3 Physical Model Description

Similitude

Similarity of form 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 = generally the vessel speed

g = gravitational constant

D = characteristic length such as depth, draft, or vessel length

The equations of hydraulic similitude, based on the Froude criteria, express the mathematical relations between the dimensions of hydraulic model and prototype quantities. General relations for transferring 1:25 scale model data to prototype equivalents are as follows:

Characteristic	Dimension[1]	Scale Relations Model: Prototype
Length	$L_r = L_p/L_m$	1:25
Area	$A_r = L_r^2$	1:625
Velocity	$V_r = L_r^{1/2}$	1:5
Time	$T_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3,125
Roughness Coefficient	$N_r = L_r^{1/6}$	1:1.71
Force	$F_r = L_r^3$	1:15,625
Revolutions or frequency	$R_r = 1/L_r^{1/2}$	5:1

[1]Dimensions are in terms of length.

However, viscous forces cannot be neglected in physical navigation models. If interest is in the forces on a vessel (for example, towing tank studies), 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 due to the larger boundary layer effects. The following section on model calibration will show how this model dissimilarity is overcome.

Model Flume and Appurtenances

The navigation effects flume (Figures 13 and 14) 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 1:25-scale Kampsville experiment site. Marine plywood sections were installed to form a composite cross section representing conditions at mile 35.2 on the Illinois River. The upstream end of the plywood section had curved entrance walls for a smooth transition into the experiment section. The data collected by the Illinois River Hydrographic Survey on 6/22/88 and the data collected by ISWS on 10/15/90 and 8/8/91 determined the composite cross section. This composite section was heavily weighted toward the ISWS data. The coordinates of the physical model section are as follows:

Distance from Thalweg , m	Elevation[1]
-213.0 (top of left bank)	428.0
-152.5	409.0
-61.0	406.5
0.0 (Thalweg)	406.5
61.0	406.5
100.6	410.0
155.5 (top of right bank)	428.0

[1] All elevations (el) cited in this report are in feet referred to the National Geodetic Vertical Datum (NGVD). To convert to meters, multiply by 0.3048.

This cross section was used along the full length of the 61-m-long plywood section.

The 1:25-scale towboat (Figure 15) was modeled after the Corps' Motor Vessel (MV) *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 diameter propellers, and can be radio controlled for self-propelled operation. The 1:25-scale sheet metal barges simulated 59.5-m-long by 10.7-m-wide barges with variable draft. Individual barges were connected by C-clamps to form the desired tow configuration. All barges had boxed ends except the lead barge the bow of which had a raked end. All experiments (except a limited series of experiments to evaluate the effects of the rake angle) were run with an 0.8-rad (45-deg) rake 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 16).

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 flows in these channel sizes. Analysis of the flow amount passing through the propellers shows that about 2 percent of the waterway is passing through the propellers, which suggests limited impact on far field effects. The present study 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 experiments without propeller operation. So, the speed to operate the propellers was a problem since prototype data collected by ISWS did not include the power or revolutions per minute (RPM) in the prototype experiments. The method used in the study described in this report first calibrated the model towboat bollard push (push when speed = 0) against propeller speed and applied voltage on a d-c power supply. Next an equation was applied that was developed by Toutant (1982) defining the bollard push 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 is the bollard push in pounds and Hp is the total towboat 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. This approximate method is appropriate for far field experiments but will not be used in subsequent physical forces studies that address the near field area beneath and immediately adjacent to the tow.

Instrumentation

Wave heights were measured with two wave gauges in the nearshore zone on both channel sides. The wave gauges were capacitance type gauges manufactured at the U.S. Army Engineer Waterways Experiment Station.

Velocity measurements were taken using eight acoustic Doppler velocimeters (ADV's) (Kraus, Lohrmann, and Cabrera 1994). Six probes were three-dimensional (3-D) and two were two-dimensional (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 enter in the water, and the measured flow is relatively undisturbed by the presence of the probe. Data are available at an output rate up to 25 Hz. The horizontal velocity range is ±2.5 m/sec and no zero-offset in the velocity output. Data can be collected as close as 5 mm from a solid boundary. The ADV's require certain size particles 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. Using low or no ambient velocity causes a problem since the seed will settle to the bottom while waiting for the model to stop moving as a result of distributing the seed. However, this was not a major problem because ambient velocities were high enough to keep the seed in suspension. Positive x-velocities were downstream and positive y-velocities were toward the left bank.

The ADV's and the wave gauges were positioned at approximately the midpoint of the plywood experiment section at station 62 (62 m from downstream end of concrete flume). A wave gauge and 2-D and 3-D ADV's are shown in Figure 17.

When the physical model was selected for studying navigation effects on the UMRS, the ambient conditions in the physical model were envisioned as free from the significant variations observed in the prototype data. This was not the case since the model had significant variations in ambient conditions. These variations were attributed to pump variations, eddies in the approach and exit to the plywood experiment 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 frequency greater than 0.02 Hz.