MEASUREMENT OF SCOUR-DEPTH NEAR BRIDGE PIERS

By John V. Skinner

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ILLUSTRATIONS

CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for terms used in this report are listed below.

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	.3048	meter per second (m/s)
square foot (ft^2)	.09294	square meter (m^2)
horsepower (hp) (550 ft·lbf/s)	745.7	watt (W)
knot	.514	meter per second (m/s)
pound, avoirdupois (lb)	453.6	gram (g)
pound-foot (lbf·ft)	1.356	joule (J)
ton, long	1.016	megagram (Mg)

SYMBOLS AND ABBREVIATION

vac- - - - - - - - - - -volts of alternating current or volts root-mean-square

Hz - - - - - - - - - - -hertz

MHz- - - - - - - - - - -megahertz

MEASUREMENT OF SCOUR-DEPTH

NEAR BRIDGE PIERS

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ABSTRACT

River-bed scour is a major source of damage to bridge piers and bridge abutments. When scour depth exceeds design limits, the supporting material around the footings is washed away and the structure becomes unstable. Equations for predicting scour-depth show a significant lack of agreement so portable equipment for measuring scour is needed.

This report discusses the design of an instrumented, unmanned boat that (a) can be launched and controlled from a bridge and (b) can be maneuvered in flood flows that reach velocities of 15 feet per second. Calculations indicate the battery-powered propulsive system alone will weigh about 300 pounds and that the craft must be about 15-feet long.

Because a free-running craft will be undesirably heavy and large, other methods of obtaining scour data are proposed. A tethered craft fitted with a controllable rudder and some methods of measuring scour at a point are presented for future study and development.

INTRODUCTION

Nature of the Problem

River-bed erosion is a major source of damage to bridge piers and abutments. During a flood, water velocities may reach levels high enough to lift bed-material particles and sweep them downstream. At the base of the piers, deep scour-holes may develop because the concrete structure restricts the area through which the flood water must pass. If the depth of a scour hole exceeds design limits, the pier may settle or collapse.

Bridge designers have several equations for estimating depth of scour; unfortunately, the designers face some agonizing decisions because the equations yield different results. Davis (1984) summarizes the engineer's dilemma. "Scour is an elusive subject because of its complexity. Formulas and mathematical models are still based primarily on theoretical approaches and laboratory tests because of the lack of verifiable field data. Accurate field measurements have been difficult to obtain because of the severe three-dimensional flow patterns that occur at bridges during flooding, and the problems and costs associated with recording instruments or with attempts to get skilled personnel at bridge sites during periods of peak flow." Jones (1984) computed results from 10 predictive equations and found a significant lack of agreement. His final recommendation emphasizes the need for field data. "There is still a need to document field data for both pier scour and abutment scour. Field data should be collected during floods and should as a minimum include a full cross section at several flood stages."

Review of Field-Measurement Techniques

Mapping scour holes is a challenging task in instrumentation. Because sediment transport is a dynamic process, the stream bed may degrade and then aggrade before a flood passes. Degradation usually occurs during the period of rising flood flow: aggradation usually occurs during the recession. Dangerously deep scour holes may develop and then be completely filled by the time the flow recedes to normal levels. All or much of the mapping process must be performed during the crest of a flood when the scour holes are deepest. At this time, the water carries a heavy load of trash that complicates the process of making field measurements. Instruments attached to the bridge piers may be broken or torn free by the impact of trees and other debris.

Several types of scour-measuring instruments were proposed by the staff of Science Applications, Inc. (Anonymous, 1976) and a few of these instruments have been tested. For example, a pulsed-laser beam was studied as a means of making depth measurements; unfortunately, the field measurements showed that the beam was almost entirely absorbed by clay-size particles suspended in river water. In contrast with high-technology instruments, simple equipment such as sounding-weights have been used with limited success. Unfortunately, the weights can be used to map only a very small area below the bridge railings. The suspension cables may break or they may have to be cut if the weight becomes entangled with heavy objects such as floating branches.

A special conductivity sensor was tested for the purpose of monitoring scour at a fixed point. The sensor, which was built by researchers in Arizona, consisted of several electrodes fitted one above the other along the side of a tube planted vertically in the streambed near a pier. Wires leading from the electrodes to the bridge deck were attached to an instrument that measured conductivity between pairs of electrodes. The sensing scheme was straightforward: compared to the conductivity of clear water, the conductivity of tightly packed sand is very low. The approach consisted of comparing conductivity readings and thereby determining the number of electrodes exposed to flowing water. Records show two field tests were conducted; however, it is difficult to assess the overall feasibility of the technique. Apparently, electrode corrosion and broken wires created many problems.

A technique involving heat-flow measurements was proposed by the Sedimentation Project and is discussed later in this report. The instrument, which has not been fully developed, involves a group of electrical heaters and temperature sensors mounted in a tall, slender cylinder which can be driven into the streambed. The heaters are actuated for a short time, then the temperatures at several points along the cylinder are monitored. Sections of the cylinder above the streambed cool much faster than sections below the bed. Theoretically, the depth of scour can be gaged by comparing the temperature records.

Acoustic fathometers have been tested on several occasions. In one test, a fathometer was permanently fastened to a bridge pier; however, only a few readings were obtained before debris broke the sensing head away from its mounting. In another test, Hopkins and others (1980) fastened a fathometer to a float tethered to a trolley mounted on a long boom. The boom was cantilevered over the bridge railing and the float was maneuvered by pulling it upstream with the aid of the trolley. Depth readings were occasionally disrupted by the tilting and swaying motion of the float. This problem was eliminated by swinging the float upstream and then taking readings only while the float was drifting back toward the bridge. The boom was awkward to move; however, Hopkin's report indicates the fathometer worked quite well.

Future development of scour meters should include a re-examination of all possible alternatives. The long-range objective is to develop a portable sensor that can be mounted a safe distance above the water and that can be tilted in an upstream and downstream direction to map large areas of the river bottom. Development of a sensor having these capabilities will doubtlessly require a considerable amount of time, money, and talent.

To meet pressing short-range needs, improved methods for deploying fathometers should be investigated. Field tests show fathometers can be used to obtain the depth readings; the main difficulty is moving the fathometer from one point to another on the water surface. Several bridge engineers have suggested the possibility of using a remote-controlled boat to carry a fathometer between and around the piers. This report explores the feasibility of using such a craft and then suggests some other avenues of development that seem promising.

Purpose and Scope of This Study

The scope of this study is divided into the following sections:

1. Calculating the size and shape of the hull of a remotely controlled boat for carrying a fathometer.

2. Calculating the size of propulsion system for the boat.

3. Investigating methods of sending information to and from the boat.

4. Investigating a tethered boat.

5. Proposing new methods for making point-measurements of scour.

Acknowledgments

This study was conducted with financial assistance from the following federal agencies: Geological Survey, Army Corps of Engineers, Forest Service, Bureau of Reclamation, Agricultural Research Service, Federal Highway Administration, and Bureau of Land Management.

Mr. Joseph Beverage made a theoretical study of the optical data-transmission scheme and supervised the laboratory tests. He also ran the computer study of the tethered boat.

Mr. Joseph Szalona studied the point gage and suggested the improvements shown on figure 11.

BOAT DESIGN AND OPERATION

Design of a Remotely Controlled Boat

The following design objectives are believed to be important in the design of the boat and its propulsive system.

1. The boat must be portable so that it can be quickly moved to the site of a flood.

2. The hull must be narrow so that it can be safely moved along bridge walkways.

3. The boat must be lightweight so that it can be lifted and lowered by hand or with a portable crane.

4. The boat, its propulsive system, and its cargo of instruments must be inexpensive.

5. The boat must be maneuverable and stable in flow velocities of 15 ft/s.

6. The boat must support a cargo of about 150 pounds. As we will see later, most of this weight will be in the propulsive system and not in the instruments.

7. The boat hull and the propulsive system must operate in debris-laden flow.

Inner-Tube Boat

A boat hull made from an automobile inner-tube has several attractive features; the craft will be rugged, portable, and inexpensive; however, as we will see later, the boat's small size and its blunt shape will produce drag forces that are rather large. To make the craft serviceable, the inner tube must be changed slightly by covering its bottom with a sheet of material strong enough to serve as a deck for the instruments and the propulsion system. The fabric will also reduce drag by straightening the flow pattern under the boat.

The drag on a closed-bottom inner tube has not been measured; however, bodies with a similar shape have been tested by Hay (1947). More precisely, Hay's test-bodies were right-circular cylinders with flat ends. Hay tested each cylinder after fastening it to a dynamometer mounted on a towing carriage resting on rails aligned with a flume. The dynamometer registered drag force as the cylinder was pulled through still water ponded in the flume. Each cylinder was only partly submerged and its axis was vertical.

Drag computed from Hay's data will, to some degree, differ from the drag on an inner-tube boat. For one thing, Hay's cylinders were clamped so the cylinders could not pitch or move vertically. A free-running inner tube boat will not be constrained in this manner: the boat will be free to pitch, roll, and heave in response to flow forces. The submerged end of Hay's cylinders had sharp, square corners that added a considerable amount of drag. By comparison, an inner tube has smooth, rounded corners. The last point of difference is in regard to size. Hay's biggest cylinder was 8 inches in diameter, considerably smaller than an inner tube. Fortunately, Hay's curves are plotted against dimensionless length ratios and Froude numbers so the drag forces can be scaled up.

Based on Hay's data, the drag force on a 3-foot diameter inner tube with a draft of 0.41 foot is given by $R_T = 0.84V^2$. In this equation, R_T is the total drag in pounds and V is the boat's advance speed in ft/s. The boat must overcome a drag of 84 pounds in order to travel at a speed of 10 ft/s. Data presented in the next few sections reinforce the notion that a chubby-shaped boat is not compatible with high-speed travel.

Five-Foot-Long Catamaran

Boat designers agree that a catamaran is ideally suited for high-speed travel. Consisting of a slender float mounted on each side of a broad platform, a catamaran is both streamlined and stable. For scour-measurement applications, a catamaran can probably be built from two 5-foot sections of plastic pipe bolted under a plywood deck. The length of the pipes (5 feet) was chosen arbitrarily, then the diameter of the pipes (10 inches) was selected to provide the required displacement added to a generous safety factor. With the dimensions of the pipe hulls in hand, we turn to the computation of drag forces.

Computing accurate values for drag is a complicated process that falls in the realm of naval architecture. Fortunately, a simple method can be used if we are willing to accept approximate values. Saunders (1957) compiled drag values for several large vessels (such as tankers and destroyers) and several smaller vessels (such as tug boats and high-speed motor boats). He found that all drag data plotted along one curve, which is reproduced on figure 1 of this report. His curve shows that the total drag of a ship (R_T) is determined primarily by the craft's displacement (Δ), its length (L), and its speed through the water (V).

