CHANSON, H. (2007). "Hydraulic Performances of Minimum Energy Loss Culverts in Australia." *Journal of Performances of Constructed Facilities*, ASCE, Vol. 21, No. 4, pp. 264-272 (doi:10.1061/(ASCE)0887-3828(2007)21:4(264)) (ISSN 0887-3828).

HYDRAULIC PERFORMANCES OF MINIMUM ENERGY LOSS CULVERTS IN AUSTRALIA

by Hubert Chanson ([1])

Abstract

Culverts are among the most common hydraulic structures. Modern designs do not differ from ancient structures and are often characterised by significant afflux at design flows. A significant advance was the development of the Minimum Energy Loss (MEL) culverts in the late 1950s. The design technique allows a drastic reduction in upstream flooding associated with lower costs. The development and operational performances of this type of structure is presented. The successful operation of MEL culverts for more than 40 years is documented with first-hand records during and after floods. The experiences demonstrate the design soundness while highlighting the importance of the hydraulic expertise of the design engineers.

Subject headings : Culverts, Flood plains, Flow, Hydraulic design

Keywords: Culverts, Minimum Energy Loss design, Critical flow, Operation, Experience, Urban drainage.

Introduction

Culverts are among the most common civil engineering structures (Fig. 1). Modern designs are very similar to ancient designs, and they are characterised by some significant afflux at design flow conditions. The afflux is the rise in upstream water level caused by the hydraulic structure. It is a measure of upstream flooding. During the late 1950s and early 1960s, a new design of minimum energy loss (MEL) culvert was developed in Australia to achieve zero or minimum afflux (Fig. 2). Minimum Energy Loss culverts are also called Minimum Energy culverts (McKay 1971), Constant Energy structures, Minimum Specific Energy (MSE) culverts (McMahon 1979), Constant Total Energy structures, or Energy culverts (Lowe 1970). The term Minimum Energy Loss structure is however a more accurate terminology (Apelt 1983, Chanson 1999).

It is the purpose of this paper to review the operational performances of Minimum Energy Loss (MEL) culverts. After a brief review of the first development and designs, the successful operation of several large structures for more than 40 years is documented by field inspections and surveys of existing structures.

Culvert design

A culvert is a covered channel of relatively short length designed to pass water through an embankment. Its purpose is to carry safely flood waters, drainage flows, and natural streams below the earthfill structure (Fig. 1 & 2). Culverts have been used for more than 3,500 years. Although the world's oldest culvert is unknown, the Minoans and the Etruscans

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built culverts in Crete and Northern Italy respectively (Evans 1928, O'Connor 1993). The Romans built also numerous culverts beneath roads and aqueducts (Ballance 1951, O'Connor 1993). For example, a multicell culvert was built beneath the Nîmes aqueduct and the structure design was capable of discharging a rainfall runoff in excess of 10 times the maximum aqueduct flow rate (Chanson 2002).

Modern designs of culverts (Fig. 1) do not differ much from Etruscan and Roman culverts. The primary design constraint is the minimum construction costs, but additional constraints might include maximum acceptable upstream flood level and scour protection at outlet. The discharge capacity of the barrel is primarily related to the flow pattern : free-surface barrel flow or drowned barrel. In any case, the standard culverts are characterised by significant afflux at design flow. Numerous solutions were devised to reduce the afflux for a given design flow rate, by rounding the inlet edges, using throated entrances and warped wing walls, introducing a bellmouth intake : e.g., California Division of Highways (1956), Neill (1962), Federal Highway Administration (1972,1985), Hamill (1999). These solutions are expensive and marginal.

Development of Minimum Energy Loss culverts

The concept of Minimum Energy Loss (MEL) culvert was developed by late Professor Gordon McKay (McKay 1971, 1978) (App. I). The first MEL structure was the Redcliffe storm waterway system, also called Humpybong Creek drainage outfall, completed in 1960 (Chanson 2003). It consisted of a drop inlet followed by a 137 m long MEL culvert discharging into the Pacific Ocean. The design discharge was Q_{des} = 26 m^3/s, the barrel internal width was B_{min} = 5.5 m, the barrel internal height was D = 3.5 m, and the barrel invert slope was 0.0016. The inlet weir was designed to prevent salt intrusion in Humpybong Creek without afflux, while the culvert discharged flood water underneath a shopping centre parking. The structure passed floods greater than the design flow in several instances without flooding (McKay 1970). It is still in use (Fig. 2A).

