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Hysteresis Loop in OSD Outflow Rating Curve

by

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SUMMARY

On-site detention (OSD) is imposed on many new developments in urban areas as a means of reducing site discharge. An OSD facility may either be an underground storage tank or an above ground ponding area. In both cases the discharge is often released to the gutter at the kerb line. In designing these type of facilities 'inlet control' or 'orifice control' is assumed. Experiments were conducted at the University of Technology, Sydney to study the head-discharge relationship of outflow from OSD through an orifice. The head versus outflow rate follow either one of two rating curves. The first is the 'inlet or orifice' control rating curve and occurs when the discharge pipe is flowing part-full. The other is governed by 'outlet control' conditions and generally occurs when the discharge pipe is flowing full. The latter rating curve is lower, i.e for a given flow rate the head is smaller. The two rating curves are commonly thought to be independent of each other and the applicable rating curve depends primarily on the tailwater conditions. However, the experimental results shows that the head-flowrate relationship can revert between the two rating curves and a hysteresis loop exist between the two curves. The mechanism of its formation is explained. The flow rates over which the hysteresis loop occurs virtually covers the range of outflow from OSD facilities. Hysteresis loops means that OSD facilities designed using 'inlet control' assumption will not perform as intended. The PSD may actually be exceeded and the OSD storage will not be fully utilised since smaller amount of runoff is detained.

1 INTRODUCTION

Rapid expansion of urbanised areas and redevelopment of established suburbs have significantly increased the risk of flooding in Sydney. Many existing stormwater drainage systems were designed for low density development (20 - 30% impervious area). The increase in impervious area as a result of medium and high density development (up to 50 - 60% impervious area), such as dual-occupancy dwellings, townhouses and home-units, is expected to produce higher stormwater runoff which is beyond the capacities of these existing systems. As a means of reducing site discharges, most Local Government Councils and Drainage Authorities now require on-site detention (OSD) on new development.

On-site detention is a structural element of a property drainage system which temporarily stores the stormwater runoff and slowly releases the site discharge into the street drainage system. The storage may be in the form of an underground storage tank or above ground ponding area such as car parking or landscaped areas. OSD storage volume varies with the relevant Council's or Drainage Authority's OSD policy specifications but a typical requirement for small development is between 10 - 20 cubic-metres.

An underground storage tank is normally connected to an inspection pit which has a grated cover, a trash rack or screen and silt trap. An above-ground storage is usually connected to a grated surcharge pit. OSD storage is drained by gravity from the pit through an outflow pipe which has a typical diameter of 100 mm or 125 mm to the street kerb gutter. Orifice plates of diameters down to 50 mm are commonly used as an outflow control device to achieve the permissible site discharge (PSD). PSD for the post-development condition is usually restricted to the existing site discharge for the same design storm intensity. Typical values for small developments are in the range of 10 - 25 L/s.

The main objective of this paper is to present some experimental results of head-discharge relationship of outflow from OSD through an orifice.

2 HEAD - DISCHARGE RELATIONSHIP

The sizing of OSD storage volume may be done by hydraulic routing of an inflow hydrograph through the detention tank. Relationships between head versus storage and head versus discharge are needed for this calculation. The former relationship depends on the geometry of the tank whilst the latter depends on the flow characteristics in the outflow pipe. The optimum size of the tank is determined so that the outflow hydrograph's peak is below the PSD. Other methods such as the mass curve method or Phillips' method may also be used to obtain the storage volume.

For the case of an outflow pipe without orifice, the head discharge relationship is considered similar to that of a pipe culvert. Boyd (1986) presented two empirical formulae for circular pipe culvert with square edged entrance under inlet controlled condition;

for $H_W / D < 1.2$

$$Q = 1.32\,(D)^{0.87}\,(H_W)^{1.63} \tag{1}$$

for $H_w / D \geq 1.2$

$$Q = 1.62\ (D)^{1.87}\ (H_w)^{0.63} \qquad (2)$$

where

D = diameter of the pipe culvert,

H_w = headwater or water depth above the pipe invert at the inlet,

Q = discharge through the pipe culvert

The first equation, 1, represents the inlet controlled condition where the outflow is governed by the critical depth at the pipe inlet. The second equation, 2, describes the situation where the pipe inlet is submerged and operates like an orifice.