It's reasonable to wonder if Saunders' chart, which is based on data for large ships, is applicable to small boats of the type we are considering. Two experimental data points seem to indicate the curve should be shifted upward to yield higher values of R_T/Δ. One data-point pertains to a 17-ft aluminum canoe loaded with 150 pounds of cement blocks. The author of this report measured the drag on the canoe by towing it behind a small fishing boat. The canoe's water-line length (L on Saunders' chart) was about 14 feet; the displacement (Δ) was 0.10 long tons, computed from the weight of the cargo plus the weight of the canoe. At a speed of 3.6 knots (V on Saunders' chart) the total drag was about 7 pounds. The vertical distance between the canoe point (see fig. 1) and Saunders' "tentative meanline" curve is surprisingly large; however, data on an eight-oared racing shell (Saunders, 1957) also falls above the "tentative meanline." Drag values for the racing shell (Saunders, 1957, p. 752) are as follows: R_t = 77 lb, Δ = 0.81 long tons, L = 62 ft and V = 10. knots. Figure 1 shows the data point for this small, slender craft.

The reason for the high R_T/Δ values for the canoe and the racing shell is probably related to skin drag. On the canoe and racing shell, much of the total resistance is produced by skin friction: on larger vessels, most of the resistance is produced by form drag and waves shed from the bow and stern. Doubtlessly, data on the racing shell is more accurate than data on the canoe. The canoe moved forward with a yawing motion: most of the time the craft was misaligned with the direction of travel. In one sense, the length of the canoe measured in the direction of motion was foreshortened by this yawing action. If foreshortening had been taken into account, the T_q for the canoe would plot to the right of the point shown on figure 1.

The canoe and shell data points indicate a drag curve for small craft probably lies above the "tentative meanline" on figure 1; however, locating the exact position of the curve is difficult because of so little experimental data. Pending the completion of additional tests, the "small craft" line on figure 1 will be used.

We now return to the drag computations for the catamaran. Dividing the weight of the cargo and the weight of the deck in half and then adding this value to the weight of one pipe hull, we obtain a displacement per hull of 120 pounds or about 0.054 long ton. Next, an arbitrary value of speed, V, is selected and the ratio R_T/Δ is read opposite $V/\sqrt{L}$. If the pipe-hulls are separated far enough to eliminate mutual interference from bow waves, we can double the R_T value from the chart and thereby obtain drag on the two pipes. Figure 2 shows drag values plotted for a range of speeds.

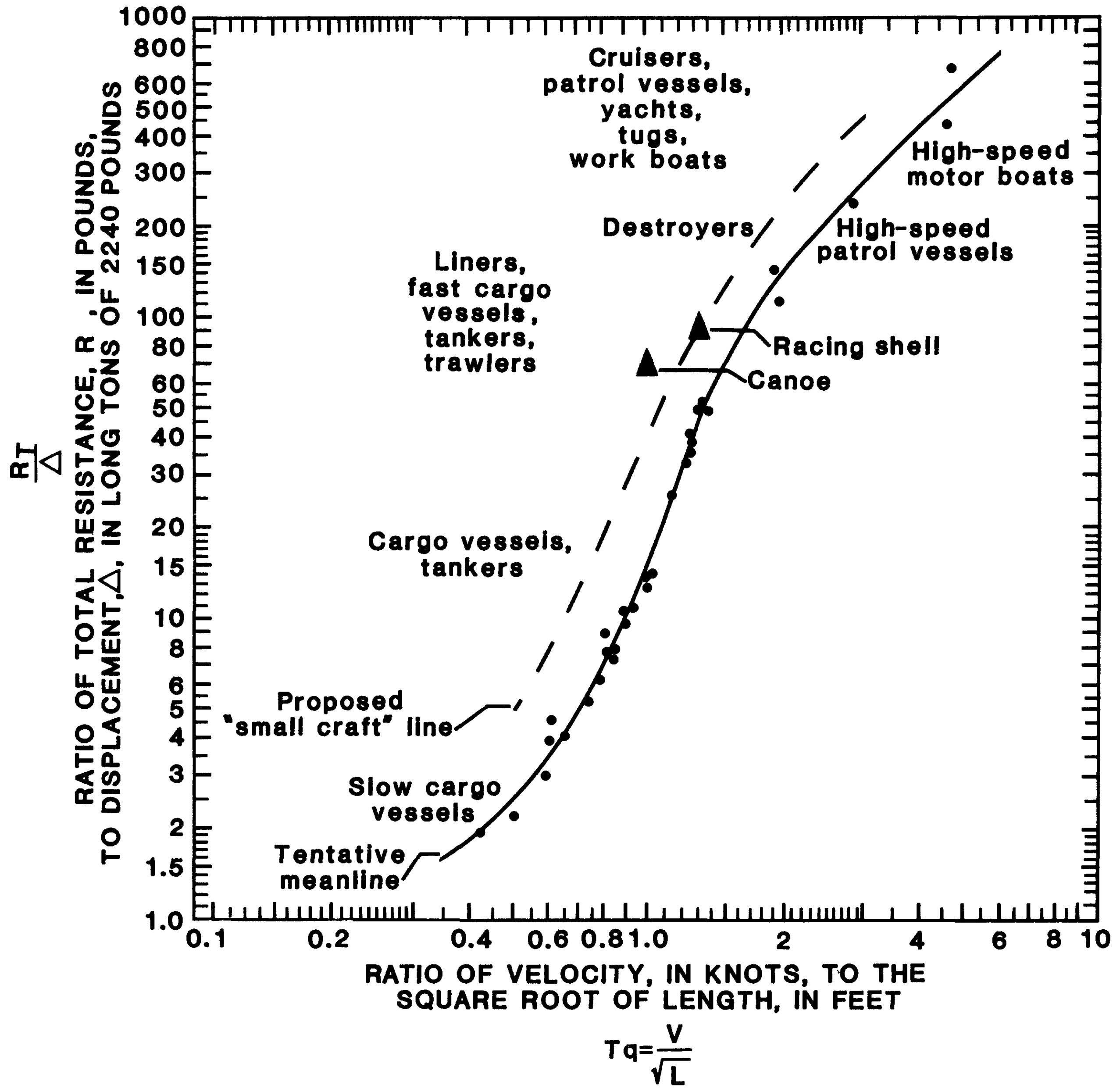


Figure 1.--Drag on boat hulls (modified from Saunders, 1957)

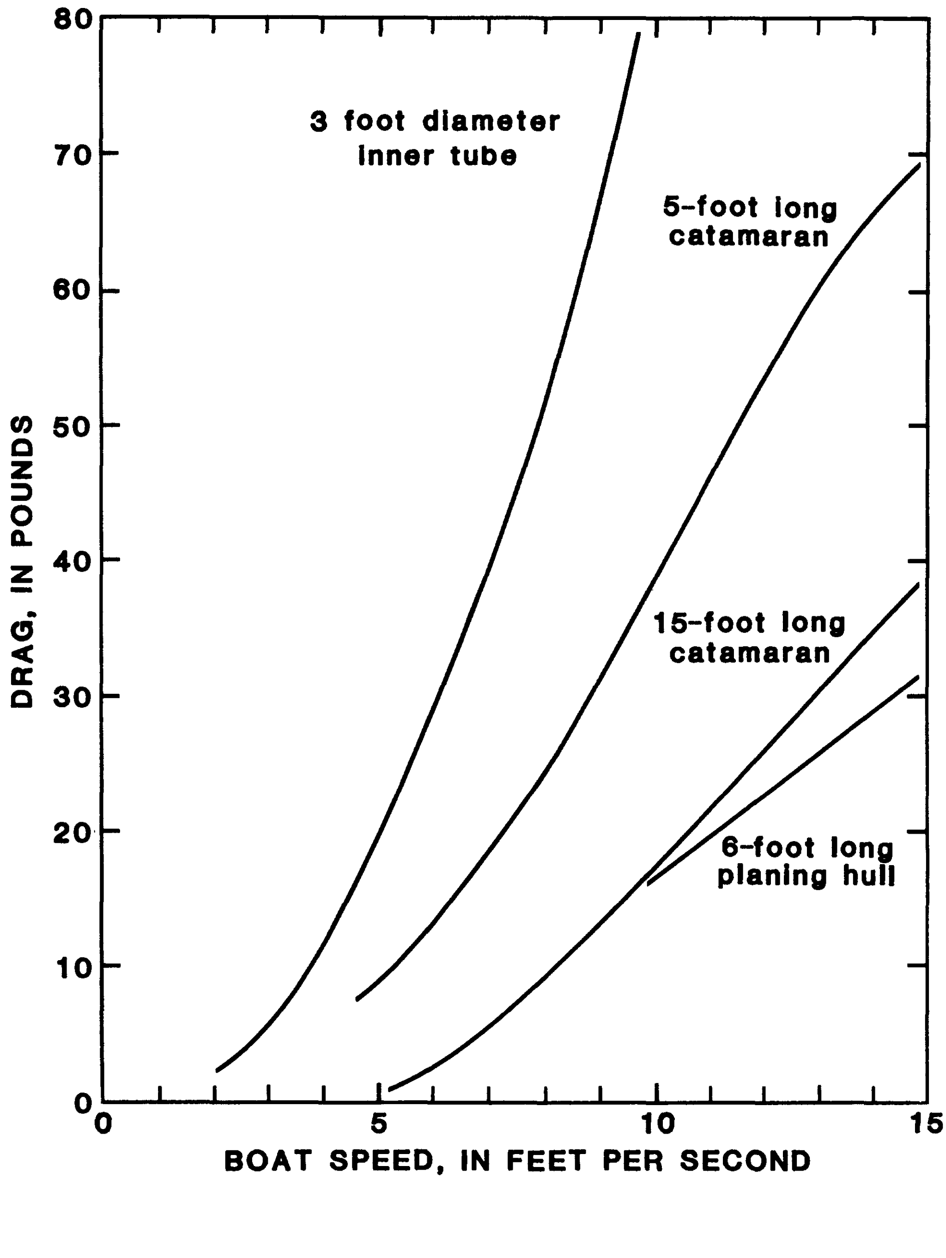


Figure 2.--Drag on small boat hulls carrying 150 pound cargos

Digressing for a moment, let us return to the inner-tube boat and chart its location on figure 1. Moving at a speed of 15 ft/sec (8.9 knots), a 3-ft diameter inner tube has a $V/\sqrt{L}$ ratio of 5.14. Notice that a ratio of 5 is exceeded only by high-speed motor boats. Again, we see that high speeds and short hulls form unsuitable combinations.

Fifteen-Foot Long Catamaran

Figure 1 shows that if a boat's displacement cannot be reduced significantly, the best way of reducing drag is to increase the length of the boat's hull. In this section we examine the drag on a catamaran having two hulls made of 15-ft plastic pipes.

