ERDC/CRREL TR-04-9

Cold Regions Research and Engineering Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Laboratory Test of Scour Under Ice: Data and Preliminary Results

Decker Hains and Leonard Zabilansky

April 2004

Best Available Copy

20040511 074

ERDC/CRREL TR-04-9
April 2004

Laboratory Test of Scour Under Ice: Data and Preliminary Results

Decker Hains and Leonard Zabilansky

Cold Regions Research and Engineering Laboratory
U.S. Army Engineer Research and Development Center
72 Lyme Road
Hanover, New Hampshire 03755

ABSTRACT

An ice cover may be a major factor determining how alluvial channel morphology evolves in rivers, and a significant influence on bridge pier scour. This was confirmed with real-time monitoring of the bed elevation and extensive bathometry measurements made in the Mississippi River, the Missouri River, and the White River in Vermont. In all cases, the sediment process was significantly different from what existing sediment equations would predict. This laboratory study examined the sensitivity of various parameters affecting sediment transport under ice. Twenty tests were conducted in CRREL's refrigerated flume using mean flow velocities in the clear-water scour range. Three surface conditions were modeled: open water, a floating cover, and a fixed cover, simulating ice frozen to the river banks and a bridge pier, with a superimposed hydrostatic head that could be created by an upstream ice jam. The ice cover was simulated using Styrofoam with both smooth and rough surfaces. Under clear-water scour, the equilibrium scour depths for the fixed and floating covers were similar, but up to 21% higher than those found for open water. The cover roughness altered the velocity distribution and caused live-bed scour even when the mean flow velocity was 0.86 times the critical velocity for bed movement. When the average velocity was 0.93 times critical velocity, the pressure flow caused live-bed scour. A combination of increased cover roughness and pressure flow resulted in the largest equilibrium scour depth.

CONTENTS

ILLUSTRATIONS

TABLES

PREFACE

This report was prepared by Captain Decker Hains, PhD Candidate, Lehigh University, and Leonard Zabilansky, Ice Engineering Team, Engineering Resources Branch U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Documenting the effects of an ice cover on bed degradation in general and bridge pier scour specifically required developing a unique set of flume experiments. To accomplish the test series within the limited resources without compromising quality required a unique team of technicians. Rosanne Stoops fabricated the ice restrain system that could be quickly installed or removed, minimizing the effect on the bed. Jesse Stanley developed the instrumentation package, including refining the laser distance measuring system for profiling the bed through static water. Tom Morgan, Chris Donnelly, and Bill Burch fabricated the adjustable weir and bed leveling system. John Gagnon documented the scour process during the tests using a series of web cameras.

The Commander and Executive Director of the Engineer Research and Development Center is COL John W. Morris III, EN. The Director is Dr. James R. Houston.

Laboratory Test of Scour Under Ice: Data and Preliminary Results

DECKER HAINS AND LEONARD ZABILANSKY

1 BACKGROUND

The influence of an ice cover on bathometry is a complex interaction among the ice cover, ice roughness, fluid flow, sediment, bed geometry, water depth, and channel geometry. An ice cover approximately doubles the wetted perimeter of the river, adding to the flow resistance. The process is further complicated if the cover becomes frozen to the riverbank and bridge piers, which restrain it from freely responding to changes in the stage. Conveying a discharge similar to the open-water value or any increase in discharge above the freezeup datum has to be accommodated by an increase in the mean velocity. This complex interaction can have dramatic effects on rate of bed and bank degradation and scour around the bridge piers, as the increase in velocity creates a corresponding increase in the erosive shear stresses at the bed.

Three field monitoring programs were conducted in three rivers, i.e., a navigation pool on the Mississippi River near Andalusia, Illinois; the White River in White River Junction, Vermont; and the Fort Peck reach of the Missouri in Montana, with the objective of documenting changes in bed elevations as a function of the hydraulic and ice conditions (Zabilansky 2002). The sites were instrumented with Time Domain Reflectometry (TDR) to monitor the bed elevation, with water pressure transducers for water level, and thermistors for monitoring air and water temperature. Ice conditions were visually documented with web cameras.

For an appreciation of the observation, we will recap the finding at the respective sites.

Mississippi River near Andalusia, Illinois

The site is downstream of Rock Island, Illinois, in a backwater area approximately 1000 ft (300 m) from the dredged navigation channel. The river is on the order of 1500 ft (450 m) wide in the study reach. The objective here was to explain discrepancies between the actual rate of sediment deposition in a small dredged channel into a wetland habitat and the results of a numerical model used to design the channel. The model grossly underestimated the rate of deposition and the channel needs frequent dredge maintenance. A dam maintained the stage of the navigation pool downstream of the site and water velocity in the study area was very low. As the ice cover formed, the loss in conveyance attributable to the increase in the hydraulic radius caused an increase in the stage. The ice cover remained static at the freezeup datum, with the flow area and sediment capacity of the river in balance. While the river was completely ice covered, the six TDR's did not detect any change is bed elevation. Once the navigation channel opened in the spring, a disproportional segment of the flow could be conveyed in the open water region and the open water also provided a relief for any hydrostatic pressure under the ice cover. Both conditions resulted in a decrease in the velocity in the ice-covered regions and caused sediment deposition in the study area. This process follows more traditional thinking that an ice cover decreases the energy gradient and subsequently reduces the sediment carrying capacity of a river.

White River, White River Junction, Vermont

On 26 January 1990, the Bridge Street Bridge on the White River in White River Junction, Vermont, collapsed during ice breakup. Although installed as a temporary bridge in 1964 when two spans of the original bridge were pushed off the pier by ice forces, this bridge lasted for nearly 26 years. Based on historical flow and weather data, the bridge had been subjected to ice breakups on other occasions with potentially more ice, ascribable to lower temperatures or higher stage levels or both (Fig. 1).

The primary cause of the failure was attributed to scour aggravated by the ice and, specifically, to the deterioration of the structural integrity of the foundation from the cumulative effect of scour (Fig. 2) (Zabilansky 1996).

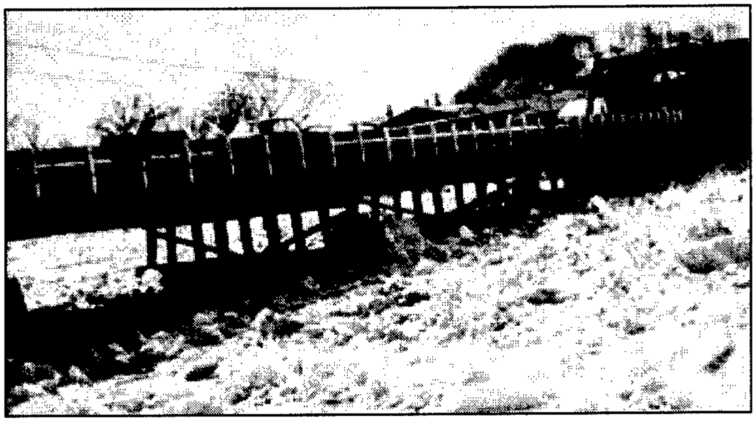


Figure 1. Temporary bridge piers subjected to ice forces in 1969.

