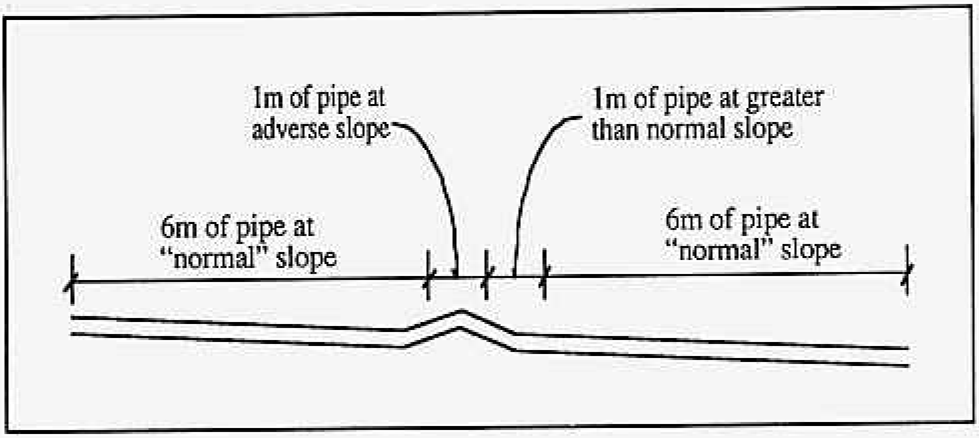

Figure 8 Schematic of the general arrangement of the glass pipes to simulate slope defects