The 15-ft version will develop sufficient displacement if the pipe hulls are 6-inches in diameter. The drag computations follow the format outlined for the 5-ft long catamaran. The total weight of the cargo, deck, and hulls is about 300 pounds so the displacement of each hull is about 0.067 long tons. We enter the chart on figure 1, read R_T/Δ values for several $V/\sqrt{L}$ values, and then double the R_T values to account for two hulls. Figure 2 shows the computed drag values plotted against speed.

The width of a catamaran is another factor that influences the boat's drag. If the hulls are close together the bow waves from the hulls intersect in a zone that lies between the hulls. The disturbance created in this zone reflects back toward the hulls and disturbs the flow pattern near the stern. This phenomenon, known as mutual interference, is detrimental because it creates an additional component of drag. The critical value for hull-spacing is determined by drawing a line that starts from one bow and forms an angle of 20° with the keel. This line, which coincides with the hull's bow wave, must not intersect the other hull. Designating the length of the hulls as "L" and the critical spacing between the hulls as "W", we obtain the following relationship: $W = 0.34\ L$. Based on this equation, the critical spacing for a 15-ft catamaran is about 5.1 ft. A boat this wide will be difficult to move along a narrow walkway on a bridge.

Six-Foot Long Planing Hull

A planing-hull boat travels in two modes. When standing still or moving at low speeds, the boat is buoyed up by hydrostatic pressure developed by the hull's displacement. The craft sits low in the water and plows its way through the approaching flow. When moving at high speeds, the boat is supported by reaction forces that develop as water accelerates downward and away from the hull. The craft now rides high in the water and moves forward with a skimming action.

One form of planing hull has a flat bottom that slopes forward and upward at an angle of only a few degrees. This type of hull is easy to build; however, it is rather unstable at high speeds. The hull responds as if balanced on a single fulcrum. The location of the fulcrum depends on the center of gravity of the cargo and the forward speed of the boat. Even small perturbing forces may cause the hull to alternately pitch up and down with a porpoise-like motion.

A more stable craft is built with a notch-like step running laterally across the bottom of the hull. The notch divides the hull into two planing surfaces--one near the bow and one near the stern. This hull, which was first proposed by C. M. Ramus (Saunders, 1957, p. 425), responds as if supported on two fulcrums. Details of the design are rather sketchy; however, the literature stresses the importance of ventilating the notch. At high speeds, water traveling under the notch tends to entrain air and reduce the pressure. If the air lost through entrainment is not continuously replenished, suction pulls the water surface up into the notch and, thereby, destroys the planing action. The literature also stresses the importance of sharp-edged chines, the edges formed where the sides of a boat intersect its bottom. The high pressure under the keel of the boat produces a lateral flow that appears as spray thrown to the left and right. Curved chines inhibit flow separation and cause the lateral flow to sweep around the chines and up along the sides of the craft. This type of flow increases the wetted surface of the hull and, thereby, increases drag.

A few "rules of thumb" (Saunders, 1957, p. 424) have been established for setting the overall dimensions of a planing hull. To maintain a reasonable degree of stability, the length/beam quotient should lie between 3 and 6.2. The draft at rest is another important factor. A craft having a deep draft will obviously require an excessive amount of power to push the craft through the transition speed that divides displacement-hull operation from planing-hull operation. To establish a low planing speed, the draft/beam quotient should lie between 0.17 and 0.36.

The maximum safe speed of a planing hull is set primarily by the craft's overall length. Figure 1 indicates that a $V/\sqrt{L}$ quotient of five is not unusual. According to Saunders (1957, p. 423), the quotient may exceed 20, however; in all likelihood, this value applies only to hulls that are meticulously shaped to yield the ultimate in high-speed performance.

A planing hull with a water-line length of 6 ft, a beam of 2 ft, and a draft of about 0.25 ft, comes close to meeting the "rules of thumb". The draft is based on a total weight of 190 pounds--a 40-pound hull carrying a 150-pound cargo. The speed at which the hull begins to plane is of major interest particularly when the craft must move upstream against fast currents. According to one estimate, a craft reaches planing speed when the $V/\sqrt{L}$ quotient is about 2.5. This criterion indicates the boat will plane at any speed higher than about 6.1 knots (10 ft/s).

The drag on a planing hull is usually determined experimentally by towing the craft in a special test facility. Lacking tow-test data, we must settle for rough estimates of the drag forces. On figure 1, the boats and ships are not explicitly classified according to hull type; however, it is reasonable to assume that the upper end of the "tentative meanline," which is based on performance data on high-speed patrol vessels and high-speed motor boats, applies to planing hulls. Data from this meanline were used to compute the "planing hull" curve on figure 2.

Boat Propulsive System

Any water craft is acted upon by two horizontal forces--the drag exerted by the water and the thrust exerted by the propulsive system. When the craft is moving at a steady speed, these two forces are balanced. Having established values for drag, we now examine some propulsive devices and the power required to operate them.

Essentially all types of propulsive devices operate on the same principle--they develop thrust by accelerating a liquid, a gas, or a solid. In this report, we consider screw-type propellers that accelerate air or water.

Ducted Fan

Large fans are commonly used to propel swamp-boats designed to run through shallow, debris-laden water. A fan's immunity to fouling from such debris is an attractive feature for bridge-scour work; however, measurements indicate the size of the fan and its power requirements will be rather large.

Experimental data were collected on a 19-inch diameter window fan having five blades driven by a shaded-pole induction motor. The motor was rated at 2.6 amperes, 115 vac; however, it actually drew 2.1 amperes at rated voltage and speed. The power delivered to the shaft of the fan was about 0.06 hp, obtained by computing the volt-ampere input to the motor and then applying corrections for power factor and electro-mechanical efficiency. Thrust was measured by first suspending the fan from wires and then measuring the force with spring scales. Running at rated voltage, the fan developed a pull of about 0.85 pounds.

Figure 2 indicates a fan must develop a thrust of about 40 pounds to propel the 15-ft catamaran at a speed of 15 ft/s. Assuming that a fan's power requirements and thrust are proportional to its disc area if speed remains constant, we obtain the following two equations:

$$A_p = A_m(T_p/T_m)$$

and

$$P_p = P_m(A_m/A_m)$$

In these equations, A, T, and P refer to disc area, thrust, and power, respectively. Subscripts "m" and "p" refer to model and prototype, respectively. Evaluating these two equations, we obtain

$$A_p = (1.96)(40/0.85) = 93 \text{ square feet.}$$

$$P_p = (0.06)(93/1.96) = 2.85 \text{ horsepower.}$$

The calculated value for A_p is probably too large because the assumption neglects the fact that lengthening the blades on a fan improves its thrust efficiency. By taking this fact into account and by optimizing blade shape, blade pitch, and blade speed it is possible to reduce the disc area; however, power requirements climb as disc area decreases. As the size of the fan decreases, the weight of the power source increases. Later, we will see that weight poses some serious problems. Although the value of 2.85 hp was determined by crude methods, it agrees reasonably well with values determined for underwater propellers discussed in following sections.

A fan has a disadvantage related to its interaction with wind. Strong side winds may blow the craft off course: strong head-winds will lower the fan's thrust and may cause the craft to lose headway and gradually drift downstream.

Shifting to an underwater propeller is one way of making the propulsive system more compact. The advantage of a propeller over a fan is shown by the equation $T = \rho Q(\Delta U)$ which relates thrust "T", fluid density "ρ", flow rate through the propeller (or fan) "Q", and change in velocity imparted to the fluid "ΔU". As this equation shows, accelerating water instead of air gives rise to a dramatic increase in thrust because the density of water is much greater than the density of air. The following two sections discuss the size and thrust of underwater screw-type propellers.

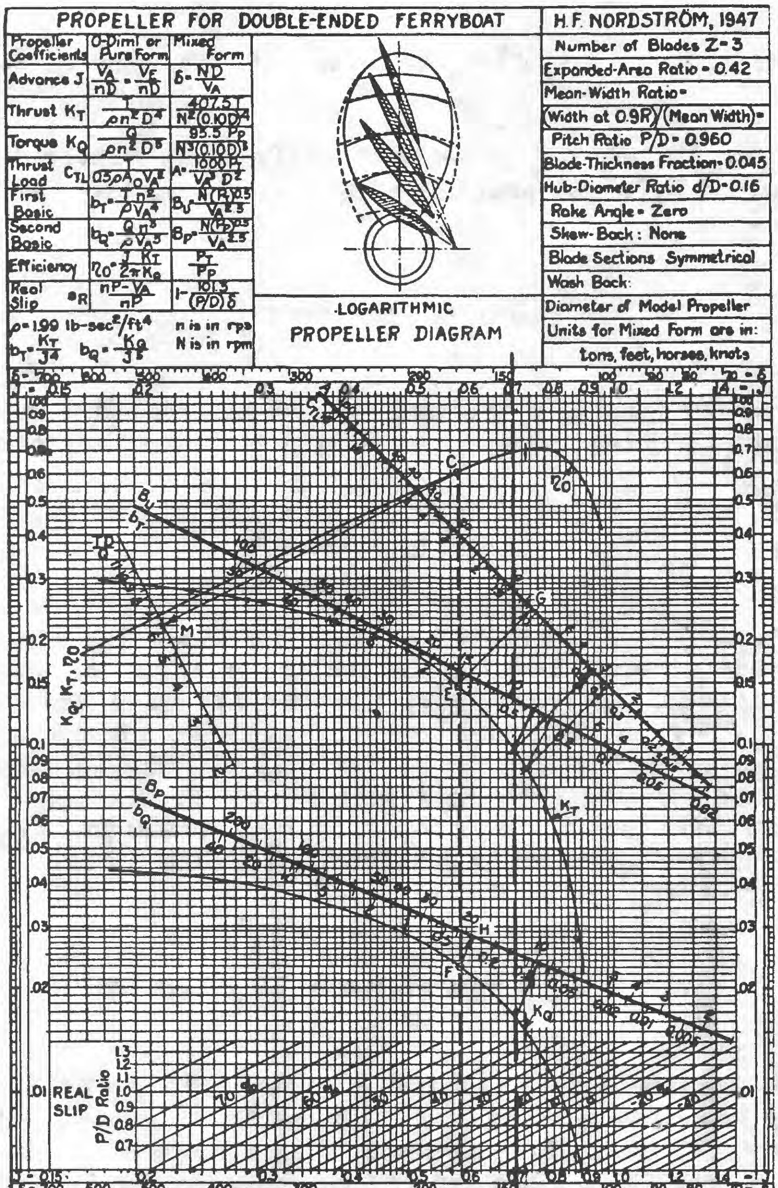
Nordstrom's Logarithmic Propeller

Figure 3 is a design chart for Nordstrom's propeller, one of many underwater propellers that have been tested under controlled conditions. For a particular boat speed, characteristics of the propeller are determined by drawing a vertical line upward from the appropriate J-value on the abscissa of the chart. This line is extended until it intersects the curves labeled η_o, K_t, and K_Q. Then perpendiculars are dropped from the intersection points to the straight-line scales. The pattern for the perpendiculars is shown by the arrowed lines on figure 3.