The Minimum Energy Loss (MEL) culverts are designed with the concept of minimum head loss and nearly constant total head along the waterway. The flow in the approach channel is contracted through a streamlined inlet into the barrel where the channel width is minimum, and then is expanded in a streamlined outlet before being finally released into the downstream natural channel. Both inlet and outlet must be streamlined to avoid significant form losses (Fig. 2 and 3). The MEL culvert is further designed to operate at critical, or trans-critical, flow conditions from the inlet lip to the outlet lip for the design discharge. At critical flow, the discharge per unit width is maximum for a given specific energy (Henderson 1966, Chanson 2004a). The barrel invert is often lowered to increase the discharge capacity or to reduce the barrel width.

The design flow parameters are the design flow rate Q_{des} and the upstream specific energy E_o in the flood plain in absence of culvert. For a culvert design with zero afflux, the width of the inlet lip must satisfy the Bernoulli principle:

$$B_{max} = \frac{Q_{des}}{\sqrt{g * \left(\frac{2}{3} * E_o\right)^3}} \tag{1}$$

where the inlet lip width B_{max} is measured perpendicular to the streamlines (Fig. 3).

Equation (1) derives from the definition of critical flow conditions for a rectangular channel. In the inlet and outlet, there is an unique relationship between the width B and the excavation depth Δz (Chanson 2004a). The barrel width must satisfy :

$$B_{min} = \frac{Q_{des}}{\sqrt{g * \left(\frac{2}{3} * (E_o + \Delta z_o)\right)^3}} \qquad (2)$$

where Δz_o is the maximum excavation depth (Fig. 3).

The inlet and outlet design is based basically upon a flow net analysis using irrotational flow theory (e.g. Vallentine 1969). In the inlet, the contour lines (i.e. lines of constant invert elevation) are equipotential lines and they must be perpendicular to the flow direction (i.e. streamlines) everywhere. The flow net forms a network of converging "quasi-square" elements. The design theory is well understood for man-made structures with rectangular cross-sections. Professor C.J. Apelt presented an authoritative review (Apelt 1983) while the author highlighted the wide range of design options and illustrated prototypes (Chanson 1999,2000). Some audio-visual and Internet references are presented in Table 1.

In practice, a MEL culvert design is selected only if it is cheaper than a standard culvert design. The cost of the entire structure is connected with the design specifications (design flow, upstream design head, maximum afflux), the topography and construction costs, and the design costs. The experience in Australia suggests that the MEL design compares favourably in flat flood plains with limited available afflux, and for long culvert barrels, despite the higher design and construction costs.

Australian developments

Since the first structure in Redcliffe (Fig. 2A), about 150 structures were built in Eastern Australia (Table 2). While a number of small-size structures were built in Victoria, primarily under the influence of Norman Cottman, shire engineer, several major structures were designed, tested and built in South-East Queensland where little head loss was permissible in the culverts and most MEL culverts were designed for zero afflux. The largest MEL waterway is the Nudgee Road MEL system near the Brisbane international airport with a design discharge capacity of 800 m^3/s. Built between 1968 and 1970, the waterway passed successfully floods in excess of the design flow. The channel bed is grass-lined and the structure is still in use. Several MEL culverts were built in southern Brisbane during the construction of the South-East Freeway in 1975 connecting Brisbane to the Gold Coast. The design discharge capacity range from 200 to 250 m^3/s. The culverts operate typically several days per year and the author organises regularly undergraduate student field works there (Fig. 2B, 4A & 5A). Figure 2B shows the inlet of a MEL culvert designed to pass Q_{des} = 170 m^3/s with zero afflux. The inlet lip width is B_{max} = 25.2 m, the barrel width is B_{min} = 12.3 m, the barrel length is L_{barrel} = 129.4 m, and the excavation depth is Δz_o = 1.6 m.

For floods larger than the design flow, the MEL culvert barrel operates typically with a supercritical flow, some afflux is observed and a hydraulic jump occurs downstream of the outlet. Some prototype experience, at Redcliffe, and during the 1974 flood in Brisbane, demonstrated that the MEL culvert structures can operate successfully with discharges larger than the design flow. Some physical modelling conducted at the University of Queensland showed further that the MEL culvert design can pass successfully floods of up to 150% of the design flow with relatively small afflux.

McKay (1971) indicated further MEL culverts built in Northern Territory near Alice Springs in 1970 (Table 2). Cottman (1976) described the Newington bridge MEL waterway completed in 1975 (Q_{des} = 142 m^3/s). In 1975 and

1988, the structure passed successfully 122 and 150 m^3/s respectively without any damage (Cottman and McKay 1990).

Developments outside of Australia

The MEL culvert designs received strong interests in Canada, USA and UK. For example, Lowe (1970), Loveless (1984), Federal Highway Administration (1985, p. 114), Cottman and McKay (1990). A design patent was established in 1978 : i.e., Patent No. 428.025 (Australia), 1.253.896 (UK), 3.593.527 (USA) and 69/2799 (South Africa) (Matthews and McKay 1978).