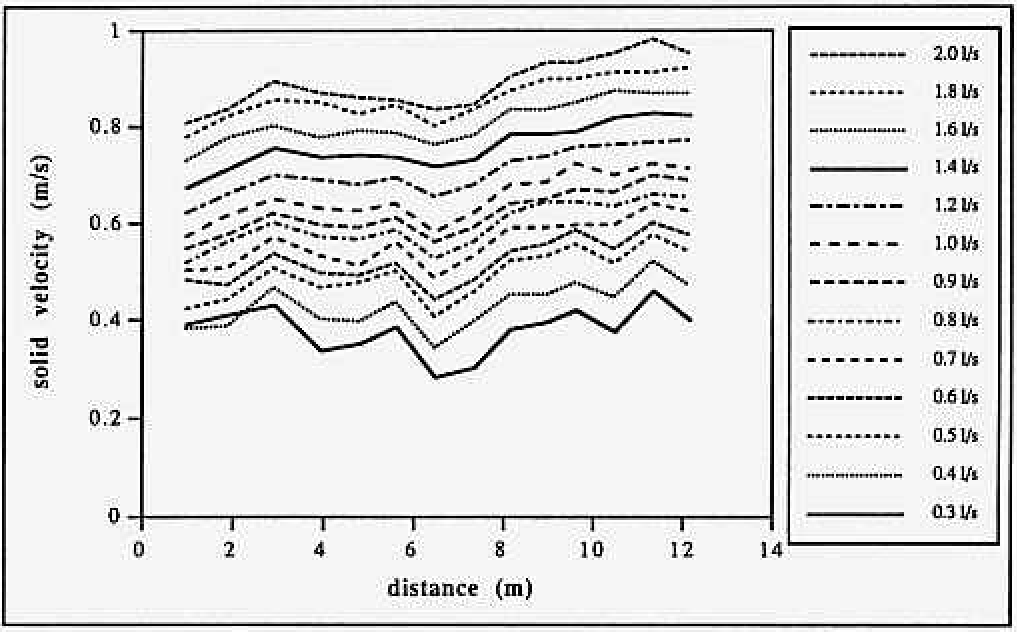

Figure 9 Solid velocities recorded on a pipe with a 5mm slope defect

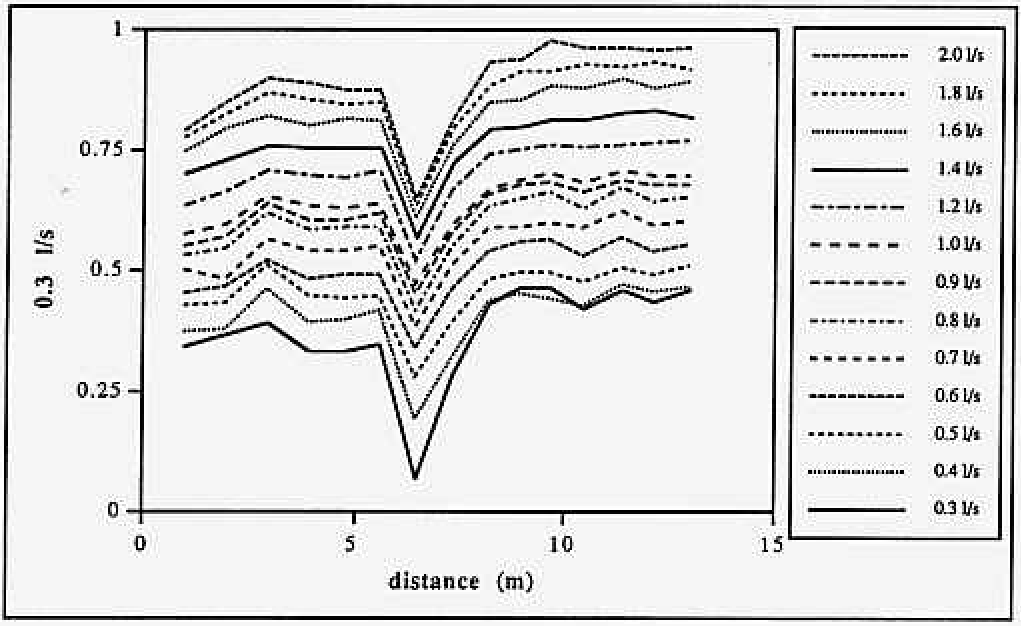

Figure 10 Solid velocities recorded on a pipe with a 10mm slope defect

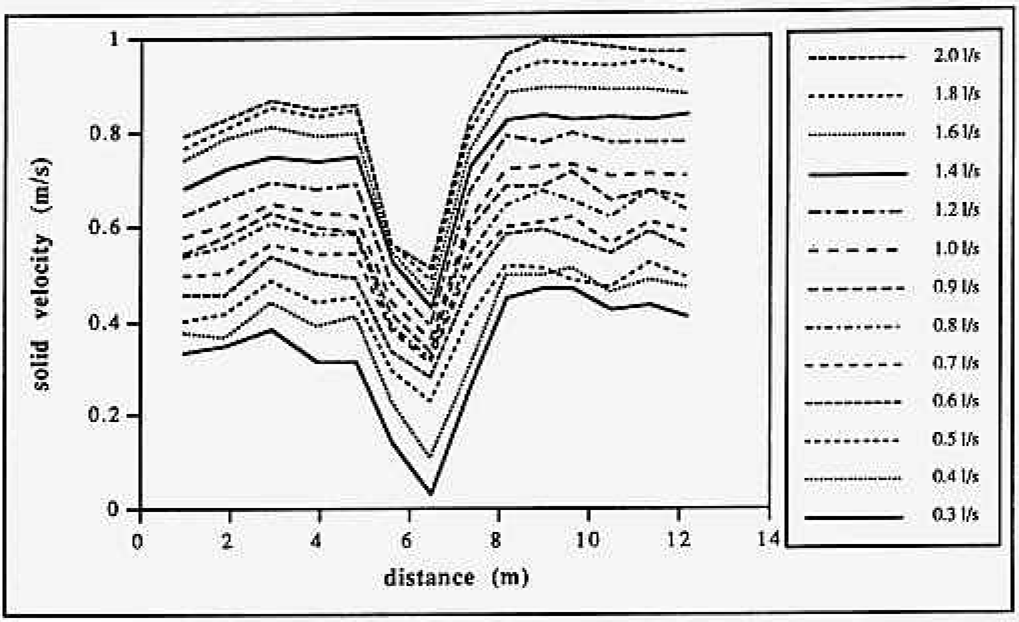

Figure 11 Solid velocities recorded on a pipe with a 15mm slope defect

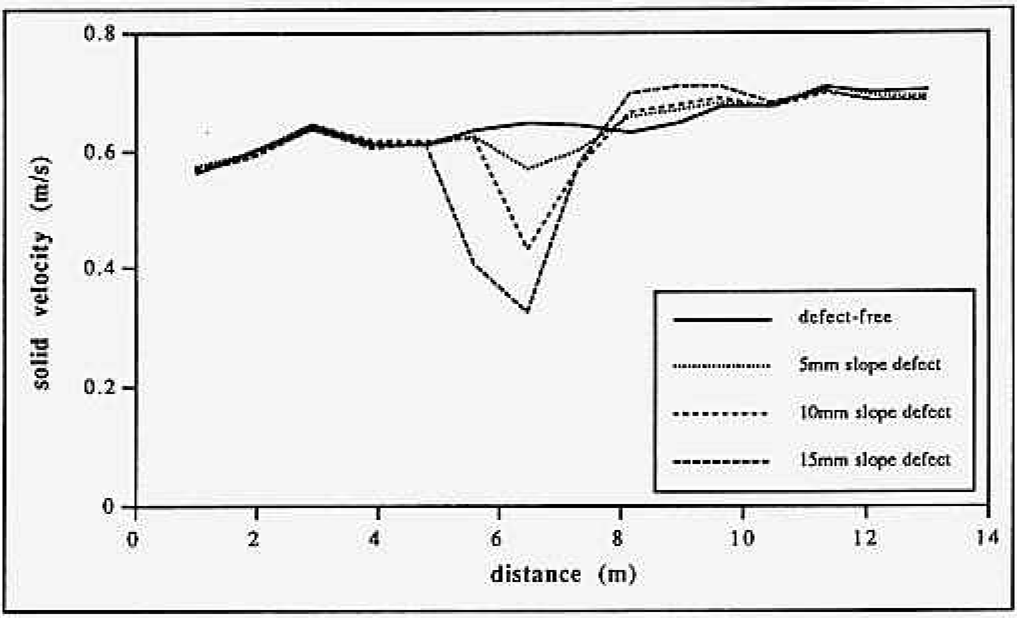

Figure 12 Comparison of solid velocities in a defect–free pipe and in pipes with increasing slope defects

The respective slopes of the first metre section in the three cases are 0.005, 0.000 and -0.005 (a negative slope representing a backfall), whilst those of the second metre section are 0.015, 0.020 and 0.025.

The solid velocities recorded on these three defective setups are shown in Figures 9, 10 and 11.

Whilst the average velocities shown in Figure 11 for the 15mm slope defect come very close to zero at the backfall, the solid clears the defect at all flow rates. What is not apparent from the graph is that, at the lowest flow rates, the solid comes to rest on coming into contact with the hydraulic jump upstream of the backfall. The depth of water behind the solid then gradually increases until the pressure has built up sufficiently to move it.

The defective runs are compared with the defect-free run in Figure 12, the velocities for the various flow rates having been averaged to give the profiles shown.

3.2 Obstructions

Artificial obstructions as detailed in Figure 13 were constructed from aluminium sheet and fitted into the central joint of the pipe. The obstructions are intended to represent coupling defects and the like. The ramped part of the defect was added to prevent the solids merely coming to rest at the vertical aluminium sheet, and was also intended to model more closely conditions encountered in installed drainage systems, where a ramped deposit of silt builds up over a period of time ahead of any obstruction. The results of runs with 10mm and 20mm high obstructions are shown in Figures 14 and 15. In contrast with the slope-defect runs, the solids are brought to rest at the lowest flow rates. The obstructed and defect free runs are compared in Figure 16.