Let us apply the chart to the 15-ft catamaran. To drive the craft at 15 ft/s, the propeller must develop 40 pounds of thrust and should operate at or very near its maximum open-water efficiency "η_o". A vertical line drawn upward from a "J" value of 0.72 meets this efficiency requirement. A value of 0.47 for C_{TL} is read from the perpendicular line drawn from the intersection on the K_T curve. Next, we insert values for thrust "T", water density "ρ", (1.94 for fresh water), and advance speed "V_a" into the following equation:

$$C_{TL} = T/(0.5 \rho A_o V_a^2)$$

Solving this equation for the disc area of the propeller "A_o", we obtain 0.39 ft^2. In other words, the propeller must have a diameter of 0.71 ft--a dimension that is compatible with the portability requirement.



LOGARITHMIC CHART OF C. W. PROHASKA FOR A SINGLE SCREW PROPELLER

Figure 3.--Design chart for Nordstrom's propeller (reproduced from Saunders, 1957 and published with permission)

The rotational speed of the propeller "n" must be about 30 revolutions per second. This value is obtained from the following equation which defines the advance coefficient "J":

$$J = V_a/(nD)$$

In this equation, D is propeller diameter (0.71 ft) and V_a is advance speed (15 ft/s).

The torque "Q" at the propeller shaft must be about 4.9 lbf·ft. This value is obtained by first reading 0.089 for b_q and then solving the following equation for Q:

$$b_q = (Qn^3)/(\rho V_a^5)$$

The power transmitted through the propeller shaft must be about 1.7 hp obtained by substituting values for "n" and "Q" into the following equation:

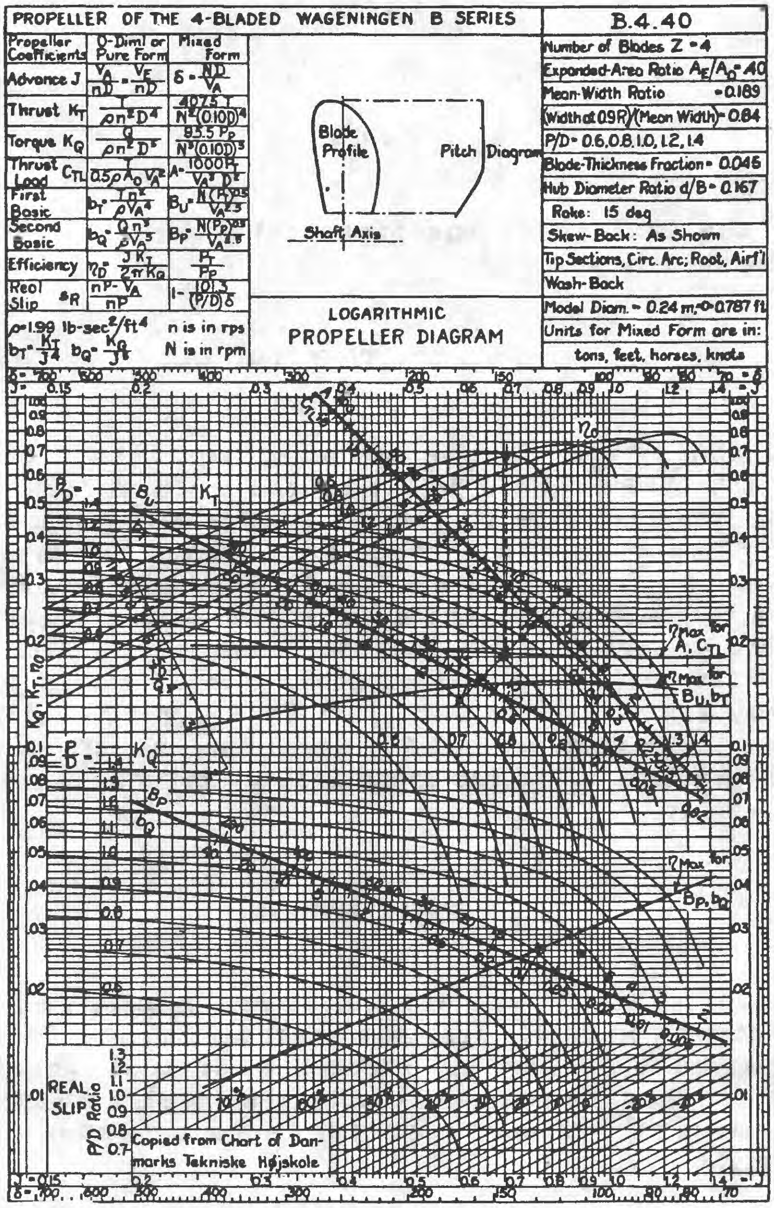
$$P = 2\pi nQ/550$$

The value of 1.7 hp is probably too low because the design chart was drawn from data collected under ideal conditions some of which cannot be fully met in scour applications. For example, the charted data were collected with an unobstructed flow around the propeller. Around a catamaran the flow approaching the propeller will be disturbed by the hulls. For the design-chart tests, the propeller was submerged deep enough to eliminate all water-surface effects. On a catamaran, the propeller may occasionally draw air from the surface when the boat pitches in rough water. This vortex action will severely reduce the propeller's thrust.

Wageningen's B-Series Propeller

Figure 4 is a design chart for a Wageningen propeller. Following the calculations outlined in the previous section, we find that a high-pitch Wageningen requires slightly less power than a Nordstrom. The power savings is too small to be significant at this stage; however, an important generalization can be drawn by considering the reason for the power reduction.

Comparing the η_o curves on figure 3 and figure 4, we note differences in maximum efficiencies. The Nordstrom peaks at about 0.7; whereas the Wageningen peaks at about 0.8. Recognizing that efficiency differs from one propeller design to another, we may reasonably ask, "How much power is required to drive the catamaran if we use a propeller having a peak efficiency of "1.0"?



LOGARITHMIC CHART OF C. W. PROHASKA FOR FIVE PROPELLERS, WAGENINGEN B.4.40 SERIES

Figure 4.--Design chart for a Wageningen propeller (reproduced from Saunders, 1957 and published with permission)

A power-requirement equation for an "ideal" propeller is obtained from the following propeller-coefficient equations:

$$\eta_o = (JK_T)/(2\pi K_Q)$$

$$J = V_A/(nD)$$

$$K_T = T/(\rho n^2 D^4)$$

$$K_Q = Q/\rho n^2 D^5$$

Substituting the last three equations into the first equation and then simplifying the result, we obtain

$$\eta_o = V_A T/(2\pi nQ)$$

The numerator, "$V_A T$" in the preceding equation, is the boat's speed multiplied by the thrust required to push the craft through the water. Stated in other terms, the numerator is the power delivered to the craft's hull. The denominator, "$2\pi nQ$" in the preceding equation, is proportional to the rotational speed of the propeller shaft multiplied by the torque exerted on the shaft. Stated in another way, the denominator is the power delivered to the propeller. The equation shows that an "ideal" propeller takes all power transmitted to its shaft and, without loss, transmits this power to the boat's hull. Substituting 40 pounds for T, 15 ft/s for V_A, 1.0 for η_o, and then solving for the power delivered to the propeller, we obtain 600 ft-lb/s or 1.1 hp. Even with the most efficient propeller, we cannot reduce the power demand below this threshold.

Power Sources

Having estimated power requirements, we now examine relative attributes of engines and motors for developing the necessary power. In this context, the term "engine" applies to internal combustion devices (gasoline engines) and "motor" refers to electric devices (electric motors). Before choosing between a motor and an engine, one must consider factors related to speed controls, safety, and weight.

From the standpoint of simplicity of controls, motors appear to have a definite advantage over engines. Speed controls for motors and engines are simple if the controls can be adjusted by hand; however, the controls become more complicated if they must be adjusted by remote signals. The control for a gasoline engine on a remote-controlled boat must detect the signals and then transform them to mechanical motions in order to adjust the carburetor setting. On the other hand, a control for a motor can be a solid-state device with no moving parts.

In matters of safety, motors have a big advantage over engines. A motor can be started remotely by simply closing a relay actuated by a float or radio signal. Small gasoline engines are usually fitted only with rope starters; consequently, an operator must start the engine manually before lowering the boat to the water surface. Working close to a propeller running at high speeds is definitely a hazardous situation. Another problem with an engine is related to its supply of cooling water: an outboard engine overheats quickly if the engine runs with its cooling-water intake exposed to air.

On the basis of weight, a gasoline engine is superior to an electric motor. The engine's advantage stems more from the weight of its fuel rather than the weight of the engine itself. Gasoline contains about 21 million joules (watt-seconds) of energy per pound. By comparison, a high-efficiency battery weighing 20 pounds stores about 540,000 joules: only 27 thousand joules per pound.

A heavy bank of batteries will be required to power an underwater propeller. As we have seen, a Nordstrom propeller requires about 1.7 hp (1268 watts) to drive a catamaran at a speed of 15 ft/s. Let's assume the batteries must drive the motor for 2 hours between recharge cycles; furthermore, assume the motor's efficiency (measured from electric power input to shaft output) is 80 percent. The motor's voltage rating is of only minor importance at this stage; however, to estimate the amperage, assume the motor is rated at 36 volts dc and is supplied by three 12-volt marine batteries connected in series. The current at the motor terminals is given by

$$I = 1268/(0.8)(36) = 44 \text{ amperes.}$$

Each battery in the bank must deliver this 44-ampere drain for 2 hours. A heavy-duty deep-cycle battery weighing 50 pounds can deliver only 30 amperes for 2 hours; consequently, 6 batteries will be required! The weight (300 pounds) of this battery bank is a major obstacle in designing a powered craft for scour surveys.

Because the size and weight of a free-running boat (along with its propulsive system) seriously conflict with requirements for portability, the feasibility of the concept is questionable.

The problems stem from the fact that all of the drive power is expended to simply hold the boat at a fixed location in the river. In essence, the boat runs on a treadmill formed by the approaching water flow. The task of holding the craft against the flow can be performed with no expenditure of power by fastening the boat to a line anchored to some object upstream of the bridge. If the line is sufficiently long, the boat can be thrust out into the river with a propeller <u>mounted on the side of the boat instead of on the transom</u>. Alternatively, we can reduce power requirements even further by using a rudder to generate lateral thrust.