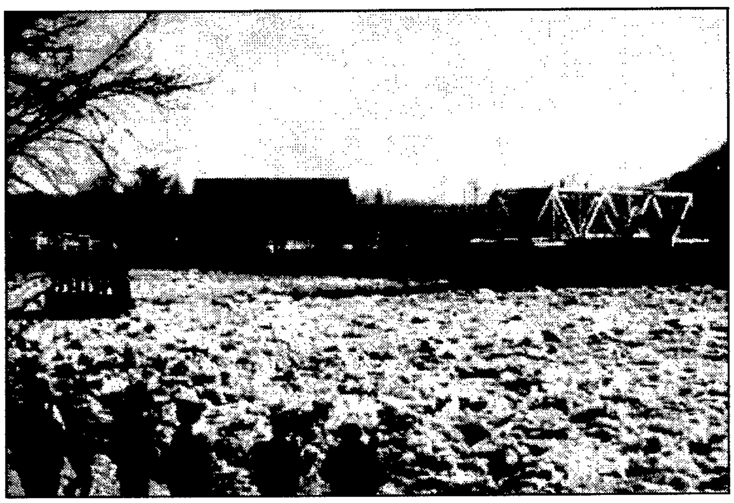


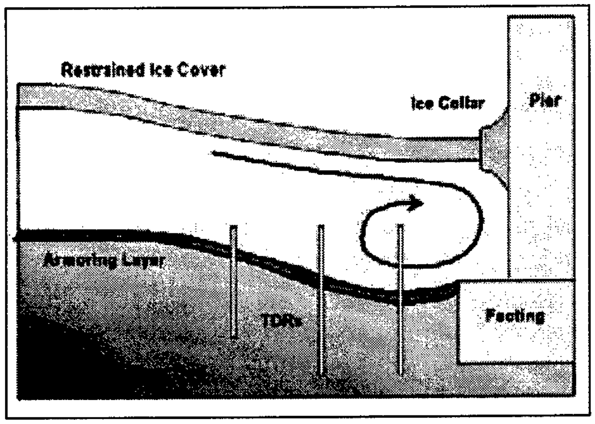
Figure 2. Failure of the Bridge Street Bridge, 26 January 1990, looking downstream.

During construction of the replacement bridge, an ice force panel was incorporated into the design, but the piers were heavily armored against scour. As an alternative, the US Route 5 bridge, which is just upstream, was instrumented for scour. Three TDRs were installed immediately upstream of the bridge pier to document the ice effects on bridge pier scour. The river is shallow, about 150 ft (45 m) wide, and freezeup is generally by consolidation and freezing of frazil ice pans. The ice cover forms at the stage corresponding to the freezeup discharge and freezes to the riverbanks and bridge structures, fixing the stage elevation in the area surrounding the bridge. The Bridge Street Bridge case study and subsequent monitoring in the White River at the Route 5 Bridge illustrate the cyclic nature and cumulative effect of scour under ice covers.

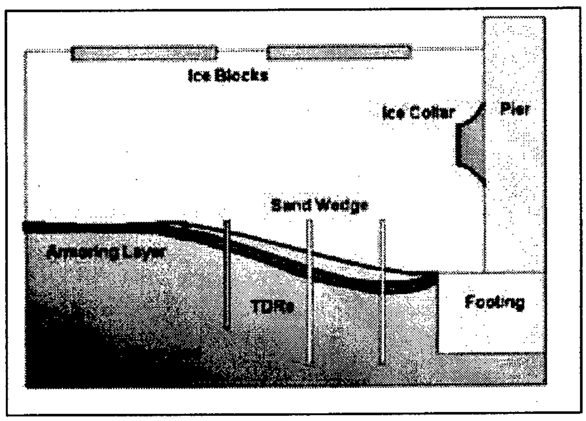
As observed at White River, the cycle under a fixed ice covers begins with the initial formation of the ice cover, typically at relatively low discharges. During the winter, the ice thickens and attaches to the bridge elements and the riverbank. Any increases in discharge above this freezeup datum can lead to a rapid increase in flow velocity and local scour. Generally, the ice cover will not break up until the upstream stage increases two to four times the ice thickness (Donchenko 1975). With the ice attached, the ice cover defines the water surface elevation and the flow becomes pressurized, as just mentioned, with any increase in discharge that is above the freezeup discharge. Although significant for cold regions, this time-dependent effect of the fixed ice cover has yet to be considered in scour predictions.

The scour process is exacerbated by ice jams forming upstream of the structures. These jams impede water flow and generate a hydrostatic head under ice covers attached to the shore. As the ice jams progress downstream, the water waves associated with the cyclic formation and release of the jam cause a fluctuation of pore pressure, which encourages resuspension of the sediment. Once the fixed ice cover breaks up, the stage increases, and the flow velocity decreases. Both the fine-grained, suspended sediment that can no longer be carried through the low-velocity zones near the scour holes and suspended sediment are deposited in the scour holes. Moreover, as the spring hydrograph continues, the gravel being transported as bed-load deposits on top of the sediment layer, restoring the gravel wedge upstream of the pier by early summer (Fig. 3).

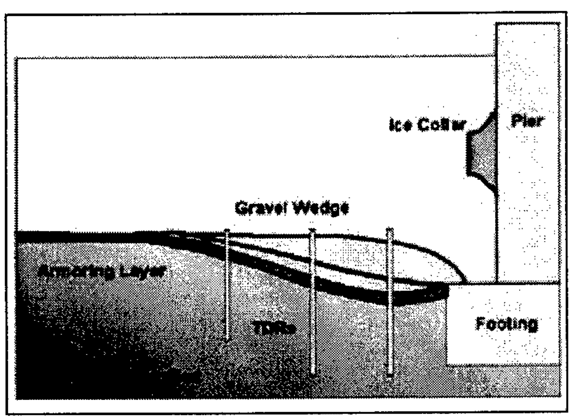
Because sediment deposits back in the scour hole, camouflaging its depth, sounding rods and acoustic sonar, which are typically used to profile scour, do not define the total scour depth. These measurements will indicate that either there was no scour under the ice cover or that it was insignificant. However, during the next winter, this non-structural fill is quickly removed and scours resumes. Thus, the scour process has a cumulative effect.



a. Initial stage before breakup.



b. Conditions immediately following breakup.

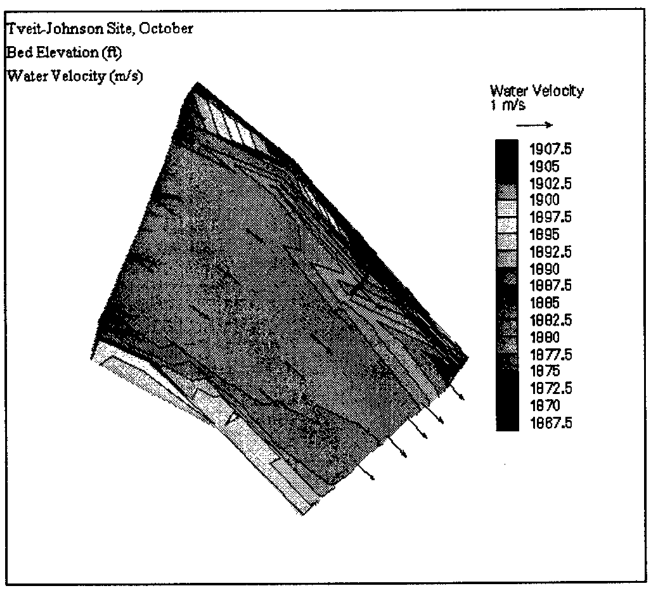


c. Conditions during the rising limb the spring hydrograph following breakup.

Figure 3. Typical conditions during the scour cycle.

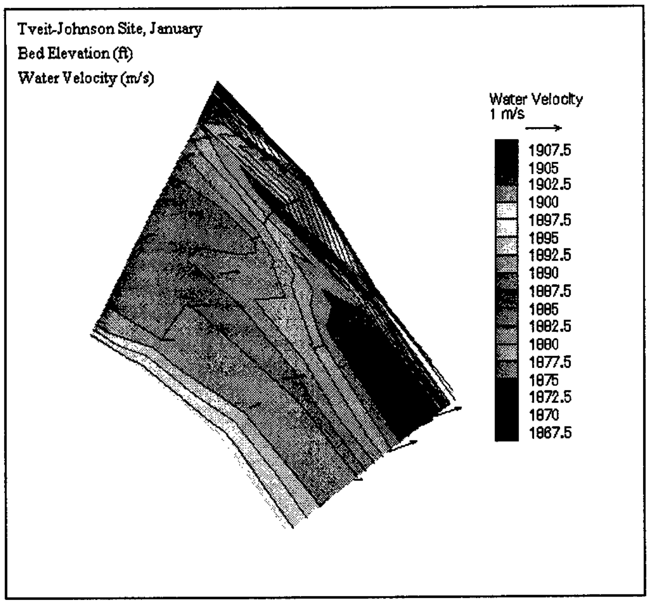
Fort Peck Reach of the Missouri River

During the winter of 1998–1999, seven TDR probes were incorporated into a comprehensive study to assess the effect of an ice cover on river morphology and bridge scour on the Missouri River in Montana (Zabilansky et al. 2002). The TDRs were used to continuously monitor the bed elevation near the Route 16 Bridge over the Missouri River in Culbertson, Montana. The ice cover had a dramatic effect on the rate of scour and significantly changes the river bathometry. Observations made at the Culbertson site were reinforced by the periodic bathometry and velocity measurement at four other sites along the Fort Peck Reach. Four surveys were conducted at the five sites: October during open water, January after the ice was safe, February just prior to breakup, and in April following breakup with the objective of correlating ice processes with the sediment process. Scour holes that developed between the January and February survey were basically filled in by the open water survey in April. One example is a 35-ft (10-m) scour evolution hole at Tveit-Johnson site (Fig. 4).