Two pertinent studies in Canada (Lowe 1970) and UK (Loveless 1984) demonstrated that MEL culverts can pass successfully ice and sediment load without clogging nor silting. These laboratory findings were confirmed by inspections of MEL culvert structures after major flood events demonstrating the absence of siltation and debris as observed first hand by the writer.

Performances and experiences

The first MEL structures were designed with the concept of constant total head, hence zero afflux, associated with some solid physical modelling. The MEL culvert designs were typically tested in 1:12 to 1:36 undistorted scale models with fixed bed. They have been in operation for more than 45 years with a range of hydrological conditions including semi-temperate, semi-tropical, tropical and arid weathers. The characteristics and operational record of a number of MEL structures were documented, and this was complemented by recent field inspections including during flood events (Fig. 4 & 5), new surveys, and oral discussions with designers. Some results are summarised in Table 2. Note that most MEL structures are still in use. Basic design parameters include the design flow Q_{des}, the throat width B_{min}, the excavation depth Δz_o that are listed in Table 2.

Several structures were observed operating at design flows and for floods larger than design. Inspections by hydraulic experts during and after flood events demonstrated a sound operation associated with little maintenance (Fig. 4 & 5). Figures 4 and 5 show two Minimum Energy Loss structures in operation for discharges less than the design flow rate. Both structures are located in a catchment in the city of Brisbane. The design flow conditions correspond to an intense rainstorm with a concentration time of 2 hours yielding a runoff discharge of between 150 and 220 m^3/s. A total of 5 Minimum Energy Loss structures were built to operate with zero afflux at design flow rate on the same stream (Norman Creek). Figure 4 presents a MEL waterway designed to pass the runoff beneath the freeway without flooding the street beside on the left bank (Fig. 4). The MEL channel was completed in 1975 for Q_{des} = 200 m^3/s and zero afflux. The inlet lip width is B_{max} = 33.5 m, the throat width is B_{min} = 11.2 m, the throat length is L_{barrel} = 87.3 m, and the excavation depth is Δz_o = 1.3 m. Figure 4A shows a typical dry weather conditions, and the low flow channel is seen on the far left and in the background. Figures 4B and 4C illustrate some flood flows. The flood shown in Figure 4C occurred after a series of rain storms through the morning and early afternoon with some heavy rainfall between 12:30 until 13:30. Some free-surface standing waves were seen in the barrel. Free-surface undulations, or standing waves, are a typical feature of critical and trans-critical flows (e.g. Chanson 1999). Figure 5 shows another Minimum Energy Loss culvert completed in 1975 for Q_{des} = 220 m^3/s and zero afflux. The inlet lip width is B_{max} = 42 m, and the barrel width is B_{min} = 21.3 m. Figure 5A presents a dry weather situation with a student standing above the low flow drain.

Figure 5B highlights the occurrence of a small hydraulic jump in the inlet. That feature is common to MEL culverts operating with discharges less than the design flow rate because the barrel flow is subcritical and the inlet flow is supercritical. At design discharge, the flow is critical from the inlet lip to the outlet lip including in the barrel, and no hydraulic jump takes place. Figure 5C illustrates the outlet flow that is often subcritical and relatively smooth.

While McKay (1970,1971) gave general MEL culvert guidelines, Professor Colin Apelt stressed that a successful design must follow closely two basic design concepts: streamlining of the flow and trans-critical flow conditions (Apelt 1983). Importantly flow separation and recirculation must be avoided at all cost. In one structure, some separation was observed in the inlet associated with some flow recirculation in the barrel (Cornwall St, Brisbane). The structure cannot pass more than 50% of its design flow rate without road overtopping. MEL culverts may be designed for trans-critical flow operation (Fr = 0.6 to 0.8) and supercritical flow conditions must be avoided at design flow rate. This is particularly important in the outlet where separation must be avoided as well (Apelt 1983).

The successful operation of large MEL culverts for over 40 years has highlighted further practical considerations. MEL culverts must be equipped with adequate drainage to prevent water ponding in the barrel invert. Drainage channels must be preferred to drainage pipes. For example, the MEL structures shown in Figures 4 and 5 are equipped with a well-designed drainage system seen in the middle of Figure 5C. One issue is the loss of expertise in MEL culvert design. In Brisbane, two culvert structures were adversely affected by the construction of a new busway 25 years later. Figure 6 shows one of the concrete piers built in the middle of the culvert inlet to support the busway. The MEL culvert was completed 1975, and designed for Q_{des} = 170 m^3/s and zero afflux. Figure 6 looks downstream at the inlet flow, and one of the concrete piles built in the inlet in 1999-2000 to support a new busway is clearly visible. As a result, one major arterial road (Marshall Rd, Brisbane) will be overtopped during a design flood because the inflow streamlining is disturbed by the piers, and no remedial measure was considered since. This new busway is visible in Figure 4B above the MEL waterway outlet, but this structure was not affected.

