3 Physical Model Description

Similitude

Similarity of resistance, flow patterns, and water surface changes in navigation models is best achieved when the ratio of inertia to gravitational forces is the same in model and prototype. This ratio, the Froude number *F*, is defined as

$$F = \frac{V}{\sqrt{gD}} \tag{1}$$

where *V* is generally the vessel speed, *g* is the gravitational constant, and *D* is a characteristic length such as depth, draft, or vessel length. The equations of hydraulic similitude, based on the Froude criteria, expressed mathematical relations between the dimensions of hydraulic model and prototype quantities. General relations for transferring 1:30 scale model data to prototype equivalents are as follows:

Characteristic	Dimension[1]	Scale Relations Model: Prototype
Length	$L_r=L_p/L_m$	1:30
Area	$A_r=L_r^2$	1:900
Velocity	$V_r=L_r^{1/2}$	1:5.48
Time	$T_r=L_r^{1/2}$	1:5.48
Discharge	$Q_r=L_r^{5/2}$	1:4929.5
Roughness coefficient	$N_r=L_r^{1/6}$	1:1.76
Force	$F_r=L_r^3$	1:27000
Revolutions	$R_r=1/L_r^{1/2}$	5.48:1

[1] Dimensions are in terms of length.

Viscous forces cannot be neglected in physical navigation models. If interest is in the forces on a vessel, the relatively higher viscous forces in the physical model cause greater frictional resistance on the model vessel. If the interest is in the forces the vessel imposes on the waterway (such as this study), the relatively higher viscous forces in the model cause the model vessel to be effectively larger than the prototype vessel. The following section on model calibration will show how this model dissimilarity is overcome.

Model Flume and Appurtenances

The navigation effects flume (Figures 6-8) is 125 m long, 21.3 m wide, and has a maximum 1.22-m depth. The last 1.52 m on both ends has a 2.13-m depth. Ten pumps, each having an approximate discharge capacity of 0.16 cu m/sec, recirculate flow through the flume. A sharp-crested overflow weir at the upstream end of the flume evenly distributes the flow across the flume.

The center 61 m of the flume was used for the 1:30-scale Clark's Ferry experimental reach. Marine plywood sections were installed to form the composite cross section representing 1.8 km of river conditions near mile 468.2 on the Mississippi River. The upstream end of the plywood section had curved entrance walls for a smooth transition into the experimental section. The data collected by the Mississippi River Hydrographic Survey in 1945 and in 1994 and data collected by the Illinois State Water Survey on 5/13/91 - 5/24/91 and 10/15/91 - 10/20/91 determined the composite cross section. This composite section was heavily weighted toward the ISWS data. The 1994 hydrographic survey was dike center-line elevations and some data on either side of the center line. One obvious difference between model and prototype was that the model was straight with a constant cross section whereas the prototype is rarely straight and has a variable cross section. The coordinates of the section used in the physical model are shown as follows:

Distance from Thalweg, m	Design Elevation, NGVD	As-built at Sta 63 NVGD
-370.4 (top of left bank)	572.7	572.7
-370.4	538.0	548.0
-329.0	537.5	538.5
-256.1	537.4	538.2
-182.9	536.7	536.9
-73.2	530.7	531.1
0.0 (Thalweg)	528.8	528.8
109.8	530.0	531.0

Distance from Thalweg, m	Design Elevation, NGVD	As-built at Sta 63 NVGD
182.9	533.7	534.3
248.5	540.1	540.5
259.1	554.5	554.5
259.1 (top of right bank)	572.7	572.7

The same cross section was used along the full length of the 61-m-long plywood section. The left bank dikes shown in Figures 6 and 7 were about 340 m long, extended from the thalweg elevation of 528.8 up to el 538.0 at 85.3 m from the thalweg. From there the dikes extended over to el 539.0 at the left bank. The dikes were angled with the channel center line at 78 deg and the side slopes were 1V:3H.

The towboat (Figure 9) is modeled after the Corps' Motor Vessel Benyaurd and is 52 m long by 12.3 m wide by 2.74 m draft. The model towboat is equipped with two main and four flanking rudders, open-wheel, 2.74-m-diam propellers, and can be radio-controlled for self-propelled operation. The 1:30 scale plexiglass barges simulated 59.5 m long by 32 m wide by variable draft. Sets of barges were connected by C-clamps to form the desired tow configuration. All barges had boxed ends except for the lead barge, which had a raked end. Experiments were conducted with either a 45- or a 26-deg rake angle on the lead barge.

