Reasons to Build a Hydraulic Model

• Determine discharge coefficient for large flow measurement structure (spillway or weir)
• Develop effective method for energy dissipation at outlet of hydraulic structure
• Development of economic & efficient hydraulic structure (spillway)
Purpose for River Models

• Pattern of flood wave through river
• Effect of artificial structures on sedimentation and hydraulic effects upstream and downstream
Model vs. Prototype

Hydraulic Model

• Use principles of **similitude** to correlate model and prototype behavior

• Principle on which hydraulic model studies are based comprises the theory of **hydraulic similitude**

• Desired that the physical behavior of **model** simulate that of the **prototype**

• **Dimensional analysis** – basic relationship of the physical quantities involved in the dynamic behaviors of water flow in a hydraulic structure
Principles of Similitude

• Physical behavior of the model should simulate in a known manner the behavior of the prototype
  – Can use data from the model can be used to predict response of the prototype
• Principles of similitude correlate model to prototype behavior
• **Three** basic types of similitude
  1. Geometric similarity
  2. Kinematic similarity
  3. Dynamic similarity

• Forces dominate hydraulics for models require **Dynamic Similarity**
Principles of Similitude

• **Geometric Similarity** – all homologous dimensions on model and prototype are equal

• **Kinematic Similarity** – all homologous velocities and accelerations are equal between model and prototype

• **Dynamic Similarity** – all homologous forces the same between model and prototype
Geometric Similarity

- Implies similarity of form
- Fixed ratio (scale) for all lengths in the prototype and model
- Quantities of geometric similarity are:
  - Length ($L$)
  - Area ($L^2$)
  - Volume ($L^3$)

Scale Ratio = $L_p / L_m = L_R$
Geometric Similarity

Area

\[ \frac{A_P}{A_M} = \frac{L_P^2}{L_M^2} = L_r^2 \]

Volume

\[ \frac{Vol_P^3}{Vol_M^3} = \frac{L_P^3}{L_M^3} = L_r^3 \]
Kinematic Similarity

- Implies similarity of **motion**
- Involves **time** scale and **length**
- Time ratio \( (T_r) \) for homologous particles to travel homologous distance in model and prototype

\[
\frac{T_m}{T_P} = T_r
\]

- **Time**

\[
\frac{V_P}{V_M} = \frac{L_P}{L_M} = \frac{T_P}{T_M} = \frac{L_r}{T_r}
\]

- **Velocity**
Kinematic Similarity

\[
\frac{a_P}{a_M} = \frac{\frac{L_P}{T_P^2}}{\frac{L_M}{T_M^2}} = \frac{L_r}{T_r^2}
\]

\[
\frac{Q_P}{Q_M} = \frac{\frac{L_P^3}{T_P}}{\frac{L_M^3}{T_M}} = \frac{L_r^3}{T_r}
\]
Dynamic Similarity

- Implies similarity of forces in motion
- **Force ratio** \( F_r \) for homologous forces in model and prototype is constant

\[
F_r = \frac{F_p}{F_M}
\]

- **Dynamic Similarity** requires and implies kinematic similarity and geometric similarity
- Must evaluate forces of (1) inertia, (2) pressure, (3) gravity, (4) viscosity, (5) surface tension, (6) elasticity
Dynamic Similarity

- **Force** is mass time acceleration and mass is density time volume:

\[
F_r = \frac{M_p a_p}{M_M a_M} = \frac{\rho_p V_{p} a_p}{\rho_M V_{M} a_M} = \rho_r L_r^4 T_r^{-2}
\]

- **Work**

\[
\frac{W_P}{W_M} = \frac{F_P L_P}{F_M L_M} = F_r L_r
\]
Dynamic Similarity

- True dynamic similitude requires that all five types of forces be the same between the model and prototype.

\[
F_r = \frac{(F_I)_P}{(F_I)_M} = \frac{(F_P)_P}{(F_P)_M} = \frac{(F_G)_P}{(F_G)_M} = \frac{(F_V)_P}{(F_V)_M} = \frac{(F_T)_P}{(F_T)_M} = \frac{(F_E)_P}{(F_E)_M}
\]

- Hydraulic models are not capable of simulating all the forces simultaneously.
- In practice model designed to study the effect of only a few dominant forces.
- Flow in most hydraulic structures for example determined by the effect of gravity.
Hydraulic Phenomenon Governed by Gravity – Froude Law

- When inertia and gravity are considered to be the only dominant forces of fluid motion then the Froude Number of the prototype and model must be the same.

\[ N_F = \frac{V}{\sqrt{gL}} = \frac{\text{inertia}_{force}}{\text{gravity}_{force}} \]

