Energy losses at overflowing pits

Pertes d'énergie au niveau des regards et des avaloirs d'assainissement

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RÉSUMÉ

Dans les réseaux d'assainissement pluviaux, il peut y avoir surverse au niveau des avaloirs ce qui a pour conséquence de modifier leur fonctionnement habituel. Les pertes de charge pour les avaloirs agissant comme exutoires ont été analysés en laboratoire. Le système expérimental est composé uniquement d'un tuyau et d'un regard avec un avaloir. En plus des pertes de charges habituelles au niveau des regards, des pertes de charge importante ont lieu au niveau de l'avaloir lorsque le ratio entre la surface de l'avaloir et la surface du collecteur est inférieur à 25%. Les pertes de charge ont été calculées pour différents types d'avaloir et de regards, et pour différents débits. Ces résultats pourront être utilisés pour calculer la ligne de charge totale au niveau des regards et des avaloirs, et donneront une condition aux limites lors des calculs hydrauliques dans le réseau. Ces résultats sont aussi applicables au niveau des regards des réseaux d'assainissement des eaux usées.

ABSTRACT

Pits in stormwater pipeline systems overflow in various circumstances, reversing the usual inflows. Energy losses for pits operating as outflows have been measured in a laboratory model pit with one inlet pipe and no outlet pipes. In addition to expansion and circulation losses in the pit, significant losses can occur at outlets where the ratio of the outlet opening area to the horizontal pit cross-section area is less than 25%. Loss coefficients related to the velocity head in the inlet pipe have been calculated for circular orifices, grates, kerb inlets and lifted manhole lids over a range of flowrates. These can be used to define the height of the energy grade line above the level of the opening, providing a boundary condition for pipe network calculations. The results are also applicable to manholes in sanitary sewer systems.

KEYWORDS

Stormwater pits, manholes, overflow, surcharge, energy loss

1 OVERFLOWING PITS

In piped drainage systems in Australia, stormwater pits collect surface runoff, provide a node where sizes and directions of pipes can change, and an entry point for inspection and maintenance. Pits can also overflow or surcharge, with water escaping. This can occur when:

(a) flows in an inlet pipe or pipes exceed the hydraulic capacity of the outlet pipe system during severe storms;

(b) outlet pipes or pipes further downstream are blocked; or

(c) overflows are deliberately induced in situations where they can be safely brought to the surface, or where a designer intends that flows are to be divided.

Surcharge pits may be installed to limit the lengths and costs of piped drainage systems, and often operate only in larger storms. They can be used as outlets to siphons running under obstructions.

The pits where overflows occur are usually standard types of inlet pits, although special surcharge chambers or pits are specified by some drainage authorities. With the direction of flow being reversed, inlets become outlets. A common design assumption for a pit without a downstream pipe is that all kinetic energy in upstream flows is lost at the pit, so pressure at the pit surface level will be atmospheric, and the energy will be 1.0 $V_i^2/2g$ above this, where V_i is the velocity in the main upstream pipe that enters the pit, and g is gravitational acceleration.

Surprisingly, there is little engineering literature on overflowing pits, with the Queensland Urban Drainage Manual (Queensland DEWS, 2013) being the only publication located that deals specifically with this topic. Section 7.14.16 of QUDM describes surcharge chambers. For those without an outlet pipe, QUDM defines energy losses comprising a bend loss, an expansion loss, a screen loss, an exit loss and a friction loss in the chamber. For chambers with outlet pipes, estimates of pit energy losses are also included, and guidance on calculations is provided. However, no hydraulic information specific to these chambers or pits is cited.

The purpose of this study was to obtain quantitative information on energy losses at overflowing pits to aid designers and modellers needing to define starting points for water surface profile calculations in pipe systems, or boundary conditions for computational procedures. This was done with the aid of a physical laboratory model employed in a project by Crook (2015). Only the case of a pit with one inlet pipe and no outlet pipes is presented here. Modelling work is continuing on pits with an outlet pipe.

2 LABORATORY TESTING AND DATA PROCESSING

The test rig used in this study, shown in Figure 1, was adapted from a rig used to determine pressure changes at pits in previous studies (O'Loughlin and Kandasamy, 2014).

