Teaching Hydraulic Design in an Australian Undergraduate Civil Engineering Curriculum

By H. Chanson[1]

Abstract: Since the early European settlements, Australia's economy has been highly dependent upon its water supply, although limited because of the dry climate. Today, the Australian continent is equipped with a large number of hydraulic structures per capita, and hydraulic engineering expertise is critical to future developments. In the universities, the civil engineering and environmental engineering undergraduate courses include a significant number of fluid mechanics and hydraulics subjects, including an introduction to hydraulic design. At the University of Queensland, the teaching of hydraulic design is focused on the sound application of the basic principles of fluid mechanics. Basic applications include the hydraulic design of spillways and culverts. Each type of design is supported by a series of lectures and a case study involving homework, a field visit, and a series of tutorials. Practical classes (laboratory and field visit) are an indispensable complement of the lectures. The subject assessment is based upon a combination of homework, practicals, and end-of-semester examination grades.

INTRODUCTION

Since the early European settlements in Australia, the coastal and continental development of the country has been coupled with the availability of water supply. For two centuries, Australia's economy has been highly dependent upon its surface irrigation and, today, more than 85% of water diversions are for agricultural purposes (irrigation and stock watering only). Water supply is limited because of the dry climate. Although the average annual rainfall is about 420 mm, the spatial and temporal variability is high. The rainfall may vary from zero for several years to extreme hydrological events, e.g., 515 mm in 6 h at Dapto, New South Wales in 1984. The median annual rainfall is <300 mm over 60% of the Australian continent. The rainfall takes place usually during a wet season, associated with intense falls, and the rest of the year is very dry. For example, the annual rainfall intensity ranges from 24 to 132 mm/24-h period in southeast Australia (Victoria, New South Wales and South Queensland). During the dry periods, rainfall is scarce and the median monthly rainfall ranges from 0 to 100 mm in southeast Australia. High evaporation coupled with the variability of surface runoff make conservation and development of water resources more expensive and less effective than in many other countries. Therefore, hydraulic engineering expertise is critical to any future development.

In the universities, the civil engineering and environmental engineering courses include a significant number of fluid mechanics and hydraulics subjects, including hydraulic design. The writer's university is a typical example. (Although the University of Queensland might not be strictly characterized as an average university, it is one of the leading universities in the country and its undergraduate curriculum is representative.) Hydraulic design (Subject E2321: Open Channel Hydraulics and Design) is taught to third year civil engineering and environmental engineering students with class size of typically 120–145 students. In both undergraduate courses the students studied two fluid mechanics subject in the second year (E2232: Fluid Mechanics 1 and E2233: Fluid Mechanics 2) and one hydraulic subject in the third year (E2320: Catchment Hydraulics) before undertaking the hydraulic design subject (Table 1); all four subjects are compulsory. Table 1 presents the details of each subject including its weight (column 3, number of credit points); amount of lectures, tutorials, and practicals (column 5); and independent study requirements (column 6). A postgraduate subject in advanced hydraulic design is also available.

The present paper reviews the teaching of hydraulic design in the undergraduate civil engineering course of an Australian university. The teaching philosophy and method of instruction are outlined. It is shown that both traditional lectures and project-based resources are combined. Practical works are an indispensable complement of the lectures.

HYDRAULIC DESIGN IN UNDERGRADUATE CURRICULUM

The hydraulic design subject is an introductory subject to the design of hydraulic structures, e.g., conveyance canals, culverts, and spillways of small dams. It is assumed that the students have had an introductory course in fluid mechanics and that they are familiar with the basic principles of continuity, momentum, and energy, and their application to open channel flows. The subject is designed to convey a basic understanding of the hydraulics of rivers, waterways, and man-made structures. It is a basic introduction to professional design of hydraulic structures and the application of the basic principles to real design situations with the analysis of complete systems.

Subject Pedagogy

The subject material is structured to guide the students from the basic principles of fluid mechanics to their application to engineering design. Hydraulic modeling is introduced as a series of tools used by professionals to compare the performances of various design options. For example, it is essential to accurately predict the behavior of hydraulic structures under the design conditions, operation conditions, and emergency situations. During design stages, the engineers need reliable prediction "tools" to compare the performances of various design options. Two types of hydraulic models are commonly used, i.e., computational and physical models. Numerical models are computer software that solves the basic fluid mechanics equations, e.g., numerical integration of the backwater equation to predict the longitudinal free-surface profile of a gradually varied open-channel flow. Their application, within the context of an undergraduate subject on hydraulic design, is restricted however to simple flow situations and boundary conditions for which the basic equations can be numerically integrated and

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TABLE 1. Summary of Fluid Mechanics/Hydraulics Subjects Taught in Civil Engineering at University of Queensland