A towing carriage maintained consistent speed and alignment for the model tow and operated on steel rails set to grade that extended the length of the flume. The connection between the tow and the towing carriage was designed to allow complete freedom of vertical movement, push the tow at one point near the center of gravity, and maintain the desired tow alignment (Figure 10).

This study focuses on the far field effects of the tow. A previous study by Maynord (1990) conducted with and without propeller operation suggests the propeller has little impact on far field return velocity and drawdown adjacent to the vessel in these channel sizes. Analysis of the flow amount passing through the propellers shows that about 1 percent of the waterway is passing through the propellers, which suggests limited impact on far field effects. The Kampsville study (Maynord and Martin 1997) began with a series of experiments to further evaluate the effects of propeller flows on far field velocity and drawdown. Results of the physical model experiments suggested little impact but were not conclusive enough to conduct those experiments without propeller operation. Propeller operation was used in the Clark's Ferry experiments as well. Propeller speed had to be estimated, since prototype data collected by ISWS did not include the applied power or rpm. The model towboat was calibrated for bollard push (push when speed = 0) against propeller speed and applied voltage on a DC power supply. An equation developed by Toutant (1982) was used to define the bollard push (*BP*) for an open-wheel propeller as

$$BP_o = 23.57\,(Hp)^{\,0.974} \tag{2}$$

or for a kort nozzle as

$$BP_k = 31.82\,(Hp)^{\,0.974} \tag{3}$$

where

BP = bollard push, pounds

hp = total horsepower

Knowing towboat horsepower from the ISWS data, the BP was computed using the Toutant equations. This BP provided an upper limit for a given horsepower towboat. The power setting, with some adjustment for tow speed, used 75 percent of the upper limit in most experiments.

Physical Model Instrumentation

The instrumentation was positioned laterally across the channel at approximately the midpoint of the plywood experimental section at station 63 (63 m from downstream end of concrete flume, Figure 6). A wave gauge and two-dimensional (2-D) and three-dimensional (3-D) acoustic Doppler velocimeters (ADV's) are shown in Figure 11.

Wave heights were measured by using two wave gauges placed in the near-shore zone on both channel sides. The wave gauges were capacitance type gauges manufactured at the U.S. Army Engineer Waterways Experiment Station and sampled at 25 Hz.

Velocity measurements were taken using eight ADV's (Kraus, Lohrmann, and Cabrera 1994). Four probes were 3-D downward-looking probes and four were 2-D side-looking probes that measured velocity in the horizontal plane. One and sometimes two of the 3-D probes were upward-looking probes and the remainder were downward-looking probes. The ADV's took data approximately 5 cm from the transmit and receive transducers. The side-looking 2-D probes were needed for shallow-water velocities since the 3-D probes would not work in shallow water due to the 5-cm offset. The ADV's use acoustic sensing techniques to measure flow in a remote sampling volume. No cables were in the water and the measured flow is relatively undisturbed by the presence of the probe. Data were available at an output rate of up to 25 Hz. The horizontal velocity range is ±2.5 m/sec and there is no zero-offset in the velocity output. Data can be collected as close as 5 mm from a solid boundary. The ADV's require that a certain size of particles be present in the water to measure the water velocity. Hollow glass spheres having a mean diameter of 10 microns and specific gravity slightly greater than one were used as the seed material in the model. Under low or no ambient velocity conditions, a problem occurs with settlement of the seed between experiments. Generally, ambient velocities were high enough to keep seed in suspension. Positive *x* velocities were downstream and positive *y* velocities were toward the left bank.

Observations of ambient conditions in the physical model were found to have significant variations similar to the prototype. These variations were attributed to pump variations, eddies in the approach and exit to the plywood experimental section, and long-period oscillations in the basin set up by vessel movement. To overcome these variations, the physical model data were filtered like the prototype data. After scaling the physical model data to its prototype equivalent, an FFT filtered out all data with a frequency greater than 0.02 Hz.