Use of a Tethered Boat

The tethered-boat scheme is illustrated on figure 5, which shows a plan view of a river in the vicinity of a bridge crossing. The boat is attached to a tether line anchored to a remote-controlled winch at point "A". Personnel at stations B and C determine the boat's location by triangulation. Lines-of-sight are depicted by the dotted lines drawn from the two stations. The operator at B controls the winch by transmitting radio signals to set the winch's drum speed and direction of rotation. In this manner, line can be paid out or retrieved. The operator also controls the angle of attack on the rudder and, thereby, set the amount of lateral thrust exerted on the boat. By adjusting both line length and rudder angle, the operator can maneuver the boat upstream of the bridge.

Maneuverability is limited in large measure by the hydraulic drag on the tether line and by the lift (side thrust) and drag of the rudder. If the line drag is large compared to rudder lift, the boat is restricted to a slender zone downstream from point A. On the other hand, if the line drag is low compared to rudder lift, the boat can move over a broad area and can follow a path nearly perpendicular to the flow. The degree of maneuverability can be judged after computing some values for "x" and "y" on figure 5.

A computer program (fig. 6) yields the relationship between "x" and "y" by computing a series of values for x' and y'. First, the rudder's area, its aspect ratio, and its attack angle are set, then drag and lift forces on the rudder are computed. Next, line tension and the angle between the line and the approaching flow are adjusted to balance rudder forces and drag forces exerted on the boat. The program now solves for the shape of the tether-line curve by an iterative process that begins at the boat and moves out along the line toward point A.

Figure 7 shows the x-y relationship for a boat tethered on a 1/8" diameter line and fitted to two different rudders, one having an area of one square foot and the other having an area of 4 ft^2. The figure shows that for a given x, the downstream drift, "y", is reduced substantially by the larger rudder: this rudder will push the craft 400 ft out from the shore while holding the downstream drift to only 175 ft. The tether line and winch must be rather sturdy because the big rudder will exert a pull of about 1,000 pounds.

The tether line has a debris-collection problem that must be carefully considered. Debris collecting on the line will accumulate near the boat and thereby limit its maneuverability. The boat must be periodically reeled to shore where the trash can be cleared.

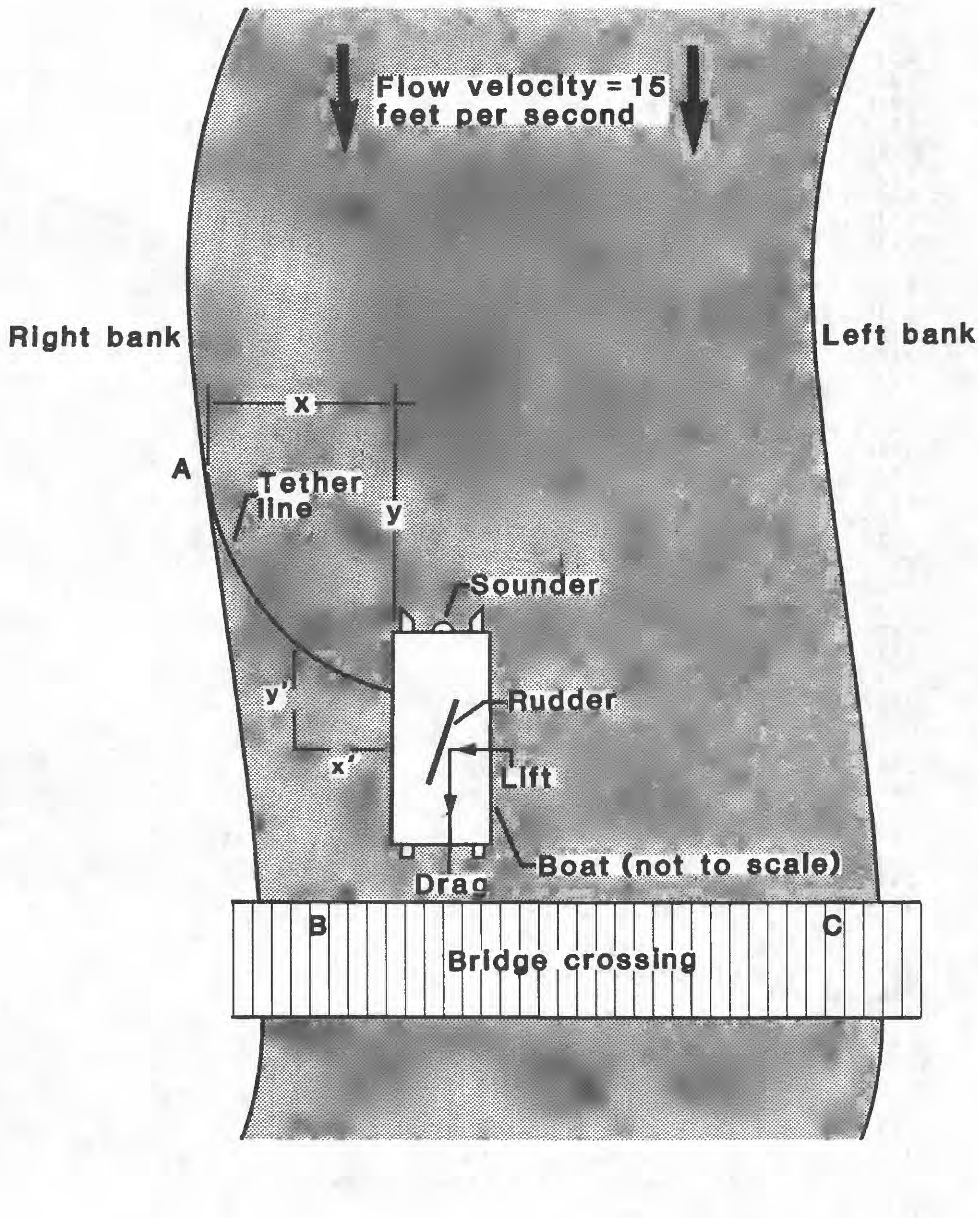


Figure 5.--Schematic drawing of boat fitted with a rudder and a tether line

```
1000 '
1010 '                      PROGRAM:   TETHER
1020 '
1030 '                          MBASIC VERSION 6 DEC 84   JPBEV
1040 '
1050 '
1060 '
1070  PRINT CHR$(27)"*"
1080  PRINT "TYPE LIFT FORCE, DRAG FORCE, AND VELOCITY"
1090    INPUT FL, FD, V
1100     PRINT FL, FD, V
1110  PRINT "WHAT IS THE DATA FILE NAME?"
1120   INPUT D$
1130   PRINT D$
1140  DIM YO(210),CL(210),DX(210),AN(210)
1150  P6=10^6
1160  D=400!
1170  I = 0
1180  YO=0!
1190  KW= .01519
1200  WS = FL
1210  WC= 0!
1220  KM= .0057594
1230  DX=0!
1240  CL=0!
1250  Y=YO
1260   VSQ = V*V
1270  TMAX=0!
1280  TS=SQR(FL*FL+FD*FD)
1290  A0=ATN(FD/FL)
1300  A1=A0
1310  TEN=TS
1320  Y = Y + 1
1330  CA=COS(A1)
1340  FX=KW*VSQ*CA*CA+TEN*SIN(A0)
1350  FY= -KW*VSQ*CA*SIN(A1)+TEN*COS(A0)+WC/CA
1360  A1= ATN(FX/FY)
1370  D1= .99995 * A1
1380 D2 =1.00005 *A1
1390 F1 = KM*VSQ*COS(D1)-.5*WC*SIN(D1)-TEN*SIN(D1-A0)
1400 F2 = KM*VSQ*COS(D2)-.5*WC*SIN(D2)-TEN*SIN(D2-A0)
1410 F3 = F2*(D1-D2)/(F1-F2)
1420 A2 = A1 - F3
1430 TR = F3 / A2
1440 TR = INT(TR*P6+.5)/P6
1450 IF TR = 0!  THEN 1510
1460 D1 =D2
1470 D2 =A2
1480 A1 =A2
1490 F1 =F2
1500  GOTO 1400
1510  A0=A2
1520  CA=COS(A1)
1530  FX=KW*VSQ*CA*CA+TEN*SIN(A0)
1540  FY= -KW*VSQ*CA*SIN(A1)+TEN*COS(A0)+WC/CA
```

Figure 6.--Computer program

```
1550  CL=(1/COS(A2)) + CL
1560  DX= TAN(A2)+ DX
1570  TEN= SQR(FX*FX+FY*FY)
1580  IF TEN<TMAX GOTO 1600
1590  TMAX = TEN
1600  Y = Y+1
1610  IF Y > D THEN 1630
1620  GOTO 1330
1630  PRINT"X/S DIST.= ";D-YO;"  CL= ";CL;"  U/S DIST.= ";DX;"  ANGLE= ";A2*57.2958
1640  PRINT
1650  I=I+1
1660  YO(I)=YO
1670  CL(I)=CL
1680  DX(I)=DX
1690  AN(I)=A2*57.2958
1700  DX = 0!
1710  CL = 0!
1720  YO = YO + 20!
1730  IF YO = D  THEN 1760
1740  Y = YO
1750  GOTO  1280
1760  PRINT CHR$(7)
1770  OPEN"O",1,D$
1780  WRITE□1,I
1790  WRITE□1,"    ",D$
1800  WRITE□1,"   X/S DIST.         CL          U/S DIST.           ANGLE"
1810  WRITE□1," "
1820  FOR N= 1 TO I
1830     PRINT□1,USING"□□□□□.□□□□□□    ";D-YO(N);CL(N);DX(N);AN(N)
1840  NEXT N
1850  CLOSE□1
1860  PRINT
1870  PRINT CHR$(7),CHR$(7),CHR$(7),CHR$(7)CHR$(7)
1880  END
```