- Also is velocity divided by celerity of gravity wave
- Applicable to model studies of most hydraulic structures including weirs, spillways, gates, chutes, stilling basins, locks, transitions, and others
Froude Law Ratios

• Froude Number ratio

\[
(N_F)_r = \frac{V_r^2}{g_r L_r}
\]

• Usually \( g_r = 1 \) if both subject to same gravitational field and same fluid is used so that

\[
V_r = \sqrt{L_r}
\]
Froude Law Ratios

- Discharge: \( Q_r = A_r V_r = L_r^{5/2} \)
- Pressure: \( P_r = \gamma_r L_r = L_r \) if same fluids
- Force: \( F_r = \gamma_r (\text{Volume})_r = L_r^3 \)
- Energy: \( E_r = F_r L_r = L_r^4 \)
- Power: \( P_r = E_r T_r = L_r^{5/2} \)
- Momentum: \( M_r = m_r V_r = \rho_r (\text{Volume})_r L_r^{1/2} = L_r^{7/2} \)
- Time: \( T_r = L_r / V_r = L_r^{1/2} \)
Hydraulic Phenomenon Governed by Viscosity – Reynolds Number Law

• Fully enclosed flow (ie. pipe) gravity and surface tension have no effect
• Viscosity alone will control velocity and pressure from friction with inelastic flow
• Reynolds Number \( (N_R) \) must be equal in model and prototype

\[
N_R = \frac{\text{inertia}}{\text{viscous}} = \frac{\rho LV}{\mu}
\]
Hydraulic Phenomenon Governed by Viscosity  
– Reynolds Number Law

• Important application of Reynolds Law is study of **drag forces** on immersed objects (ie. ships)

• Difficulties are encountered with Reynolds Law model studies if the number is **high**
  – Velocity ratio is inversely proportional to the length ratio, model **velocities have to be high**
  – Requires a wind tunnel with air as fluid
Reynolds Law Ratios

- **Velocity**
  \[ V_r = \frac{v_r}{L_r} = \frac{1}{L_r} \] if same fluids

- **Discharge**
  \[ Q_r = A_r \cdot V_r = L_r^2 \cdot \frac{v_r}{L_r} = v_r \cdot L_r = L_r \]

- **Pressure**
  \[ P_r = \frac{1}{L_r^2} \] if same fluids

- **Force**
  \[ F_r = 1.0 \]

- **Energy**
  \[ E_r = F_r \cdot L_r = L_r \]

- **Power**
  \[ P_r = E_r \cdot T_r = \frac{1}{L_r} \]

- **Momentum**
  \[ M_r = m_r \cdot V_r = \rho_r \cdot (Volume) \cdot \frac{v_r}{L_r} = \mu_r \cdot L_r^2 \]

- **Time**
  \[ T_r = \frac{L_r}{V_r} = \frac{v_r \cdot L_r^2}{L_r} = L_r^2 \]
Model Studies With Both Gravity and Viscous Forces

• Example of this case
  – Open Channel on mild slopes
  – Surface vessels moving through water
  – Shallow water waves in open channels

• Both Froude number and Reynolds number

\[ N_F = N_R \]

\[ \frac{\rho_r L_r V_r}{\mu_r} = \frac{V_r}{\left( g_r L_r \right)^{1/2}} \]
Model Studies With Both Gravity and Viscous Forces

- Simplifies to
  \[ \nu_r = L_r^{3/2} \]

- Almost impossible to meet requirement since special model fluid with kinematic viscosity ratio
  - For example a 1:10 scale model requires model fluid with **kinematic viscosity 30 times less than water**

- Solution for ship resistance, the model is based on Reynolds law and operates in towing tank by Froude Law
Open Channel Models

Fixed Bed

• **Fixed Bed Study** is distinguished from **Moveable Bed Study**

• Channel models are concerned with velocity and slope patterns so effect of **bed roughness** is very important

• Empirical hydraulic relation **Manning equation** used for similarity between model and prototype

\[
V_r = \frac{V_p}{V_m} = \frac{R_r^{2/3} S_r^{1/2}}{n_r} = \frac{R_r^{2/3} (y_r / L_r)^{1/2}}{n_r}
\]
Open Channel Models

Fixed Bed

• For the condition of an **undistorted model** then \( S_r = 1 \) and \( R_r = L_r \) so:

\[
V_r = \frac{L_r^{2/3}}{n_r}
\]

• Since \( V_r = L_r^{1/2} \) then \( n_r = L_r^{1/6} \)

• However, model velocity will be so **small** (or model roughness large) as to make accurate measurement difficult