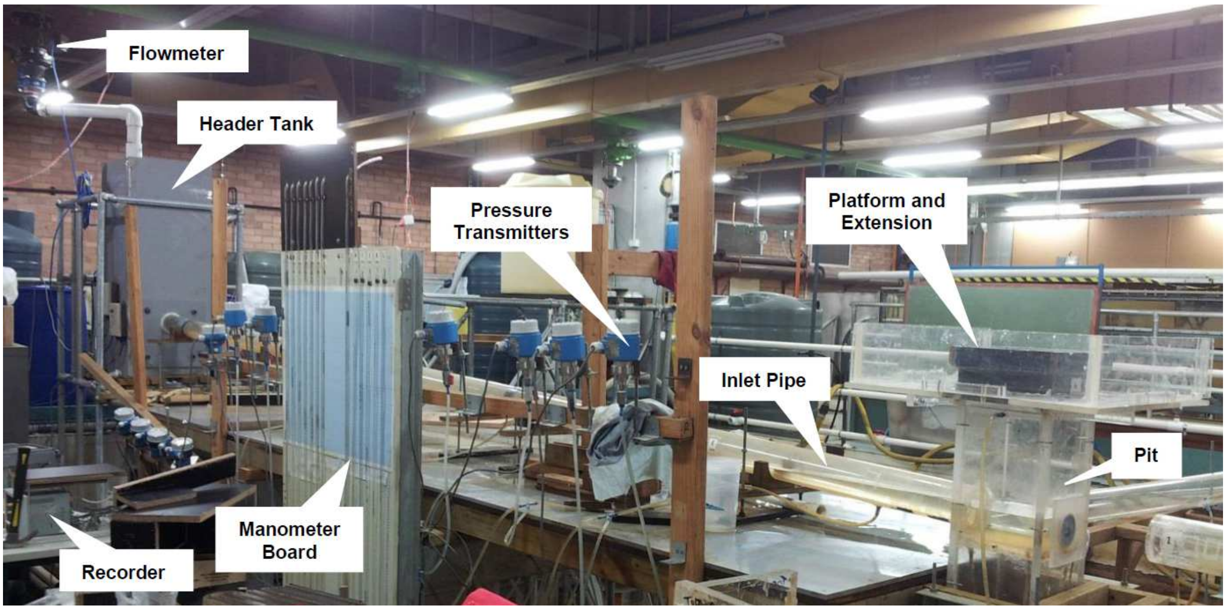

Figure 1 Photograph of Experimental Rig

Water from a header tank ran through a 100 mm diameter acrylic pipe, approximately 7 m long, and entered the overflow pit, where it rose and flowed onto a 640 mm × 640 mm platform. Walls were installed on three sides of the platform to avoid splashing. The pit was square, with horizontal dimensions of 200 mm × 200 mm. It was 325 mm high, and made from clear acrylic panels. Since overflowing water formed a pond on the platform, in some experiments a 100 mm vertical extension of the pit was added to lift the outlet above this influence. This extension and the pit outlet models were constructed from plywood.

As shown in Figure 2, tappings and tubes connected to pressure transmitters measured pressures at five locations along the inlet pipe (spaced 600 mm apart), and at two locations within the pit. A magnetic flowmeter measured flowrates in the inlet pipe. For various flowrates, data were collected in steady-state steps lasting for 5 to 6 minutes, transferred to an electronic data recorder and exported in comma-separated variable format. Pressures and flowrates were recorded at 1 second intervals and averaged over each flowrate step in a spreadsheet. A least-squares fit was applied to project the pressure or hydraulic grade line (HGL) to the centre of the pit. When the pressure head in the inlet pipe, $V_i^2/2g$, was added to this, the energy grade line (EGL) was established.