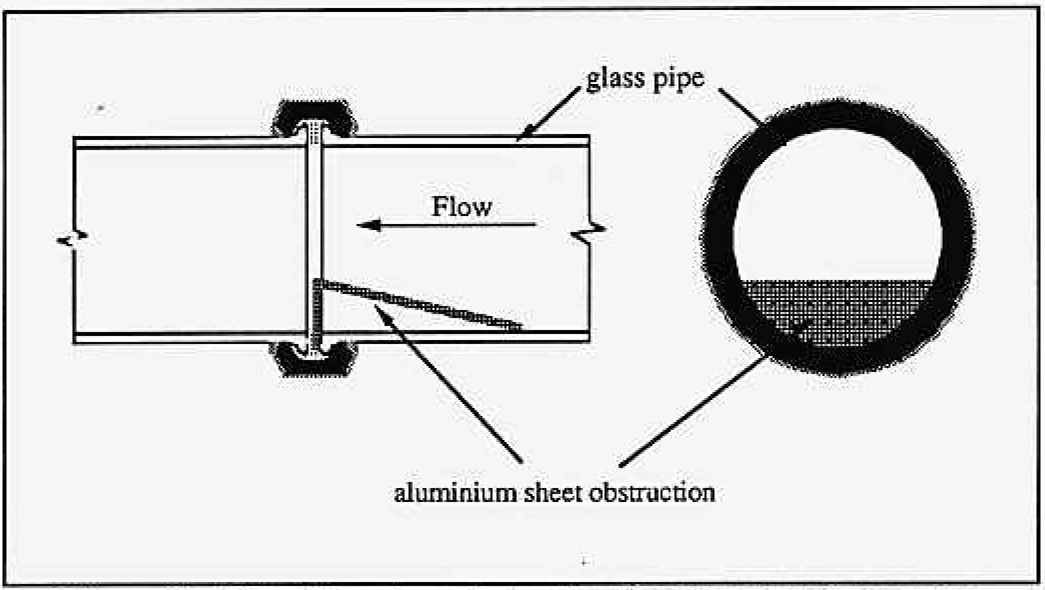

Figure 13 Aluminium sheet obstruction fitted to joint of glass pipe

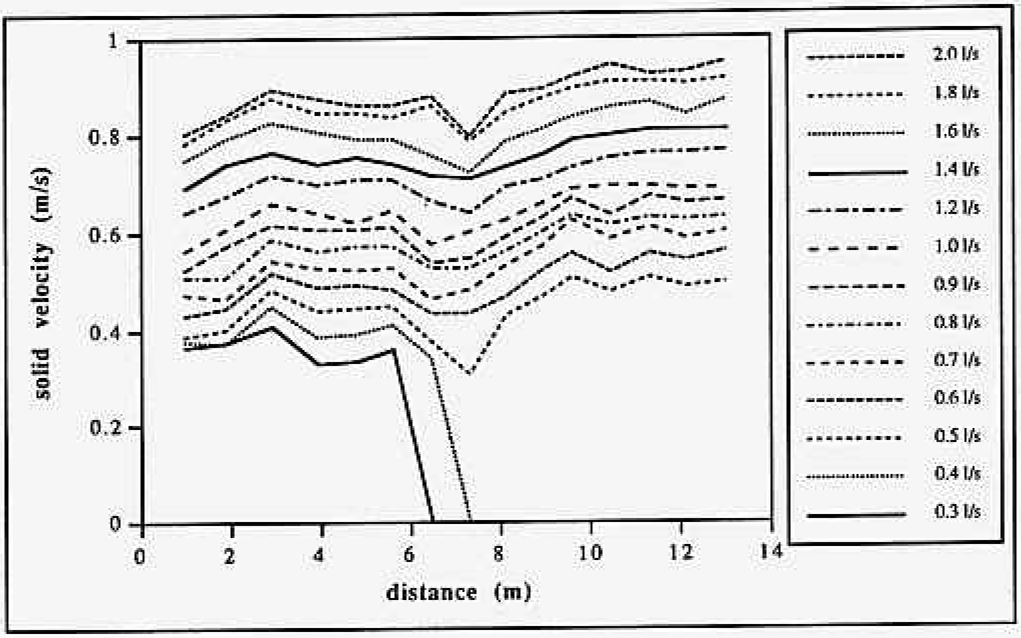

Figure 14 Solid velocities recorded on a pipe with a 10mm obstruction

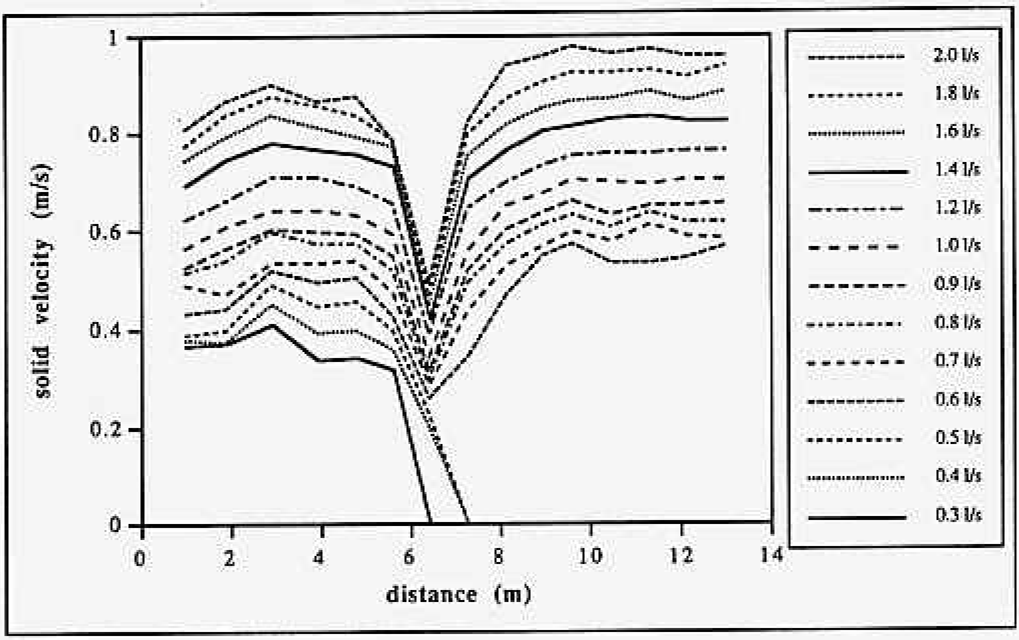

Figure 15 Solid velocities recorded on a pipe with a 20mm obstruction

3.3 Modelling the Influence of the Defect on Solid Transport Performance

Solid velocity versus flow condition models described by Figures 4 to 7 allowed the prediction of solid velocities in steady flows and in unsteady flows where the rate of change of flow conditions is sufficiently gradual. It has been shown previously that the flow conditions following w.c. discharge fall into this category, Swaffield and Galowin (1992), and thus the model may be used to predict the influence of defects on solid transport.

Figure 12 illustrated the influence of a backfall defect upon solid velocity in a steady flow. Such pipe defects would be expected to have a similar effect upon solids transported within an attenuating w.c. flush, however the presence of the defect may be sufficient to lead to premature deposition.

Figure 17 illustrates the predicted influence of a backfall defect on the solid velocity versus distance travelled history for a typical model solid. It will be seen that the defect leads to a marked reduction in solid velocity in the region of the pipe defect.

It must be appreciated that a w.c. flush attenuates as it passes along any drain. Thus the location of the defect relative to drain entry, or w.c. discharge entry location, becomes a factor, as does the severity of the defect itself. Additionally the position of the solid within the w.c. flush materially affects it transport, Bocor (1982), Swaffield and Galowin (1992), and would affect the degree of solid velocity reduction