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Minimum Energy Loss Structures in Australia: Historical Development and Experience

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SUMMARY Culverts and weirs are among the most common hydraulic structures. Modern designs do not differ much from ancient structures and are characterised by significant afflux at design flow conditions. A major advance in hydraulic engineering was the development of Minimum Energy Loss (MEL) structures by the late Professor Gordon McKAY in the late 1950s. The design technique allows a drastic reduction in afflux associated with lower costs. The successful operation of MEL culverts and weirs for more than 40 years demonstrate the design soundness while highlighting the importance of streamlining and near-critical flow conditions throughout the structure. The novelty of the MEL design should be acknowledged by the Australian engineering community and general public.

1. INTRODUCTION

Culverts and weirs are among the most common civil engineering structures. Both types of hydraulic structures have been used for more than 3,000 years. Modern designs do not differ much from ancient designs and they 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 was developed in Australia to achieve zero afflux.

It is the purpose of this paper to document the historical development of MEL structures. Their successful operation for more than forty years is detailed with recent field inspections and surveys of existing structures.

Definitions

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. 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). Later the Romans built numerous culverts beneath roads and aqueducts (BALLANCE 1951, O'CONNOR 1993, CHANSON 2002). Modern designs of culverts do not differ much from Etruscan and Roman culverts. The primary design constraint is minimum construction costs, but additional constraints might include maximum acceptable upstream flood level and scour protection at outlet. 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. These solutions are expensive and marginal.

Weirs and small dams were used early in Antiquity for water storage (SMITH 1971, SCHNITTER 1994). Early in Antiquity, dam engineers learned the risks of dam erosion associated with large floods, and it was usual to design dams with provision for water spills. Flood waters were discharged above, below or beside the dam, with some energy dissipation, hence some afflux. Modern designs do not differ much from early Egyptian and Nabataean dams. During a flood event, the structures are characterised by some rise in upstream water level which may induce significant upstream flooding.

2. HISTORICAL DEVELOPMENT OF MINIMUM ENERGY LOSS STRUCTURES

The concept of the Minimum Energy Loss (MEL) structure was developed by late Professor Gordon McKAY (McKAY 1971,1978, APELT 2002) (App. I). The first MEL structure was the Redcliffe storm waterway system, also called Humpybong Creek drainage outfall, completed in 1960. It consisted of a MEL weir acting as culvert drop inlet followed by a 137-m long MEL culvert discharging into the Pacific Ocean. The weir was designed to prevent beach sand being washed in and choking the culvert, as well as to prevent salt intrusion in Humpybong Creek without afflux. The culvert discharged flood water underneath a shopping centre parking. The structure is still in use (Fig. 1A) and passed floods greater than the design flow in several instances without flooding (McKAY 1970).

2.1 Minimum energy loss culverts

Minimum Energy Loss 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 and the flow is critical from the inlet lip to the outlet lip. The barrel invert is often lowered to increase the discharge capacity (Fig. 1).

(A) Outlet of Redcliffe Minimum Energy Loss (MEL) culvert in Sept. 1996

(B) Inlet of Minimum Energy Loss (MEL) culvert in Brisbane during undergraduate field work in May 2002

(C) Inlet of MEL culvert in Wynnum North, Brisbane in Sept. 2002 - Note passing cars on Gateway motorway and undergraduate students in inlet

Figure 1. Minimum energy loss culvert designs

Professor C.J. APELT presented an authoritative review (APELT 1983) and a well-documented audio-visual documentary (APELT 1994). The writer highlighted the wide range of design options and illustrated prototypes (CHANSON 1999,2000,2001).

The first structure was the Redcliffe MEL culvert completed in 1960 (Fig. 1A). Since about 150 structures were built in Eastern Australia. While a number of small-size structures were built in Victoria, primarily under the influence of Norman COTTMAN, shire engineer, major structures were designed, tested and built in South-East Queensland where little head loss is permissible in the culverts and most MEL culverts were designed for zero afflux (App. II). The largest MEL waterway is the Nudgee Road MEL system near Brisbane international airport with a design discharge capacity of 800 m^3/s. Built between 1968 and 1970, it is believed that 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 1970-1971. The design discharge capacity ranges from 200 to 250 m^3/s. The culverts operate typically several days per year and the writer organises regularly undergraduate student field works there (Fig. 1B). McKAY (1971) mentioned further MEL culverts built in Northern Territory near Alice Springs in 1970. 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).