Year	Semester	Subject name and credit points	Syllabus	Time schedule for semester	Individual study	Remarks
2	1	E2232: Fluid Mechanics 1 (6 CP)	Introduction to fluid mechanics; fluid statics; continuity, momentum, and energy principles	13 L + 13 T + 9 P	3 h/week	3 laboratory experiments
2	2	E2233: Fluid Mechanics 2 (6 CP)	Applications of basic principles to steady and quasisteady flow	13 L + 13 T + 6 P	3 h/week	2 laboratory experiments
3	1	E2320: Catchment Hydraulics (9 CP)	Introduction to catchment hydrology, open-channel flows, and sediment transport in rivers	26 L + 13 T + 6 P	5 h/week	2 laboratory experiments
3	2	E2321: Open-Channel Hydraulics and Design (8 CP)	Hydraulic design; physical and numerical modeling	26 L + 13 T + 6 P + 3 F	4 h/week	2 laboratory experiments and 1 field trip
3	2	E2308: Advanced Fluid Mechanics (8 CP)	Ideal-fluid (irrotational) flows; real fluid flows and fluid-structure interactions	26 L + 13 T	4 h/week	—
4	1	E2447: Environmental Issues (5 CP)	Municipal wastewater management; soil and water conservation	20 L	2 h/week	—
4	1	E2429: Coastal and Estuarine Processes (6 CP)8	Introduction to coastal processes	26 L	2 h/week	Elective subject
P/G	—	E2822: Hydraulic Design (12 CP)	Advanced hydraulic design; design of medium- and high-head spillways; numerical modeling of flood plains	26 L + 13 T	6 h/week	Postgraduate subject

Note: 8 CP = 8 credit points (award of Bachelor of Engineering degree requires successful completion of 400 credit points); 1 L = 1 h of lecture; 1 T = 1 h of tutorial; 1 P = 1 h of practical class (laboratory work); 1 F = 1 h of field work; P/G = postgraduate subject.

are meaningful. The calibration and validation of computational models are extremely difficult, and most computer models are applicable only in a very specific range of flow conditions and boundary conditions. Most often physical models must be used for hydraulic structures, including for the validation of computational models.

Hydraulic design is then presented with a focus on the application of the basic hydraulic principles to real design situations. The design process is based on a system approach. A hydraulic structure must be analyzed as part of the surrounding catchment and the hydrology plays an important role. The design is a complex exercise because of the interactions between structural, hydraulic, and geotechnical engineering.

For example, the construction of a weir across a river relies upon the stream hydrology and the catchment characteristics. If the catchment can provide sufficient water year-round (i.e., mean annual characteristics), the maximum peak inflow must be predicted, i.e., extreme events. The design of the weir is based upon structural, geotechnical, and hydraulic considerations. Political matters may also affect the weir site location and the decision to build the dam. A consequent cost of the structure is the spillway, designed to safely pass the maximum peak flood. In addition, the impact of the weir on the upstream and downstream valleys must be considered, e.g., sediment trap, fish migration, downstream water quality (e.g., dissolved oxygen content), modifications of the water table, and associated impacts (e.g., salinity).

Another example, the design of a culvert, requires a hydrological study of a stream to estimate the maximum (design) discharge and to predict the risks of exceptional (emergency) floods. The dimensions of the culvert are based on hydraulic and structural considerations as well as geotechnical matter, as the culvert height and width affect the size and cost of the embankment. Further, the impact of the culvert on the environment must be taken into account, e.g., potential flooding of the upstream plain.

In summary, the design process must be a system approach. First, the system must be identified. What are the design objectives? What are the constraints? What is the range of options? What is the ''best choice''? Its detailed analysis must be conducted. The engineers should ask Is this solution really satisfactory?

Delivery of Subject Material

The lecture material on hydraulic modeling addresses the application of the basic principles of similitude and dimensional analysis to open channels, and the numerical integration of the energy equation (1D flow modeling) (Chanson 1999, pp. 257–308). The second part of the subject addresses the design of hydraulic structures for the storage and conveyance of water: design of dams, weirs and spillways, design of drops and cascades, and design of culverts (standard box and minimum energy loss culverts) (Chanson 1999, pp. 311–434). In parallel, the delivery mode progresses from traditional lectures and tutorials, to professional applications and project-based works.

In the course introduction, the basic concepts of similitude (e.g., π theorem) are applied to the optimum choice of a physical model. The students have to make simple decisions on the suitable geometric size of the model, the required flow rate, and the manufacturing of the model, e.g., roughness. Numerical modeling is introduced with 1D modeling, i.e., backwater equation. Professional software (e.g., Hydrochan) are used in parallel with simple spreadsheet calculations. The results are compared with laboratory measurements in a 20-m long flume. The agreement and discrepancies between numerical and physical model results are discussed.

