Hydraulic Performances of Minimum Energy Loss Culverts in Australia

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Abstract: Culverts are among the most common hydraulic structures. Modern designs do not differ from ancient structures and are often characterized by significant afflux at the 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 the 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.

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Introduction

Culverts are among the most common civil engineering structures (Fig. 1). Modern designs are very similar to ancient designs, and they are characterized by some significant afflux at design flow conditions. The afflux is the rise in the 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). MEL culverts are also called minimum energy culverts (McKay 1971), constant energy structures, minimum specific energy culverts (McMahon 1979), constant total energy structures, or energy culverts (Lowe 1970). The term MEL structure is, however, a more accurate terminology (Apelt 1983; Chanson 1999).

It is the purpose of this paper to review the operational performances of 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 (Figs. 1 and 2). Culverts have been used for more than 3,500 years. Although the world's oldest culvert is unknown, the Minoans and the Etruscans 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 ten times the maximum aqueduct flow rate (Chanson 2002).

Modern designs of culverts (Fig. 1) do not differ much from the Etruscan and Roman culverts. The primary design constraint is the minimum construction costs, but additional constraints might include the maximum acceptable upstream flood level and scour protection at the 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 characterized by significant afflux at the 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 MEL culvert was developed by the 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 the Humpybong Creek without afflux, while the culvert discharged flood water underneath a shopping center parking. The structure passed floods greater than the design flow in several instances without flooding (McKay 1970). It is still in use [Fig. 2(a)].

The MEL culverts are designed with the concept of minimum head loss and nearly constant total head along the waterway. The

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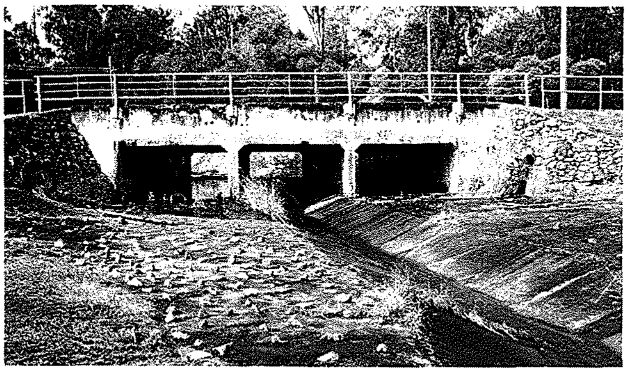


Fig. 1. Standard culvert outlet at Algester Rd., Algester (Brisbane)

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 the inlet and the outlet must be streamlined to avoid significant form losses (Figs. 2 and 3). The MEL culvert is further designed to operate at critical, or transcritical 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 a culvert. For a culvert design with zero afflux, the width of the inlet lip must satisfy the Bernoulli principle

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

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

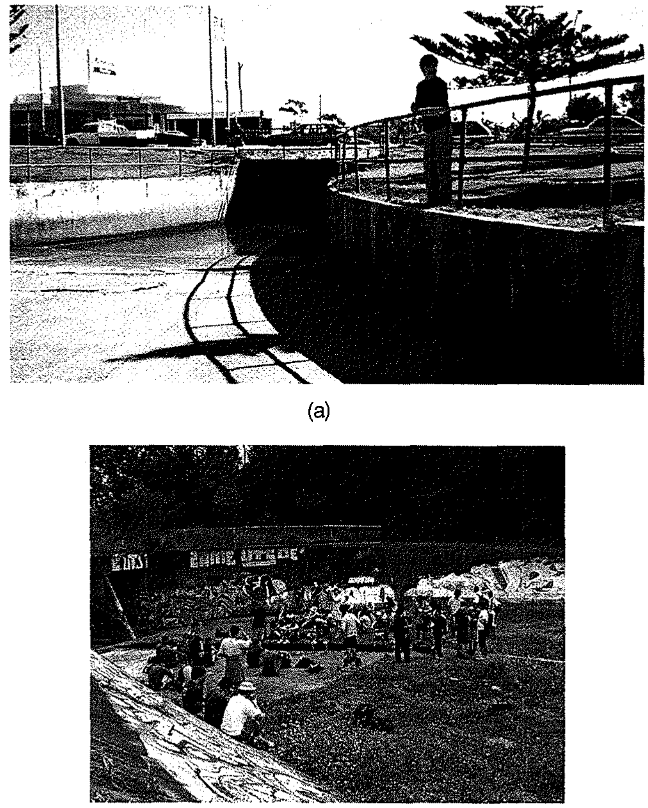
Eq. (1) derives from the definition of the critical flow conditions for a rectangular channel. In the inlet and outlet, there is an unique relationship between the width B and the excavation depth Δz (Chanson 2004a). The barrel width must satisfy