For the case of an outflow pipe with orifice, the pipe is usually assumed to run part full and the orifice flow is not affected by the downstream condition.

$$Q = C_d A \sqrt{2g(H_w - D/2)} \qquad (3)$$

where

A = cross sectional area of the orifice,

C_d = coefficient of discharge, taken as 0.6 for sharp edged orifice,

D = diameter of the pipe,

g = gravitational acceleration

For the case of an outflow pipe running full, the standard closed conduit flow equation is used to determine the head-discharge relationship. Total energy loss includes losses at entry and exit, other minor losses and the pipe friction loss.

$$H_w + S_o L - mD = \frac{V^2}{2g}(K_e + K_o + K_m + f\frac{L}{D}) \qquad (4)$$

where

f = friction factor of the outflow pipe,

K_e = entry loss coefficient at pipe inlet,

K_m = minor loss coefficient,

K_o = exit loss coefficient at pipe outlet,

L = length of the outflow pipe,

m = ratio of water depth to pipe diameter at the pipe outlet

S_o = slope of the outflow pipe,

V = mean velocity in the outflow pipe

The ratio of water depth to pipe diameter (m) at the pipe outlet is normally assumed 0.5, but experimental results presented by Li & Patterson (1956) indicated that the ratio varied from 0.5 to almost 0.8 depending upon the Froude number.

3 EXPERIMENTAL SET-UP AND PROCEDURES

A series of experiments were conducted in the Hydraulics Laboratory of the University of Technology, Sydney. The set-up consisted of a 600 mm wide, 600 mm long and 1200 mm high PVC tank, discharging into a 95 mm diameter perspex pipe. The length of the pipe was about 2 m long or about 20 times the pipe diameter. The outlet of the pipe discharged freely without any backwater effects. A circular orifice plate could be fitted to the pipe inlet whose invert level was set slightly above the tank bottom. This set-up is similar to a typical arrangement in practice of an inspection pit connected to an OSD tank. The bottom of the inspection pit is set at a lower invert level than the outflow pipe to trap sediment.

Water was supplied to the tank from the laboratory supply main via a perforated ring pipe at the bottom of the tank. The flow rate was measured using an electro-magnetic flowmeter. Piezometers were attached at several longitudinal locations along the pipe to measure the hydraulic head levels. Head in the tank was measured relative to the centreline of the pipe at the inlet. Results were obtained for pipe slopes of 1 and 2 % and with orifice opening of 50, 65 and 80 mm diameter.

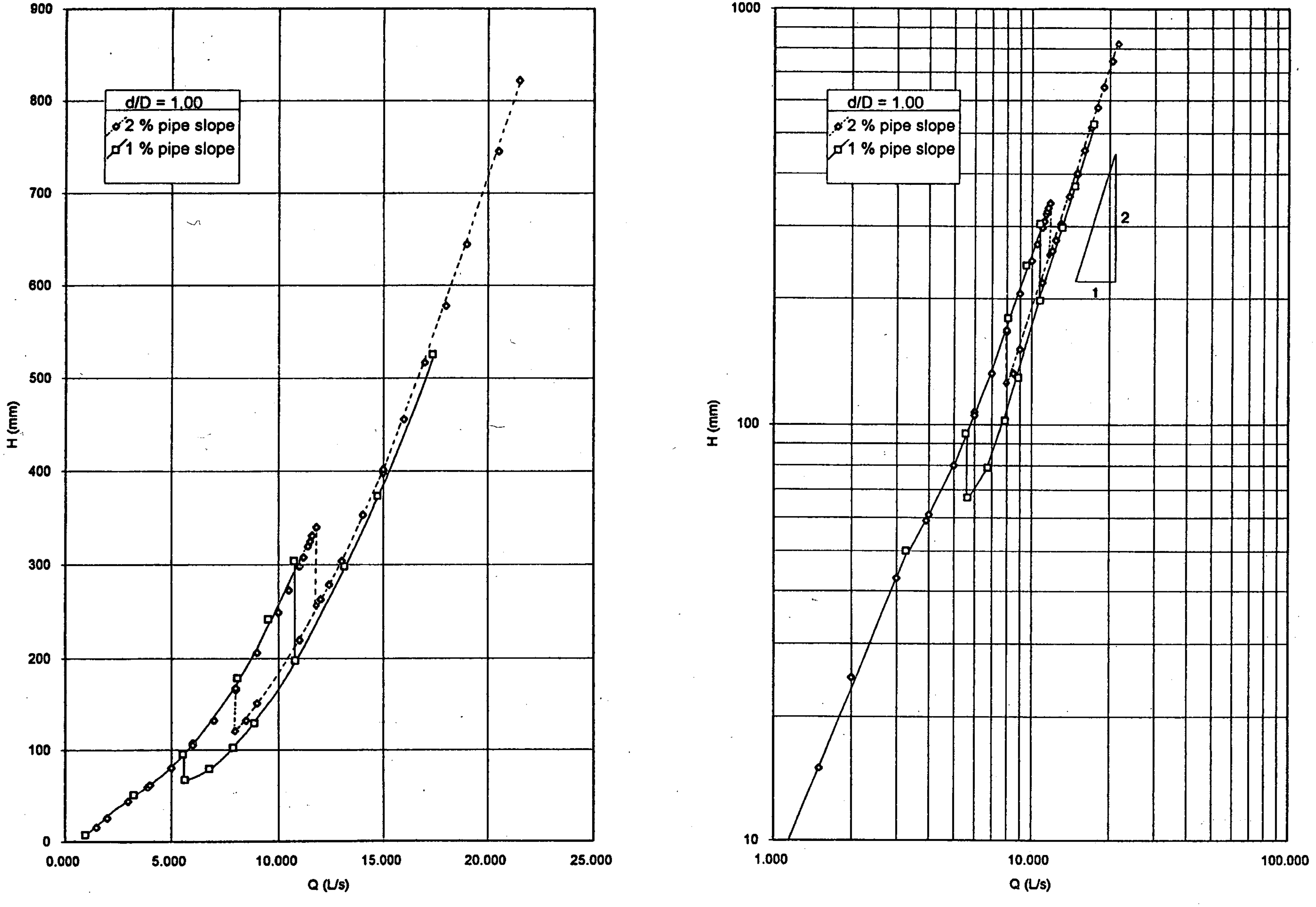
The experiment commenced at a low flow rate so that the pipe initially ran part-full. The flow rate was progressively increased up to about 20 L/s until the head tank was nearly full and/or the pipe was running full under pressure. At each flow rate, the corresponding hydraulic grade line was measured and the flow characteristics in the pipe was also noted. In the case of smaller orifices, the height of the tank was not high enough to cause self-priming action, as explained in the next section, and the pipe-full flow had to be induced by partially blocking the pipe outlet.