for tether-line curve

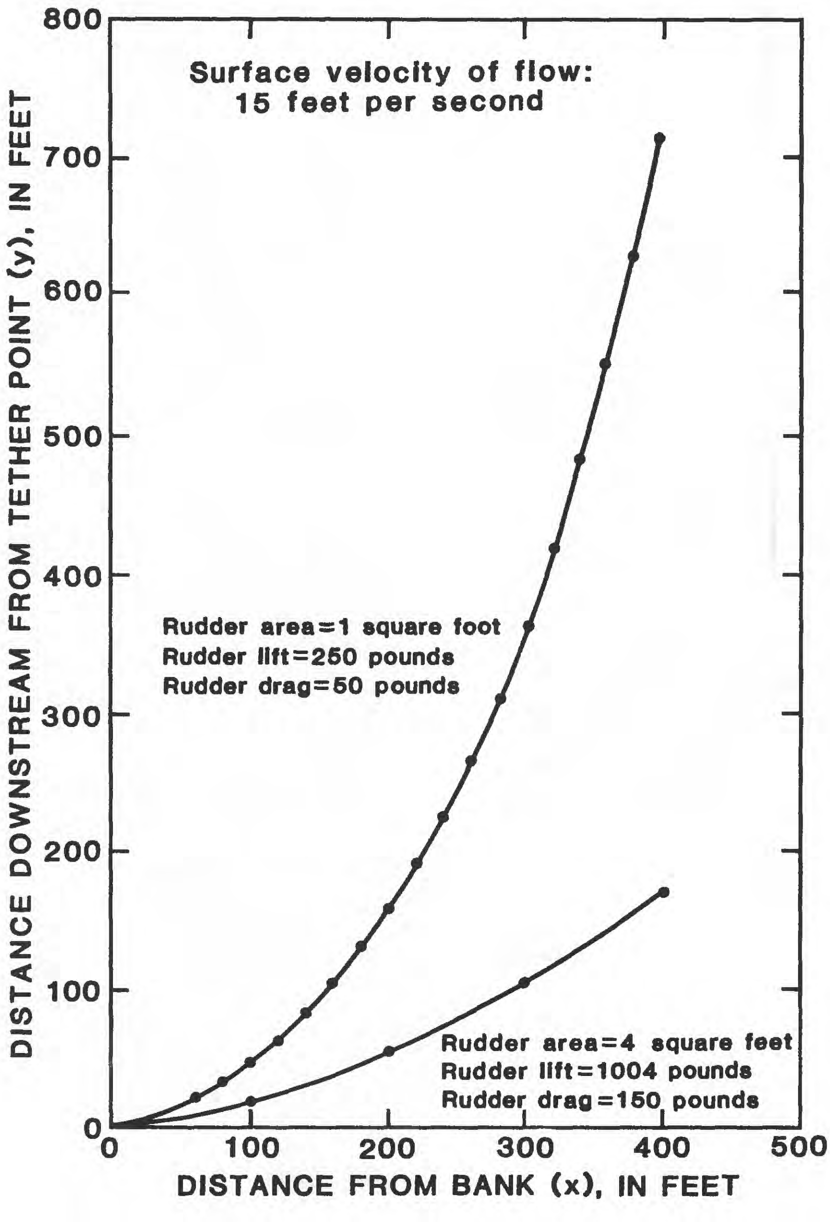


Figure 7.--Locus of boat tethered on a 1/8-inch line

Data Transmission

Mapping scour holes requires two kinds of data: the precise location of the unmanned boat and the depth of water under the boat. As the boat moves, a continuous stream of data must be recorded so it can be processed at a later time.

The recorder should be located on the bridge instead of in the boat: if the boat capsized, an expensive piece of gear may be damaged or lost. Placing the recorder on the bridge also simplifies the problem of tracking and logging the boat's position.

Position data can be collected by using two telescopes each one connected to a potentiometer on a tripod. An operator at each telescope moves the cross hairs to keep the boat in the field of vision. The base line connecting the two telescopes, and the angles between the base line and sight lines define a triangle having the boat at its vertex. Each potentiometer must be arranged so that its resistance varies with the line-of-sight angle. The two resistance readings can be transmitted through cables leading from the potentiometers to the recorder.

Depth readings can be relayed from the boat to the recorder by using a wire, a radio transmitter and receiver, or a flash tube. If the boat is attached to a tether line, the same line can be used as a data-transmission cable. If a tether cannot be used, then a radio is probably the best alternative to pursue. Signals from a CB radio will travel 2 or 3 miles, so a distance of a few hundred feet between the boat and the bridge should not pose a problem.

A flash tube transmitter was tested; however, the results were discouraging. Light pulses transmitted from a photographic flash gun were transformed to voltage pulses by a phototransistor with a built-in narrow-angle focusing lens. The voltage pulses were displayed on a sensitive oscilloscope. The first series of tests were run indoors under low-intensity incandescent lights. After traveling 100 ft, light flashes were easy to detect; however, when the tests were repeated outdoors under bright sunlight, the maximum range dropped to only 12 ft. Calculations indicate the maximum range under bright sunlight can be increased by using large lenses; however, the cost and bulkiness of the additional parts make the approach unattractive.

Point Measurements of Scour Depth

This section presents some techniques that may be useful for depth and scour measurements at a single point. Some or all of the techniques may have to be discarded after all of their limitations have been revealed by field tests; however, at this stage, nothing should be dismissed without a careful review.

Ground-Penetrating Radar

Ground-penetrating radar systems are being improved and are finding new applications in hydrologic studies. For example, figure 8 shows a lake-bottom profile published by Geophysical Survey Systems, Inc. Some of this company's systems are small, battery-powered units that can be hand-carried. A radar system appears to have one big advantage over sonar equipment: the radar antenna can be held above the water, whereas a sonar transmitter must be submerged. Debris that will damage or interfere with a sonar transmitter will float under a radar antenna.

Radar waves traveling through water attenuate rapidly; however, their range may be sufficient for some applications. Ulriksen (1982) observed that "Due to the low conductivity and high permittivity of freshwater, excellent radar records can be obtained. Penetration is about 10 m for an 80-MHz antenna and though the wavelength of this antenna is 3.75 m in air it is only 0.42 m in water which gives a good resolution."

Heat-Dissipation Gage

Another promising technique involves heat dissipation. The technique, which was proposed earlier by the Sedimentation Project, can best be explained with the aid of figure 9. The assembly consists of electric heaters and temperature sensors fastened together end-to-end to form a long rod. The rod is driven or jetted into the stream bed near a bridge pier and the wires leading from the assembly are routed up to a convenient point on the bridge deck. Installation must be performed during a period of low flow when the water is calm. During a flood, the operator connects the heating wires to a battery and thereby raises the temperature of all sensors in the rod. After a few minutes, the operator disconnects the power and allows the sensors to cool. During the heating cycle and the cooling cycle, the resistance of each temperature sensor is monitored continuously. Figure 10 shows resistance records that were measured on a crude model consisting of only one sensor and one heating coil. The record taken with the sensor buried in sediment differs from the record taken with the sensor exposed to moving water. During a field measurement, the operator determines the number of sensors exposed to flowing water by examining the heating and cooling records.

Although the soundness of the heat-transfer idea has been verified, the hardware must be improved for field use. The temperature-measuring coils should be replaced with thermistors which are smaller and far more temperature sensitive than the copper wires used in the original model. Figure 11 shows an improved design that includes thermistors and a continuous length of steel pipe. The pipe strengthens the rod and also forms a clear passageway for flowing water needed to jet the assembly into a stream bed.

Casting-Resin Gage

The devices shown on figure 9 and figure 11 have three disadvantages: a large number of wires must be routed up to the bridge, many electrical

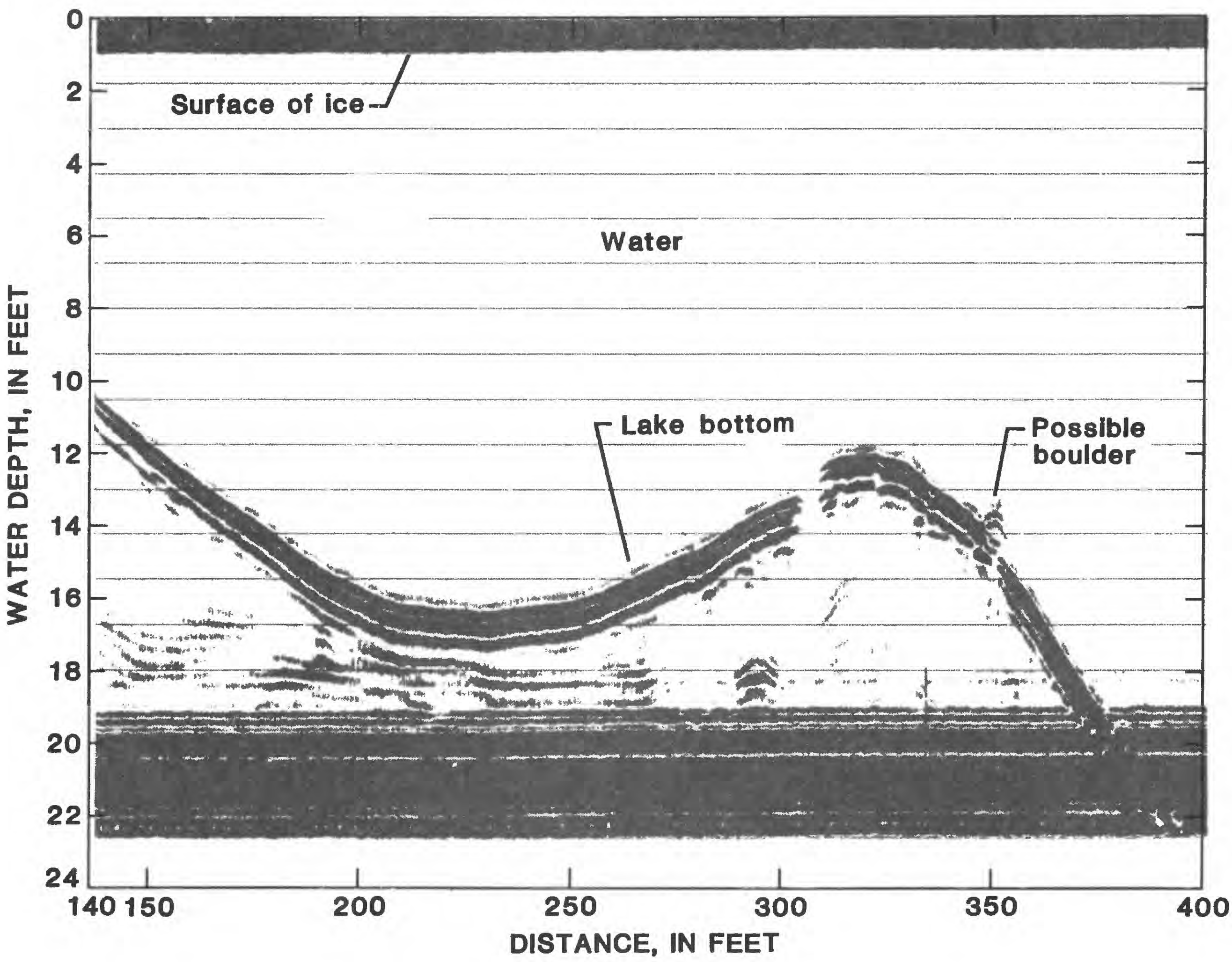


Figure 8.--Depth records obtained with a ground-penetrating radar system (reprinted with permission from Geophysical Survey Systems, Inc. brochure)