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

where Δz_o=maximum excavation depth (Fig. 3).

The inlet and outlet design is based basically upon a flow net analysis using an 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 "quasisquare" 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, and maximum afflux), the topography and construction costs, and the design costs. The experience in Australia suggests that the MEL design compares favorably in flat flood plains with limited available afflux, and for long culvert barrels, despite the higher design and construction costs.



(a)

(b)

Fig. 2. MEL culverts: (a) outlet of the Redcliffe MEL culvert in September 1996, looking upstream with some water ponding in the barrel after a storm; (b) MEL culvert inlet along Norman Creek at Ekibin beneath the South-East Freeway (Brisbane) on September 18, 2003 during a student field trip

Australian Developments

Since the first structure in Redcliffe [Fig. 2(a)], 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 200–250 m^3/s. The culverts operate typically several days per year, and the author organizes regularly undergraduate student field works there [Figs. 2(b), 4(a), and 5(a)]. Fig. 2(b) shows the inlet of a MEL culvert designed to pass Q_{des}=170 m^3/s with zero afflux. The

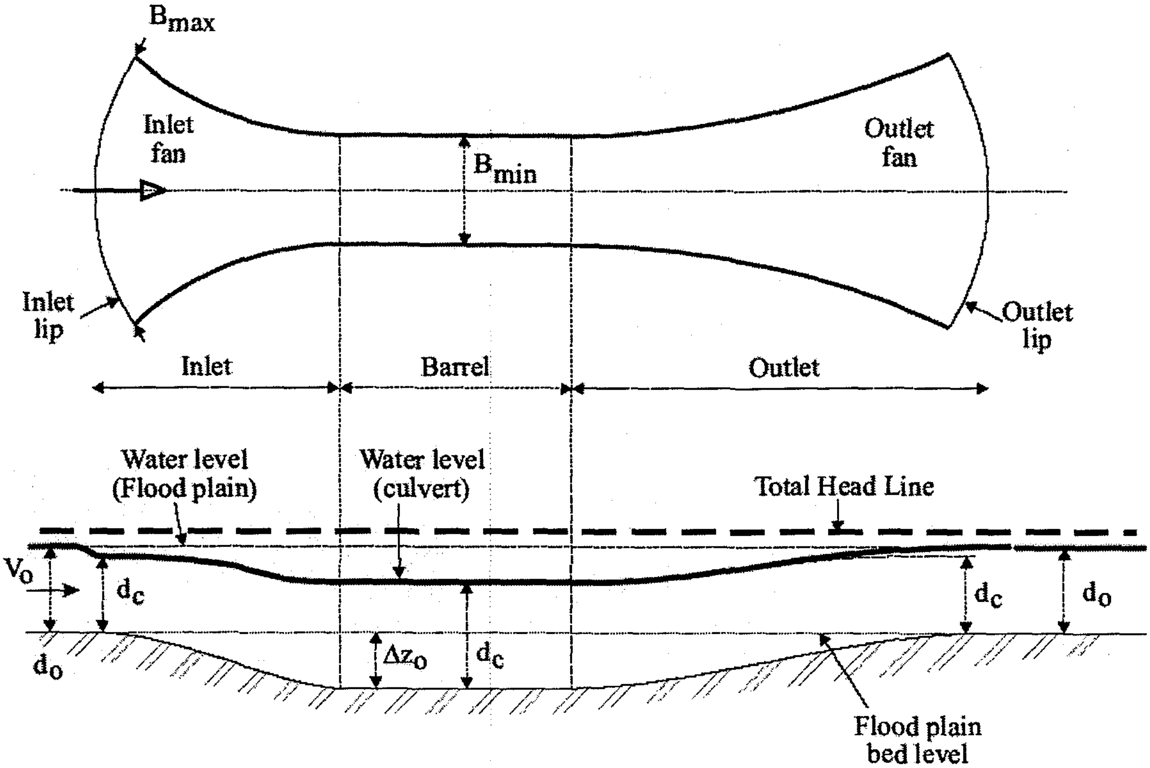


Fig. 3. Sketch of a MEL culvert operating at design flow with zero afflux

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 $\Delta z_o=1.6$ 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 modeling 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 the 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, United States of America (USA) and United Kingdom (UK). For example, Lowe (1970), Loveless (1984), Federal Highway Administration (1985, p. 114), and 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 the UK (Loveless 1984) demonstrated that MEL culverts can pass successfully ice and sediment load without clogging nor silting.