4 DISCUSSION OF RESULTS

4.1 Hysteresis Loop

Table 1 summarises the results of the experiments. The variation of head with discharge for the case of an outflow pipe with no orifice is depicted in Figure 1 (a). It can be seen that two different rating curves are obtained for the part-full and full flow conditions. Both curves when plotted in log-log scale in Figure 1 (b) show linear relationships with approximately the same slope of 2. This indicates that flow rate is proportional to the square of head as indicated by equations 3 and 4. Similar results are obtained for pipe slopes of 1 and 2%.

For the pipe slope of 1% in Figure 1 (a) and (b), the part-full flow in the pipe changes to full flow at the flow rate of 10.7 L/s. This self-priming action causes the head to drop from 304 to 198 mm as the result of sudden increase in flow area when the pipe runs full. Further increase in flow rate will follow the rating curve for full flow which is below that of the part-full flow.



(a) (b)

Figure 1 Head versus Flow Rate Relationship for Pipe with No Orifice plotted on a) Normal Scale b) Logarithmic Scale

Table 1 Summary of Experimental Results

Orifice Diameter in 95 mm pipe	Slope (%)	Flow Range (L/s)	Head Range (mm)	Change-Over from Part-Full to Full Flow		Change-Over from Full to Part-Full Flow	
				Head (mm)	Flow rate (L/s)	Head (mm)	Flow rate (L/s)
No Orifice	1	1.0 - 21.1	7 - 812	304 → 198	10.7	67 → 95	5.6
	2	1.5 - 21.5	15 - 821	349 → 262	12.0	116 → 168	8.0
80 mm	1	1.0 - 19.7	10 - 874	678 → 424	13.9	61 → 78	4.3
	2	1.0 - 20.0	10 - 868	804 → 503	15.3	64 → 75	4.1
65 mm	1	1.0 - 11.7	21 - 1037	induced		116 → 159	3.6
	2	1.0 - 12.8	21 - 1100	induced		110 → 164	3.8
50 mm	1	1.0 - 6.0	47 - 1010	induced		393 → 502	3.6

When the flow rate is decreased to below 10.7 L/s, the full flow in the pipe is still maintained until the flow rate of 5.6 L/s is reached. At this point the full flow breaks down to part-full and the head suddenly increases from 67 to 95 mm. The rating curves therefore show a hysteresis loop at the middle range of flow rate from 5.6 to 10.7 L/s. For the 2 % pipe slope, the hysteresis loop lies in the flow rate range of 8.0 to 12.0 L/s. Within these ranges of flow rate, the pipe can be primed to run full by partially blocking the pipe outlet for a short time. Once the pipe runs full, regardless of whether it is induced by partial blockage of the pipe outlet or by self-priming action, the pipe remains full until the flow rate is decreased below the lower end of the hysteresis loop.

