CIVL3140 Introduction to Open Channel Hydraulics - TUTORIAL 5: Hydraulic design of culvert

The course is a professional subject in which the students are expected to have a sound knowledge of the basic principles of continuity, energy and momentum, and understand the principles of fluid flow motion. The students should have completed successfully the core course Introduction to Fluid mechanics in semester 2, 2nd Year (CIVL2131).

Past course results demonstrated a very strong correlation between the attendance of tutorials during the semester, the performances at the end-of-semester examination, and the overall course result.

More exercises in textbook pp. 471-475 & 480-485.
"The Hydraulics of Open Channel Flow: An Introduction", *Butterworth-Heinemann Publ.*, Oxford, UK, 2004.

Revision problems
Each and every student is strongly encouraged to work on the Revision exercises and Problems in the textbook, pages 476-484, 533-540 and 551-572. Further relevant information are listed in the textbook, pages 440-471 & 492-511.

Part 1

A culvert is to be built to pass 25 m^3/s under a road embankment crossing a flood plain. The ground level is R.L. 22.000 m and the water level corresponding to this flow is expected to be R.L. 23.300 m. Both levels are at the centreline of the embankment which is 20 m wide at its base. The flood gradient is 0.004. (The culvert will be a multi-cell standard box culvert made of precast concrete boxes 1.5 m high and 1 m wide. Assume square-edge inlets.)
(a) Design a standard box culvert (with invert set at ground level) to carry the flood flow without causing any increase in flood level upstream *and operating under inlet control*.
(b) If the number of boxes is reduced to four (i.e. 4-cell box culvert), (i) calculate the change in flood level if the design discharge remains unaltered assuming inlet control. (ii) Check whether inlet control is the correct assumption.
Use figures :
- "Hydraulic calculations of upstream head above invert bed for box culverts with inlet control (Concrete Pipe Association of Australasia 1991, p. 39)"
- "Flow characteristics of box culverts flowing full (Concrete Pipe Association of Australasia 1991)" assuming k_e = 0.5 for square-edge inlet.)

Solution
(a) q = 2.6 m^2/s (in barrel) ⇒ 10 boxes

(b) Inlet control : q = 6.25 m^2/s ⇒ $H_1 - z_{inlet}$ = 3 m (change in flood level: 1.7 m). Outlet control : L = 20 m, q = 6.25 m^2/s ⇒ ΔH = 1.6 m, $H_1 - z_{inlet}$ = 2.92 m (change in flood level: 1.62 m). The largest control ⇒ Inlet control for Q < 30-32 m^3/s, Outlet control for Q > 30 to 35 m^3/s
Discussion : if the design discharge is a small to moderate flood flow (e.g. ARI = 1 year), the culvert may flow with outlet control operation for larger floods. If the design flow is a major flood (e.g. 1 in 40 years), most flood flow situations will correspond to inlet control operation.

Part 2

A culvert is to be built to pass 61 m^3/s under a road embankment crossing a flood plain. The ground level is A.H.D. 8.500 m and the water level corresponding to this flow is expected to be A.H.D. 10.150 m. Both levels are at the centreline of the embankment which is 85 m wide at its base. The flood gradient is 0.005 and the flood plain width is 45 m. The culvert will be built as a multi-cell box culvert using precast units with inside dimensions 1.8-m wide by 1.8-m high. The total wall thickness between adjacent cells can be taken as 100 mm.

You are required to design a means of carrying the flood flow through the embankment without causing any increase in flood level upstream ("NO AFFLUX").

2.1 Design the culvert, using the principles of minimum energy loss waterways, to minimise the length of the road crossing required. The greatest depth of excavation allowable is 0.95 m below natural surface. Your design must include the details of inlet and outlet fans. Assume that the waterway will be concrete-lined.
USE the "simple method" design developed by Professor C.J. APELT. Estimate the exit loss. Comment.

2.2 Calculate the width of waterway required to achieve the same objective of no afflux if standard box culverts are used with *rounded inverts* set at natural ground level and operating under inlet control. Select a barrel size which minimises the construction costs (by minimising the cross-section area of the barrel).
Use the inlet flow conditions equations developed by Professor F.M. HENDERSON (1966).