Table 1. Audiovisual and Internet Resources on Minimum Energy Loss Culverts and Waterways

Description	Reference
Audiovisual resources	
Minimum energy loss culvert	Apelt (1994). "The minimum energy loss culvert." Videocassette VHS color, Dept. of Civil Eng., University of Queensland, Australia, 18 minutes.
Norman Creek flood on November 7, 2004	Chanson (2004c). "Storm and flood at Norman Creek, Brisbane (Australia) on November 7, 2004." IAHR Media Library, ⟨http://www.iahrmedialibrary.net/⟩, Urban drainage, video-clip, 6 minutes.
Internet resources	
Hydraulics of minimum energy loss 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	Date	S_o	Q_{des} m^3/s	d_{tw} m	B_{max} m	L_{inlet} m	Δz_o m	B_{min} m	D m	L_{barrel} m
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.[a]	1970	—	58.0	1.0	—	—	0.6	17.1	1.5	—
Stuart Highway, N Alice Springs NT[a]	1970	—	—	—	—	—	—	4.3	1.4	—
Stuart Highway, N Alice Springs NT[a]	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*	—
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.[a]	—	8 cells.	—	—	—	—	Field observations.			
Stuart Highway, N Alice Springs Nt[a]	—	Several culverts: 2 cells.	—	—	—	—				
Stuart Highway, N Alice Springs Nt[a]	—	Several culverts: single cell.	—	—	—	—				

Table 2. (*Continued.*)

Description	Date	S_o	Q_{des} m^3/s	d_{tw} m	B_{max} m	L_{inlet} m	Δz_o m	B_{min} m	D m	L_{barrel} m
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∅). 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 and 1 outlet channel.	61	—	155.5	—	Field observations on Oct. 25–28, 1975 (122 m^3/s) and Sept. 3, 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; and Δz_o=barrel excavation depth. Sources: Apelt (1973, 1974, 1975); Chanson (1999); Cottman (1976); McKay (1970, 1971); Porter (1978); Present study.

[a]Structure no longer in use.