Design experiences

Most hydraulic structures, including Minimum Energy Loss culverts, are designed for an optimum use at the most economical cost. The hydraulic design of a culvert is basically the selection of an optimum compromise between discharge capacity and head loss or afflux, and design, construction and operation costs. The selection of a Minimum Energy Loss culvert derives always from a comparison with a standard culvert design that is cheaper to build but less hydraulically efficient. A MEL design is selected only if it is the cheapest. For example, the Redcliffe MEL culvert (Fig. 2A) costed the equivalent of US$460,000 (in 2006) and he allowed the development of a commercial centre valued at 32 millions of US$. The MEL waterway at Newington Bridge was 6 times cheaper than a conventional waterway.

A main characteristic of the MEL culvert design is the small head loss. It results in a small or zero afflux. The flow velocities in the culvert are larger than in a standard culvert. The wingwalls and floors must be adequately protected. However the MEL culvert streamlining yields low turbulence and the erosion potential is reduced : e.g., fans can be made of earth with grassed surface as at Newington Bridge and Nudgee waterway. For zero afflux, the size of a MEL culvert (inlet, barrel, outlet) is smaller than that of a standard culvert with identical discharge capacity. Hee (1969) indicated that, for a very long culvert, the MEL culvert design tends to be more economical. An additional consideration is the greater factor of safety against flood discharges larger than the design discharge. Model and prototype observations have shown conclusively that MEL culverts can pass safely flood flows significantly larger than the design flow conditions. This is not always the case with standard culverts.

McKay (1978) recommended strongly to limit MEL design to rectangular cross-section waterways. For non-rectangular waterways, the design procedure becomes far too complex and it might not be reliable. Lastly a MEL culvert does not need to symmetrical and it may have a curved shape : e.g., the Newington Bridge waterway and the MEL waterway shown in Figure 4.

Discussion

During a non-cohesive embankment breach, the movable boundary flow tends to an equilibrium that is associated with minimum specific energy conditions. Professor McKay suggested first an analogy between natural scour below a small bridge and the shape of minimum energy loss inlet design (McKay 1971). Several field studies of lagoon breakouts highlighted the hourglass (Venturi) shape of the breach and some analogy with the MEL inlet shape (Gordon 1981,1990, Brodie 1988, Visser et al. 1990). Recent studies of non-cohesive embankment breach documented the challenging similarity during breach development (Coleman et al. 2002, Chanson 2004b). That is, the total head was basically constant from the inlet lip to the throat, the breach flow was streamlined and the flow conditions were trans-critical ($0.5 < Fr < 1.8$).

In a natural breach, the cross-sectional shape is irregular, and its characteristics must satisfy simultaneously :

$$Fr = \frac{Q}{\sqrt{g * \frac{A^3}{B}}} = 1 \qquad \text{critical flow conditions (3)}$$

$$H = z_{wl} + \frac{1}{2} * \frac{Q^2}{g * A^2} = \text{constant} \qquad \text{Bernoulli principle (4)}$$

where A is the flow cross-section selected perpendicular to the streamlines, B is the free-surface width and z_{wl} is the free-surface elevation. Natural breach inlet lengths L_{inlet}, measured along the breach centreline between inlet lip and throat, satisfied L_{inlet}/B_{max} = 0.5 to 0.6, where B_{max} is the free-surface width at the upper lip. The result was close to the optimum inlet length recommended for MEL culvert design : "*the minimum satisfactory value of length/B_{max} is 0.5*" (Apelt 1983, p. 91).

CONCLUSION

A major advance in culvert design was the development of the Minimum Energy Loss culvert under the leadership of late Professor Gordon McKay. The MEL culverts were developed in the late 1950s to achieve minimum, and often zero, afflux at design flow conditions in the flat Australian flood plains. The first MEL structure was the Humpybong Creek waterway in Redcliffe (Qld 1960). The MEL design allows a drastic reduction in upstream flooding associated with lower total costs. The MEL culvert design is based upon the streamlining of the waterway to reduce form losses and an operation with trans-critical flow conditions at design discharge.

The successful operation of MEL culverts for more than 40 years demonstrate the design soundness while highlighting the importance of streamlining throughout all the structure. Past experiences showed further than the design must be based upon expert hydraulic engineering and that subsequent modifications of the structure must be carefully analysed to minimise some adverse effect on the flood flow. The MEL culvert construction can be undertaken with simple, local materials, earthwork equipments, and it does not require sophisticated equipment nor manpower.

Acknowledgments

The writer thanks Professor Colin J. Apelt (University of Queensland) for his valuable advice. He acknowledges the assistance of numerous students who surveyed the structures and Dr M.R. Gourlay (The University of Queensland) and Dr J.H. Loveless (University of Bristol) who provided him with relevant information.