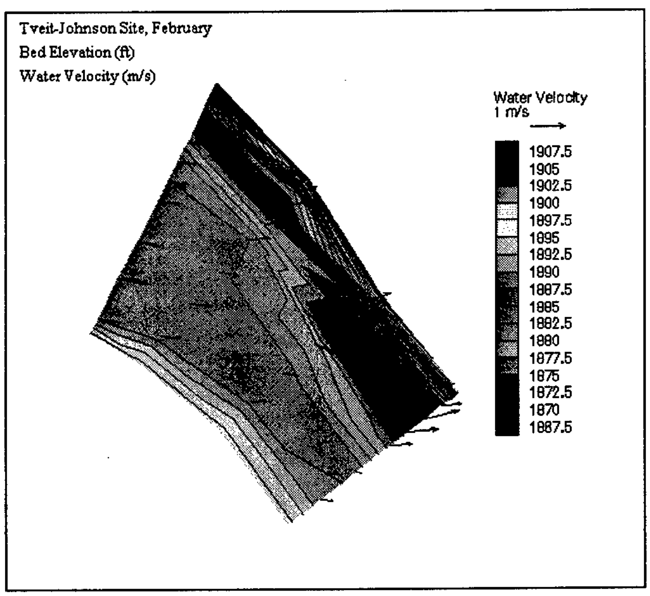


a. October.

Figure 4. Scour hole at the Tveit-Johnson site (bed elevations in feet).

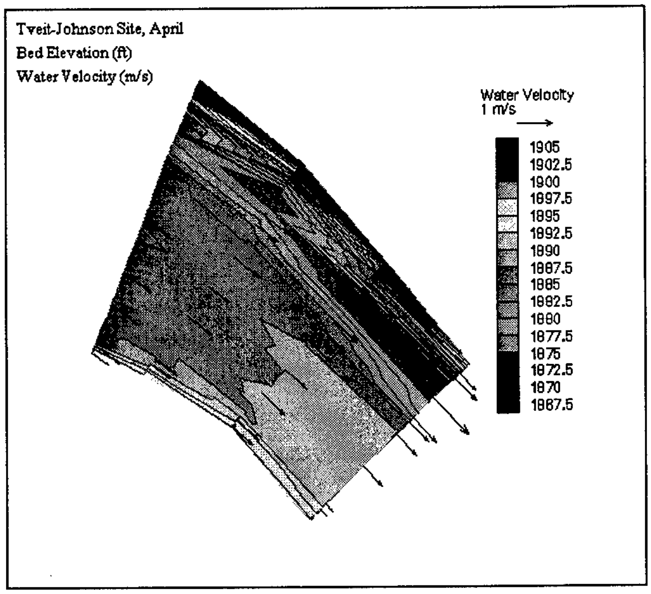


b. January.



c. February.

Figure 4 (cont'd).



d. April.

Figure 4 (cont'd). Scour hole at the Tveit-Johnson site (bed elevations in feet).

Data from this study on the Missouri River in Culbertson, Montana, reinforces the results from theWhite River. The rate of bed erosion increased while ice pans accumulated to form an ice cover with an irregular and rough bottom. The added roughness increases near-bed velocity to above the sediment transport threshold. The bed elevation is stabilized as bed erosion and the smoothing of the underside of the ice increase the flow conveyance of the cross section. This equilibrium is disturbed in the early stages of breakup, as the discharge increase and ice pieces from upstream are conveyed under the ice cover, adding bottom roughness.

The need for additional research in scour under ice is specifically addressed as a research need by the Federal Highway Administration (1993). They state that

> Laboratory studies are needed to better understand certain elements of the scour processes and develop alternate and improved scour countermeasures. Only through controlled experiments can the effect of the variables and parameters associated with scour be determined. Through these efforts, scour prediction equations can be improved and additional design methods for countermeasures developed. Results from these laboratory experiments must be verified by ongoing field measurements of scour.

Furthermore,

> Laboratory and field research is needed to:
>
> a. Improve methods to predict scour depths associated with pressure flows….[and]
>
> e. Determine methods to predict scour depths where there is ice or debris build-up at a pier or abutment.

2 TEST OBJECTIVES

General

The purpose of this study was to define the effect of pressure flow under a fixed ice cover on bed erosion and scour at bridge piers using a laboratory flume. The study was conducted in the clear water scour regime for three cover conditions: open channel with no cover, a floating cover, and a fixed ice cover.

The study has four major objectives:

1. To obtain scour depth, scour pattern, and velocity profiles under a fixed ice cover condition in a laboratory flume.
2. To compare the results from the fixed ice cover conditions to the open water and floating cover conditions.
3. To understand the mechanisms of local scour under pressure flow to include the effect of the ice cover roughness.
4. To compare results of open water and floating cover conditions to previous research to validate the results.

The objectives will be accomplished by determining:

1. The depth of scour at the upstream, center face of the bridge pier for three surface conditions (open water, floating cover and fixed cover) as a function of time.
2. The vertical velocity profiles located twelve feet upstream of the pier and at three locations across the flume.
3. The resulting scour hole pattern upstream and downstream of the pier in three dimensions.

This study deals exclusively with clear water scour at a cylindrical bridge pier to which simulated ice is attached. It is the first investigation focusing on developing a method to evaluate and understand scour at a bridge pier under a fixed ice cover.

Unique Aspects of the Study

As the first research of this kind, this study has several distinguishing features.

- Simulating the early stage of breakup by restraining the ice cover to create the pressure flow condition.

- Recording the scour process via a small camera installed inside the clear cylindrical pier.
- Installing pressure transducers at key cross sections to monitor and record water surface elevations and pressure head above the ice cover.
- Profiling the resulting scour hole using the Banner LT3NU, long-range time-of-flight, self-contained class 2 laser distance measurement instrument through the water.
- Sampling velocity using the acoustic doppler, Sontek 2-D probe and sampling at 1-cm elevations at a rate of one per second for 2 minutes.
- Maintaining the water temperature at approximately 2°C (35°F) to replicate the sediment capacity of cold water during breakup

3 EXPERIMENTAL SETUP

For our investigation of the influence of the ice cover on bed erosion and local bridge pier scour under varying flow and cover conditions, we focused on the scour around the model pier to capitalize on previous open water and floating ice cover tests using bridge piers. Table 1 lists the general conditions for the 20 tests that were conducted.

Table 1. Test conditions.

Number of tests	Cover condition	Relative cover roughness
6	Open water/free surface	N/A
5	Floating	Smooth
1	Floating	Rough
6	Fixed	Smooth
2	Fixed	Rough

The following parameters were documented during the tests:

d_s = depth of scour (cm or in.)

Q = flow rate (m^3/s or ft^3/s or gal./min)

V = mean flow velocity (m/s or ft/s)

y_a = approach flow depth or equivalent hydrostatic pressure (cm or in.)

y_{fixed} = flow depth under the fixed cover (cm or in.)

S_f = slope of flume.

Flow System

The experimental apparatus used in this study is the recirculating titling bed flume housed in a cold room within the Ice Engineering Facility at CRREL. The flume is 120 ft (36.58 m) long, 4 ft (1.22 m) wide, and 2 ft (0.61 m) deep, and can be tilted from a 1 to –2° slope. To avoid the interdependence between the ice cover and the sediment transport process, we elected to use simulated ice with stable engineering properties rather than to refrigerate the room and freeze an ice cover with potentially ever-changing engineering properties. To replicate water conditions at breakup, the water was chilling using refrigerated coils, which are submerged in a reservoir in the facility's basement. A resistance temperature device within the reservoir monitors the water temperature and, in conjunction with the programmable logical controller, maintained the water temperature at 1.6°C (35°F).