caused by any defect encountered. Thus the influence of a particular defect on solid transport becomes a complex issue dependent upon drain parameters; ie., diameter, roughness and slope, as these determine wave attenuation; the severity of the defect itself; ie., its degree of backfall or structure height; and the performance of the w.c. itself, defined by its discharge profile and the position of solids within that profile.

The numerical model is capable of investigating all of these interactions. Figure 18 illustrates the effect of a particular defect upon solid deposition in a 75mm diameter drain at a slope of 0.01, following discharge from a 1.6 US gallon w.c., the solid being discharged 2 seconds into the flush. As the position of the defect is altered ie., is moved further away from the drain entry, its effect on solid deposition is seen to change. While the defect is close to drain entry it reduces considerably the solid velocity and transport distance, deposition occurring beyond the defect at a distance shorter than that achieved in a defect free drain. However a point is reached when the solid deposition occurs prior to the position of the defect, this affect being due to the interaction between the solid and the hydraulic jump ie., local flow depth increase, formed upstream on the defect. This materially reduces solid velocity and leads to deposition, either in the "downhill" drain section carrying the hydraulic jump, or on the "uphill" section of the defect itself.

These results confirm and emphasis the importance of a systems approach to the design of drainage networks and the appliances that serve those networks. Clearly the performance of the w.c. and the effect of the defects to be encountered with in a drainage system are interactive and therefore require suitable numerical modelling in