In the second part of the subject, the students are exposed to two types of hydraulic structures with an increasing level of difficulty. That is, spillway design and culvert design. These are selected because of their relevance to the Australian continent and to the Queensland state. Australia is equipped with a large number of hydraulic structures per capita, and the state of Queensland is subjected to a tropical and subtropical climate characterized by intense rainfall in summer. Spillway and culvert designs must be adequately sized, often for discharges close to the probable maximum flood. In the lectures, the lecturer emphasizes the concept of iterative process to achieve an optimum design of the complete system. Spillway design is introduced first. The students are provided with lecture materials on crest design (e.g., broad-crest, ogee), chute calculations (e.g., smooth-invert, stepped), and energy dissipators (e.g., hydraulic jump, plunge pool). They must then apply the knowledge to a practical case study associated with a field trip (Fig. 1). Appendix I describes a typical case study.

The hydraulic design of culverts covers both standard box culverts and minimum energy loss waterways. The former calculations are relatively straightforward, i.e., there is a unique solution for given hydraulic constraints. The latter type of design introduces individual originality. A minimum energy loss (MEL) culvert is a structure designed with the concept of minimum head loss. The basic concepts of MEL culvert design are streamlining and critical flow conditions throughout all the waterway (inlet, barrel, and outlet) (Fig. 2). The flow in the approach channel is contracted through a streamlined inlet into the barrel where the channel width is minimum, and then it is expanded in a streamlined outlet before being finally released

