CIVL3140 Introduction to Open Channel Hydraulics - TUTORIAL 4: Physical modelling in hydraulic engineering

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. 253-274, 371-373, 533-540 and 551-572.
"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 371-373, 533-540 and 551-572. Further relevant informations are listed in the textbook, pages 253-274.

Note: Prototype means full-scale size.

Part 1

The butterfly valve of a crude oil pipeline is to be tested in laboratory to determine the head loss coefficient at full valve opening. The prototype size will be 0.5 m diameter and it will be manufactured from cast steel with machined surfaces (roughness height estimated to be about 0.3 mm). The maximum discharge to be transported is 1200 kg/s. The laboratory model is at a 5:1 scale.

First assume that the same fluid is used in model and prototype.
1.1 What surface condition is required in the model? What model discharge is required to achieve complete similarity with the prototype, if crude oil is used in both?
1.2 Can these conditions be achieved? (Compute the required model total pressure and model flow rate, and compare these with the pump performances of the AEB Hydraulics laboratory.)
1.3 If the maximum flow available for model tests is 120 kg/s, would you be able to predict accurately prototype discharge coefficients from the results of the model tests? (Justify your answer)
For crude oil at 20 Celsius, assume $\rho = 860$ *kg/m*^{3}, $\mu = 8E\text{-}3$ *Pa.s.*

Secondly assume that water is used in the physical model.
1.4 What model discharge is required to achieve complete similarity with the prototype, if water is used in model?
1.5 Calculate the required model total pressure. (Compare these with the pump performances of the Hydraulics laboratory)
1.6 If the maximum flow available for model tests is 35 l/s, would you be able to predict accurately prototype discharge coefficients from the results of the model tests? (Justify your answer. Discuss the practical differences between using crude oil and water in laboratory.)

Solution
1.1 This is a fully enclosed flow implying a Reynolds similitude.
Model roughness (60 microns) very difficult to achieve!
Kinetic energy pressure: $(\rho\times V^2/2)_m = 540$ kPa $\Rightarrow$ pressure in the pipe > 550 kPa (large pressure)
$(Q_m)_{max} = 0.279$ m^3/s corresponding to 240 kg/s $\Rightarrow$ fairly large discharge
1.2 The laboratory conditions cannot be achieved in the AEB Hydraulics laboratory at the University of Queensland in terms of pressure. (During laboratory classes, ask the tutors and technical staff about the maximum flow rate and total head available in the laboratory.)
1.3 $(\rho_p\times Q_p)_{max} = 600$ kg/s $\Rightarrow$ 50% of the maximum flow rate only (not enough)

1.4 Based upon a Reynolds similitude: $(Q_m)_{max} = 0.030$ m^3/s corresponding to 30 kg/s
1.5 Kinetic energy pressure: $(\rho \times V^2/2)_m = 7.4$ kPa $\Rightarrow$ pressure in the pipe > 7.4 kPa (small to moderate pressure)
1.6 Yes because the $(Q_m)_{max} = 0.030$ $m^3/s < 0.035$ m^3/s.

Part 2

An overflow spillway is to be designed with an un-gated broad-crest followed by a stepped chute and a hydraulic jump dissipator. The width of the crest, chute and dissipation basin will be 55-m. The crest level will be at 96.3 m A.H.D. and the design head above crest level will be 2.4 m. The chute slope will be set at 45 degrees and the step height will be 1-m. The elevation of the chute toe will be set at 78.3 m A.H.D.. The stepped chute will be followed (without transition section) by a horizontal channel which ends with a broad-crested weir, designed to record flow rates as well as to raise the tailwater level.
The spillway design will be tested in laboratory to verify/check the non-design flow performances. A 50:1 scale model of the spillway is to be built. Discharges ranging between the maximum flow rate and 10% of the maximum flow rate are to be reproduced in the model.
(2a) Calculate the maximum discharge capacity of the spillway.
(2b) Determine the maximum model discharge required.
(2c) Determine the minimum prototype discharge for which negligible scale effects occur in the model. (Comment on your result)
(2d) What will be the scale for the force ratio?
(2e) Operation of the basin may result in unsteady wave propagation downstream of the stilling basin with wave amplitude of about 0.012 m and wave period of 2 minutes (model observations).
(i) Compute the prototype wave amplitude.
(ii) Compute the prototype wave period.

Solution
(2a) Open channel flow $\Rightarrow$ Froude similitude
$(Q_p)_{max} = 348.5$ m^3/s (application of the Bernoulli principle to the broad-crested weir)
(2b) $(Q_p)_{max} = 0.020$ m^3/s
(2c) $(Q_p)_{min} = 25$ m^3/s (7% of design discharge) $\Rightarrow$ can test all flow rates from Q = 0.1 to 1.0 $\times$ Q_{des}
(2d) See lecture notes
(2e) (i) $a_p = 0.60$ m (ii) $T_p = 848$ s (14 mn 8 s)

Part 3

A Venturi meter is to be tested in laboratory to determine the discharge coefficient for various upstream heads. The prototype size will be an 2.2 m diameter throat and it will be manufactured from cast steel with machined surfaces (roughness height estimated to be about 0.5 mm). The maximum discharge to be controlled by the orifice is 15 m^3/s.
The laboratory model is at a 7.5:1 scale.
3.1 (i) What surface condition (i.e. roughness height) is required in the model? (ii) What model discharge is required to achieve complete similarity with the prototype, if water is used in both?
3.2 Can these conditions be achieved? (Yes/No, Why)
3.3 If the maximum flow available for model tests is 200 L/s, how would you be able to predict prototype discharge coefficients from the results of the model tests? (Very accurately/accurately/not accurately/poorly; Why?)
Prototype and laboratory use water.