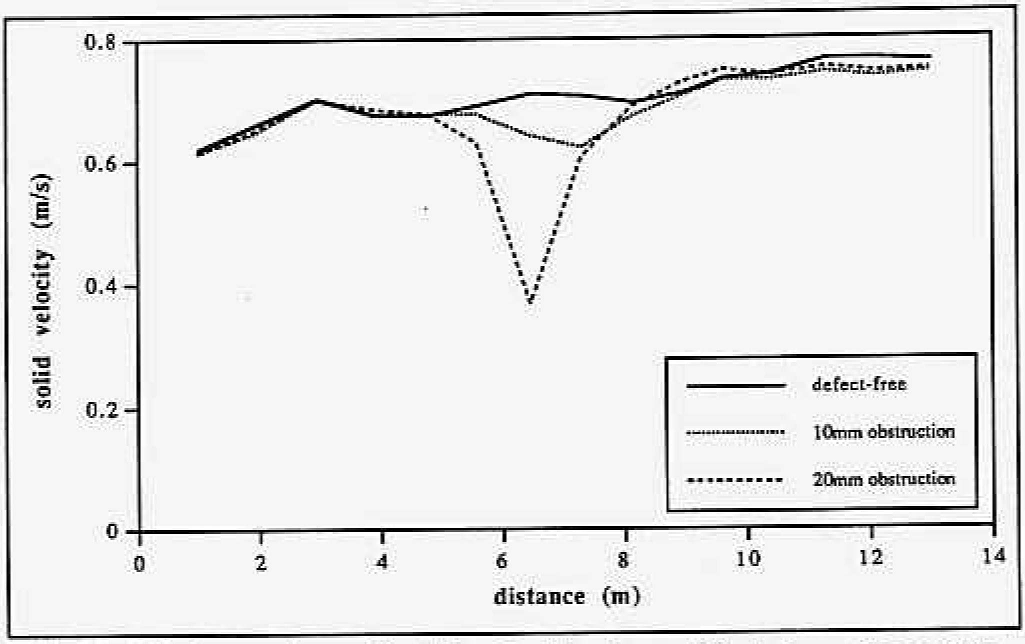

Figure 16 Comparison of solid velocities in a defect–free pipe and in pipes with increasing obstructions

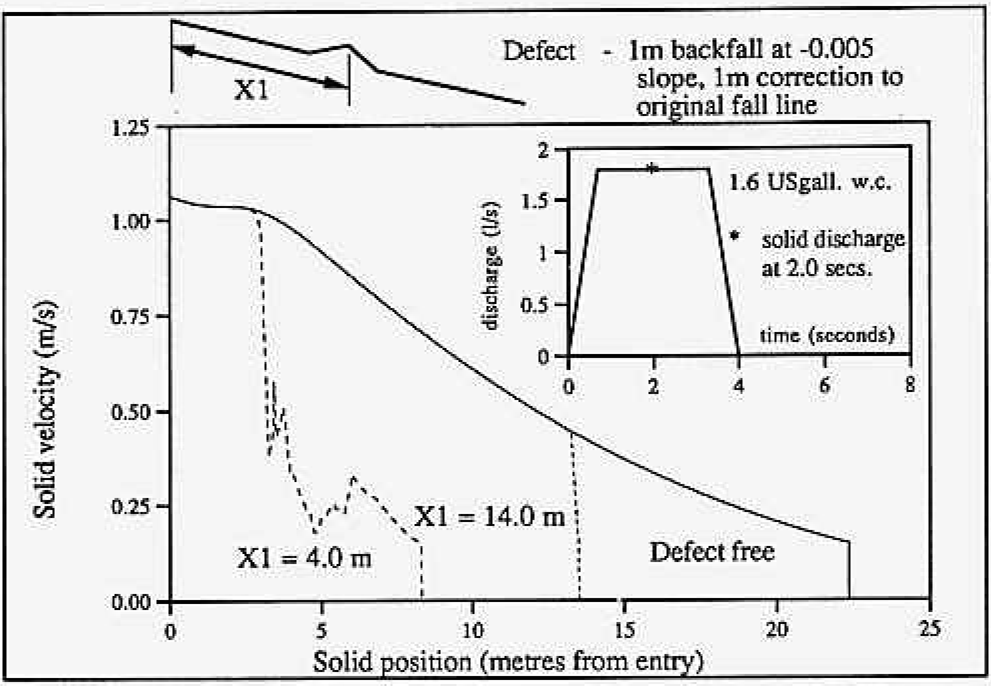

Figure 17 Comparison of solid transport performance for a range of slope defect locations. Pipe - 25m. long, 75mm dia., 0.01 slope.