Appendix I - Professor Gordon Reinecke McKay (1913-1989)

Born in Liverpool, Gordon Reinecke ("Mac") McKay was educated at Liverpool University in civil engineering, where he completed his Ph.D. in 1936. During his doctoral study, he visited Karlsruhe where he worked under the guidance of Professor Theodor Rehbock (1864-1950) who was professor at the Technical University of Karlsruhe and whose contribution to the design of hydraulic structures and physical modelling was significant. In 1950, Gordon McKay moved to Australia where he became an academic staff of the Nsw University of Technology (today University of New South Wales) in Sydney. In 1951, he was appointed in the department of civil engineering at the University of Queensland (Brisbane) where he worked until his retirement in 1978. He was appointed Professor in 1967.

Professor McKay contributed very significantly to the development of hydraulic physical models and design of hydraulic structures in Queensland. In the late 1950s and early 1960s, he developed the concepts of Minimum Energy Loss (MEL) culverts and MEL weirs : i.e., Redcliffe MEL structure completed in 1960; Clermont weir completed in 1963. In 1980, the extension of the Hydraulics Laboratory at the University of Queensland was named the G.R. McKay Hydraulics Laboratory. In 1997, a creek in western Brisbane was named after Professor McKay : i.e., the McKay Brook.

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Notation

A	flow cross-section area (m^2);
B	free-surface width (m);
B_{max}	inlet lip width (m);
B_{min}	barrel width (m);
D	barrel internal height (m);
d_c	critical flow depth (m);
d_{tw}	tailwater depth (m);
d_o	normal depth (m) in the flood plain;
E_o	upstream specific energy (m);
Fr	Froude number;
g	gravity acceleration (m/s^2);
H	total head (m);
L_{barrel}	barrel length (m);

L_{inlet}	inlet length (m);
L_{outlet}	outlet length (m);
Q	flow rate (m^3/s);
Q_{des}	design flow rate (m^3/s);
S_o	bed slope of the natural flood plain;
S_c	barrel invert slope;
z	vertical coordinate positive upwards (m);
z_{wl}	water level elevation (m);
ΔH	head loss (m);
Δz_o	excavation depth (below natural ground level) (m);

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Table 1 - Audio-visual and Internet resources on Minimum Energy Loss culverts and waterways

Description (1)	Reference (2)
Audio-visual resources The Minimum Energy Loss Culvert	Apelt, C.J. (1994). "The Minimum Energy Loss Culvert." Videocassette VHS colour, Dept. of Civil Eng., University of Queensland, Australia, 18 minutes.
Norman Creek Flood on 7 November 2004	Chanson, H. (2004c). "Storm and flood at Norman Creek, Brisbane (Australia) on 7 November 2004." IAHR Media Library {http://www.iahrmedialibrary.net/}, Urban drainage, video-clip, 6 minutes.
Internet resources Hydraulics of Minimum Energy Loss (MEL) Culverts and Bridge Waterways	{http://www.uq.edu.au/~e2hchans/mel_culv.html}
Design of waterways and culvert structures on Norman Creek, Queensland	{http://www.uq.edu.au/~e2hchans/civ4511.html#Project}

Table 2 - Characteristics of successful designs of Minimum Energy Loss culverts and waterways (All structures are still in use unless indicated)