These laboratory findings were confirmed by the 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 modeling. The MEL culvert designs were typically tested in 1:12–1:36 undistorted scale models with a fixed bed. They have been in operation for more than 45 years with a range of hydrological conditions including semitemperate, semitropical, 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 (Figs. 4 and 5), new surveys, and oral discussions with designers. Some results are summarized 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}, and 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 (Figs. 4 and 5). Figs. 4 and 5 show two MEL 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 h yielding a runoff discharge of between 150 and 220 m^3/s. A total of 5 MEL structures were built to operate with zero afflux at design flow rate on the same stream (Norman Creek). Fig. 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 $\Delta z_o=1.3$ m. Fig. 4(a) shows typical dry weather conditions, and the low flow channel is seen on the far left and in the background. Figs. 4(b and c) illustrate some flood flows. The flood shown in Fig. 4(c) occurred after a series of rain storms through the morning and early afternoon with some heavy rainfall from 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 transcritical flows (e.g., Chanson 1999). Fig. 5 shows another MEL 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. Fig. 5(a) presents a dry weather situation with a student standing above the low flow drain. Fig. 5(b) 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. Fig. 5(c) 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 transcritical 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 transcritical flow operation (Fr=0.6–0.8) and supercritical flow conditions must be avoided at the 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 Figs. 4 and 5 are equipped with a well designed drainage system seen in the middle of Fig. 5(c). One issue is the loss of expertise in the MEL culvert design. In Brisbane, two culvert structures were adversely affected by the construction of a new busway 25 years later. Fig. 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. Fig. 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 Fig. 4(b) above the MEL waterway outlet, but this structure was not affected.

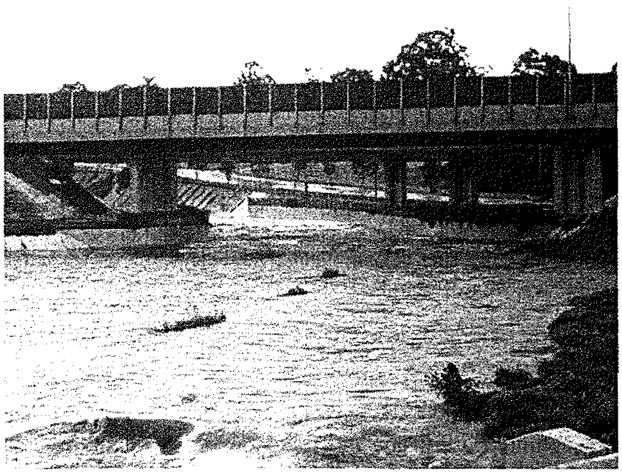
Design Experiences

Most hydraulic structures, including MEL 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 MEL 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. 2(a)] costed the equivalent of U.S. $460,000 (in 2006), and he allowed the development of a commercial center valued at US$32,000,000. The MEL waterway at the Newington Bridge was six 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 the grassed surface as at the Newington Bridge and Nudgee waterway. For zero afflux, the size of a MEL culvert (inlet, barrel, and 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 the MEL design to rectangular cross section waterways. For nonrectangular waterways, the design procedure becomes far too complex and it might

(a)



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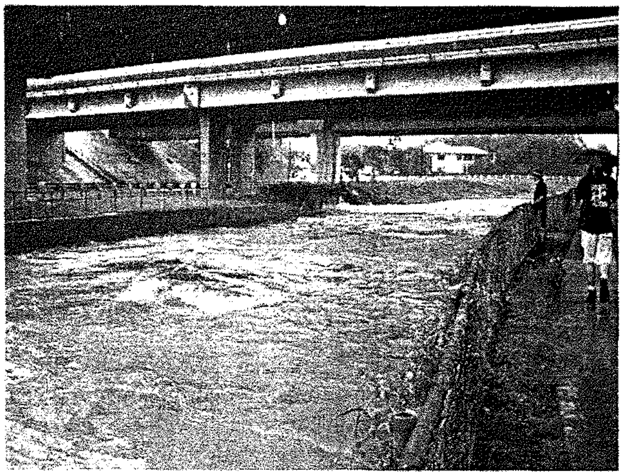
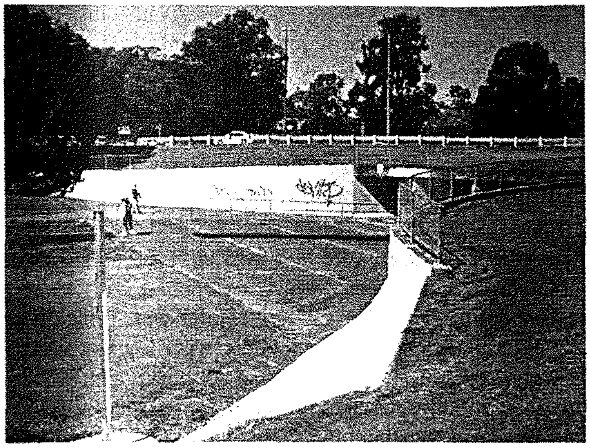