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) (also HAMILL 1999). 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 culverts after major flood events demonstrating the absence of siltation (Present study).

2.2 Minimum energy loss weirs

The first MEL weir was the Clermont weir (Qld, Australia 1963) (Fig. 2A) if the control weir at the entrance of Redcliffe culvert is not counted. The largest, Chinchilla weir (Qld, Australia 1973), is listed as a "large dam" by the International Commission on Large Dams. Figure 2B shows the ungated spillway inlet at Swanbank. It was designed with the concept of minimum energy loss, in a fashion somehow similar to the design of a MEL culvert inlet (McKAY 1971).

The concept of the Minimum Energy Loss (MEL) weir was developed by late Professor G.R. McKAY to pass large floods with minimum energy loss. MEL weirs were designed specifically for situations where the river catchment is characterised by torrential rainfalls and by very small bed slope (Fig. 2) (App. III). A MEL weir is typically curved in plan with converging chute sidewalls and the overflow spillway chute is relatively flat (Fig. 2). 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.

(A) Sandy Creek weir, Clermont QLD during construction in Sept. 2002 (Courtesy of Keith JAMES) - View from the right bank

(B) Spillway inlet at Swanbank, Ipswich (Australia) in Sept. 2002

Figure 2. Minimum energy loss weir designs

3. EXPERIENCE LEARNED

The first MEL structures were designed with the concept of constant total head, hence zero afflux, associated with solid physical modelling. MEL culvert designs were typically tested in 1:12 to 1:36 undistorted scale models with fixed bed, while MEL weirs were scaled typically at 1:48. The characteristics and operational record of a number of MEL structures were documented, and this was complemented by recent field inspections, new surveys and oral discussions with designers. Note that most MEL structures are still in use (Fig. 3).

3.1 Model and prototype experience of MEL culverts

Several structures were observed operating at design flows and for floods larger than design. Inspections during and after flood events demonstrated a sound operation associated with little maintenance (Fig. 1 & 3B). While McKAY (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 near-critical flow conditions (APELT 1983). 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. The latter point is particularly important in the outlet where separation must be avoided as well.

(A) Sandy Creek weir, Clermont QLD on 8 March 1993 (Courtesy of A.J. HOLMES) - View from the right bank

(B) Minimum Energy Loss culvert in Brisbane - Outlet operation on 31 Dec. 2001 for about 80 m^3/s, looking from right bank

(C) Chinchilla weir (Qld, Australia 1973) - Small overflow view from the right bank on 8 Nov. 1997

(D) Minimum Energy Loss waterway in Brisbane - Outlet operation on 31 Dec. 2001 for about 80 m^3/s

Figure 3. Operation of Minimum Energy Loss structures

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 culvert shown in Figure 1B & 3B is equipped with a well-designed drainage system. 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. As a result, one major arterial will be overtopped during a design flood (Marshall Rd, Brisbane). For completeness, MEL culverts may be designed for non-zero afflux. The design process is similar (e.g. CHANSON 1999).

3.2 Prototype experience of MEL weirs

Several structures were observed operating at design flows and for floods larger than design : e.g., Clermont and Chinchilla weirs (Fig. 3A & 3C). Inspections during and after flood events demonstrated a sound operation associated with little maintenance. Professor Colin APELT stressed that improper inflow conditions could affect adversely the chute operation. Streamlining the inflow is essential.

The successful operation of several structures for over 40 years has highlighted further considerations. MEL weirs are typically earthfill structures and the spillway section is protected by concrete slabs. An efficient drainage system must be installed underneath the chute slabs. Construction costs are minimum. A major inconvenient however is the overtopping risk during construction : e.g., Clermont weir in April 1963, Chinchilla weir twice in 1972 and 1973.

4. CONCLUSION

A major advance in culvert and weir design was the development of the Minimum Energy Loss structures under the leadership of late Professor Gordon McKAY. MEL culverts and weirs 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 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.