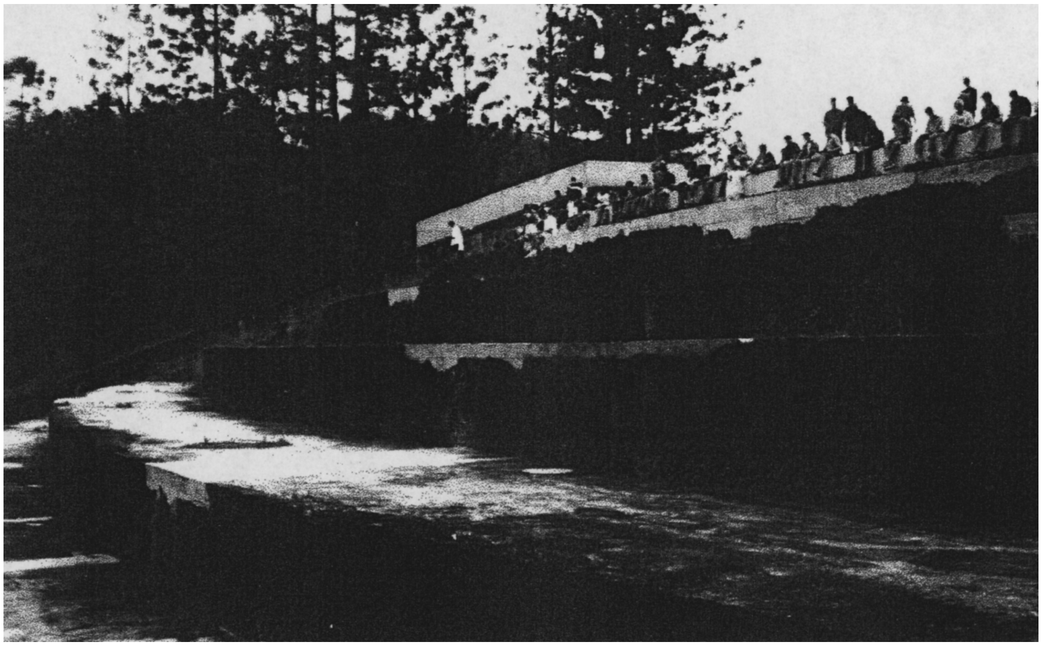

FIG. 1. Students Inspecting Gold Creek Dam Stepped Spillway, August 1998

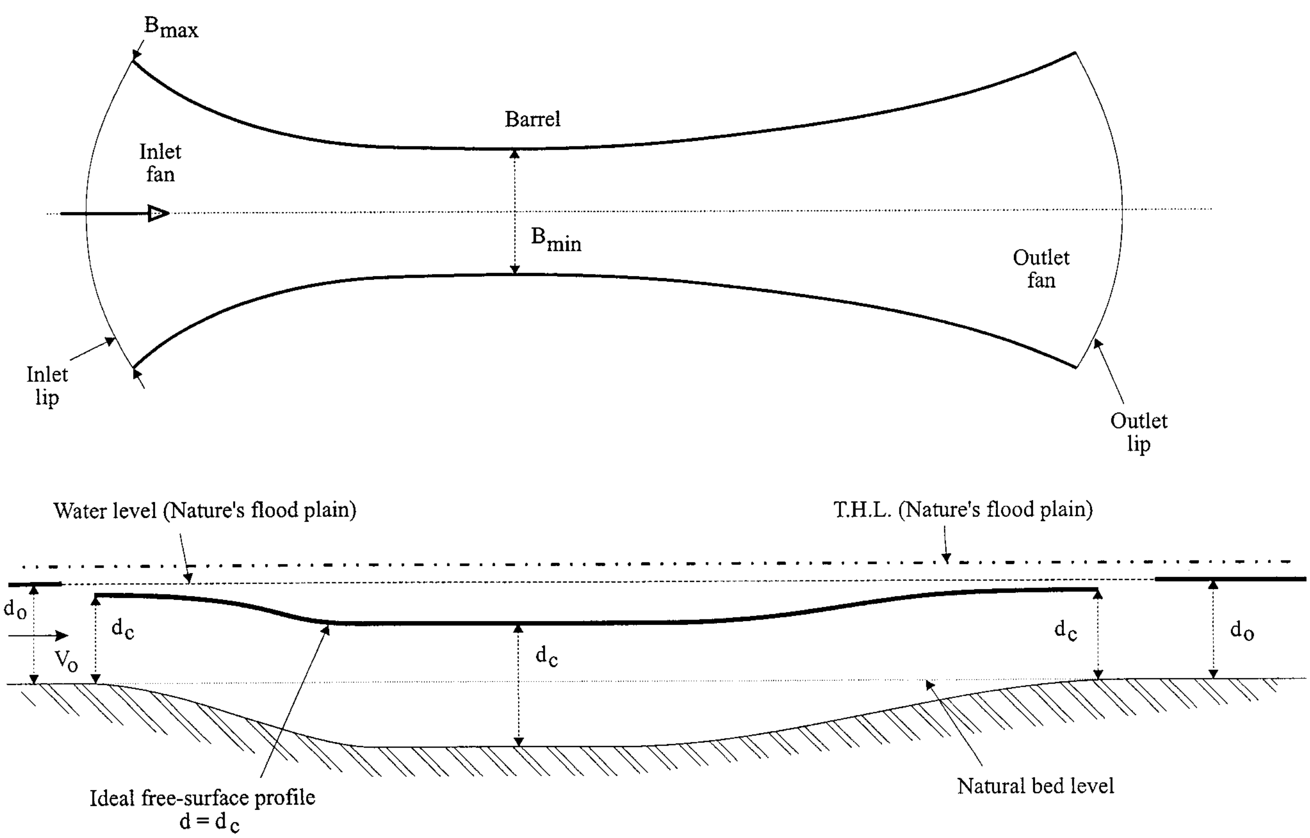

FIG. 2. Minimum Energy Loss Waterway (after Chanson 1999)

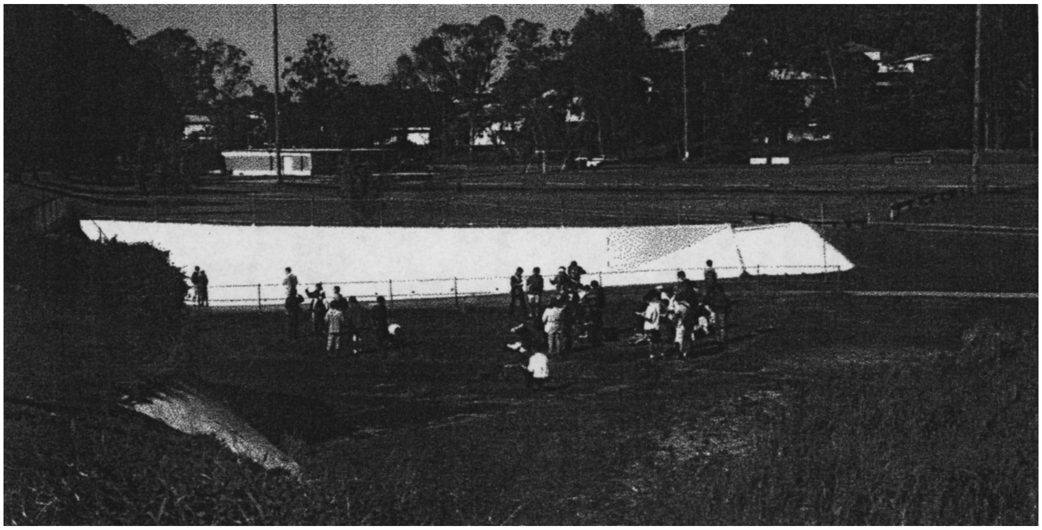

FIG. 3. Minimum Energy Loss Culvert Underneath Ridge St., Brisbane, Australia (Photo Taken on August 5, 2000, during Field Trip): View of Inlet