(c)

Fig. 4. Operation of the MEL waterway on Norman Creek: (a) waterway on September 18, 2003 during typical dry conditions—looking downstream at the inlet (foreground), barrel and outlet (in background); (b) operation on December 31, 2001 around 6:00 for about 60–80 m^3/s, looking upstream—the storm took place after a night of successive rain storms; and (c) operation on November 7, 2004 for about 80 m^3/s around 1:15 p.m., looking downstream from the right bank, with some standing waves in the barrel



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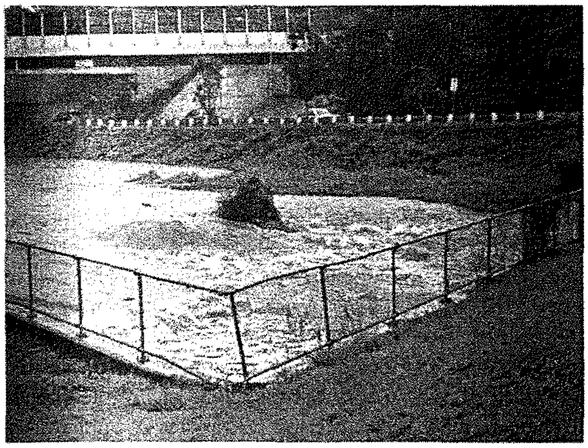

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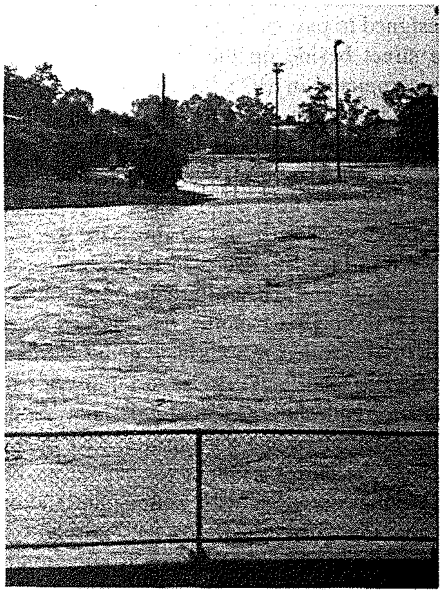

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Fig. 5. Operation of the Ridge St. MEL culvert on Norman Cr: (a) outlet on August 30, 2004 during a typical dry weather, view from the left bank; (b) inlet operation on November 7, 2004 for about 80 m^3/s around 1:00 p.m.—looking upstream at a small hydraulic jump in the inlet; and (c) outlet operation on November 7, 2004 for about 80 m^3/s around 1:00 p.m.—looking downstream at the subcritical flow from the road embankment

Fig. 6. Inlet of the MEL culvert at Marshall Road, Brisbane at the end of a storm on December 31, 2001—looking downstream at the inlet flow with one of the concrete piles

not be reliable. Last, a MEL culvert does not need to be symmetrical and it may have a curved shape: e.g., the Newington Bridge waterway and the MEL waterway shown in Fig. 4.

Discussion

During a noncohesive 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 the MEL 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 noncohesive embankment breach documented the challenging similarity during the 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 transcritical ($0.5 < \mathsf{F} < 1.8$).