Description (1)	Date (2)	S_o (3)	Q_{des} m^3/s (4)	d_{tw} m (5)	B_{max} m (6)	L_{inlet} m (7)	Δz_o m (8)	B_{min} m (9)	D m (10)	L_{barrel} m (11)
MEL waterways										
Norman Creek, beneath SE-Freeway, Brisbane Qld	1975	0.00184	200	--	33.5	28.8	1.3	11.2	4.0	87.3
Nudgee Rd, Schultz canal, Brisbane Qld	1968-69	0.00049	850.0	1.7	209.7	122.0	0.8	137.0	--	18.3
MEL culverts										
Humpybong Creek, Redcliffe Qld	1960	--	25.8	Tidal	19.5	30.5	1.2	5.5	*3.5*	152.4
Burnett highway, Goomeri Qld	1969	--	32.3	0.9	21.9	3.7	0.9	6.1	1.5	*7.1*
Jerry's Downfall, Beaudesert Rd Qld (+)	1970	--	58.0	1.0	--	--	0.6	17.1	1.5	--
Stuart Highway, N Alice Springs NT (+)	1970	--	--	--	--	--	--	4.3	1.4	--
Stuart Highway, N Alice Springs NT (+)	1970	--	--	--	--	--	--	2.1	1.4	--
Settlement Shore - Flood outlet Structure A, Port Macquarie Nsw	1973	0.0119	317.1	1.5	101.8	56.4	2.8	24.7	--	0.0
Settlement Shore - Flood outlet Structure B, Port Macquarie Nsw	1974	0.01212	577.7	1.4	206.7	91.4	3.2	50.0	--	0.0
Norman Creek, Marshall Rd, Brisbane Qld	1971-75	--	170.0	--	--	--	--	--	--	--
Norman Creek, Birdwood St, Brisbane Qld	1971-75	0.00089	170.0	--	--	21.4	0.7	10.8	3.0	106.0
Norman Creek, Ekibin (Station 100), Brisbane Qld	1975	0.00673	169.9	2.8	25.2	15.1	1.6	12.3	3.6	129.4
Norman Creek, Ridge St, Brisbane Qld	1975	0.00562	220.0	1.9	42.0	23.8	1.5	21.3	3.0	53.5
Newington Bridge, Sheepwash Creek, Stawell Shire, Vic	1975	*0*	141.5	0.8	125.0	73.2	2.4	9.6	2.4	21.3
Bridge d/s Genorchy, Wimmera River, Stawell Shire, Vic	1975-78?	--	720.0	2.1			1.2		--	--
Illawarra to Mt Dryden Rd, Stawell Shire, Vic	1977-78	0.00259	140.0	1.1	90.0	80.0	0.9	20.3	2.5	10.0
Fox's bridge, Bulgana Rd, Bulgana Parish, Stawell Shire, Vic	1977-78	0.005	55.2	--	120.0	90.0	3.1	6.6		*40.0*
Wynnum, South, Brisbane Qld	1985-86	--	220.0	--	62.0	34.0	--	*18.0*	*3.0*	--
Wynnum North, Brisbane Qld	1985-86	--	100.0	--	90.0	60.0	--	*19.8*	*1.6*	--

Description (1)	S_c barrel (12)	Construction details (13)	L_{outlet} m (14)	B_{outlet} m (15)	Total length m (16)	ΔH available m (17)	Remarks (18)
MEL waterways							
Norman Creek, beneath SE-Freeway, Brisbane Qld	0.00366	Concrete lined.	24.1	38.81	140.2	--	Surveyed in May 2002 and Apr. 2005.
Nudgee Rd, Schultz canal, Brisbane Qld	--	Grass-lined. Tidal effects.	122	--	245.3	--	Model tests (1:48 undistorted scale, fixed bed). Field observations.
MEL culverts							
Humpybong Creek, Redcliffe Qld	0.0016	Single cell. MEL weir at inlet. Tidal tailwater conditions.	30.48	22.86	198.1	1.16	Model tests in 1960 (1:12 scale model). $Q > Q_{des}$ at least 3 times.
Burnett highway, Goomeri Qld	--	3 cells	3.7	--	--	--	
Jerry's Downfall, Beaudesert Rd Qld (+)	--	8 cells.	--	--	--	--	Field observations.
Stuart Highway, N Alice Springs Nt (+)	--	Several culverts: 2 cells.	--	--	--	--	
Stuart Highway, N Alice Springs Nt (+)	--	Several culverts: single cell.	--	--	--	--	
Settlement Shore - Flood outlet Structure A, Port Macquarie Nsw	N/A	1 bridge pier. Tidal tailwater conditions.	71.63	57.0	128.0	0.427	1:48 scale model tests.
Settlement Shore - Flood outlet Structure B, Port Macquarie Nsw	N/A	2 rows of circular bridge piles (1.22 m Ø). Tidal tailwater conditions.	109.73	103.9	201.2	0.274	1:48 scale model tests.
Norman Creek, Marshall Rd, Brisbane Qld	--	2 cells.	--	--	146.0	--	Culvert inlet flow affected by Busway pile in channel.
Norman Creek, Birdwood St, Brisbane Qld	0.00377	4 cells.	18.4	29.7	145.8	--	Surveyed in May 2002 and Apr. 2005.
Norman Creek, Ekibin (Station 100), Brisbane Qld	0.0023	4 cells. Outlet with flip bucket design.	15.9	*15 ?*	178.3	--	Model tests in 1970-71 (1:36 scale, fixed bed). Surveyed in May 2002 and Apr. 2005. Inlet wingwall affected by new busway.
Norman Creek, Ridge St, Brisbane Qld (also called Ridge St deviation)	0.005	7 cells.	36.55	37.5	113.8	--	Model tests in 1971 (1:36 scale). Surveyed in May 2002 and Apr. 2005
Newington Bridge, Sheepwash Creek, Stawell Shire, Vic	--	Paved throat. 2 inlet channels & 1 outlet channel.	61	--	155.5	--	Field observations on 25-28 Oct. 1975 (122 m^3/s) & 3 Sept. 1988 (150 m^3/s).
Bridge d/s Genorchy, Wimmera River, Stawell Shire, Vic	--		--	--	--	--	
Illawarra to Mt Dryden Rd, Stawell Shire, Vic	0.005		180	107	270.0	--	
Fox's bridge, Bulgana Rd, Bulgana Parish, Stawell Shire, Vic	--		90	120	220.0	--	
Wynnum, South, Brisbane Qld	--	6 cells.	--	--	--	--	
Wynnum North, Brisbane Qld	--	11 cells.	75	--	--	--	