into the downstream natural channel. Ideally, the flow is critical at any cross section, from the inlet lip up to the outlet lip, as maximum discharge per unit width is achieved at critical flow conditions for a given specific energy. Minimum energy loss culverts are typically designed to have zero afflux; that is, no increased flooding in the upstream catchment for all flow rates up to design flow. Apelt (1983) presented an authoritative review on MEL culvert design and Hamill (1999) presented a brief summary. Chanson (1999) explained the design basics and also detailed prototype experiences. The students are provided with lecture material on culvert design followed by a case study associated with a field trip (Fig. 3 and Appendix II). The MEL culvert design in Fig. 3 has a design flow rate of 220 m^3/s and a barrel consisting of seven precast concrete box cells, each with inside dimensions of 3.5 m in height and 2 m in width, designed for zero afflux, MEL culvert design is challenging for most students because there are an infinity of correct designs as well as an infinity of wrong designs for a given minimum energy loss structure. For example, Fig. 4 presents several inlet designs for the Nudgee Road waterway (Appendix II), illustrating plan views of the two sidewalls (thin lines, $y = 0$ on the centerline) and vertical cross sections of invert (thick solid line). The flow direction is from left to right. The designs on the left [Figs. 4(a and b)] will safely pass the design flow rate (850 m^3/s) without significant afflux, while others [Figs. 4(c and d)] would ''choke'' for flow rates less than the design flow rates. (Choking would be associated with bridge submergence and significant upstream flooding for the design flow rate.) The designs in Figs. 4(c and d) would not operate properly although their dimensions differ only slightly from the correct designs [Figs. 4(a and b)]. The design in Fig. 4(c) would be characterized by a hydraulic jump in the inlet at design flow rate. The jump would be associated with some scour of the grass-lined inlet and some head loss. The design in Fig. 4(d) could not pass more than 815 m^3/s without upstream flooding.

Discussion: Unstable Nature of Critical Flows in MEL Culvert Barrel

At critical flow conditions, the flow may be characterized by the establishment of stationary free-surface undulations. For the designers, the characteristics of the free-surface undulations are important for the sizing of the culvert height. If the waves leap on the roof, the flow might cease to behave as an open-channel flow and become a pipe flow. The writer observed experimentally that a 20% free-space clearance between the mean free-surface level and the barrel roof is a minimum value when the barrel flow conditions are undular (Chanson 1996).

In practice, perfect-critical flow conditions in the barrel are difficult to establish. (They may be characterized by ''choking'' effects and free-surface instabilities.) Usually a good practice is to design the barrel for a Froude number of about 0.6–0.8, leading to much smaller wave heights while the discharge per unit width is nearly maximum.

OBSERVATIONS

The teaching pedagogy is to develop appropriate state-of-the-art expertise, know-how, and basic understanding in the undergraduate program. Three important components of the teaching material are the textbook, the practical classes, and the homework assessment.

Textbook

The hydraulic design is supported by the textbook ''The Hydraulics of Open Channel Flow: An Introduction'' (Chanson 1999). The text is used in the introductory subject on open-channel hydraulics as well as in hydraulic design to the benefit of the students. The hydraulic design subject is supported by Sections III and IV of the textbook. The students may also use the book's Internet material. (The support Web site of the book is located at ⟨http://www.bh.com/companions/0340740671/⟩. Exercises and solutions are located at ⟨http://www.bh.com/companions/0340740671/exercises/exercisesP1.htm⟩.) Additional Web site resources are provided by the writer at the following addresses: ⟨http://www.uq.edu.au/~e2hchans/e2321.html⟩, ⟨http://www.uq.edu.au/~e2hchans/photo.html⟩, ⟨http://www.uq.edu.au/~e2hchans/over_st.html⟩, and ⟨http://www.uq.edu.au/~e2hchans/tim_weir.html⟩.

Practical Classes: Laboratory Experiments and Field Visit

Practical classes are an integral component on the subject. They include two laboratory experiments and one field trip (Table 2). In the laboratory, the students are involved with both physical and numerical modeling. Audiovisual documentaries are also shown. An emphasis is on visual observation including nondesign flow situations. For example, the students can visualize culvert submergence and road overtopping, or the occurrence of a hydraulic jump caused by upstream and downstream control operation. During each laboratory practical, the students must compare their laboratory measurements with