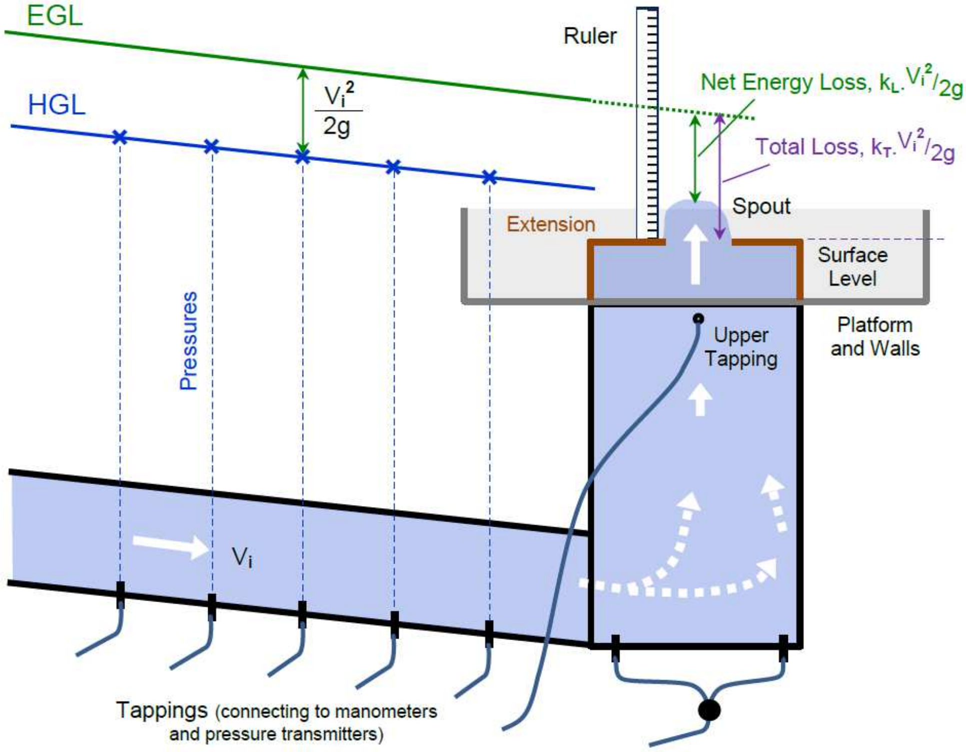

Figure 2 Diagram of Pipe and Pit, showing Grade Lines

At each steady flowrate, the height of the spout of water emerging from the pit was measured with a ruler, using the level of the platform or extension as a base. This data was included in the spreadsheet calculations and energy losses were defined in the two ways shown in Figure 2:

Net energy loss, h_L = projected level of EGL at centre of pit – elevation of top of spout,

Total energy loss, h_T = projected level of EGL at centre of pit – elevation of surface of platform or extension (representing the ground level). This assumes that the kinetic energy of the discharging water is lost.

The net energy loss can only be determined at outlets where flows exit vertically. The total loss can be defined for all outlets, and is more convenient for determining positions of EGLs in design calculations.

3 RESULTS

3.1 Open Pit

As a control or reference for assessing other results, a test was made without any restrictive outlet. Water was allowed to overflow out of the 200 mm × 200 mm pit. The energy loss h_L increased with flowrate as shown in Figure 3, and similar results were obtained for h_T. Proportional relationships were obtained when the velocity head in the inflow pipe, $V_i^2/2g$, were plotted against energy loss, with the coefficient k_L in $h_L = k_L.V_i^2/2g$ being 1.25. This agrees well with a value of 1.2 noted in QUDM, taken from bend losses in Miller (1990).