References

APELT, C.J. (1983). "Hydraulics of Minimum Energy Culverts and Bridge Waterways." *Australian Civil Engrg Trans.*, I.E.Aust., Vol. CE25, No. 2, pp. 89-95 (ISSN 0819-0259).
CHANSON, H. (2007). "Hydraulic Performances of Minimum Energy Loss Culverts in Australia." *Jl of Performances of Constructed Facilities*, ASCE, Vol. 21, No. 4, pp. 264-272 (ISSN 0887-3828).
HENDERSON, F.M. (1966). "Open Channel Flow." *MacMillan Company*, New York, USA.

Solution
2.1 5 cells structure
Full design with a 7° straight divergent :

Distance from C.L. embankment (m)	Depth excavation (m)	Natural Ground level (AHD m)	Invert level (AHD m)	Width m
-50.70	0.000	8.7535	8.7535	16.37
-48.03	0.206	8.7401	8.5337	13.77
-46.00	0.413	8.7300	8.3170	11.78
-44.41	0.619	8.7221	8.1026	10.24
-42.50	0.826	8.7125	7.8865	9.0
0.00	0.858	8.5000	7.6417	9.0
42.50	0.891	8.2875	7.3969	9.0
47.98	0.668	8.2601	7.5922	10.35
54.97	0.445	8.2251	7.7798	12.06
64.14	0.223	8.1793	7.9566	14.31
72.53	0.000	8.1373	8.1373	16.37

S_c = 0.0058 (calculation performed for one cell).
The total drop in invert elevation is 0.62 m. The estimated head loss is 0.53 m (ideal flow) and 0.23 m (real fluid flow). That is, the predicted energy loss is 40% of the total head loss available. Physical modelling is advised.

Note: in the 5-cells structure, the freeboard in the barrel is 0.04 m: i.e., much less than the 20% clearance; hence the design must be revised; instead a 6-cells structure must be selected and the entire design must be revised.

2.2 10 cells

Part 3

A culvert is to be built to pass 115 m^3/s under a road embankment crossing a 150 m wide floodplain. The ground level is AHD 12.100 m and the water level corresponding to this flow is expected to be 13.750 m. Both levels are at the centreline of the embankment which is 32 m wide at its base.
The longitudinal slope of the flood plain is 0.004. The culvert is to be a multicell box structure using precast units with inside dimensions 1.8 m wide and 2.0 m high.

(3.1) Design a minimum energy loss multicell box culvert for this situation. The greatest depth of excavation allowable is 0.900 m below the natural surface. (*Use "simple" method for design. "NO AFFLUX" design.*)

(3.2) Compare your M.E.L. culvert with a standard multicell box culvert placed at ground level *operating under inlet control* for the following cases :

(3.2.1) The standard culvert has the same number of cells as the minimum energy loss one : calculate (Case a) the change in capacity for the flood level to remain unaltered, and (Case b) the change in flood level if the discharge remains unaltered.
(3.2.2) The standard culvert has sufficient cells to pass the discharge without significant afflux.
(3.2.3) If the standard culvert has the same number of cells as the minimum energy loss one and the discharge remains unaltered, determine whether inlet control is the correct assumption.
Use design charts from Concrete Pipe Association of Australasia (1991), with $k_e = 0.5$ *for square-edged inlets.*

(3.3) Considering the MEL culvert design (3.1), an alternative design includes the design of a broad-crest at the inlet lip, with crest elevation set at AHD 13.220 m. Design the inlet lip and barrel size for a maximum afflux of 0.05 m.
The broad-crest is introduced to prevent downstream water intrusion into the upstream catchment. (For example, see the Redcliffe MEL culvert design, Textbook, pp. 504-505 & Fig. A4.17.)