A rubber-lined impeller pump, capable of pumping a maximum of 0.11 m^3/s (1800 gal./min), circulated water through the flume. A closed-loop control system, consisting of a magnetic flow meter, process controller, and frequency drive on the motor, maintains a tight tolerance on the pump discharge of ±0.5% of the full scale or 0.5 L/s (±9 gal./min). The magnetic flow meter was calibrated in accordance with ANSI/Z540 and is traceable to the National Institute of Standards and Technology just prior to the test. Although the flume is capable of recirculating sediment, this feature was not used because the tests were conducted in the clear water scour regime.

The pump discharges into the head box of the flume and the flow enters the flume through a bundle of parallel 1.25-in. (3.175-cm) diameter, 24-in. (61-cm) long PVC pipes designed to straighten the flow (Fig. 5). Achieving a relatively uniform flow near the head box maximizes the working length of the flume and ensures relatively uniform, fully developed flow in the test region. To control the stage in the flume, an adjustable weir was located near the tail box of the flume (Fig. 6).

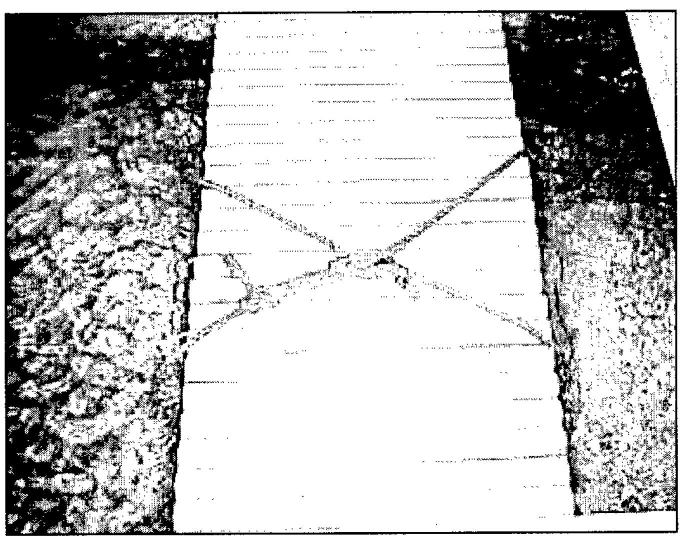


Figure 5. Flow passes through the flow straighteners before entering the flume.

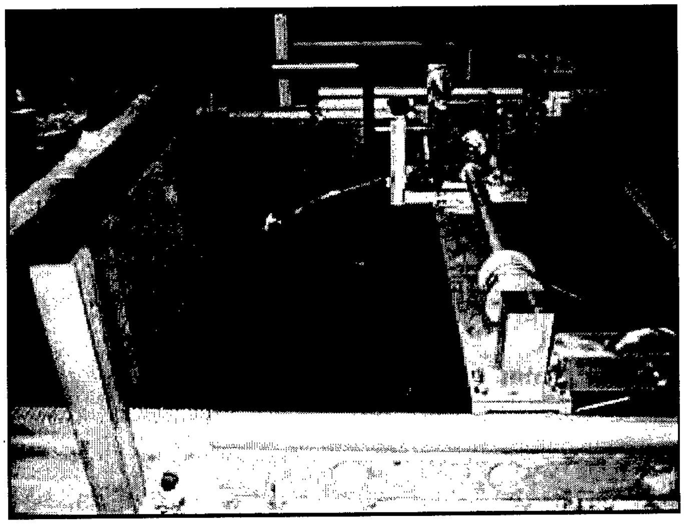


Figure 6. Adjustable weir used to control the water surface level in the flume.

Sediment Characteristics

Downstream of the entrance transition section, the flume was filled to a depth 7.5 in. of (19.05 cm) with uniform sand. The sand has a mean grain diameter (d_{50}) of 0.005 in. (0.13 mm) and a sediment uniformity coefficient (σ_g) of 1.417. Table 2 lists the average grain size distribution and Figure 7 shows the sediment gradation curve. To avoid any bed erosion attributable to end conditions, 7.5-in. (19.05-cm) high bulkheads were installed at both ends of the sediment test section.

Table 2. Average grain size distribution.

Sieve size	Sieve size (mm)	Percent passing
#20	0.840	100.0
#40	0.420	99.9
#60	0.250	97.6
#100	0.149	67.4
#200	0.074	4.5

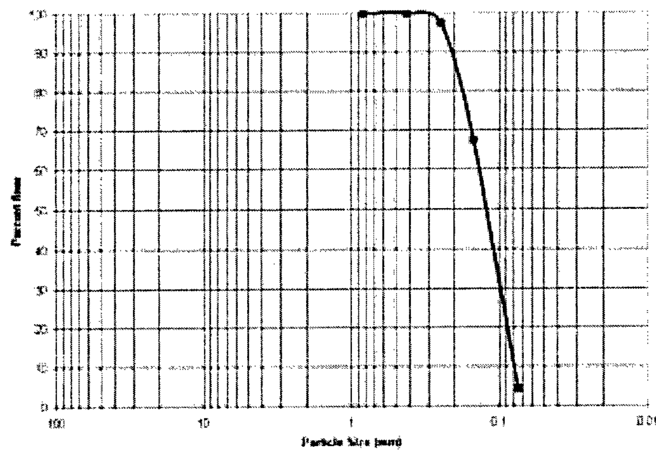


Figure 7. Grain size distribution for flume sediment.

Model Bridge Pier

The bridge pier was simulated by a smooth, transparent Plexiglas cylinder with an outside diameter of 2 in. (5.1 cm), placed 90 ft (27.4) m downstream from the flume entrance. It was glued at a 90° angle to a ¼-in.-thick, 12- × 12-in. (6.35-mm-thick, 30.5- × 30.5-cm) square plate that was, in turn, glued to the bed of the flume (Fig. 8). Velocity measurements were taken 12 ft (3.7 m) upstream of the pier. Figure 9 depicts the key cross section of the experimental set-up.

Figure 8. Pier model.

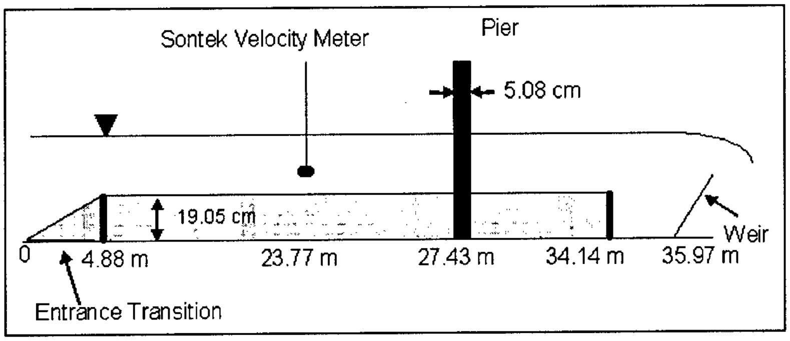


Figure 9. Experimental set-up: key cross-sections; flow is from left to right.

Simulated Ice Covers

The ice cover was simulated using 2-in. (5-cm) thick Styrofoam insulation panels that were glued together and trimmed for an overall dimension of 47 in. by 8 ft (1.1938 by 2.4384 m) long. A tongue and groove interconnection was used to provide shear transfer between adjacent panels. To investigate the effect of cover roughness, two surface roughness conditions were simulated. The manufactured Styrofoam finish was used for the smooth ice cover (Fig. 10). For the rough cover, an open mat geo-textile called Enkamat, manufactured by Maccaferri, was attached to the Styrofoam (Fig. 11). Manning's *n* for the smooth cover is reported as 0.016 (Wuebben 1986). From an in-situ resistance test, Manning's *n* was determined to be 0.048 for the rough cover (Maccaferri Engineering, 2002).

Figure 10. Smooth cover.