Solution
Solution
3.1 This is a fully enclosed flow implying a Reynolds similitude.
Model roughness (67 microns) fairly difficult to achieve !
Kinetic energy pressure: $(\rho \times V^2/2)_m = 440$ kPa $\Rightarrow$ pressure in the pipe > 450 kPa (large pressure)
$(Q_m)_{max} = 2$ m^3/s $\Rightarrow$ very large discharge
3.2 The laboratory conditions cannot be achieved in the AEB Hydraulics laboratory at the University of Queensland. (During laboratory classes, ask the tutors and technical staff about the maximum flow rate and total head available in the laboratory.)
3.3 $(Q_p)_{max} = 1.5$ m^3/s $\Rightarrow$ 10% of the maximum flow rate only (totally inappropriate)

Part 4

Tests will be made on an undistorted model sea wall of 1/18 prototype size.

4.1 If the prototype wave climate is: wave period = 15 seconds, wave length = 20 m, wave amplitude = 2.1 m, what wave period, wave length and wave amplitude should be used in the model tests?

4.2 If the maximum force exerted by a wave on the model sea wall is 95 N, what corresponding force will be exerted on the prototype?

Note that the tests will be carried out in a hydraulic laboratory using tap water.

For seawater, the fluid density, dynamic viscosity and surface tension are respectively: ρ = 1,024 kg/m^3, μ = 1.22 E-3 Pa.s, σ = 0.076 N/m.

Solution

(4.1) Open channel flow $\Rightarrow$ Froude similitude

Note the differences in prototype versus laboratory fluid properties which must be taken into account.

Model wave period: 3.5 s, wave length: 1.1 m, wave amplitude: 0.12 m.

(4.2) F_p = 568 kN

Part 5

An artificial concrete channel model is to be built. Laboratory facilities limit the scale ratio to 45:1 and maximum model discharge is 55 L/s. The maximum full-scale discharge is 152 m^3/s, the cross-section of the channel is approximately rectangular (50-m bottom width) and the bed slope is 0.14 m per kilometre. (Note: The roughness height of the prototype is estimated as 5 mm while the smoothest model surface feasible has a Darcy friction factor of about f = 0.025.) Discharges ranging between the maximum flow rate and 20% of the maximum flow rate are to be reproduced in the model.

5.1 For an undistorted model: (a) what would be the model discharge at maximum full-scale discharge? (b) what would be the prototype flow depth at maximum full-scale discharge? (c) what would be the model flow depth at maximum full-scale discharge? (d) what would be the Darcy friction coefficient of the model flow? (e) what would be the Darcy coefficient of the prototype channel? (f) comment and discuss your findings. (*Assume normal flow conditions*)

5.2 A distorted model is to be built. Determine the acceptable maximum and minimum values of the vertical scale ratio Z_r. Select a suitable scale for practical use, and calculate the corresponding model values of the Darcy coefficient, maximum discharge and normal depth (at maximum discharge). (*Assume normal flow conditions*)

Solution

(5.1) Open channel flow $\Rightarrow$ Froude similitude & undistorted model

Uniform equilibrium flow: $(d_o)_p$ = 2.55 m & $(d_o)_m$ = 0.064 m. Note that the model flow depth was calculated using momentum considerations. Darcy friction factor: f_p = 0.017. Model: f_m = 0.025.

The normal depths do not satisfy $(d_o)_r$ = 45 because the Darcy friction factor is not the same in model and prototype. Hence we cannot achieve a true dynamic similarity.

(5.2) Froude similitude and distorted model

Calculations yield: $(Z_r)_1$ = 15.6, $(Z_r)_2$ = 31 (assuming f_m = 0.025), $(Z_r)_3$ = 24.4.

The vertical scale ratio must satisfy: $(Z_r)_1 < Z_r < \text{Min}[(Z_r)_2, (Z_r)_3]$.

$\Rightarrow Z_r$ = 18 (any value between 17 and 22 would be reasonable)

$(Q_m)_{max}$ = 0.044 m_3/s, $(d_o)_m$ = 0.121 m.

Part 6

A fixed bed model is to be made of a river with a surface width of 115 m. The river bed slope is 0.33%. The Gauckler-Manning coefficient for the river bed is estimated at 0.030 s/m$^{1/3}$. Scale ratios of X_r = 175 and Z_r = 35 have been selected.

6.1 Find the required model value(s) of the Gauckler-Manning coefficient corresponding to prototype depths of water of 2.0 and 5.0 m, if the cross-sectional shape is assumed to be rectangular.

6.2 What material would you recommend to use in the laboratory model for a prototype depth of 2.0 m?

6.3 Assuming normal flow conditions, calculate the flow depth in both model and prototype for Q_p = 160 m^3/s (assume a wide channel).

Solution

(6.1) Open channel flow $\Rightarrow$ Froude similitude & undistorted model

$(n_{Manning})_m = 0.037$ s/m$^{1/3}$
(6.2) $(n_{Manning})_p = 0.030$ s/m$^{1/3}$ corresponds to some gravel bed. $(n_{Manning})_p = 0.030$ s/m$^{1/3}$ is a very rough invert material for a model !!!
(6.3) $(d_o)_p = 0.84$ m, $(d_o)_m = 0.024$ m $\Rightarrow$ the model depth is small compared to the gravel height, is it not !? - In sediment transport, gravel is defined for grain sizes between 2 mm and 64 mm (textbook p. 156).