• **Solution** is to use a **distorted model**
Open Channel Models

Distorted Model

- Distorted model where the vertical scale and horizontal scale ratios do not have same value
- Choose smaller vertical scale ratio or $X_r > Y_r$
- Means model Slope greater than prototype
- Case 1 – Roughness values known for model and prototype then the distortion calculated from:

$$S_r = \frac{y_r}{L_r} = \frac{n_r^2 y_r}{R_r^{4/3}}$$
Open Channel Models
Distorted Model

**Case 2** — Distortion ratio is fixed based on space considerations then model roughness calculated from:

\[ n_r = \frac{S_r^{1/2} R_r^{4/3}}{L_r^{1/2}} = \frac{R_r^{2/3}}{L_r^{1/2}} \]

- Means model roughness must be adjusted by trial and error until required flowrate obtained

\[ Q_r = A_r V_r = L_r y_r V_r = L_r \sqrt{V_r V_r} = V_r^{3/2} \]
Model Design - General

- Model required when established design procedures and available technical information fails to provide solution to hydraulic problems
- Hydraulic problems should be thoroughly examined
- Define the accuracy of results from model
- First and most important step is to select scale
- For maximum similarity model should be large as possible
- Large model improves accuracy of measurements and results
  - Difficulty in operation and costs
Open Channel Model Scale Selection

- Channel model scales typically range from 1:15 to 1:70
- Scale depends on the following
  - Type of problem
  - Relative roughness between model and prototype
  - Size of prototype
- Scale ratios of 1:15 to 1:30 for supercritical wave patterns and outlet works having gates or valves
- Same scale used for “sectional models” of drop structures, spillways
Open Channel Model Scale Selection

- Canal structures, such as chutes and drops have scales ratios **1:3 to 1:20**
- Smaller ratios **1:30 to 1:70** are used for general model studies of “long channels”
- River model scale ratios **1:100 to 1:1000**
- Vertical scale for **distorted** river models ratios **1:20 to 1:100**
Open Channel Model Scale Selection

- Flow measurements may control scale selection
- Most models of channel are generally built to give depths of flow about 0.5 feet
- Channel widths of 1 to 2 feet
- Common scales used by the Los Angeles ACOE District Hydraulic Laboratory are **1:25 to 1:40**
EAST GARDEN GROVE – WINTERSBURG CHANNEL

Physical Model Study at I-405
Model Study Centered on I-405 Culvert System

Physical Model Study
Reach = 1000 ft
100-yr Q = 5330 cfs Upstream of Confluences
100-yr Q = 5910 cfs Downstream of Confluences
Limitations of Computer Modeling

- Unequal lengths, slopes & geometries of the C05 culverts
- Assumption of uniform flow distribution across channel section
Limitations of Computer Modeling

- Confluence Angles of C05 culverts and tributary channels
- Secondary currents, turbulence, and vortex action resulting from non-uniform flow patterns
Physical Model Objectives

1. Evaluate Channel Performance at Design Discharge
   – Establish 100-yr water surface profiles for C05 & C05S01

2. Determine Maximum Channel Capacity
   – Test different flow combinations in main channel and tributaries

3. Improve Channel Capacity
   – Test various modifications to reduce energy loss
Physical Model Design

- 3D CAD Model channel designed using as-buils and proposed improvement drawings for Newland & Edinger facilities
15:1 Scale Selection Driven by Project Budget

• Measurement accuracy (allowable error)
  – small scaled error can become large prototype error

• Channel roughness (material selection)
  – Scaled manning's roughness value for concrete = 0.0089

• Available Warehouse Space
Hydraulic Properties of 15:1 Scale Model

- Model hydraulics influenced by inertial and gravitational forces
- Scale to prototype relationships, hydraulic similitude, based on Froude Number Law

<table>
<thead>
<tr>
<th>Parameter / Variable</th>
<th>Froude Relationship</th>
<th>Prototype</th>
<th>Model (L_r = 1:15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>L_r</td>
<td>60 ft</td>
<td>4 ft</td>
</tr>
<tr>
<td>Length</td>
<td>L_r</td>
<td>800 ft</td>
<td>53 ft</td>
</tr>
<tr>
<td>Height/Depth</td>
<td>L_r</td>
<td>13 ft</td>
<td>0.87 ft</td>
</tr>
<tr>
<td>Slope</td>
<td>1</td>
<td>S_D/S = 0.00117 to S_U/S = 0.00039</td>
<td>same</td>
</tr>
<tr>
<td>Velocity</td>
<td>L_r^{1/2}</td>
<td>12.4 fps</td>
<td>3.2 fps</td>
</tr>
<tr>
<td>Time (hydrograph)</td>
<td>L_r^{1/2}</td>
<td>6 hrs</td>
<td>93 mins</td>
</tr>
<tr>
<td>Flowrate</td>
<td>L_r^{5/2}</td>
<td>5,910 cfs</td>
<td>6.78 cfs (3,037 gpm)</td>
</tr>
<tr>
<td>Water Surface Difference</td>
<td>L_r</td>
<td>4.0 ft</td>
<td>0.27 ft</td>
</tr>
<tr>
<td>Froude Number</td>
<td>1</td>
<td>0.77</td>
<td>0.77</td>
</tr>
</tbody>
</table>
Hydraulic Model Structure