For the outflow pipe with orifice diameter of 80 mm, (Figure 2 (a) and (b), the hysteresis loop occurs over a much wider range of flow rate from 4.3 to 13.9 L/s and from 4.1 to 15.3 L/s for pipe slope of 1% and 2% respectively. This virtually covers the whole range of typical PSD discharges from small developments.

For smaller orifices, the maximum head in the tank of about 1100 mm is not high enough to cause self-priming action. But full flow can be induced by partial blockage of the pipe outlet. The lower end of the hysteresis loop is around 3-4 L/s for orifice diameter of 50 and 65 mm, Table 1

4.2 Change-Over from Part-Full to Full Flow

The change-over from part-full to full flow in a pipe culvert was studied in detail by Li & Patterson (1956). Three distinctive types of self-priming action were observed and can be described as follows:

(a) Self-priming after a hydraulic jump

For extremely mild slope, the flow is controlled by both the inlet and outlet. At the upstream end of the pipe, the water surface is covered with weak diamond-shaped standing waves, indicating that the flow is super-critical. The sub-critical flow at the downstream end follows a draw-down profile towards the pipe outlet. A hydraulic jump is expected to form near the upstream end of the pipe. When the water depth after the hydraulic jump reaches the pipe obvert, self-priming action occurs. This type of self-priming action is only possible when the pipe has very mild slope and sufficient length.

(b) Self-priming with a divergent flow

For relatively long pipe, a divergent flow of either M3 or S3 type of longitudinal profile is observed. The surface of the divergent flow is also covered with standing waves which increase in magnitude at larger discharges. Self-priming occurs when the divergent flow reaches the pipe obvert at some distance upstream from the pipe outlet.

(c) Self-priming due to standing waves

Under high heads, standing surface waves are created by the flow from the inlet in the form of an unsubmerged jet, part of which, upon impinging on the bottom of the pipe, curls up the sides and then drops back into the main part of the flow. The water surface is in constant agitation, and there is rapid entrainment of air. The first wave crest nearest to the pipe inlet is largest in magnitude and hence self-priming action is more likely to start at this section. When one of the standing surface waves reaches the pipe obvert and the air space is suddenly taken by water, the cross section becomes full. Self-priming action quickly moves down the pipe and the whole pipe becomes full within seconds.