It is the writer's opinion that the development of MEL structure design marked a breakthrough in hydraulic engineering worldwide. This unique development took place in Australia and it should be officially recognised by the engineering comunity, the Institution of Engineers, Australia and local authorities.

5. ACKNOWLEDGMENTS

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The Minimum Energy Loss (MEL) weir design. An overflow earthfill embankment dam
{http://www.uq.edu.au/~e2hchans/mel_weir.html}
Hydraulics of Minimum Energy Loss (MEL) Culverts and Bridge Waterways
{http://www.uq.edu.au/~e2hchans/mel_culv.html}

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 Th. REHBOCK (1864-1950). In 1950, he 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.

APPENDIX II. CHARACTERISTICS OF SUCCESSFUL DESIGNS OF MINIMUM ENERGY LOSS CULVERTS AND WATERWAYS (ALL STRUCTURES ARE STILL IN USE UNLESS INDICATED)

Description (1)	Q_{des} m^3/s (2)	B_{max} m (3)	B_{min} m (4)	D m (5)
MEL waterways				
Norman Creek, beneath SE-Freeway, Brisbane QLD 1975	200	33.5	11.2	4.0
Nudgee Rd, Schultz canal, Brisbane QLD 1968-69	850.0	209.7	137.0	--
MEL culverts				
Humpybong Creek, Redcliffe QLD 1960	25.8	19.5	5.5	*3.5*
Burnett highway, Goomeri QLD 1969	32.3	21.9	6.1	1.5
Jerry's Downfall, Beaudesert Rd QLD 1970 (+)	58.0	--	17.1	1.5
Stuart Highway, N Alice Springs NT1970 (+)	--	--	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	317.1	101.8	24.7	--
Settlement Shore - Flood outlet Structure B, Port Macquarie NSW 1973	577.7	206.7	50.0	--
Norman Creek, Marshall Rd, Brisbane QLD 1975	170.0	--	--	--
Norman Creek, Birdwood St, Brisbane QLD 1975	170.0	--	10.8	3.0
Norman Creek, Ekibin (Station 100), Brisbane QLD 1975	169.9	25.2	12.3	3.6
Norman Creek, Ridge St, Brisbane QLD 1975	220.0	42.0	21.3	3.0
Newington Bridge, Sheepwash Creek, Stawell Shire, VIC	141.5	125.0	9.6	2.4
Bridge d/s Genorchy, Wimmera River, Stawell Shire, VIC 1975-78	720.0	--	--	--
Illawarra to Mt Dryden Rd, Stawell Shire, VIC 1977-78	140.0	90.0	20.3	2.5
Fox's bridge, Bulgana Rd, Bulgana Parish, Stawell Shire, VIC 1977-78	55.2	120.0	6.6	--
Wynnum, South, Brisbane QLD 1985-86	220.0	62.0	18.0	3.0
Wynnum North, Brisbane QLD 1985-86	100.0	90.0	19.8	1.6

Notes : Q_{des} : design discharge; B_{max} ; inlet lip width; B_{min} : barrel width; D : barrel height; (+) : structure no longer in use.

APPENDIX III. CHARACTERISTICS OF MINIMUM ENERGY LOSS WEIRS AND SPILLWAYS (ALL STRUCTURES ARE STILL IN USE)

Structure (1)	Q_{des} m^3/s (2)	H_{dam} m (3)	B_{max} m (4)	B_{min} m (5)
MEL weirs				
Redcliffe QLD 1959	25.8	1.2	19.5	5.5
Sandy Creek weir, Clermont, Central Qld 1962-63	849.5	6.1	115.8	< 53 m
Chinchilla weir, Chinchilla QLD 1973	850.0	14.0	410.0	--
Lemontree weir, Condamine QLD 1979	--	4.0	--	--
MEL spillways				
Lake Kurwongbah, Sideling Creek dam, Petrie QLD 1958-69	849.5	25.0	106.7	*30.48 ?*

Swanbank Power House, Ipswich QLD 1965	160.0	~ 6 to 8	45.7	7.31

Notes : Q_{des} : design discharge; B_{max} : crest width; B_{min} : chute toe width; H_{dam} : dam height.