Notes : B_{max} ; inlet lip width; B_{outlet} : outlet lip width; d_{tw} : tailwater depth at design flow; L_{inlet} : inlet length; L_{outlet} : outlet length; S_c : barrel invert slope; S_o : flood plain bed slope; ΔH available : total head loss available; Δz_o: barrel excavation depth; ($^+$) : structure no longer in use.

References : Apelt (1973,1974,1975), Chanson (1999), Cottman (1976); McKay (1970,1971), Porter (1978), Present study.

Figure captions

Fig. 1 - Standard culvert outlet at Algester Rd, Algester (Brisbane)

Fig. 2 - Minimum Energy Loss culverts

(A) Outlet of the Redcliffe Minimum Energy Loss (MEL) culvert in Sept. 1996, looking upstream with some water ponding in the barrel after a storm

(B) Minimum Energy Loss culvert inlet along Norman Creek at Ekibin beneath the South-East freeway (Brisbane) on 18 Sept 2003 during a student field trip

Fig. 3 - Sketch of a Minimum Energy loss culvert operating at design flow with zero afflux

(A) Waterway on 18 Sept. 2003 during typical dry conditions - Looking downstream at the inlet (foreground), barrel and outlet (in background)

(B) Operation on 31 Dec. 2001 around 06:00 for about 60-80 m^3/s, looking upstream - The storm took place after a night of successive rain storms

(C) Operation on 7 Nov. 2004 for about 80 m^3/s around 13:15, looking downstream from the right bank, with some standing waves in the barrel

Fig. 5 - Operation of the Ridge Street Minimum Energy Loss culvert on Norman Creek

(A) Outlet on 30 Aug. 2004 during a typical dry weather, view from the left bank

(B) Inlet operation on 7 Nov. 2004 for about 80 m^3/s around 13:00 - Looking upstream at a small hydraulic jump in the inlet

(C) Outlet operation on 7 Nov. 2004 for about 80 m^3/s around 13:00 - Looking downstream at the subcritical flow from the road embankment

Fig. 6 - Inlet of the Minimum Energy Loss culvert at Marshall Road, Brisbane at the end of a storm on 31 Dec. 2001 - Looking downstream at the inlet flow with one of the concrete piles

CHANSON, H. (2007). "Hydraulic Performances of Minimum Energy Loss Culverts in Australia." *Journal of Performances of Constructed Facilities*, ASCE, Vol. 21, No. 4, pp. 264-272 (doi:10.1061/(ASCE)0887-3828(2007)21:4(264)) (ISSN 0887-3828).

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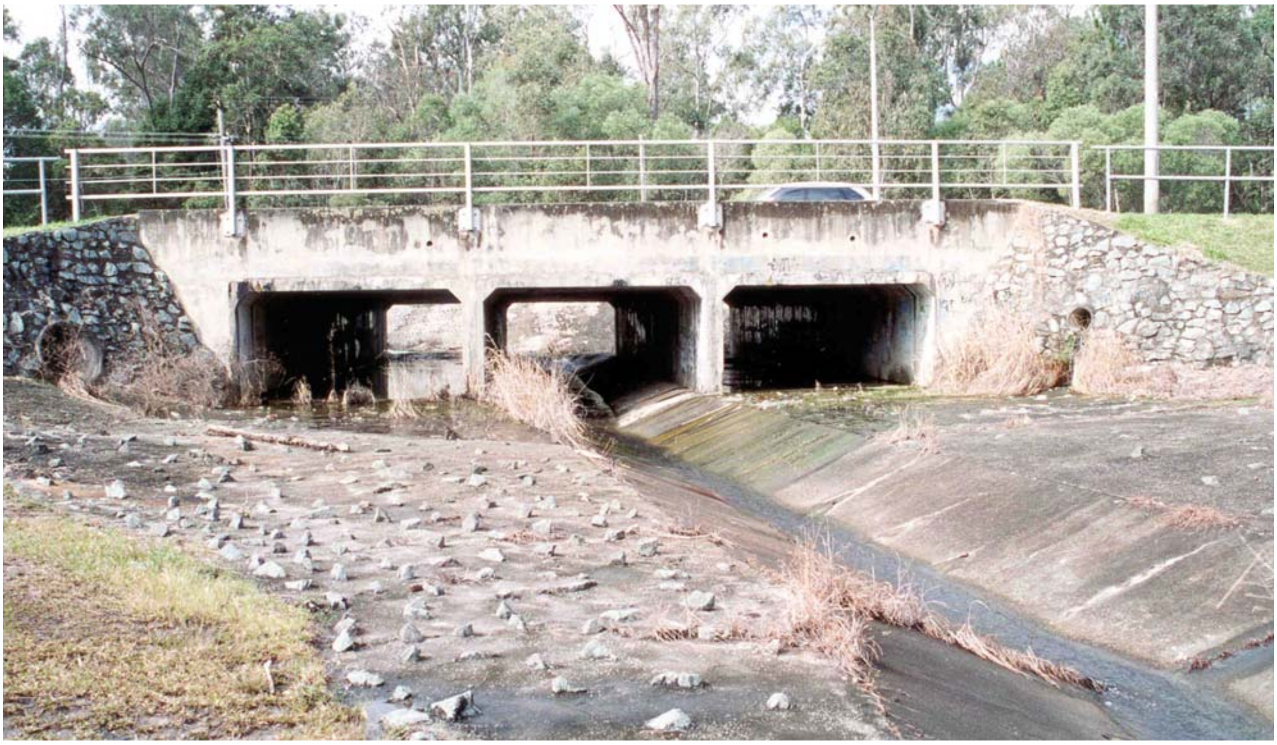