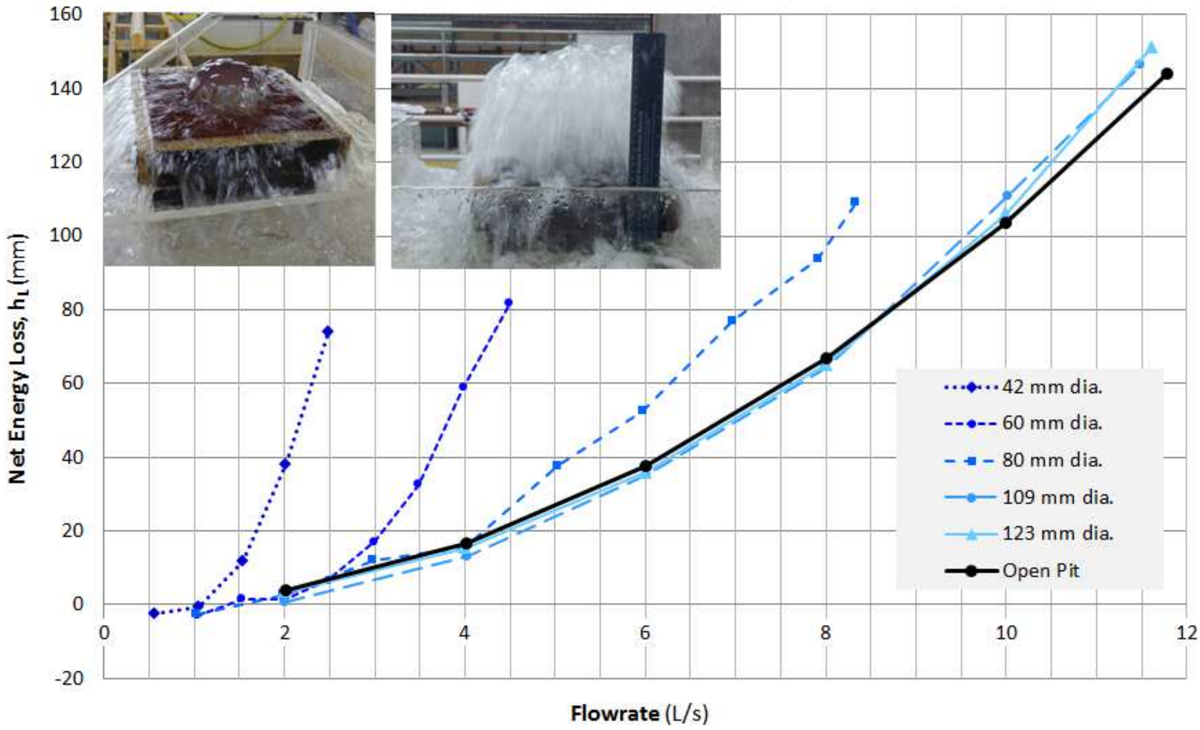

Figure 3 Test Results for an Open Pit and for Orifices of Various Diameters

3.2 Orifices

The first outlets tested were circular sharp-edged orifices, cut into wooden boards 17 mm thick. Orifices are seldom used as pit inlets or outlets, but are the most convenient shape to test the effects of outlet size on energy losses. Orifice diameters from 42 mm to 123 mm were tested, yielding the results shown in Figure 3. Losses for any given flowrate increase as the orifice becomes smaller. However, there appears to be a threshold, between the 80 mm and 109 mm diameters, where energy losses are effectively the same as for the open pit.

Relationships between the velocity heads in the inlet pipe and energy and total losses are plotted In Figure 4. Straight lines can be fitted to these with a high degree of certainty ($R^2 > 0.98$ for diameters of 80 mm and above). k_L and k_T coefficients for the various tests are shown in Table 1. If the ratio of opening area is greater than 20%, k_L coefficients are similar to those for the open pit. This indicates that the main energy losses occur within the pit for openings greater than 20%. As these become more restricted, energy losses at the orifice outlet increase and may far exceed those within the pit.

Table 1 Numerical Results for Orifices

Orifice Diameter	**42 mm**	**60 mm**	**80 mm**	**109 mm**	**123 mm**	**Open Pit**
Opening Area (mm^2)	1385	2827	5027	9331	11,882	40,000
% Opening	3	7	13	23	30	100
k_L Coefficient (& R^2)	12.53 (0.89)	4.06 (0.87)	1.85 (0.99)	1.31 (0.99)	1.31 (1.00)	1.25 (1.00)
k_T Coefficient (& R^2)	72 (1.00)	21 (0.99)	7.77 (0.99)	3.28 (0.99)	2.72 (0.98)	1.62 (0.98)

Pressures measured in the pit show that losses between the bottom and upper tappings are very small. The main losses occur (a) within the lower part of the pit, due to expansion of the incoming jet, collision of the jet with the pit wall and general mixing, and (b) at the outlet. The pit losses are expressed by the k_L and k_T coefficients of 1.3 and 1.6 for an open pit, and exit losses can be taken to be the differences between the higher coefficients obtained for the various outlets tested and these open pit coefficients.

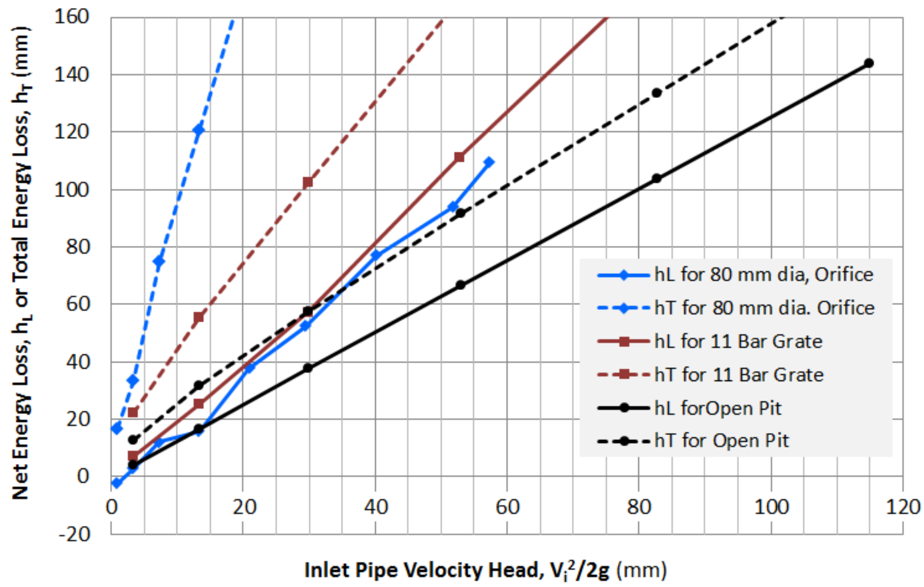

Figure 4 Open Pit and Test Results Comparing Losses with the Velocity Head in the Inlet Pipe

