HISTORY OF MINIMUM ENERGY LOSS WEIRS AND CULVERTS 1960-2002

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Abstract : Culverts and weirs are among the most common hydraulic structures. Modern designs do not differ much from ancient structures. A major advance was the development of the Minimum Energy Loss structures by Professor Gordon McKAY in the late 1950s. The design technque allows a drastic reduction in afflux associated with lower costs. The successful operation of MEL structures for more than 40 years demonstrate the design soundness while highlighting the importance of streamlining and near-critical flow conditions throughout all the structure. An analysis of breach profiles demonstrates futrher that breach inlet flow operates in a similar manner as in a MEL structure.

Keywords : weirs, culverts, minimum energy loss, engineering heritage, Queensland

INTRODUCTION

Culverts and weirs are among the most common hydraulic structures. Both types of structures have been used for more than 3000 years : e.g., BALLANCE (1951), O'CONNOR (1993) and CHANSON (2002) for ancient culverts, SMITH (1970) and SCHNITTER (1994) for historical weirs and dams. Modern designs do not differ much from Etruscan and Roman culverts, and Assyrian and Nabataean dams. Both standard culverts and small dams are characterised by 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) weir and culvert ([1]) was developed in Queensland (Australia) under the leadership of late Professor Gordon R. McKAY.

It is the purpose of this paper to document the historical development of MEL structures. The successful operation of several large structures for more than 40 years demonstrate the soundness of the MEL design.

HISTORICAL DEVELOPMENT OF MINIMUM ENERGY LOSS (MEL) STRUCTURES

A Minimum Energy Loss (MEL) structure is designed with the basic concepts of streamlining and near-critical flow conditions throughout the structure to minimise upstream flooding as well as to maximise the discharge per unit width. The concept was developed in Australia in the late 1950s under the leadership of late Professor Gordon R. McKAY (1913-1989) and first applied to the Humpybong Creel waterway (Redcliffe, QLD 1960). More than 200 MEL culverts and weirs were built, and prototypes listed in Tables 1 & 2 are still in use.

MINIMUM ENERGY LOSS WEIRS

The concept of Minimum Energy Loss (MEL) weir was developed to pass large floods with minimum energy loss, hence with minimum afflux. MEL weirs were designed specifically for situations where the river catchment is characterised by torrential rainfalls and by very small bed slope. The first large MEL weir was the Clermont weir (Qld, Australia 1962) ([2]) (Table 1, Fig. 2.1). The largest, Chinchilla weir (Qld, Australia 1973), is listed as a "large dam" by

ICOLD. Figure 1.1 shows the spillway inlet at Lake Kurwongbah. It was designed with the concept of minimum energy loss in a fashion somehow similar to the design of MEL culvert inlet (McKAY 1971). The crest inlet fan converges into a 30.48 m wide channel ending with a small flip bucket. The MEL crest design allowed an extra 0.457 m of possible water storage.

Fig. 1 - Photographs of Minimum Energy Loss Structures

(1.1) Minimum Energy Loss spillway inlet at Lake Kurwongbah (Sideling Creek dam), Brisbane (Australia) on 12 Sept. 1999 - Completed in 1969, H = 25 m, Reservoir capacity : 15.5 Mm^3, Q_{des} : 710 m^3/s

(1.2) Inlet of MEL culvert in Wynnum North, Brisbane (Q_{des} = 100 m^3/s, B_{max} = 90 m, B_{min} = 20 m) on 14 Sept. 1997 - Note passing cars on the Gateway motorway

A MEL weir is typically curved in plan with converging chute sidewalls and the overflow spillway chute is relatively flat (Fig. 2.1). The downstream energy dissipator is concentrated near the channel centreline away from the banks. The inflow Froude number remains low and the rate of energy dissipation is small compared to a traditional weir. For example, the Chinchilla weir was designed to give no afflux at design flow (850 m^3/s). In 1974, it passed 1,130 m^3/s with a measured afflux of less than 100 mm (TURNBULL and McKAY 1974). Ideally, a MEL weir could be designed to achieve critical flow conditions at any position along the chute and, hence, to prevent the occurrence of a hydraulic jump (CHANSON 1999).

This is not always achievable because the variations of the tailwater flow conditions with discharge are always important in tropical Queensland.