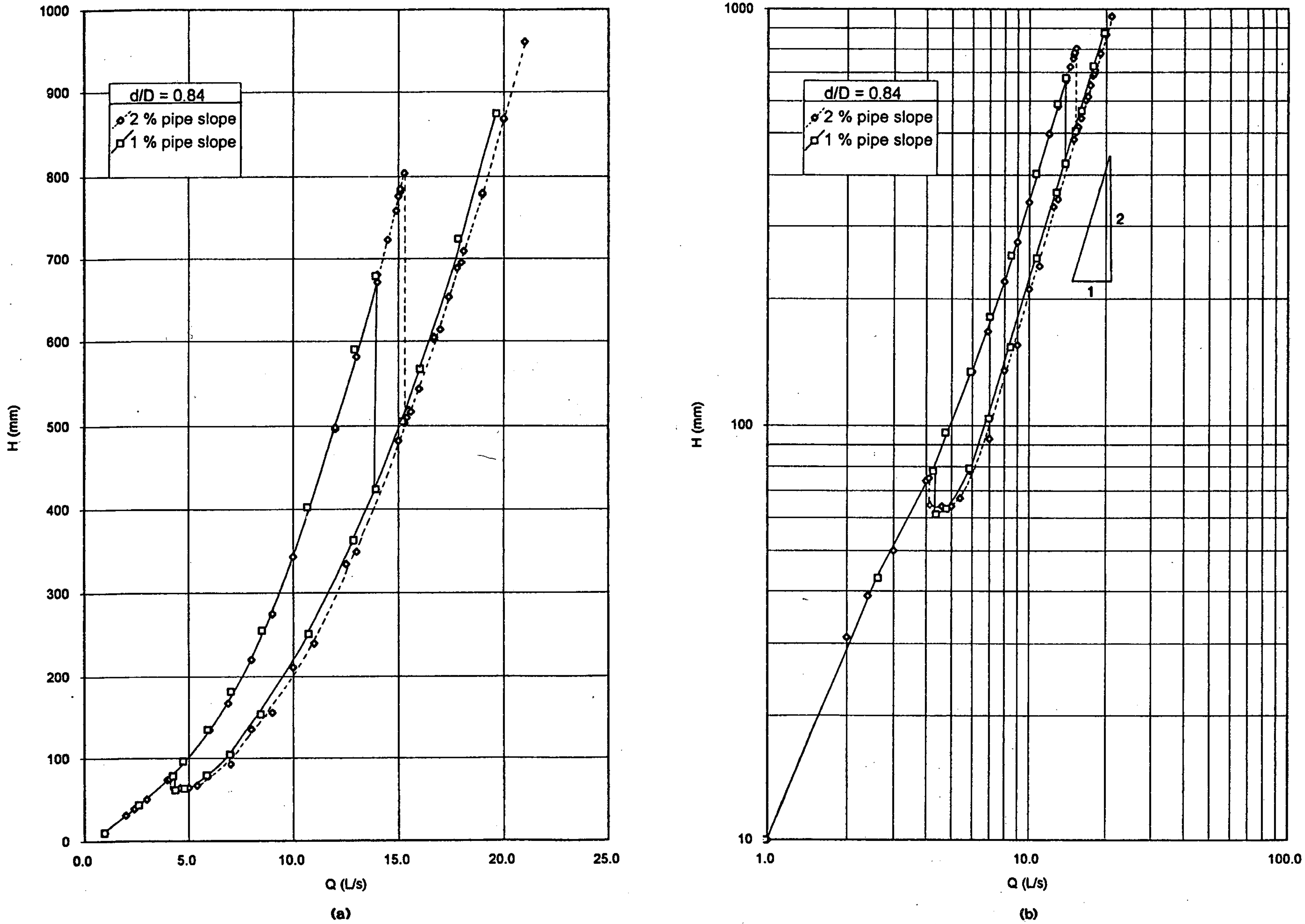


Figure 2 Head versus Flow Rate Relationship for Pipe with 80 mm Orifice plotted on a) Normal Scale b) Logarithmic Scale

Because of the short length of the pipe used in this experiment, the first type of self-priming action (after the hydraulic jump) was not at all observed. It was noticed that there was a certain degree of randomness associated with the other two types of self-priming action. Due to the highly turbulent flow after the jet hitting the bottom of the pipe, the section at which self-priming action started tended to shift in position along the pipe. Self-priming action might also occur at slightly different flow rates and sometimes the flow had to be left running for several minutes before the self-priming action was triggered. Average depth in the pipe when self-priming action occurred was about 75% of the pipe diameter.

4.3 Change-Over from Full to Part-Full Flow

The change-over from full to part-full flow was observed closely in these experiments. Two distinctive types of flow transition were noted and can be described as follows:

(a) Change-over from pipe outlet

Once the pipe runs full, it remains full until the lower end of the hysteresis loop is reached. This is because there is insufficient air supply in the pipe to form a free surface. As the flow rate is decreased, water tends to be held up to the top of the pipe by the suction pressure which exists over the lower range of the flow rate. A small free surface, breaking away the contact with the top of the pipe, is first formed at the pipe outlet. It slowly migrated upstream as the flow rate is progressively decreased until the whole pipe turns into part-full flow.

(b) Change-over from pipe inlet

The second type of change-over occurs at the upstream end of the pipe at low head. When the pipe inlet is not totally submerged, vortices are generated in the tank and tend to suck some air into the pipe and form an air pocket at the inlet. As the air pocket grows larger, the flow becomes super-critical and a hydraulic jump is formed downstream. Eventually the hydraulic jump moves down the pipe until the whole pipe turns into part-full flow.

For the pipe with no orifice or with large diameter orifice, the change-over from full to part-full usually starts from the inlet. Conversely, the change over will start from the outlet when the orifice size is small as it is more difficult for air to enter the pipe from the inlet.

4.4 Effects of the Hysteresis Loop

The size of the orifice is normally determined from the orifice equation, equation 3, based on the assumption that the pipe is part-full and there is no backwater effect from the water depth in the pipe. Since the full flow may be easily triggered by partial blockage of the pipe, the performance of the detention tank can be severely affected by the hysteresis loop. The outflow will be significantly increased and the site discharge will be higher than the PSD. Further research work is being conducted at the University of Technology, Sydney and results will be presented in due course.

5 CONCLUSIONS

Experimental results show that there are two rating curves for part-full and full flow conditions. For the same flow rate, the full flow case will have lower head because of larger cross sectional flow area and hence lower mean flow velocity. By the same argument, for the same head, the full flow case will give higher discharge. A hysteresis loop in the outflow rating curves occurs over the middle range of flow rate. This may have serious effects on the performance of OSD.

6 REFERENCES

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2 Li W.H. and Patterson C.C., *"Free Outlets and Self-Priming Action of Culverts"*, Journal of Hydraulics Division, ASCE, 1956, Vol. 82, No. HY3, pp.1009/1-22.