3.3 Grates

The next set of results is for outlets that are commonly used in practice. A series of grates with various numbers of bars were tested in the same way as orifices, producing the results shown in Figure 5 and Table 2.

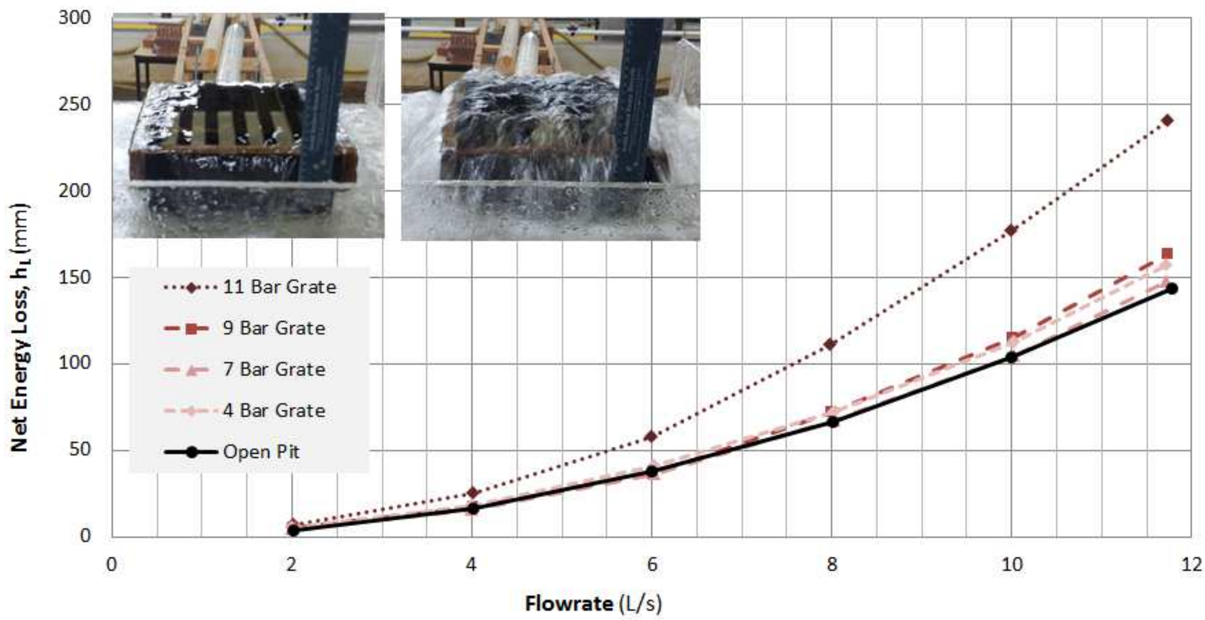

Figure 5 Open Pit and Test Results for Grates

Table 2 Numerical Results for Grates

Grate Type	11 Bar Grate	9 Bar Grate	7 Bar Grate	4 Bar Grate	Open Pit
Opening Area (mm^2)	7600	14,800	22,000	32,800	40,000
% Opening	19	37	55	82	100
k_L-Coefficient (& R^2)	2.11 (1.00)	1.4 (1.00)	1.28 (1.00)	1.25 (1.00)	1.25 (1.00)
k_T-Coefficient (& R^2)	2.99 (0.99)	2.05 (0.98)	1.86 (0.97)	1.73 (0.97)	1.62 (0.98)

For opening ratios greater than, say 25%, exit losses are negligible. The k_L values are higher than for orifices, probably due to their wetted perimeters being greater than those of the circular orifices.

3.4 Kerb Inlets

Another common type of pit inlet is the kerb inlet or side entry pit, a slot on the face of a kerb, which was modelled using boxes with specific slot heights. The total energy losses obtained are shown in Figure 6. Two types of kerb inlets were tested, one that was 200 mm wide and had slot heights of 25, 50 and 75 mm, and a longer kerb inlet, 400 mm wide, with slot heights of 25 and 50 mm.

