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Chapter 6 Hydraulic Modeling

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Chapter 6 Hydraulic Modeling

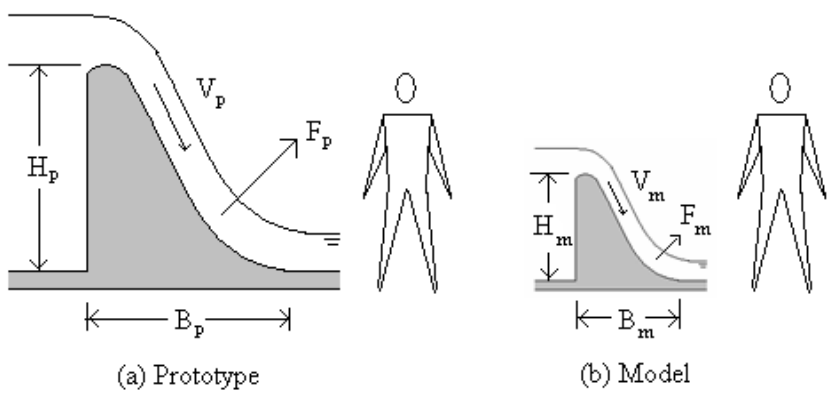
634.0600 Hydraulic Modeling

Hydraulic modeling is the practice of testing small-scale hydraulic systems (the model) in the laboratory and translating the favorable results to equivalent quantities of the full-scale system (the prototype). Hydraulic modeling should be performed if sound design and dependable operation of the prototype cannot be accomplished with other recognized methods of analyses. The practice of hydraulic modeling is based on ensuring similarity between model and prototype.

634.0601 Similarity between Models and Prototypes

A. The figure below illustrates the concept of prototypes and models. A prototype is the full-scale hydraulic system of interest and is represented by the spillway on the left-hand side. A model is a small-scale reproduction of the prototype, as illustrated on the right-hand side of figure 6-1.

Figure 6-1 : Prototype and model quantities.



B. The following figure shows the prototype and the model of a spillway flow.

Figure 6-2: Prototype and model of an ogee spillway (courtesy of the Utah Water Research Laboratory, Utah State University).

C. By building the model to resemble the shape of the prototype we ensure *geometric similarity*, as illustrated by the photographs of Figure 91. Referring to quantities in the model with the subscript *m* and those in the prototype with the subscript *p*, the ratio of corresponding lengths in model and prototype is referred to as the *length ratio*, L_r:

$$L_r = \frac{L_m}{L_p} \qquad \text{(eq. 6-1)}$$

D. Since area is calculated as the product of two lengths, the *area ratio* is defined as:

$$A_r = \frac{A_m}{A_p} = L_r^2 \qquad \text{(eq. 6-2)}$$

E. The *volume ratio* is, consequently, defined as:

$$(Vol)_r = \frac{(Vol)_m}{(Vol)_p} = L_r^3 \qquad \text{(eq. 6-3)}$$

F. Example 6-1 – Geometric similarity calculations

A spillway that is 24 ft high ($H_p = 24\ ft$) is to be built at a dam. To check the hydraulic characteristics of the spillway a model with a length ratio $L_r = 1/10$ is to be built in the laboratory. (a) What would be the height of the model, H_m? (b) If the flow cross-section in the model will have an area $A_m = 1.2\ ft^2$, what would be the equivalent area in the prototype? (c) If the volume of water over the prototype is estimated to be $(Vol)_p = 480\ ft^3$, what is the estimated volume of water over the model, $(Vol)_m$?

(i) The model height is:

$$H_m = L_r H_p = (1/10) \times 24\ ft = 2.4\ ft$$

(ii) The prototype area is:

$$A_p = A_m/A_r = A_m/L_r^2 = 1.2\ ft^2/(1/10)^2 = 120\ ft^2$$

(iii) The model volume is:

$$(Vol)_m = (Vol)_r (Vol)_p = L_r^3 (Vol)_p = (1/10)^3 \times 480\ ft^3 = 0.48\ ft^3$$

634.0602 Similarity between Models and Prototypes

A. Enclosed flow models generally require that the Reynolds number, *Re*, of the model equals the *Re* of the prototype i.e. the *Re* ratio equals 1.

B. Using Reynolds number similarity, the velocity, time, and discharge ratios are:

$$V_r = \frac{V_r}{L_r} \qquad \text{(eq. 6-4)}$$

$$T_r = \frac{L_r}{V_r} = \frac{L_r^2}{V_r} \qquad \text{(eq. 6-5)}$$

$$Q_r = A_r V_r = L_r^2 \left(\frac{V_r}{L_r}\right) = L_r \nu_r \qquad \text{(eq. 6-6)}$$

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C. Where the kinematic viscosity ratio, ν_r, is the model kinematic viscosity divided by the prototype kinematic viscosity.

Example 6-2 – Control valve model calculation (pressurized flow)

(i) A model of a control valve for a water pipeline is to be tested in the laboratory. The prototype valve has a diameter $D_p = 4.0\ ft$, while the model will have a diameter $D_m = 0.5\ ft$. If the model is tested using air, determine the velocity, time, and discharge ratios. The kinematic viscosities to use are:

$$\nu_m = \nu_{air} = 1.58\times10^{-4}\ ft^2/s,$$

$$\nu_p = \nu_{water} = 1.22\times10^{-5}\ ft^2/s.$$

(ii) The length ratio is:

$$L_r = D_m/D_p = 0.5\ ft/4.0\ ft = 1/8$$

(iii) While the kinematic viscosity ratio is:

$$\nu_r = \nu_m/\nu_p = 1.58\times10^{-4}\ ft^2/s/\ 1.22\times10^{-5}\ ft^2/s = 12.95$$

(iv) The velocity, time, and discharge ratios are:

$$V_r = \frac{V_r}{L_r} = \frac{12.950}{1/8} = 103.6$$

$$T_r = \frac{L_r^2}{V_r} = \frac{\left(1/8\right)^2}{12.95} = 1.2x10^{-3}$$

$$Q_r = L_r\nu_r = \left(\frac{1}{8}\right)12.95 = 1.62$$

634.0603 Hydraulic Modeling in Open-Channel Flow

A. Open-channel or free-surface models generally require that the Froude number, *Fr*, of the model equals the *Fr* of the prototype i.e. the *Fr* ratio equals 1.