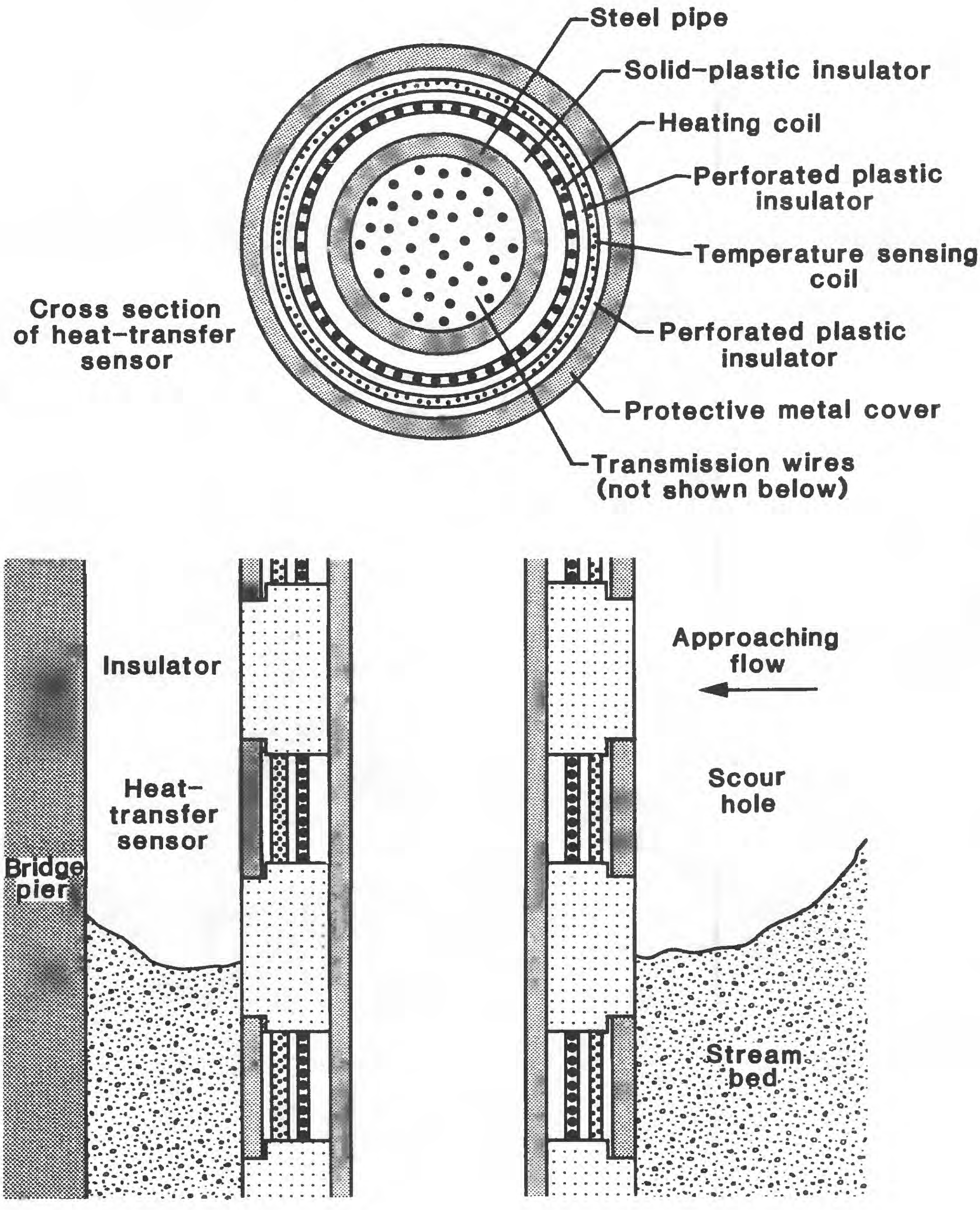


Figure 9.--A heat-dissipation point-gage for monitoring scour

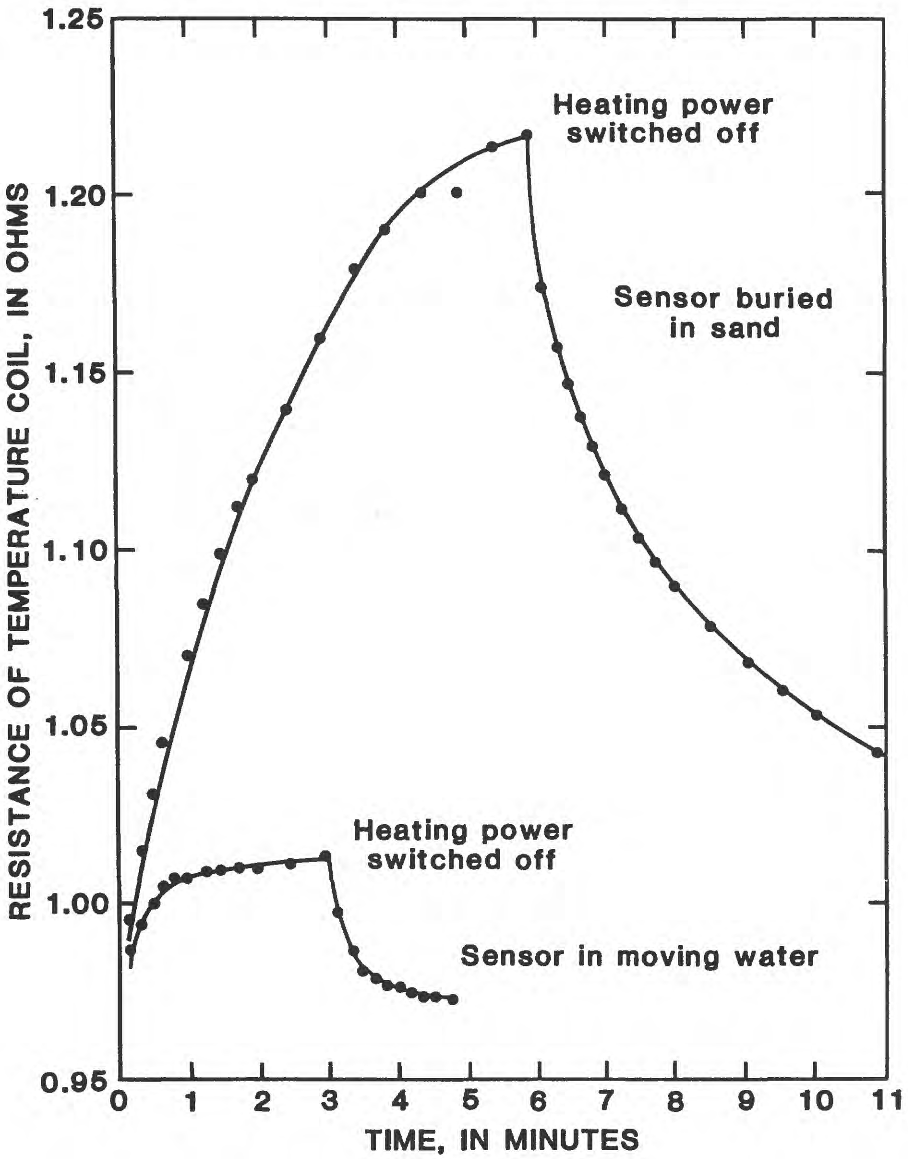


Figure 10.--Heating and cooling records for heat-dissipation gage

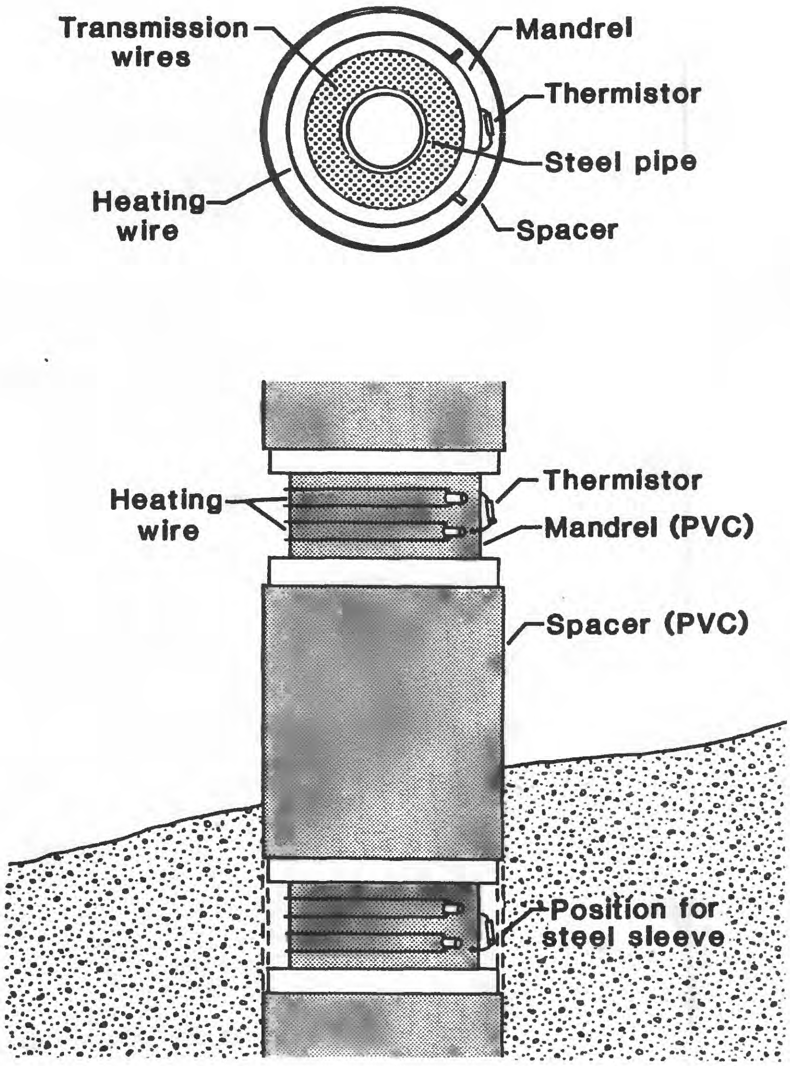


Figure 11.--An improved version of the heat-dissipation gage

connections are submerged and subjected to corrosion, and operators must make several resistance measurements to determine each value of scour depth.

It may be possible to eliminate these problems by making the sensing rod from a special casting resin. The top drawing on figure 12 shows the electrical resistivity curve for "Scotchcast brand resin number 280" resin manufactured by the 3M Company. Notice that the resistivity decreases as temperature shifts from 65°C to 125°C. For temperatures outside this range, the resistivity curve is almost flat. The step-like shape of the curve may prove useful for scour measurements.

The proposed construction of a resin-type meter is shown on the upper sketch of figure 13. Each end of the rod is fastened to a metal cap and to a wire leading up to the bridge. The overall length of the rod is L, the length exposed to flowing water is D, and the cross sectional area of the rod is A.

A scour measurement is started by connecting the two wires to a battery. After the rod has warmed sufficiently, the battery is disconnected and the rod is allowed to cool. The top portion of the rod, which is exposed to flowing water, cools much faster than the bottom portion which is insulated by silt and sand. As the rod cools, its temperature profile develops a distinct breakpoint at the stream bed.