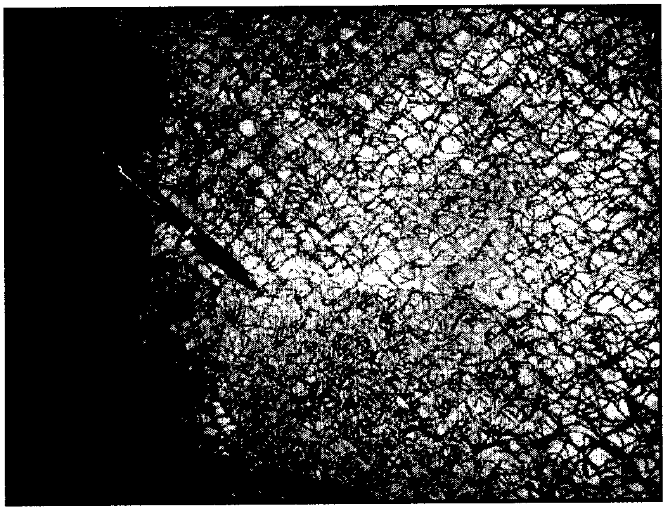


Figure 11. Rough cover.

Fixed Ice Cover System

For the fixed cover tests, the simulated ice was fixed vertically from 40 ft (12.2 m) upstream to 10 ft (3.05 m) downstream of the pier to maintain a water depth of 9 in. (22.9 cm).

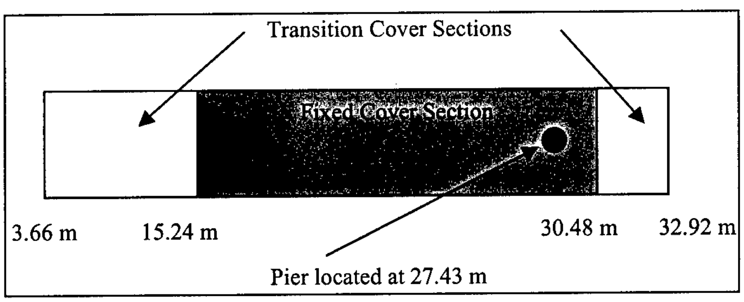


Figure 12. Fixed cover key cross-sections; flow is from the left to right.

To simulate an upstream ice jam that developed a hydrostatic head under the fixed cover section, a 38-ft-long (11.58-m-long) transition section extended immediately upstream of the fixed cover. The simulated ice in the transition section followed a linear slope from the fixed elevation (9 in. [22.9 cm]) to the hydrostatic head (open water) elevation (12 or 14 in. [30.5 or 38.1 cm]). A similar 8-ft-long (2.43-m-long) transition section extended immediately downstream of the fixed cover to the open water surface. A total of 96 ft (29.3 m) of the flume was covered with 50 ft (15.3 m) of simulated ice, fixing the flow depth. Figure 12 depicts the locations of the fixed ice cover and transition sections.

To fix the cover, a bracing system was designed to withstand the upward pressure from the flow and to be relatively easy to remove between tests for profiling of the surface and smoothing of the bed. In the design, 2×4 dimensional lumber, 16 ft (4.9 m) long, was used as longitudinal supports along the walls and in the center of the flume. The tongue and grove connection between Styrofoam panels across the flume were reinforced by 12-in. (30-cm) wide strips of ½-in. plywood, which locked under the longitudinal 2×4s. Plywood strips were added to the bottom of the longitudinal 2×4s to compensate for the plywood used to reinforce the joints. To seal against the side of the flume and top of the ice, foam rubber was attached to the underside of plywood and to the side of the dimensional lumber. Short 2×4 legs connected the longitudinal supports to a 2×4 top restraining brace, which extended across the flume perpendicular to the flow. The brace extended over the railings on each side of the flume and was clamped to the flume via a carriage bolt clamp or C-clamps (Fig. 13). The wooden top braces and frames were attached to a pulley system to facilitate the removal of the bracing system between tests (Fig. 14–17).

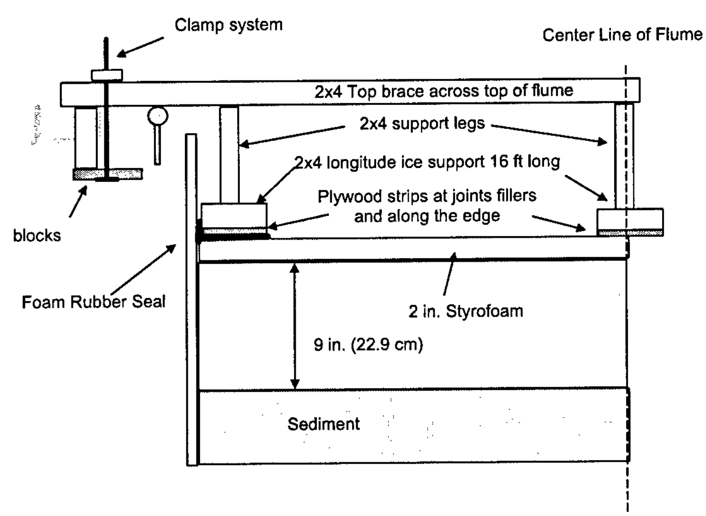


Figure 13. Basic design of the ice restraint system.

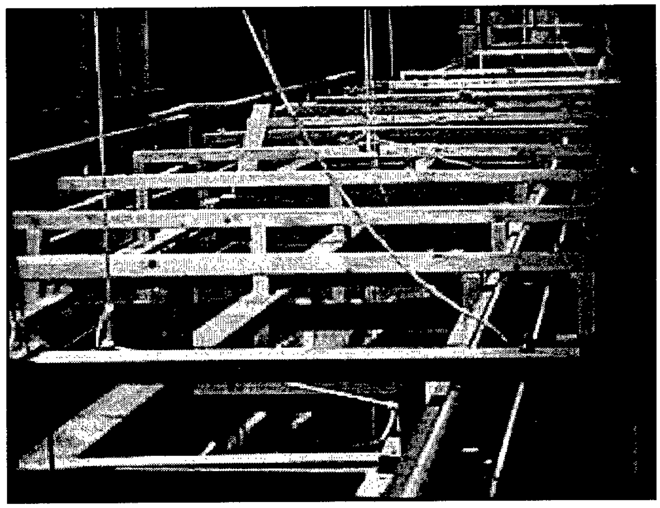


Figure 14. Ice restraint system upstream.

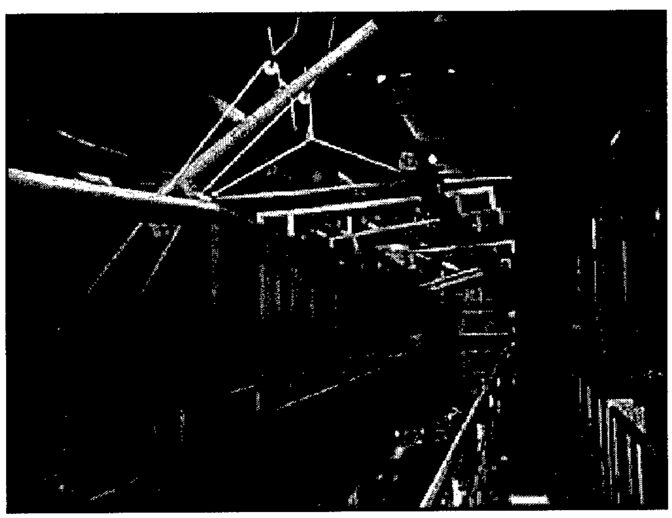


Figure 15. Raised ice restraint system.

Figure 16. Foam seals along the sides of the simulated ice cover.

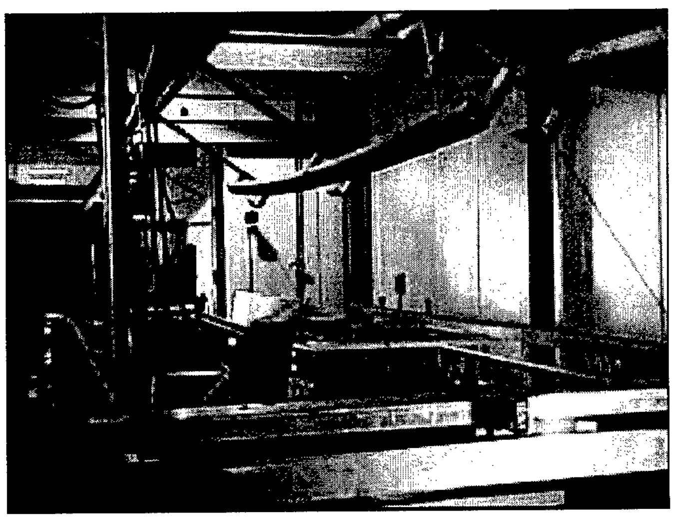


Figure 17. Raised ice restraint system allowed for the instrument carriage to be positioned.