Table 1 - Historical Minimum Energy Loss weirs and spillways

Description	H	Q_{des}	H_{des}	B_{max}	Remarks
	m	m^3/s	m	m	
(1)	(2)	(3)	(4)	(5)	(6)
Humpybong Creek weir, Redcliffe QLD 1959	1.16	25.8	0.84	19.5	Intake of MEL culvert system.
Clermont weir, Sandy Creek QLD 1962-1963 (Fig. 2.1)	6.1	849.5	2.67	115.8	Model tests in 1961 McKAY (1971). Completed in 1963. Overtopped once during construction in April 1963.
Chinchilla weir, Chinchilla QLD 1973	14	850	--	410	TURNBULL and McKAY (1974), CHANSON (1999). Overtopped twice during construction.
Lemontree weir, Condamine QLD 1979	4	--	--	--	CHANSON (1999).
MEL spillways					
Swanbank Power House, Ipswich QLD 1965	6 to 8	160	1.55	45.7	McKAY (1970,1971). Writers' field work.
Lake Kurwongbah, Petrie QLD 1958-1969	25	849.5	--	106.7	McKAY (1971). Completed in 1969 (Fig. 1.1).

Notes: B_{max} : crest width; H : dam height; H_{des} : design head above crest; Q_{des} : design flow.

MINIMUM ENERGY LOSS CULVERTS

A minimum energy loss (MEL) culvert is designed with the concept of nearly-constant total head and critical flow conditions along all 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 and the flow is critical from the inlet lip to the outlet lip (Fig. 1.2). The barrel invert is often lowered to increase the discharge capacity (APELT 1983, CHANSON 1999,2000).

The concept of MEL culvert was developed first for the Humpybong Creek water way in Redcliffe (QLD 1960) that is still in use (McKAY 1970, CHANSON 1999). Since about 170 structures were built in Eastern Australia (Table 2). While a number of small-size structures were built in Victoria, major structures were designed, tested and built in Queensland. In the coastal plains of North-Eastern Australia, torrential rains during the wet season place a heavy demand on culverts, the natural slope is often very small ($S_o \sim 0.001$) and little head loss is permissible. The largest channel is the Nudgee Road MEL waterway near Brisbane airport with a design discharge capacity of 850 m^3/s. Built between 1968 and 1969, the structure passed successfully floods up to design flow. The channel bed is grass-lined, and the waterway is still in use (CHANSON 1999). Several MEL culverts were built in southern Brisbane during the construction of the South-East Freeway in 1974-1975 (Fig. 1.2 and 2.2). The design discharge capacity range from 200 to 250 m^3/s. The culverts operate typically several days per year. McKAY (1971) indicated further MEL culverts built in Northern Territory near Alice Springs in 1970. Norman COTTMAN described the Newington bridge MEL waterway which passed successfully 122 and 150 m^3/s in 1975 and 1988 respectively without any damage (COTTMAN and McKAY 1990).

Table 2 - Historical Minimum Energy Loss culverts

Description	Q_{des}	B_{max}	Δz_o	B_{min}	Remarks
	m^3/s	m	m	m	
(1)	(2)	(3)	(4)	(5)	(6)
MEL waterways					
Nudgee Rd, Schultz canal, Brisbane QLD 1968-69	850	209.70	0.762	137	Grass-lined. Tidal conditions. Model tests (1:48 scale).
Norman Creek, beneath SE-Freeway QLD 1975	220	33.46	1.268	11.18	Concrete lined.
MEL culverts					
Humpybong Creek, Redcliffe QLD 1959-1960	25.8	19.5	1.164	5.486	1 cell. Tidal conditions. $Q > Q_{des}$ at least 3 times. Model tests (1:12 scale).
Burnett highway, Goomeri QLD 1969	32.28	21.946	0.9144	6.10	3 cells.
Settlement Shore, Outlets A & B, Port Macquarie NSW 1973-74	317.15 577.7	101.80 206.65	2.850 3.206	24.69 49.99	Tidal conditions. 1:48 scale model tests.
Norman Creek, Marshall Rd, Brisbane QLD 1975	170	--	--	--	2 cells. Culvert inlet flow affected by Busway piers.
Norman Creek, Birdwood St, Brisbane QLD 1975	170		0.73	10.8	4 cells.
Norman Creek, Ekibin (Station 100), Brisbane QLD 1975	170	25.2	1.55	12.32	4 cells. Model tests (1:36 scale). Inlet wingwall affected by new Busway.
Norman Creek, Ridge St, Brisbane QLD 1975	220	41.76	0.61	21.3	7 cells. Model tests (1:36 scale). Also called Ridge St deviation.
Newington Bridge, Sheepwash Creek, Stawell Shire, VIC	141.5	125	2.44	9.6	Grass-lined & paved throat. 2 inlet channels & 1 outlet channel.