The resistance of the rod and the distance "D" are related to one another. This relationship, a key factor in scour measurements, can be derived easily if we make a few simplifying assumptions regarding the shape of the "Scotchcast brand resin number 280" resistivity curve on figure 12.

Assume the resistivity curve shifts abruptly at 95°C and that the curve is flat above and below this temperature. In graphical form, the simplified resistivity curve is shown on the bottom sketch of figure 13. When the buried portion of the rod is warmer than 95°C and the exposed portion is cooler than 95°C, the resistance between the metal caps is

$$R = (\rho_1 D + \rho_2(L - D))/A$$

Solving for D yields

$$D = (AR - \rho_2 L)/(\rho_1 - \rho_2)$$

The factors ρ_1, ρ_2, A, and L are known; consequently the preceding equation simplifies to

$$D = C_1 R - C_2$$

In this equation, C_1 and C_2 are constants for a particular rod. The preceding equation shows that D can be calculated from only one resistance measurement if the reading is taken at the proper time during the cooling process.

The basic concept of resin-type meter is straightforward; however, an assessment of its true merit will require additional study. An early phase of the work must be aimed at reducing the resistivity of the plastic without

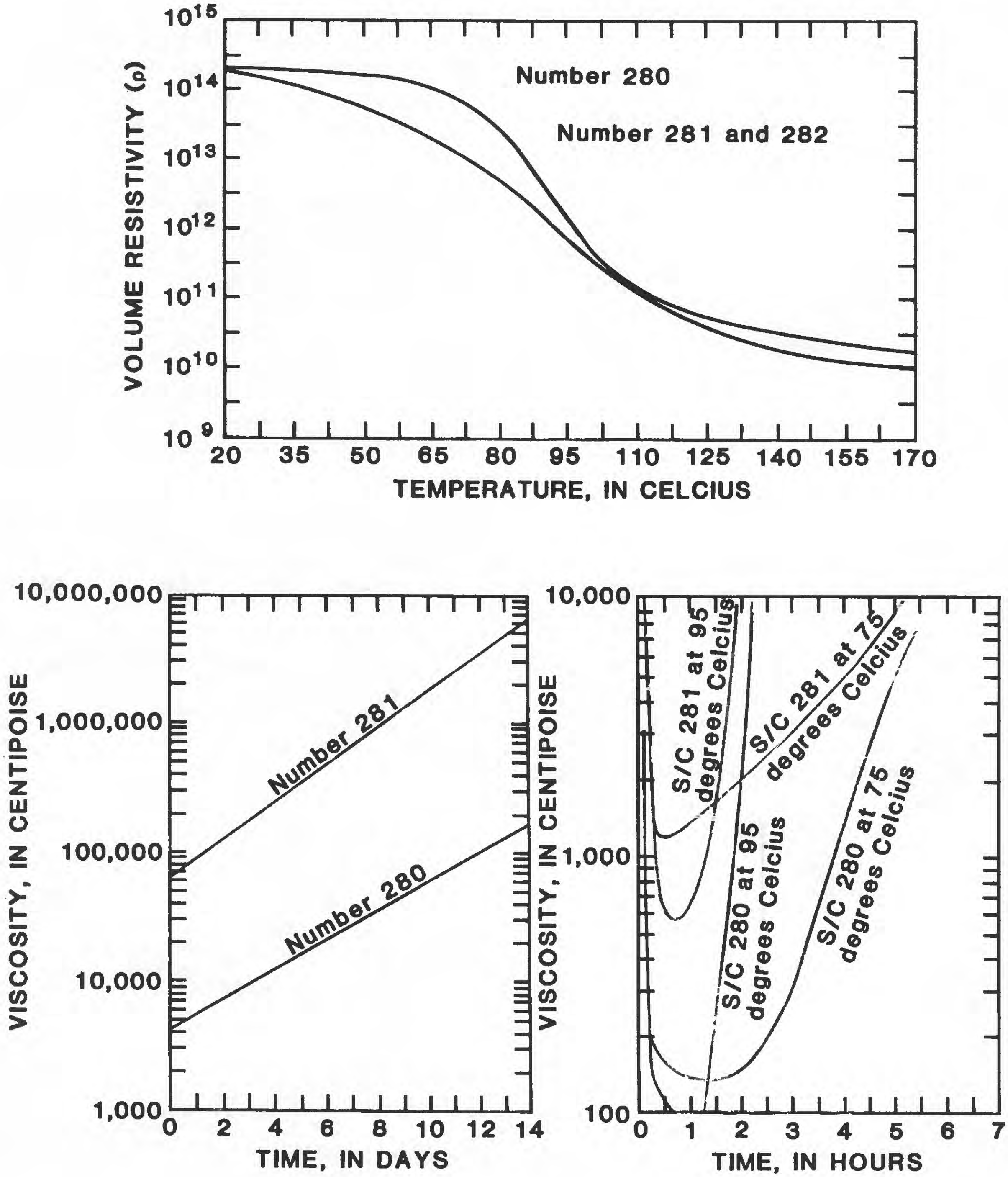


Figure 12.--Characteristics of a special casting resin

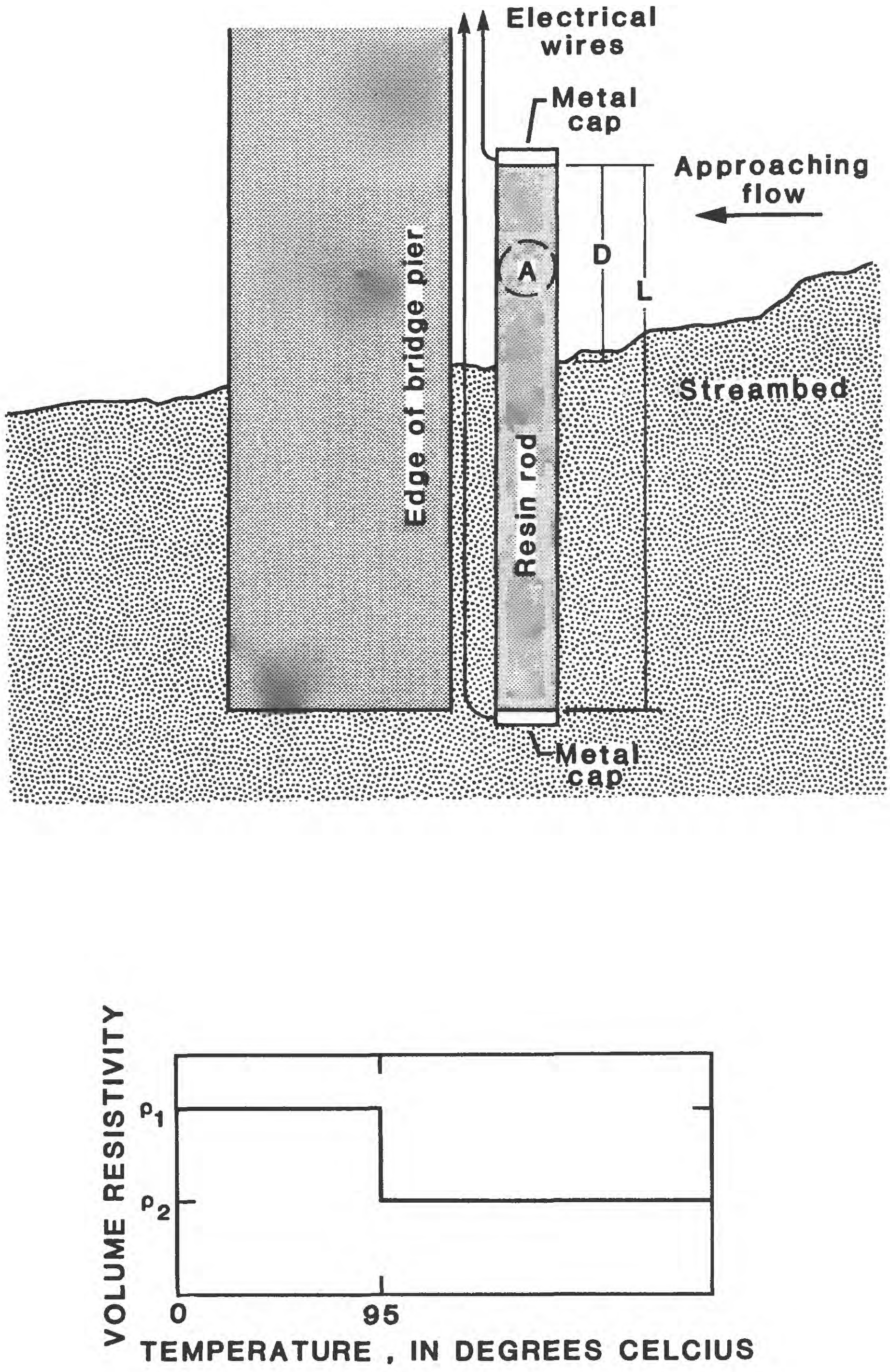


Figure 13.--A resin-type scour meter

sacrificing its step-like response curve. A rod of "Scotchcast brand resin number 280" resin has a resistance of about 1 x 10^{12} ohms, a value far too high for underwater applications. It may be possible to lower the resistivity by mixing high conductivity particles (metal filings or graphite) with the resin. Reformulating the resin, or shifting to a different resin may be helpful. If the electrical conductivity can be adjusted, then the mathematical analysis presented in this paper should be refined. A rigorous analysis will help assess sources of measurement interference, refine the operating techniques, and evaluate measurement accuracy.

CONCLUSIONS

1. Designing an unmanned craft for mapping scour holes appears feasible if the craft can be attached to a tether line or if the design speed can be reduced significantly. The design speed used in this study was 15 ft/s. If experimental work is undertaken, the first step should consist of refining the drag curves for small, shallow-draft boats.

2. An underwater propeller has a clear advantage over an air fan. Unfortunately, choosing between a gasoline engine and an electric motor is more difficult. A gasoline engine has a significant weight advantage; however, the scale tips slightly in favor of an electric motor because it's safer and easier to control.

3. A boat attached to a tether and equipped with a controllable rudder eliminates problems of supplying power. The boat will not be as maneuverable as a free-running craft; however, it can probably reach piers closer than 400 ft from the river bank.

4. A wire (possibly the tether line) or a low-power radio transmitter are probably the best ways of transmitting data from an unmanned craft to a shore-based recorder.

5. Ground-penetrating radar should be evaluated as a means of collecting scour data.

6. Gages for measuring scour at a point provide no direct information on the breadth of a scour hole; however, the gages may be useful for monitoring critical points near a pier. A prototype gage containing thermistors should be laboratory tested to evaluate the effects of corrosion. A special synthetic resin shows promise for use in point gages; however, the resin's resistivity is too high for underwater applications. Developing methods for lowering the resistivity should be the next stage of investigation.

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