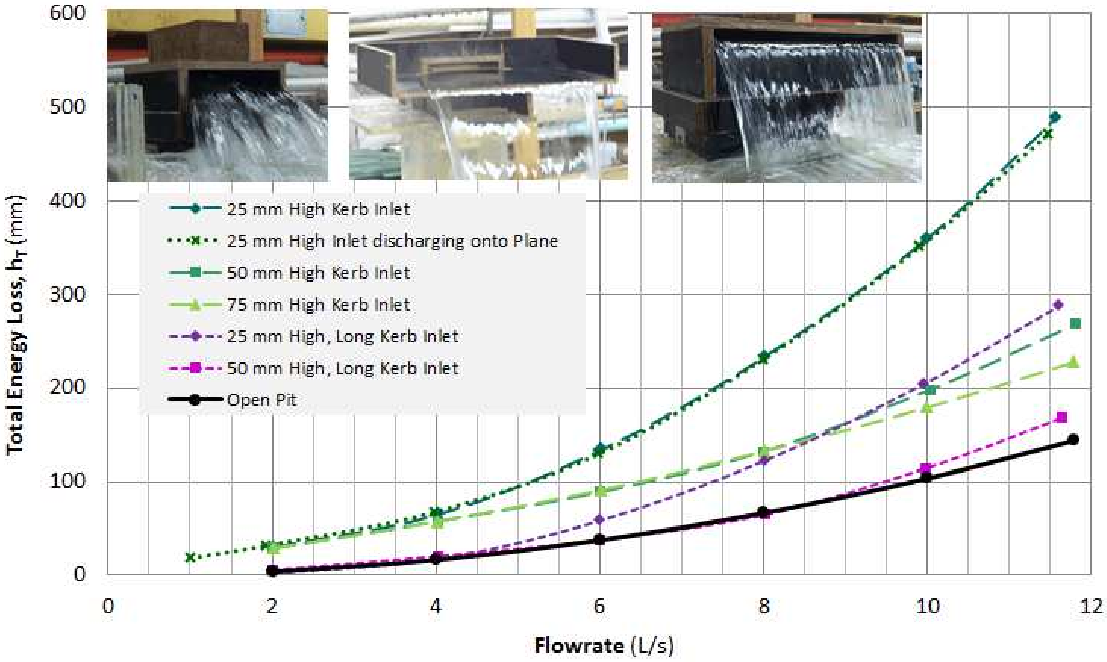

Figure 6 Open Pit and Test Results for Kerb Inlets

At low flows, these outlets act as weirs and energy losses are relatively small, but losses increase when the water level reaches the pit lid and water exits sideways as a jet. In this case, a spout height and associated h_L and k_L values cannot be determined. k_T coefficients can be defined, and relate well to the upstream pipe velocity head, like the orifices and grates in Figure 4. With a 25 mm kerb inlet, the total energy loss is the same for a free outfall as for a discharge onto a flat surface.

3.5 Other Results

The coefficients obtained from the experiments are summarised in Table 3. The following results were obtained in additional tests for the types of outlets shown in Figure 7.

(a) 'Letterbox' pits of the type shown in Figure 7(a), consisting of a solid cover or grate raised on four pillars, and effectively having four kerb inlets, were found to have low total losses (k_T = 1.7 to 2.8). Letterbox pits with a grated top provided similar results to an open pit.