Note: *For standard culverts, use design charts from Concrete Pipe Association of Australasia (1991).*

Solution
3.1 10 cells, Δz_o = 0.75 m, B_{max} = 31.5 m, B_{min} = 18.0 m, S_c = 0.0047
Note : S_c is calculated for 1 cell, taking into account sidewall friction along cell walls.
3.2.1 (a) Q = 65.7 m^3/s (b) Afflux = 0.84 m
3.2.2 18 cells
3.2.3 Inlet control operation
3.3 With 0.05 m afflux and a weir: 9 cells, Δz_o = 0.88 m, B_{max} = 111 m (inlet lip) - Remember that the weir is located immediately upstream of the inlet lip in Question 3.1. The natural ground elevation there is NOT 12.100 m AHD: it is slightly higher.

Part 4

A culvert is to be built to pass 76 m^3/s under a road embankment crossing a flood plain. The ground level is 15.100 m A.H.D. and the water level corresponding to this flow is expected to be 15.780 m A.H.D.. Both levels are at the centreline of the embankment which is 57 m wide at its base. The flood gradient is 0.0025 and the flood plain width is 145 m. The culvert will be built as a multi-cell structure using precast units with inside dimensions 1.5 m wide by 1.5 m high. The total wall thickness between adjacent cells can be taken as 100 mm.
You are required to design a means of carrying the flood flow through the embankment without causing any significant increase in flood level upstream. That is, you will consider two alternatives : (1) "No Afflux", and (2) a specified afflux.

4.1 For the design (1) (Zero afflux), design the culvert, using the principles of minimum energy loss waterways, to minimise the length of the road crossing required. The greatest depth of excavation allowable is 1.1 m below natural surface. Your design must include the details of inlet and outlet fans. Assume that the waterway will be concrete-lined.
USE the "simple method" design developed by Professor C.J. APELT. Estimate the exit loss. Comment.

4.2 For the design (2) with a maximum affux of 0.10 m, calculate the width of waterway required to achieve the afflux objective.
USE the "simple method" design developed by Professor C.J. APELT. Estimate the exit loss. Comment.

4.3 For the design (2) (maximum affux : 0.1 m), (A) specify in the table below the waterway widths and invert levels at intervals corresponding to depths of excavation equal to 0.25×(maximum excavation).

Location	Station	Distance from C.L. of embankment (+ve in d/s) (m)	Depth of excavation (m)	Invert level (m A.H.D.)	Waterway width (m)
Upstream lip	1				
	2				
	3				
	4				
Throat (u/s)	5				
Throat (midway)	6				
Throat (d/s)	7				
	8				
	9				
	10				
Downstream lip	11				

(B) Provide a dimensioned drawing of the waterway on graph paper (Plan and longitudinal section).

Solution

4.1 Inlet lip : H_1-z_{inlet} = 0.710 m, B_{max} = 74.5 m. Throat: 13 cells, B_{min} = 19.5 m, Δz_o = 1.026 m, S_c = 0.0031. Outlet: B_{max} = 74.5 m, ΔH = 0.21 m (ideal flow) & 0.085 m (real flow), Head loss available: 0.33 m.

4.2 Afflux = 0.10 m. Inlet lip : H_1-z_{inlet} = 0.810 m, B_{max} = 62.0 m. Throat: 12 cells, B_{min} = 18 m, Δz_o = 1.03 m, S_c = 0.00314. Outlet: B_{max} = 62.0 m, ΔH = 0.24 m (ideal flow) & 0.14 m (real flow), Head loss available: 0.395 + 0.10 m.

4.3

Location	Station	Distance from C.L. of embankment (+ve in d/s) (m)	Depth of excavation (m)	Invert level (m R.L.)	Waterway width (m)
Upstream lip	1	-59.49	0.000	15.249	61.98
	2	-51.74	0.257	14.972	40.86
	3	-43.99	0.514	14.696	29.51
	4	-36.25	0.771	14.420	22.58
Throat (u/s)	5	-28.50	1.028	14.143	18.00
Throat (midway)	6	0.00	1.046	14.054	18.00
Throat (d/s)	7	28.50	1.065	13.964	18.00
	8	36.25	0.798	14.211	22.78
	9	43.99	0.532	14.458	30.13
	10	51.74	0.266	14.704	42.50
Downstream lip	11	59.49	0.000	14.951	61.98