Notes : B_{max} : inlet lip width; B_{min} : throat width; Q_{des} : design flow; Δz_o : barrel excavation depth. All prototype structures are still in use. Ref. : McKAY (1970,1971), APELT (1983), CHANSON (1999) & Field measurements in May 2002

The MEL culvert design technique received considerable interest in Canada, USA and UK : e.g., LOWE (1970), LOVELESS (1984), Federal Highway Administration (1985, p. 114), COTTMAN and McKAY (1990). It was patented in 1978. Model tests and field experience showed that the MEL culvert design can pass debris and ice without damage, the siltation is rare and that downstream scour is negligible.

MODEL AND PROTOTYPE EXPERIENCE

Several structures were observed operating at design flows and for floods larger than design : e.g., Clermont and Chinchilla weirs, MEL culverts in Brisbane. Inspections during and after flood events demonstrated a sound operation associated with little maintenance. While McKAY (1971) gave general MEL design guidelines, APELT (1983) presented an authoritative treaty on MEL culvert design, and COTTMAN and McKAY (1990) described case studies. Professor Colin APELT stressed that a successful design must follow closely two basic design concepts: streamlining of the flow and near-critical flow conditions. Flow separation must be avoided at all cost. In one structure, separation was observed in the inlet associated with flow recirculation in the barrel (Cornwall St, Brisbane). MEL culverts are usually designed for Fr = 0.6 to 0.8 and supercritical flow conditions must be avoided.

Fig. 2 - Minimum Energy Loss Structures in operation

(2.1) Sandy Creek weir at Clermont QLD (H = 6.1 m, Q_{des} = 850 m^3/s) in operation in Feb. 1999 (Courtesy of A.J. HOLMES)

(2.2) MEL waterway in Brisbane (Q_{des} = 220 m^3/s, B_{max} = 33 m, B_{min} = 11 m) in operation on 31 Dec. 2001 for about 80 m^3/s, looking upstream

The successful operation of several structures (Tables 1 & 2) for over 40 years has highlighted further practical considerations. MEL weirs are typically earthfill structures and the spillway section is protected by concrete slabs. Construction costs are minimum. A major inconvenient is the overtopping risk during construction : e.g., Clermont weir in April 1963, Chinchilla weir twice in 1972 and 1973. In addition, an efficient drainage system must be installed underneath the chute slabs. 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 drainage pipe of the culvert shown in Fig. 1.2 is regularly clogged.

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. As a result, one major arterial will be overtopped during a design flood (Marshall Rd, Brisbane).

INLET SHAPE OF NATURAL BREACH

Observations of natural scour in embankment breach showed a challenging similarity with MEL inlet design (e.g. McKAY 1970, VISSER et al. 1990, GORDON 1981). Detailed breach data of non-cohesive embankment (COLEMAN et al. 2002) were re-analysed. A complete flow net of breach inlet flow is presented in Figure 3.1, showing some equipotentials and two streamlines. The breach contour lines are shown only below the water line. Flow cross-section areas and free-surface widths were measured along each equipotential. Cross-section-averaged Froude number and total head were calculated. Results are shown in Figure 3.2 where the Froude number and dimensionless total head H/H_1 are plotted as functions of the dimensionless centreline location, where H_1 is the upstream total head and L is the embankment base length. The results show that the flow is near-critical in the breach inlet (i.e. $0.5 < Fr < 0.8$, Fig. 3.2) and the total head remains constant throughout the breach inlet up to the throat. Head losses occurs downstream of the throat when the flow expands and separation takes place at the lateral boundaries. Separation is associated with form drag and head losses, and the assumption of one-dimensional flow becomes invalid (APELT 1983, CHANSON 1999). Breach inlet lengths, measured along the breach centreline between inlet lip and throat, satisfy L_{inlet}/B_{max} = 0.5 to 0.6, where B_{max} is the free-surface width at the upper lip. The result is close to the minimum inlet length recommended for MEL culvert design : "*the minimum satisfactory value of length/B_{max} is 0.5*" (APELT 1983, p. 91). For shorter inlet length, separation may be observed in the inlet.