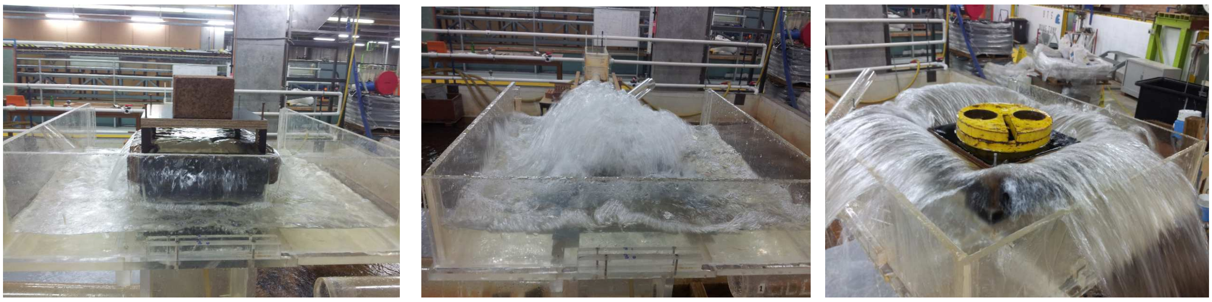

Figure 7 (a) Letterbox Pit, (b) Submerged Outlet and (c) Lifting Pit Lid

(b) Effects of partial submergence of outlets, for example at a sag pit, were examined by placing stop-logs on the platform to create ponds of various depths, as shown in Figure 7(b). For an 80 mm orifice outlet, the k_L coefficient varied from 1.9 to 3.6, 3.9 and 4.7 for submergence depths of 0, 25, 50 and 75 mm respectively. The corresponding changes to k_T coefficients were lower, from 7.8 to 8.4, 8.4 and 8.5. 25 mm high kerb inlets with submergences of 0, 25, 50 and 75 mm had k_T values of 4.4, 4.3, 4.1 and 4.5, essentially the same.

Table 3 Measured Energy Loss and Total Loss Coefficients

Outlet Configuration	**Opening Area** (mm^2)	**Area** (%)	k_L **Coeff.**	k_T **Coeff.**
Open Pit with free outfall [Discharging onto plane]	40,000	100	1.25 [1.2]	1.6 [1.9]
42 mm diameter Orifice	1385	3	13	72
60 mm diameter Orifice	2827	7	4.1	21
80 mm diameter Orifice with free outfall [Same pit discharging onto plane] {Same pit with submerged by 25, 50 and 75 mm}	5027	13	1.9 [2.2] {3.6, 3.9, 4.7}	7.8 [7.3] {8.4, 8.4, 8.5}
109 mm diameter Orifice	9331	23	1.3	3.3
123 mm diameter Orifice	11,882	30	1.3	2.7
11 Bar Grate	7600	19	2.1	3.0
9 Bar Grate	14,800	37	1.4	2.1
7 Bar Grate {Same pit with submerged by 25, 50 and 75 mm}	22,000	55	1.3 {1.7, 1.7, 1.8]	1.9 {2.0, 2.0, 2.0}
4 Bar Grate	32,800	82	1.25	1.75
25 mm slot height Kerb Inlet with free outfall {Same pit with submerged by 25, 50 and 75 mm}	5600	14	-	4.4 {4.3, 4.1, 4.5}
50 mm slot height Kerb Inlet	10,000	25	-	2.4
75 mm slot height Kerb Inlet	15,600	39	-	2.2
25 mm slot height Extended Kerb Inlet	10,000	25	-	2.8
50 mm slot height Extended Kerb Inlet	20,800	52	-	2.1
25 mm slot height Letterbox Pit with solid top	21,600	54	-	1.7
50 mm slot height Letterbox Pit with solid top	41,600	104	-	1.7
25 mm slot height Letterbox Pit with 7 Bar Grate	42,800	107	1.25	1.7
80 mm Orifice with Benching at base of pit	5027	13	1.35	8.0
80 mm Orifice with Narrowed 200 × 100 mm) Pit	5027	13	1.5	7.6
80 mm Orifice with Narrowed Pit plus Benching	5027	13	1.3	7.5
80 mm Orifice with 150 × 150 mm Pit	5027	13	2.2	7.3
150 × 150 mm Open Pit	22,500	100	1.0	1.8

For a 7 bar grate, k_L coefficients are actually slightly lower with submergence, changing from 1.9 for an unimpeded flow to 1.7, 1.7 and 1.8 for submergence depths of 25, 50 and 75 mm. k_T coefficients change from 1.9 for unimpeded flows to 2.0 for all levels of submergence. The different results obtained for the orifice and grate can be attributed to the opening area of the 80 mm diameter orifice being 13% of the pit area, while that of the 7 bar grate is 55% of this area. Overall, losses should be similar for sag and on-grade pits.

(c) Pit lids that lift when sealed pits or manholes are forced to open were tested with a square lid that slid on vertical posts when lifted by the force of escaping water squirting through the gap between the lid and its seat. As shown in Figure 7(c), by placing weights on the lid, results were obtained in four cases, with losses being higher for greater weights. Total energy losses can be plotted as straight-lines that do not pass through the origin. The relationships developed are shown in Figure 8, and empirical equations are given in Table 4. While k_T coefficients are applicable to pipes and pits of all dimensions, a scale ratio must be applied to masses. From Froude Number similarity, the ratio for masses would be (prototype scale / model scale)^3.