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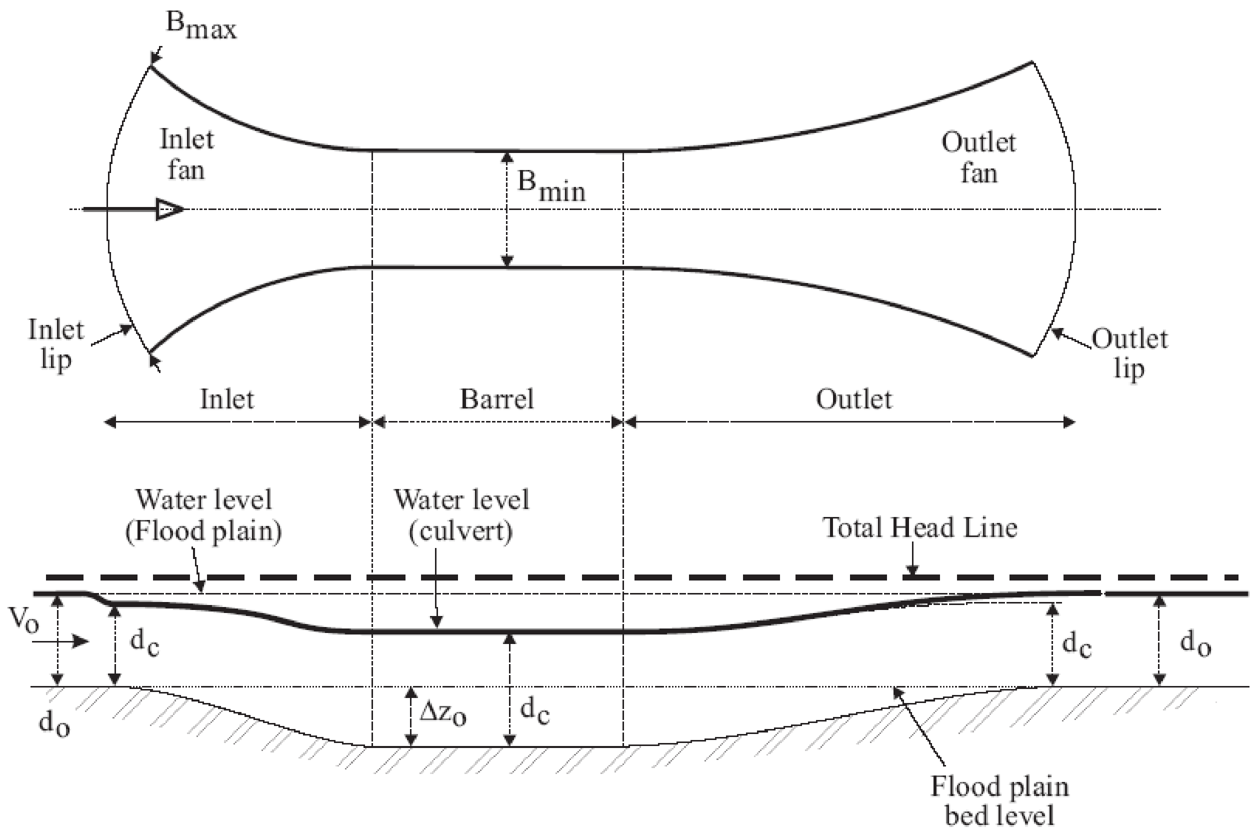

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