B. Using Froude number similarity, the velocity, time, and discharge ratios are:

$$V_r = L_r^{1/2} \qquad \text{(eq. 6-7)}$$

$$T_r = \frac{L_r}{V_r} = \frac{L_r}{L_r^{1/2}} = L_r^{1/2} (= V_r) \qquad \text{(eq. 6-8)}$$

$$Q_r = A_r V_r = L_r^2 L_r^{1/2} = L_r^{5/2} \qquad \text{(eq. 6-9)}$$

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C. Example 6-3 – Stilling basin model calculation (free-surface flow)

A model of a stilling basin is built at a length ratio $L_r = 1/20$. Using Froude similarity, what are the velocity, time, and discharge ratios? If the length of the prototype basin is designed to be *40 ft*, what is the model dimension? If the discharge of prototype is *2000 cfs*, what is the flow required for the model?

(i) Using Froude number similarity, the velocity, time, and discharge ratios are:

$$V_r = T_r = L_r^{1/2} = \sqrt{\frac{1}{20}} = 0.2236$$

$$Q_r = A_r V_r = L_r^2 L_r^{1/2} = L_r^{5/2} = \left(\frac{1}{20}\right)^{5/2} = 0.000559$$

(ii) Given the prototype basin length $L_p = 40\ ft$, then the model basin length is:

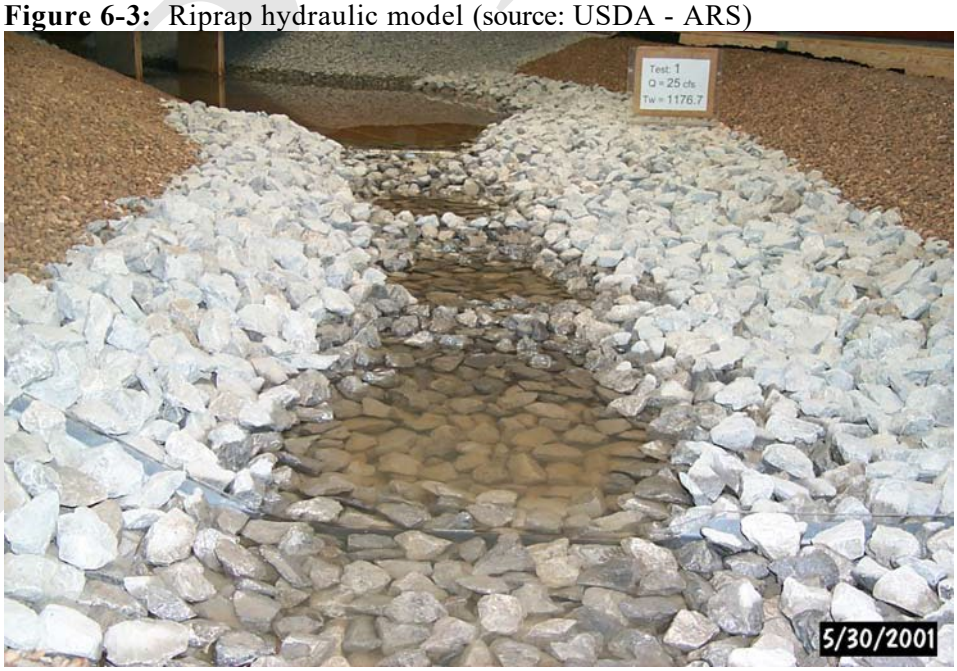
$$L_m = L_r\ L_p = (1/20) \times 40\ ft = 2\ ft$$

(iii) Finally, given the prototype discharge $Qp = 2000\ cfs$, then the model discharge is:

$$Q_m = Q_r\ Q_p = 0.000559 \times 2000\ cfs = 1.12\ cfs$$

D. An important issue in modeling open channel flow is producing the proper scaling of the surface roughness of channel lining. For example, bed roughness in streams and hydraulic structures may be provided by large, stable, rock lining known as riprap. Riprap model studies can be conducted to ensure geometric similarity. However, density differences between the riprap model material and water need to be considered if buoyancy effects are to be simulated. Figure 6-3 illustrates the use of smaller rock (of like density) to simulate the larger rock in a drop structure.

Figure 6-3: Riprap hydraulic model (source: USDA - ARS)



634.0604 Limitations of Models

The maximum size of hydraulic models is limited by laboratory physical installations (e.g., space, pumping capacity) and the minimum size of models is limited by the similarity laws. For example, if the model size in an open channel model that follows Froude similarity is too small, viscous effects may become significant. Viscosity may produce undesirable effects in such a model that are not properly scalable to the prototype. Also, if the resulting open-channel model is too shallow, surface tension effects (such as capillarity waves) may appear that would not otherwise be relevant to the prototype performance. In the case of distorted open-channel models (such as for wide, shallow streams), if the vertical model size is much larger than the horizontal size, the resulting flow may include secondary velocity components much larger than the prototype flow. The resulting flow field then would be too distorted to be scaled up to the prototype size. For a detailed discussion on model limitations and similarity laws please refer to Kobus (1980).

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