(d) Effects of pit size were examined by placing inserts in the 200 mm × 200 mm pit to reduce (i) its width to 100 mm, and (ii) the pit size to 150 × 150 mm. In tests with an 80 mm orifice outlet, k_L and k_T coefficients reduced from 1.9 and 7.8 for the standard pit to 1.5 and 7.6 for the narrowed pit. They were 2.2 and 7.3 for the 150 × 150 mm pit. Benching was added to the standard and narrowed pits, using 45^o blocks that directed flows entering the pit upwards. This reduced k_L and k_T coefficients from 1.9 and 1.5 to 1.35 and 1.3. A tentative conclusion is that the results obtained from the experimental rig will be applicable to most sizes and shapes of pits and manholes.

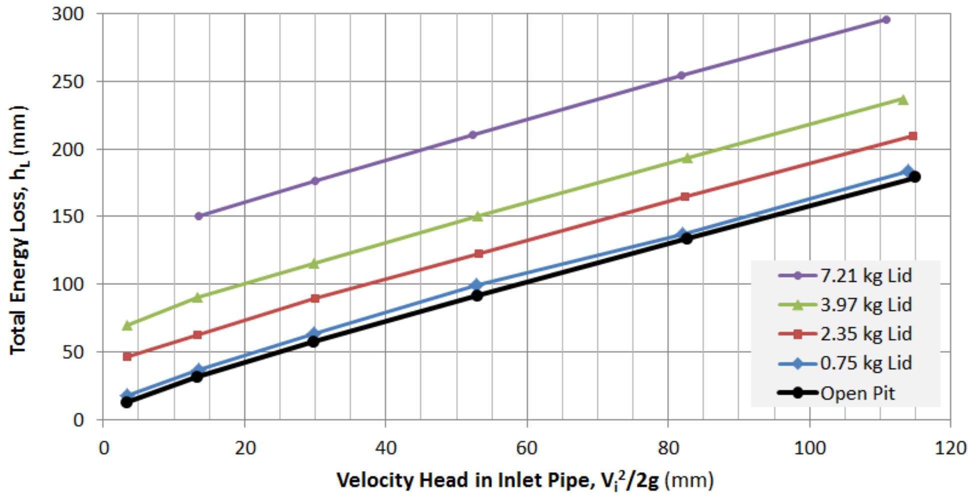

Figure 8 Open Pit and Test Results for Kerb Inlets

Table 4 Equations for Lifting Manhole Lids

Outlet Configuration	**Maximum Opening Area*** (mm^2)	**Opening Area*** (%)	**Total Energy Loss, h_T**
Lifting Lid with 0.75 kg (m_1) mass	15,000	38	1.48 $V_i^2/2g$ + 17 ≈ 1.5 $V_i^2/2g+2m_1g$
Lifting Lid with 2.35 kg total (m_2) mass	10,000	25	1.46 $V_i^2/2g$ + 44 ≈ 1.5 $V_i^2/2g+2m_2g$
Lifting Lid with 3.97 kg total (m_3) mass	8400	21	1.50 $V_i^2/2g$ + 69 ≈ 1.5 $V_i^2/2g+2m_3g$
Lifting Lid with 7.21 kg total (m_4) mass	7600	19	1.49 $V_i^2/2g$ + 131 ≈ 1.5 $V_i^2/2g+2m_4g$

* Based on the maximum height that lid was raised.

4 USE OF COEFFICIENTS IN DESIGN OR ANALYSIS

A designer or analyst of a piped drainage system can establish a downstream boundary condition for an overflowing pit by applying the k_T coefficients given in Table 3 to the velocity head in the inlet pipe for a specified flowrate.

For example, for a flow of 447 L/s through a 500 mm pipe, the pipe velocity is 2.28 m/s and velocity head $V_i^2/2g$ is 0.265 m. If the flow exits through a grate with a 33% opening area, equivalent to a 9 bar grate, and a k_T of 2.1 is selected from Table 3, the EGL will be 2.1 × 0.265 = 0.555 m above the surface level. If the grate opening is decreased to 16% by blockage, approximating an 11 bar grate, the factor rises to 3.0, and the height to 0.794 m. (Using a length scale factor of 5, this equates to 0.159 m in the test rig model with a 100 mm diameter pipe.)

5 CONCLUSIONS

The main conclusion is that energy losses through an outlet such as a grate or orifice will be small provided that the area of the opening is at least 25% of the pit cross-sectional area. Relationships have been established between loss coefficients and the flowrate and velocity head in the inlet pipe. While net energy losses cannot be defined in many situations, the position of the EGL above the outlet surface level can still be established using the k_L coefficients. Factors such as submergence, pit dimensions and benching have minor effects on losses and coefficients.

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