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

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

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

where A=flow cross section selected perpendicular to the streamlines; B=free surface width; and z_{wl}=free-surface elevation. Natural breach inlet lengths L_{inlet}, measured along the breach centerline between the inlet lip and throat, satisfied $L_{\text{inlet}}/B_{\max}=0.5-0.6$, where $B_{\max}$=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 $L_{\text{inlet}}/B_{\max}$ is 0.5 (Apelt 1983, p. 91).

Conclusion

A major advance in culvert design was the development of the MEL culvert under the leadership of the 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 transcritical flow conditions at the 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 analyzed to minimize 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 no manpower.

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Appendix. 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 the hydraulic structures and physical modeling 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.

Notation

The following symbols are used in this paper:

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);
F = 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); and
Δz_o = excavation depth (below natural ground level) (m).

References

Apelt, C. J. (1973). "Settlement shores—Port Macquarie. Flood outlet structure A." *Rep. CH15/73*, Dept. of Civil Engineering, Univ. of Queensland, Australia.

Apelt, C. J. (1974). "Settlement shores—Port Macquarie. Flood outlet structure B." *Rep. CH16/74*, Dept. of Civil Engineering, Univ. of Queensland, Australia.

Apelt, C. J. (1975). "Settlement shores—Port Macquarie. Flood outlet structure B. Appendix." *Rep. CH16/74*, Dept. of Civil Engineering, Univ. of Queensland, Australia.

Apelt, C. J. (1983). "Hydraulics of minimum energy culverts and bridge waterways." *Australian Civil Engrg. Trans.*, (*IEAust.*), CE25(2), 89–95.

Apelt, C. J. (1994). "The minimum energy loss culvert." *Videocassette VHS color*, Dept. of Civil Engineering, Univ. of Queensland, Australia.

Ballance, M. H. (1951). "The Roman bridges of the Via Flaminia." *Papers of the British School at Rome*, Vol. 19, 78–117.

Brodie, I. (1988). "Breaching of coastal lagoons. A model study." MSc thesis, Univ. of New South Wales, Australia.

California Division of Highways (1956). "California culvert practice: Reprint of a series of technical abstracts from California highways and public works." *Division of Highways*, 2nd Ed., Dept. of Public Works, Calif., 119.

Chanson, H. (1999). *The hydraulics of open channel flows: An introduction*, Butterworth-Heinemann, Oxford, U.K.

Chanson, H. (2000). "Introducing originality and innovation in engineering teaching: The hydraulic design of culverts." *Eur. J. Eng. Educ.*, 25(4), 377–391.

Chanson, H. (2002). "Hydraulics of large culvert beneath Roman aqueduct of Nîmes." *J. Irrig. Drain. Eng.*, 128(5), 326–330.

Chanson, H. (2003). "Minimum energy loss structures in Australia: Historical development and experience." *Proc., 12th Nat. Eng. Heritage Conf.*, N. Sheridan, ed., IEAust., Toowoomba Qld, Australia, 22–28.

Chanson, H. (2004a). *The hydraulics of open channel flows: An introduction*, 2nd Ed., Butterworth-Heinemann, Oxford, U.K.

Chanson, H. (2004b). "Discussion of overtopping breaching of noncohesive homogeneous embankments." *J. Hydraul. Eng.*, 130(4), 371–374.

Chanson, H. (2004c). "Storm and flood at Norman Creek, Brisbane (Australia) on 7 November 2004." *IAHR Media Library*, ⟨Category urban drainage, ⟨http://www.iahrmedialibrary.net/⟩.

Coleman, S. E., Andrews, D. P., and Webby, M. G. (2002). "Overtopping breaching of noncohesive homogeneous embankments." *J. Hydraul. Eng.*, 128(9), 829–838.

Cottman, N. H. (1976). "Fivefold increase obtained in the capacity of a small bridge using a shaped minimum energy subway." *Aust. Road Res.*, 6(4), 42–45.