The ice restraint system was not designed to completely prevent water from ponding or flowing on the top surface of the ice cover. The intent was to prevent significant flow across the top surface. Velocity measurements confirmed this assumption. For the restrained tests, the pier protruded and the entry for water velocity probe was through 4-in.-high (10-cm-high) access wells in the Styrofoam.

Data Acquisition

To compare the scour depths and scour patterns among the three test conditions, the following data acquisition goals were established:

1. Measure equilibrium depth of scour at the upstream, center face of the bridge pier.
2. Record the resulting scour hole pattern upstream and downstream of the pier in three dimensions.
3. Measure scour at the upstream, center face of the pier as a function of time.
4. Obtain vertical velocity profiles 12 ft (3.66 m) upstream of the pier at three locations across the flume. These locations are at the centerline of the flume and ±10 in. (±25.5 cm) on each side of the centerline.

Visual Documentation Camera–Mirror System

To monitor the progression of the scour hole immediate upstream of the pier, a measuring tape was installed inside the pier. The depth of scour relative to the tape was monitored using a small camera and mirror assembly, also installed inside the pier. A mirror was fastened to the diagonal face of a wooden dowel, cut at a 45° angle, to convert the horizontal image to a vertical one. This facilitated installing a camera with an integrated light source inside the pier. A threaded rod was attached to the wooden dowel and the other end was attached to a bracket holding the small camera. The short threaded rod was used to adjust the focus on the camera. The mirror–camera assembly was attached to a second threaded rod, which extended up through a plate resting on the top of the model pier (Fig. 18–20). A wing nut was used to adjust the height of the camera-mirror assembly so that the water-sediment interface was always in view. The camera images were displayed in real-time on a video monitor so the scour depth could be observed at any time during the experiment. Furthermore, images from this camera were recorded continuously by a videocassette recorder for the first several hours of each test, as well as on a web server at the rate of one image per minute throughout the entire test.

An additional camera was positioned above the pier to record the lateral scour hole development for the open water tests. A camera was also installed on the side of the flume (Fig. 21), focused on the pier to capture the scour process at the pier. This was of limited value owing to the difficulties of lighting, especially under the ice cover, and condensation on the glass sidewalls.

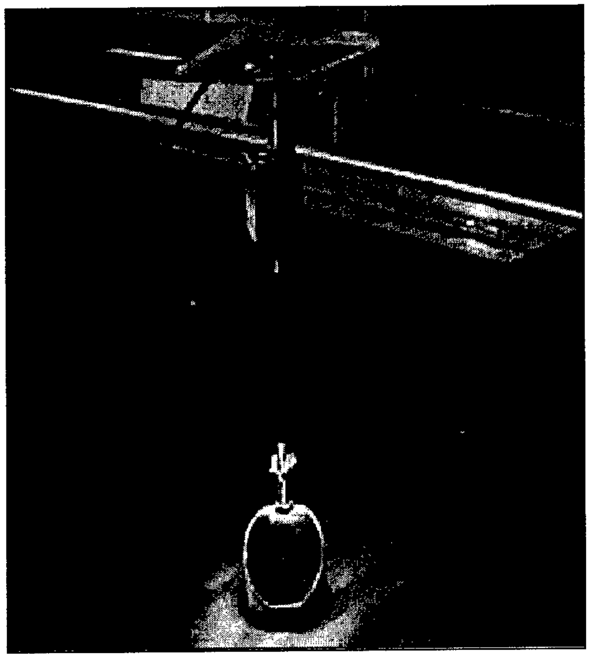


Figure 18. Camera–mirror assembly to measure scour depth at the pier.

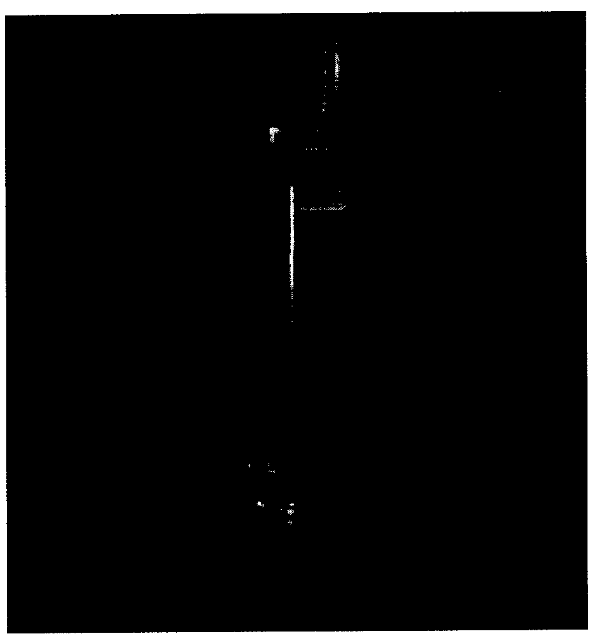


Figure 19. Camera–mirror system installed inside the pier.

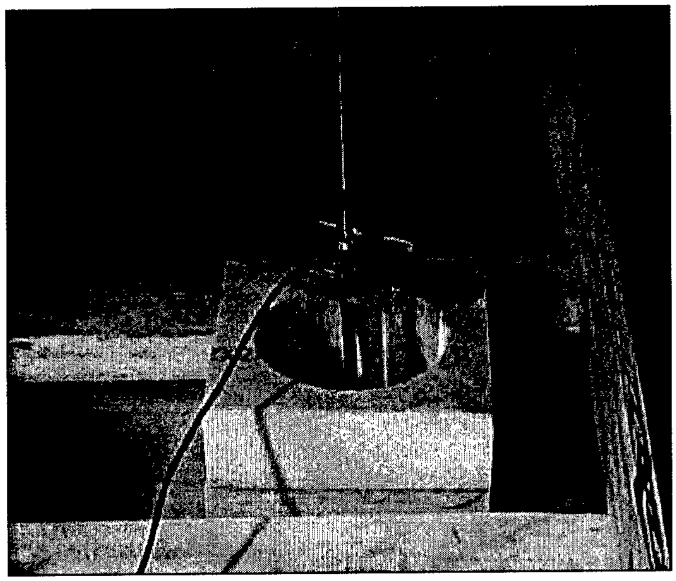


Figure 20. Camera–mirror system in place with fixed ice cover. The Styrofoam well prevented water from flowing up onto the surface of the ice cover.

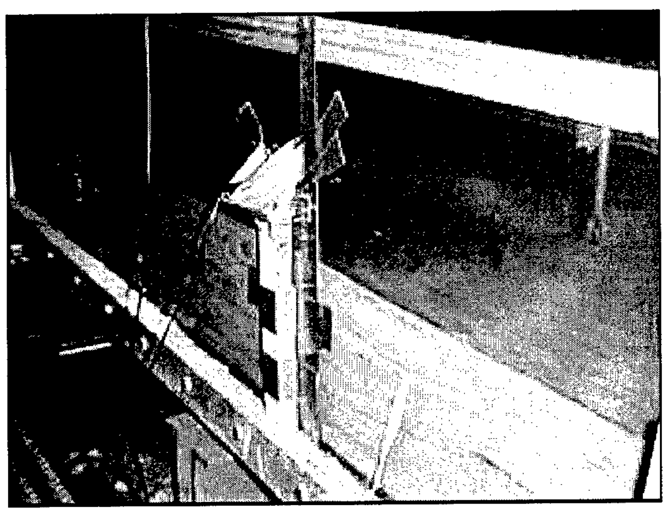


Figure 21. Camera attached to the side of the flume.