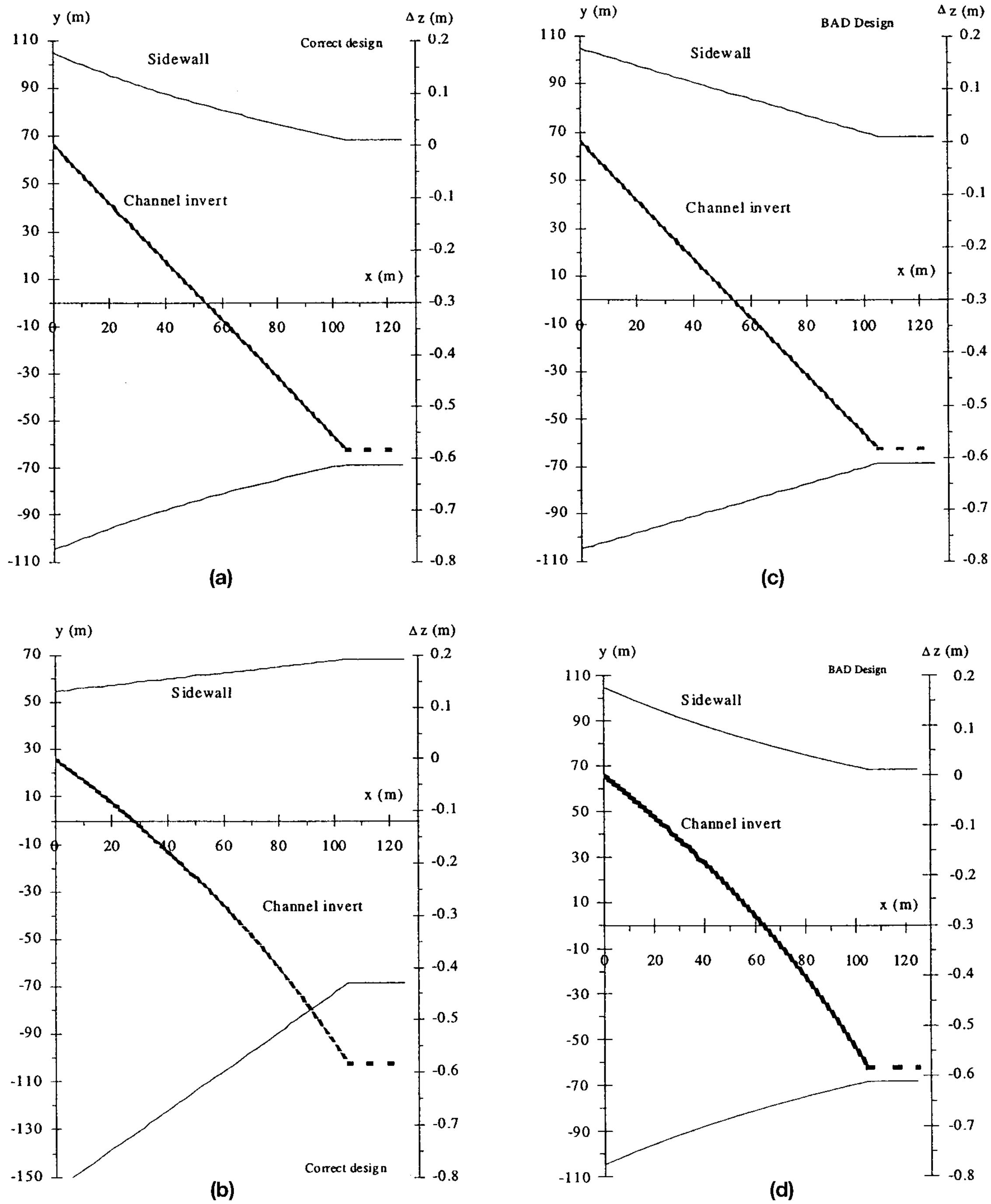

FIG. 4. Nudgee Road Minimum Energy Loss Waterway: Inlet Designs (Thin Line = Sidewalls; Thick Line = Invert Profile)

TABLE 2. Practical Classes in Hydraulic Design at University of Queensland

Name	Description	Reference
Experiment No. 1: Gradually varied flow	Laboratory experiments of the backwater profiles in a 20-m long tilting flume with a variety of hydraulic controls, e.g., sluice gates. Free-surface profile measurements, backwater calculations (spreadsheet), professional software (HydroChan).	
Experiment No. 2: Culvert design	Laboratory experiments with two physical models of culvert: a box culvert followed by a MEL culvert.	Box culvert experiment: Chanson (1999, pp. 381–382, 430–434)
	Free-surface profile measurements, flow patterns in barrel, professional software (HydroCulv).	MEL culvert experiment: Chanson (1999, pp. 388–389)
Field trip	Combined field visit between hydraulic design and structural design classes. The two lecturers provide advanced expertise on each aspect of the design and emphasize the system design approach. Examples: MEL culverts and stepped weirs; culverts and spillways.	Figs. 1 and 3

calculations derived from the lecture material as well as with results obtained using professional software. Before the end of the class, the results are discussed with the demonstrator to test the critical ability of each student.

The field trip is an exercise combined with the E2316 Structural Design subject. The students visit carefully selected prototypes with the lecturers. For example, the visit of the Nudgee Road waterway (Appendix II) involved several aspects of the design, including cost estimate. The discussion is not limited to structural and hydraulic considerations but also covers geotechnical and transportation issues, for example, the road access to Gold Creek dam during flood periods (Appendix I).