Cottman, N. H., and McKay, G. R. (1990). "Bridges and culverts reduced in size and cost by use of critical flow conditions." *Proc., Inst. Civ. Engrs.*, London, Part 1, 88, 421–437. ["Discussion." (1992). 90, 643–645.]

Evans, A. H. (1928). *The palace of Minos: A comparative account of the successive stages of the early cretan civilization as illustrated by the discoveries at Knossos*, Macmillan, London, 2, Part 1, 390.

Federal Highway Administration (1972). "Hydraulic design of improved inlets for culverts." *Hydraulic engineering circulars HEC13*, U.S. Federal Highway Administration, Bridge Division, Hydraulics Branch, 172.

Federal Highway Administration (1985). "Hydraulic design of highway culverts." *Hydraulic Design Series No. 5, Rep. No. FHWA-IP-85-15*, U.S. Federal Highway Administration, 253.

Gordon, A. D. (1981). "The behaviour of lagoon inlets." *Proc., 5th Australian Conf. Coastal and Ocean Eng.*, Perth, Wash., 62–63.

Gordon, A. D. (1990). "Coastal lagoon entrance dynamics." *Proc., 22nd Intl. Conf. Coastal Eng.*, B. L. Edge, ed., 3, Chap. 218, Delft, The Netherlands, 2880–2893.

Hamill, L. (1999). "*Bridge hydraulics*." E & FN Spon, London, 367.

Hee, M. (1969). "Hydraulics of culvert design including constant energy concept." *Proc., 20th Conf. of Local Authority Engineers*, Dept. of Local Government, Queensland, Australia, Paper 9, 1–27.

Henderson, F. M. (1966). *Open channel flow*, MacMillan, New York.

Loveless, J. H. (1984). "A comparison of the performance of standard and novel culvert designs including the effects of sedimentation." *Proc., 1st Int. Conf. Hydraulic Design in Water Resources Engineering: Channels and Channel Control Structures*, K. V. H. Smith, ed., Springer, New York, 1, 183–193.

Lowe, S. A. (1970). "Comparison of energy culverts to standard three cell box culverts." MS thesis, Univ. of Manitoba, Canada.

McKay, G. R. (1970). "Pavement drainage." *Proc., 5th Aust. Road Res. Board Conf.*, Vol. 5, Part 4, 305–326.

McKay, G. R. (1971). "Design of minimum energy culverts." *Research Rep.*, Dept of Civil Engineering, Univ. of Queensland, Brisbane, Australia, 29.

McKay, G. R. (1978). "Design principles of minimum energy waterways." *Proc., Workshop on Minimum Energy Design of Culvert and Bridge Waterways*, Australian Road Research Board, Melbourne, Australia, Session 1, 1–39.

McMahon, G. M. (1979). "The expansion characteristics of free-surface flow." MS thesis, Dept. of Civil Engineering, Univ. of Queesland, Australia, 190.

Matthews, T. G., and McKay, G. R. (1978). "The history and development of minimum energy structures in water flow control." *Aust. Road Res.*, 8(2), 47–48.

Neill, C. R. (1962). "Hydraulic tests on pipe culverts." *Alberta Highway Research Rep. No. 62.1*, Research Council of Alberta, Edmonton, 52.

O'Connor, C. (1993). *Roman bridges*, Cambridge University Press, Cambridge, U.K., 235.

Porter, K. F. (1978). "Workshop on minimum energy design of culvert and bridge waterways."*Australian Road Research Board*, Melbourne, Australia.

Vallentine, H. R. (1969). *Applied hydrodynamics*, SI Ed., Butterworths, London.

Visser, P. J., Vrijling, J. K., and Verhagen, H. J. (1990). "A field experiment on breach growth in sand dykes." *Proc., 22nd Int. Conf. Coastal Engineering*, B. Edge, ed., Delft, The Netherlands, 2, 2097–2100.