- Model Channel elevated on adjustable platform
- Storage reservoir below provides conveyance and submergence over pump intakes
- Head tank dissipates flow energy before entering channel
Pump System designed for Max Efficiency and Flexibility

Horizontal Pump Dimensions:
15 Horsepower, 3 Phase
1200 gpm at 15’ of Head
Weight = 156 lbs
Height, A = 12.875”
Min Submergence, B = 30”
Discharge Diameter, D = 6” NPT
Pump Length, E = 24.625”
Pump Width, F = 16”
Model Fabrication

- Model channel consists of ¾” plywood reinforced with a 2x4 frame and 45° kickers.
- Platform structure made up of a ¾” plywood deck over 2x8’s @ 16” o.c.
- 4x8’s span between posts & screw jacks to support the platform.
Model Channel was Waterproofed using a lot of Silicone and a Multi-coat Waterproof Paint
Low Flow Channels Upstream and Downstream of I-405 Culverts were Formed with Concrete
Model Channel Fabricated to a Tolerance of 0.002 ft

- Screw Jacks placed along both sides of flume allow for vertical adjustment
- Final adjustments made with the help of a surveyor using a total station
Dual Function Storage Reservoir

- Provides required submergence depth for pumps to operate
- Convey flow from tail box to pumps
- Captures leakage from model channel
- Waterproofed using seam welded PVC liner
Head Tanks Designed to Hold 8 ft of Water

- Structural 2x lumber used to form ribs
- Lined with 1” plywood and coated with waterproof paint
- Hanging baffles dissipate flow energy from pumps
Scaled Culvert Geometry Presents a Unique Challenge

- Scaled dimensions of elliptical culvert are 5.13” x 8.07”
- Fabricated using CNC technology to create foam molds
- Fiberglass formed around molds to correct dimensions
CNC Technology allowed for fabrication of unique culvert geometry

Complex transitions from rectangular to elliptical in a curved alignment occur at entrance and exit of each C05 elliptical culvert
Pump & Piping System Includes Multiple Valves for Fine Tuning Flow Rate
Adjustable (Tail) Gate Provides Downstream Boundary Control
Model vs Prototype Comparison
Upstream of I-405
Model vs Prototype Comparison
Downstream of I-405
Model vs Prototype Comparison
Newland Channel
Model Calibration – Surface Roughness

• Initial tests will be conducted to verify channel roughness values
• Point gages will be used to measure flow depth to the nearest 0.1 mm (0.0003’)

![Diagram of flow depth measurement](image)
Model Calibration – Flow Meter Readings

- Sharp crested weirs will be used to calibrate the Ultrasonic flow meter readings
- V-notch weir will be used for flows up to 1,000 gpm
- Rectangular weir used for flows up to 3,000 gpm
Experiments will be Classified According to Fixed Parameters

1. Downstream water surface elevation
   – estimated by WSPG model of entire C05 channel
2. Constant Flow Rate into main channel (C05) and tributary channels (C05S01 and C05S05)

Flow Combinations to be Tested:

<table>
<thead>
<tr>
<th>100-yr EV Return Interval</th>
<th>Prototype Discharges (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EGGWC Upstream C05</td>
</tr>
<tr>
<td>Case 1</td>
<td>5330</td>
</tr>
<tr>
<td>Case 2</td>
<td>4450</td>
</tr>
</tbody>
</table>

Model Discharges in gpm and (cfs)

| Case 1 | 2745.2 (6.12) | 125.7 (0.28) | 73.1 (0.16) | 99.9 (0.22) | 3044 (6.78) |
| Case 2 | 2292.0 (5.11) | 352.3 (0.78) | 204.0 (0.45) | 195.7 (0.44) | 3044 (6.78) |
Additional Tests will Evaluate Options for Improving Channel Performance

Adjustments to size and angle of Newland Channel confluence

Splitter walls, pier noses or other ways to reduce energy loss