CONCLUSION

A major advance in culvert and weir design was the development of the Minimum Energy Loss structures by Professor Gordon McKAY. The first MEL structure was the Humpybong Creek waterqay in Redcliffe (QLD 1960). The design allows a drastic reduction in afflux associated with lower total costs. The successful operation of MEL structures for more than 40 years demonstrate the design soundness while highlighting the importance of streamlining and near-critical flow conditions throughout all the structure.

An analysis of breach profiles shows that breach inlet flow operates in a similar manner as in a MEL structure. The finding suggests that, in a natural scour, the movable boundary flow tends to an equilibrium that is associated with minimum energy conditions and maximum discharge per unit width for the available specific energy.

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FOOTNOTES

(1) Minimum Energy Loss culverts are also called Energy culverts, Constant Energy culverts, Minimum Energy culverts, Constant Specific Energy culverts, ... (e.g. APELT 1983).
(2) The Sandy Creek weir in Clermont QLD is commonly called the Clermont weir.

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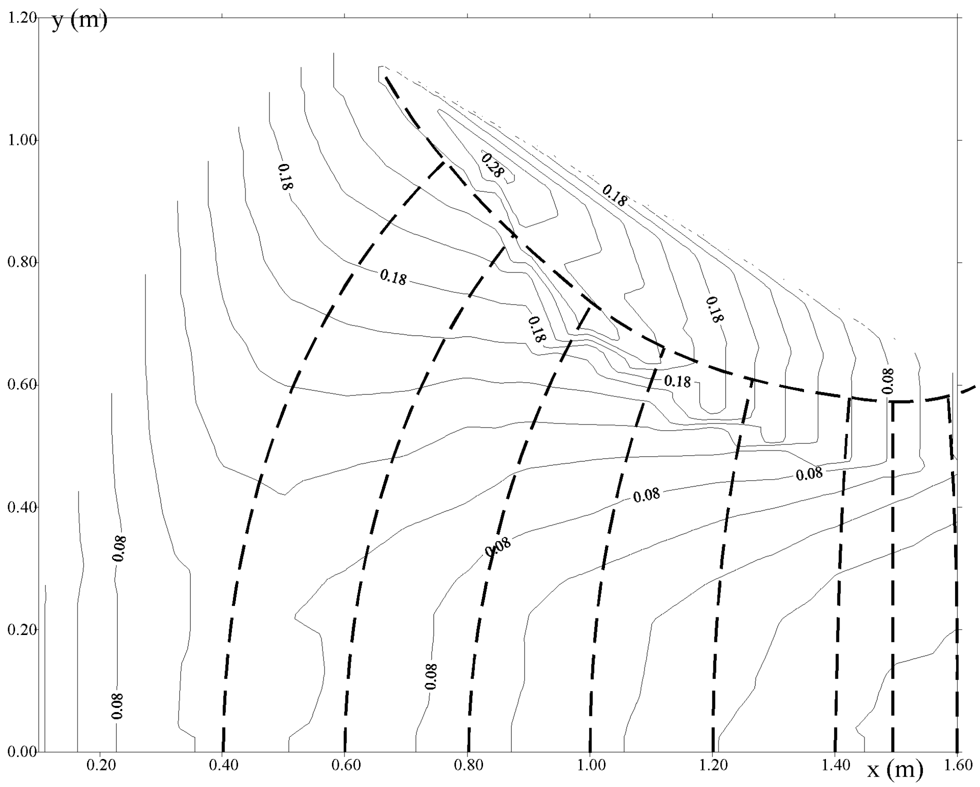
Internet resources on minimum energy loss (M.E.L.) structures

Minimum Energy Loss (MEL) weir design	{http://www.uq.edu.au/~e2hchans/mel_weir.html}
Minimum Energy Loss (MEL) Culverts and Bridge Waterways	{http://www.uq.edu.au/~e2hchans/mel_culv.html}

Fig. 3 - Inlet shape of natural non-cohesive embankment breach (Data by COLEMAN et al. 2002) - 900 mm wide breach, t = 147 s, Q = 0.071 m^3/s, H_1 = 0.3 m, L = 1.7 m, coarse sand: d_{50} = 1.6 mm (3.1) Flow net analysis of breach and contour lines of breach inlet (half breach) - Note that contour lines above the free-surface are not shown – Flow from left to right



(3.2) Centreline free-surface profiles, cross-sectional total head and Froude number