Objectively, it is very difficult to measure the importance of the field trip. However, the writer noted a huge regain of interest for the hydraulic course among all the students (i.e., from the weakest to the brightest) when a field trip was conducted timely, close to the relevant lecture material, and in conjunction with the homework case studies. Discussions with former students highlighted long-lasting memories of walking inside the barrel of a culvert, visiting a dam and its spillway, and climbing up and down a staircase chute (Fig. 1).

Homework and Overall Assessment

Two case studies (one on spillway design and one on culvert design) are developed in the subject (the selection of two cases was done to cover more than one application while providing enough in-depth coverage). Each case study is associated with some homework that covers a complete series of lectures. The homework would span over 3 to 4 weeks during which weekly tutorial meetings and discussions are held to facilitate smooth progress of the homework.

The subject assessment typically includes a semester work component (20%), the practical works (20%), and an end-of-semester examination (60%). The examination purpose is to test the basic understanding of each individual student.

SUMMARY

Water supplies are critical to the development of the Australian continent, and there is a strong emphasis in the teaching of hydraulic engineering in the universities. In the undergraduate programs (civil and environmental engineering), the students attend basic fluid mechanics subjects and one introduction to open-channel hydraulics before undertaking hydraulic design in their undergraduate course.

At the University of Queensland, the teaching of hydraulic design is focused on the sound application of the basic principles of fluid mechanics. Design applications include spillway design and culvert design. Further, a complete system approach is presented, including hydraulic, structural, geotechnical, transport, and management considerations. Each case study is taught with a combination of basic lectures, project-based homework, and a field trip. Practical classes (laboratory and field visit) are indeed an important component of the subject.

The writer believes that the Australian undergraduate curriculum includes generally a stronger emphasis on water engineering than others, e.g., the United Kingdom and the United States. For example, hydraulic design is introduced in the undergraduate curriculum. There is further a solid accent on practical works including laboratory experiments and field visits.

APPENDIX I. CASE STUDY NO. 1: GOLD CREEK DAM SPILLWAY REFURBISHMENT

The Gold Creek dam is an earthfill dam built between 1882 and 1885 near Brisbane, Australia, for the city water supply (Chanson and Whitmore 1998). The reservoir was in use up to 1991. The maximum height of embankment is at 99.1 m R.L. (i.e., above reference elevation) and the reservoir storage capacity is about 1.8 10^6 m^3. The catchment area is 10.48 km^2 of protected forest area. The dam is equipped with an ungated overflow stepped spillway (Fig. 1). The spillway consists of a broadcrest followed by the stepped chute (55-m wide). The stepped chute is followed (without transition section) by a smooth downward-sloping channel ($\theta = 1.2°$). The sloping channel is used as a dissipation channel. It is 55-m wide and its shape is approximately rectangular.

The dam owner is investigating an increase of the maximum discharge capacity of the spillway. Two options are considered: (1) design of an overflow spillway with an ogee-type crest, a smooth chute, and a hydraulic jump dissipator, the crest level being at the same level as the existing spillway; and (2) design of an overflow spillway with an ogee-type crest, smooth-invert chute, and hydraulic jump dissipator, the crest level being lowered by 1.5 m. In both refurbishment options, the chute is followed by a concrete apron. The tailwater level will be artificially raised with a broad-crested weir located at the downstream end of the concrete apron, i.e., geometry to be determined.

The project assignment includes three parts:

1. Calculation of the maximum discharge capacity of the existing spillway $Q^{(1)}_{\max}$ and estimate of the hydraulic jump location at the downstream end of the spillway (assume a skimming flow regime on the stepped chute)
2. For the new spillway design [Option (i)], computation of the maximum discharge capacity $Q^{(2)}_{\max}$ of the new spillway
3. For the new spillway design [Option (ii)], calculation of the maximum discharge capacity of the spillway $Q^{(3)}_{\max}$, design of the hydraulic jump stilling basin to dissipate the energy at the foot of the spillway, and selection of the location, elevation, and crest length of the broad-crested weir to ensure that the hydraulic jump stilling basin is always contained between the smooth chute toe and the weir for discharges ranging from $Q^{(3)}_{\max}$ down to $0.1 \cdot Q^{(3)}_{\max}$

The maximum discharge over the crest is usually computed when the reservoir free-surface elevation reaches the dam crest elevation. For an earth embankment, it is essential that no overtopping (at all) occurs and, in practice, it is safer to allow a safety margin of 0.4 m (to 1 m) for wind-wave effects, i.e., dam overtopping caused by wind-wave action. For the assignment, use a margin of safety of 0.4 m.