Scour Hole Profiling System

Before describing the scour hole profiling system, the coordinate system must be defined. The origin of the *X–Y* horizontal coordinate system is centered on the center of the pier. The *X*-axis is oriented parallel with the flow, with all points downstream of the pier having a negative *X*-coordinate and all points upstream having a positive *X*-coordinate. The *Y*-axis is the perpendicular to the flow and looking upstream; the points on the left side of the pier have positive *Y*-coordinates and points on the right side have negative *Y*-coordinates (Fig. 22). Mutually perpendicular to the *X* and *Y* plane is the vertical *Z*-axis, which parallels the pier and is used for reporting depth of flow and depth of scour.

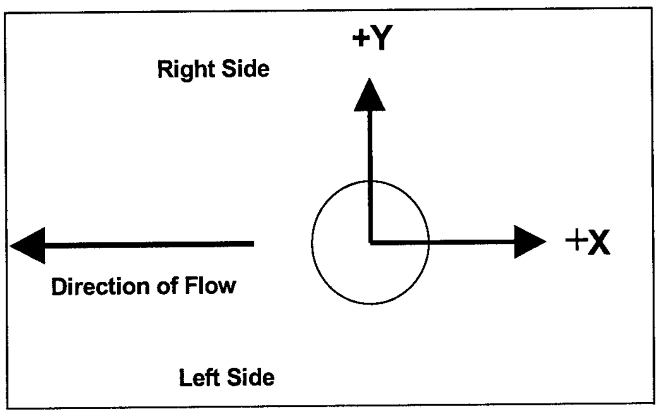


Figure 22. Coordinate system.

To measure the scour pattern in three dimensions upstream and downstream of the pier, a laser distance measuring device was installed on an instrument carriage. The instrument carriage was manually moved along the *X*-axis upstream and downstream to designated *X*-coordinates.

The laser moved across the flume on a motorized drive system and was connected to a linear motion potentiometer (LMP) with dc analog output that corresponded to the *Y*-coordinate (Fig. 23). The LMP is a cable coiled around a spring-loaded drum, designed for constant tension, eliminating slack in the system. The drum is connected to a potentiometer that has a linear change in resistance as the cable is pulled off or recoiled onto the drum. The change in resistance is detected by exciting the system with 10-Vdc and is measured through the change in voltage between the wiper and common. The linear output voltage is processed through a networked data acquisition unit (NETDAQ) and converted to the *Y*-coordinate in centimeters (Fig. 24). For each cross section (designated *X*-coordinate), the *Y*-axis motor moves the laser from the near side to the far side and then back. So for each cross section, two sets of data are collected. These are then averaged during the data processing to cancel out any hysteresis in the measurement system. Each cross section is 39 in. (1 m) wide, and centered on the pier or 19.5 in. (50 cm) on each side of the pier. There were approximately 740 data points recorded at each cross section for an average of 19 data points per inch.

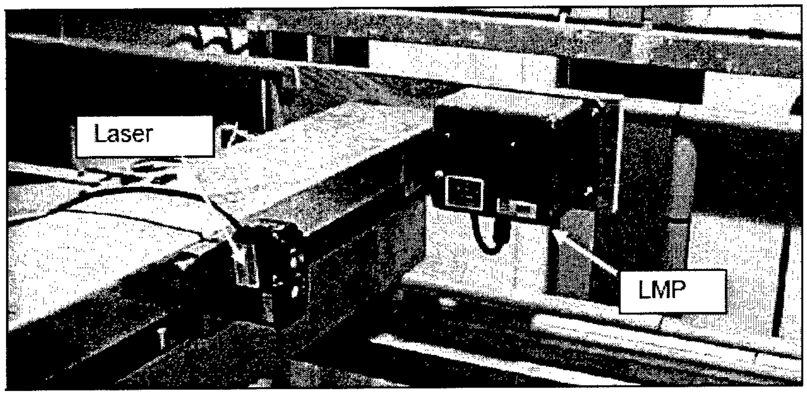


Figure 23. Laser distance measuring system with the attached LMP.

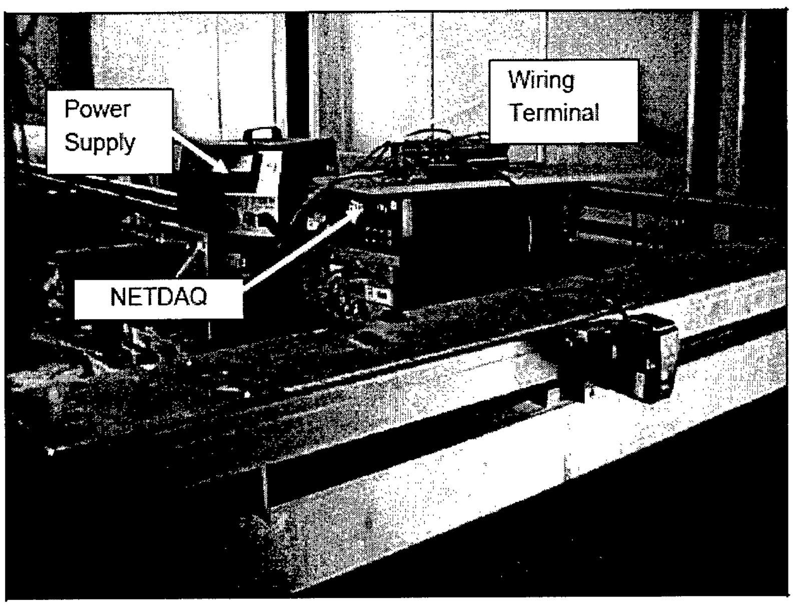


Figure 24. Laser distance measuring system.

The laser distance sensor is a Banner LT3NU, long range time-of-flight, self-contained class 2 device that was used to profile the surface (*Z*-coordinate) at any coordinate in the *X–Y* plane. Inside the Banner LT3NU, a short electrical pulse drives a semiconductor laser diode to emit a pulse of light. The emitted light is collimated through a lens, which produces a very narrow laser beam. The laser beam is reflected off of the target (water and sediment), scattering some of its light through the sensor's receiving lens to a photodiode, which creates an electrical impulse. The time interval between the two electrical impulses, i.e., transmitting and receiving the beam, is used to calculate the distance to the target using the speed of light as a constant. Multiple pulses are evaluated by the sensor's microprocessor, which calculates the appropriate output value. The analog output provides a variable signal (0 to 10 Vdc for the LT3NU model) that is proportional to the target's position within the programmed analog window limits. This output signal is then converted by the NETDAQ to the distance from the reference to the sediment in centimeters.

The initial testing of the laser revealed two limitations for measuring the depth of scour. First, the edges of the flume and the edge of the pier caused significant scattering of the laser beam and, thus, inconsistent distance measurements. This was eliminated when Banner Engineering provided a prototype model with a bandpass filter that rejected extraneous reflected signals, eliminating the side and pier wall effects.

Second, the waves on the water surface reflected some of the laser beam, which confused the laser processor, causing an error in the output signal. The alternative of draining the flume for each test to eliminate the water surface effect on the laser was not consider an option for two important reasons. First, it would be impossible not to disturb the initial bed condition, as the flume was being filled after the initial profile. Second, given the small grain size diameter used, draining the flume after the test would likely disturb the scour hole. For these reasons, the scour hole had to be profiled through the water and the issues with the laser system had to be resolved.

To eliminate the reflection off the water surface, the laser was tilted forward 5° so that any reflection from long period waves were outside of the receiver window, leaving only the return signal from the sand. To minimize the reflection from short period waves, a polarizing lens was positioned over the receiver. The polarizing lens filtered out extraneous reflected signals, resulting in the system measuring the distance to the sand surface. The laser distance measurement is sensitive to depth of water, and to provide consistent and accurate results, the laser was calibrated using an aluminum staircase step apparatus prior to each initial and final profile (Fig. 25). The calibration block rests on the flume bed downstream of the sediment section. It was fabricated from 2- × 3-in. (5- × 7.6-cm) aluminum tubing attached to an aluminum plate. Each successive step was

1.5 in. (3.8 cm) higher and, with seven steps, the calibration block's range was 26.7 cm (10.5 in.). To provide the same reflection characteristics, the interior of the tubing was filled with the bed sediment and leveled prior to each calibration. If the initial and final calibrations differed by a significant distance, an offset was applied when subtracting the surfaces. The calibration block was also used to "teach" or program the laser operating range, which corresponded to the 0–10 Vdc output signal. The depth of scour was the difference between the initial and final profiles. Both profiles were taken with the same nominal water depth, to avoid having to account for the difference in the speed of propagation between air and water.