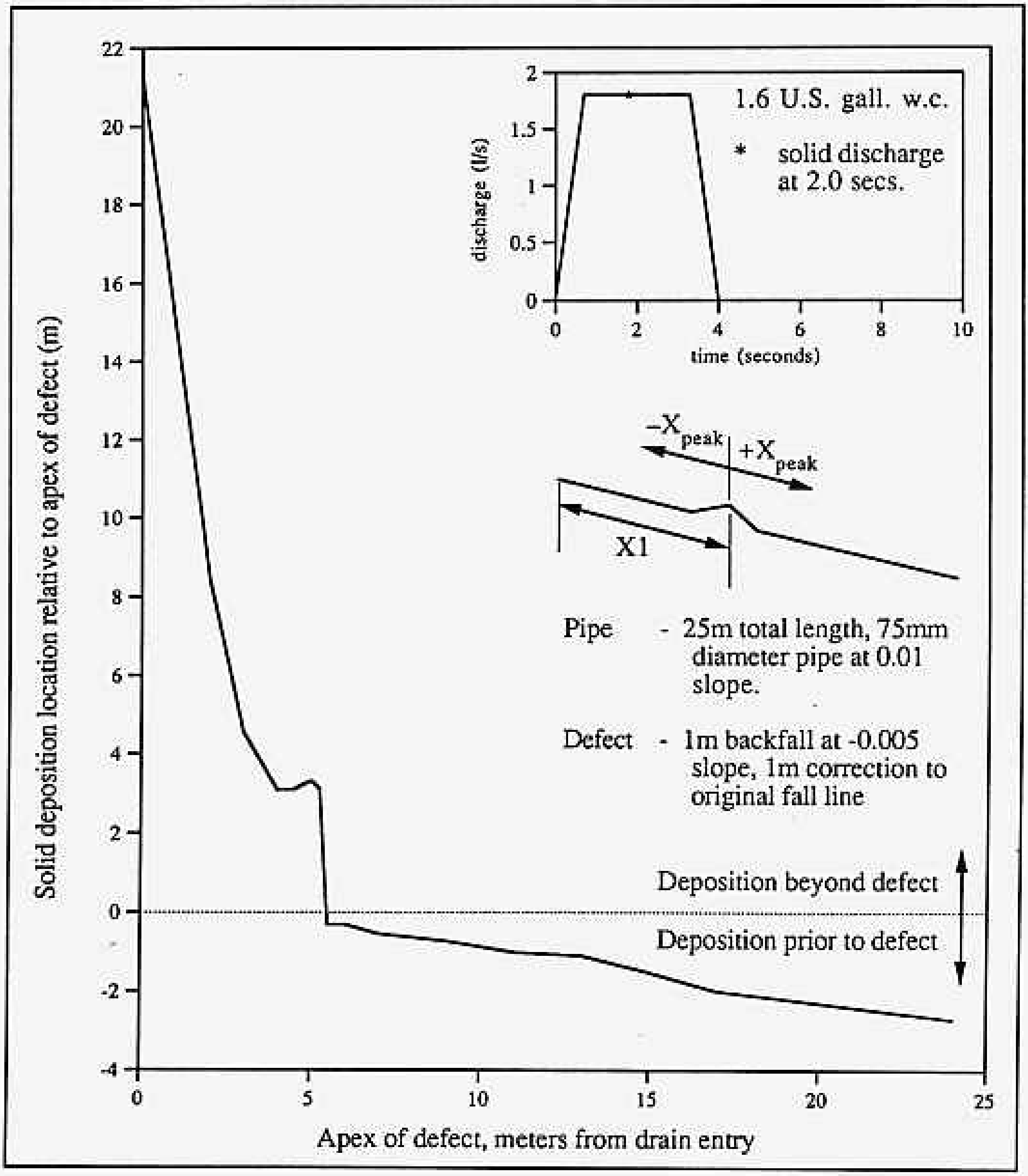

Figure 18 Influence of defect position on solid deposition

order that these interactions can be predicted as an aid to drainage design. As has been demonstrated previously, Swaffield and Galowin (1992), the numerical model utilised in this presentation is capable of dealing with both a multiplicity of drainage elements and also multiple appliance discharge. Therefore the influence of later appliance discharges upon the solids deposited in the region of a defect could be both investigated and predicted.

5 FINAL REMARKS

Based on data collected to date, our expectation is that a flow velocity model which will accurately predict solid velocities in defect-free pipes can be prepared on completion of data collection. The work done on defective systems will enable the validation of the model in defective situations.

The programme of research will continue with further laboratory measurement and analysis of solid velocities in defect-free pipes and in those with slope defects and obstructions. In addition, a site survey will be carried out to determine the extent of defects encountered in installed building drainage systems. These steps will allow the addition of a method of predicting solid velocities in real-life situations to be added to the existing model and computer program that are now capable of accurately predicting flow depth and flow rate at any given point in space and time within a building drainage network.

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