Discussion

The assignment requirements include the estimate of the discharge capacity of the old spillway. The exercise is typical of the study of old dams for which there is little or no documentation. In the second part, the students will gain some understanding of the larger discharge capacity of an ogee crest compared to a broad crest. In the third part, the effect of the spillway crest elevation is introduced. The students have further to conduct a complete backwater analysis downstream of the stepped chute.

Usually a field trip to the dam site is conducted prior to the case study (Fig. 1). The students can inspect the dam, the spillway (including walking down the stepped chute), and the downstream catchment. (The downstream catchment is inhabited; it is a western suburb of the city of Brisbane, called Brookfield. The access road to the dam travels through Brookfield. It crosses the Gold Creek river in several places. During spills, the dam is not accessible by this road because it is submerged.)

APPENDIX II. CASE STUDY NO. 2: NUDGEE ROAD WATERWAY

The Nudgee Road Bridge is a main arterial road in the eastern side of Brisbane, Australia (Chanson 1999, pp. 384, 421–423). The bridge crosses the Kedron Brook stream downstream of the Toombul shopping town and upstream of the Brisbane Airport. The natural floodplain is 400 m-wide and grasslined (longitudinal slope = 0.49 m/km). At the bridge location, the natural ground level is at R.L. 10.0 ft.

The assignment includes three parts: (1) the design of the old waterway; (2) the hydraulic design of the present waterway; and (3) the upgrading of the waterway.

Part 1: Old Waterway (Prior to 1968)

The old waterway could pass 198.2 m^3/s (7,000 ft^3/s) before overtopping the road bridge. The design parameters were: design flood flow = 198.2 m^3/s (7,000 ft^3/s), natural ground level at centerline of embankment = R.L. 3.048 m (10.00 ft), width of embankment base = 9.14 m (30 ft), road elevation = R.L. 13.00 ft, bridge concrete slab thickness = 0.152 m (6 in.), and floodplain slope = 0.49 m/km.

- Calculate the width of the old waterway (i.e., span of the old bridge) assuming that the waterway was a standard box culvert with invert set at natural ground level and operating under inlet control with squared-edged inlets.
- Use the spreadsheet you developed for the backwater calculations to calculate the flood level (i.e., free-surface elevation) for distances up to 1,500 m upstream of the culvert entrance. Plot both backwater profiles and compare with the uniform equilibrium flow profile.
- Using the commercial software HydroCulv, calculate the hydraulic characteristics of the throat flow at design flood flow.

Part 2: Present Nudgee Road Waterway (Built in 1969)

In 1969, the new Nudgee Road bridge was hydraulically designed based upon a minimum energy loss design (zero afflux). The improvement was required by the rapid development of upstream catchment. The waterway was designed to pass about 849.5 m^3/s (30,000 ft^3/s), which was the 1-in-30-year flood. The ground level (at the centerline of the new bridge) is R.L. 3.048 m (R.L. 10 ft) and the water level corresponding to this flow was expected to be R.L. 4.7549 m (R.L. 15.6 ft). The waterway throat is 137-m wide, 40-m long, and lined with kikuyu grass.

Design the minimum energy loss waterway culvert for this situation. Include details of the inlet and outlet in your design.

Part 3: Upgrading Nudgee Road Waterway (1999 to 2000)

The Nudgee Road waterway must be enlarged to pass 1,250 m^3/s. The water level corresponding to this flow is expected to be R.L. 5.029 m (at the bridge centerline, in the absence of the waterway and embankment). It is planned to retain the existing road bridge and most of the road embankment by building a 0.275-m high concrete wall along the road (on the top of the bridge and embankment) to prevent overtopping. The waterway inlet, outlet, and throat will be concrete lined to prevent scouring, which could result from the larger throat velocity. Two minimum energy loss designs (zero afflux) are considered: (1) retain the existing bridge and excavate the throat invert; and (2) extend the existing bridge and keep the throat invert elevation as in the present waterway (calculation in Part 2).

- Design the minimum energy loss waterway culverts.
- Calculate the construction cost of both designs.
- For the minimum-cost MEL waterway design, include details of the inlet and outlet in your design. Construction costs: extension of a two-lane bridge = \$10,500/m length, excavation cost = \$9/m^3, and embankment cost = \$21/m^3.

Discussion

The assignment and field trip to the Nudgee Road waterway is a combined exercise with the structural design subject E2316. In the structural design subject, the students are involved in the design of the bridge. During the site visit, the lecturer, W. Boyce, explains the structural features of the bridge while the MEL waterway design is discussed with the writer.

The project includes the hydraulic design of the waterway, the structural design of the bridge, and a cost analysis of the complete system. In the first part information is provided in imperial units. Although Australia has used the SI-unit system since 1982, the refurbishment of old structures often requires conversion between imperial and SI units.

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NOTATION

The following symbols are used in this paper:

Q_{max} = design discharge (m^3/s);
x = longitudinal distance (m);
y = lateral coordinate (m); and
Δz = excavation (m).