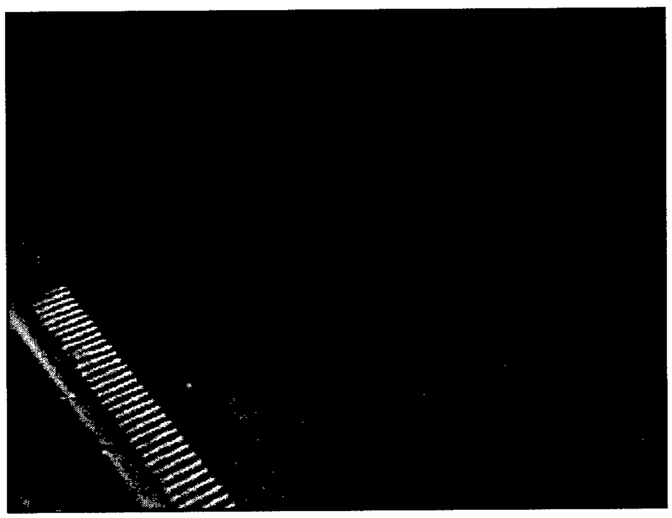


Figure 25. Calibration staircase.

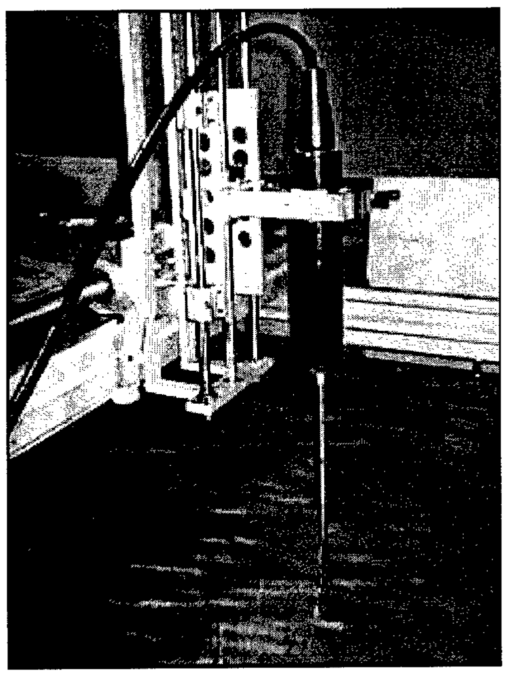
The modifications to the laser and the calibration procedure resulted in very accurate profiling of the bed.

The LMP and the laser were mounted to an instrumentation carriage that traveled along the *X*-axis. To avoid problems associated with transmitting analog signals over long cable lengths, the analog signals were digitized by a Fluke NetDac, which was also on the instrumentation carriage along with the necessary power supplies. The digital signals were transmitted to the data acquisition computer via a local intranet using a 100-MHz CAT-5 cable in an instrumentation festoon.

The NETDAQ generates a comma-separated variable file of *Y* and *Z* coordinates for each cross section based on the output of the LMP and laser, respectively. In a post-processing program, the corresponding *X*-coordinate was added to the *Y–Z* dataset from the respective cross section to develop a single *X–Y–Z* database. This database was then used to generate three-dimensional surface plots in Surfer©.

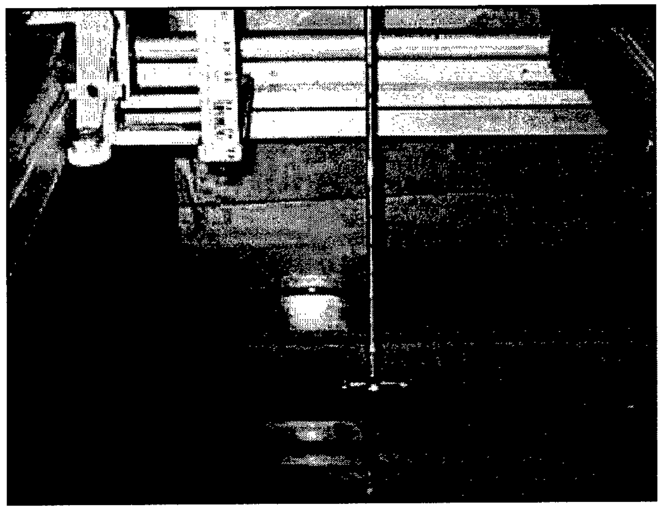
Velocity Measurements

Velocity measurements were taken 12 ft (3.66 m) upstream of the pier on the centerline and at locations 10 in. (25.5 cm) left and right of the centerline. The vertical velocity profiles were taken using a two-dimensional SonTek acoustic doppler velocimeter (ADV), with the measurement plane oriented horizontally and aligned with the *X*–Y axis. The sample rate was one per second for 2 minutes at 1-cm increments between the bed and the water surface or underside of the cover (Fig. 26 and 27).



a. ADV mounted over flume.

Figure 26. SonTek acoustic doppler velocimeter.



b. Closer view of ADV.

Figure 26 (cont'd).

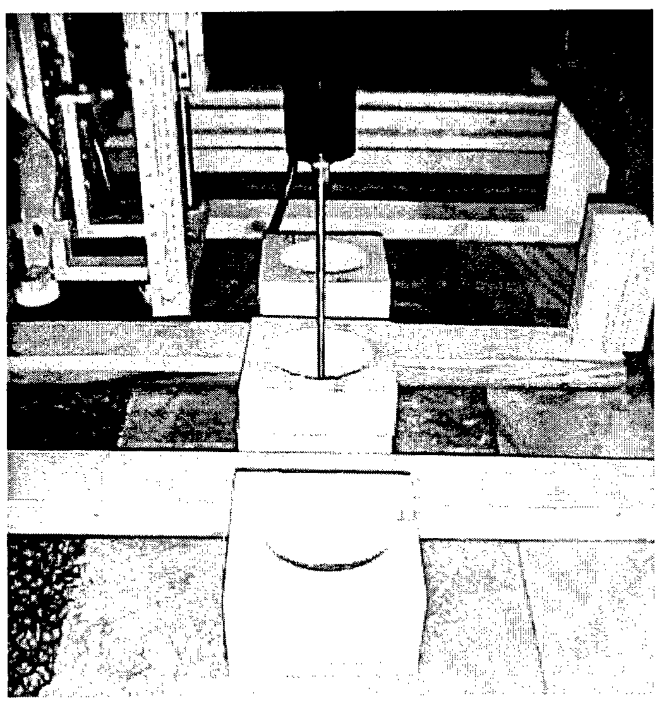


Figure 27. Velocity profiling with the fixed ice cover. The Styrofoam wells prevented water from flowing up onto the surface of the ice cover.

The SonTek ADV probe consists of a sensor that has an acoustic transmitter and an acoustic receiver (Fig. 28). The sensor is mounted on a stem, which is attached to the signal-conditioning module. A high-frequency cable leads from the signal-conditioning module to a personal computer (PC), which was equipped with the ADVLab processor card. The main ADV software (ADV.EXE) runs the real time data acquisition program and allows the user to specify the system of units, water temperature, water salinity, speed of sound, sample rate, velocity range, and the name of the binary data file. Another program, GETVEL.EXE exports the velocity portion of the binary file recorded with ADV.EXE.

The main ADV software was executed for each velocity profile, i.e., center, near side, and far side. The program allows the use of file markers. Each 1-cm (0.4 in.) elevation in the vertical velocity profile had a distinct file marker. For each profile the probe was moved to the designated vertical location, starting at 1 cm from the bed, and then the file marker was initiated. After 2 minutes of data collection, the probe was moved to the next vertical location and another file marker was initiated. The process continued until the vertical profile was complete. A post-processing program, using the file markers, corresponding elevations, and the GETVEL.EXE program, extracted the average velocity, the standard deviation of the velocities, and the maximum and minimum velocities in both the X and Y directions. Only the first 120 data points were used in this analysis as the probe was moved after 2 minutes of sampling.

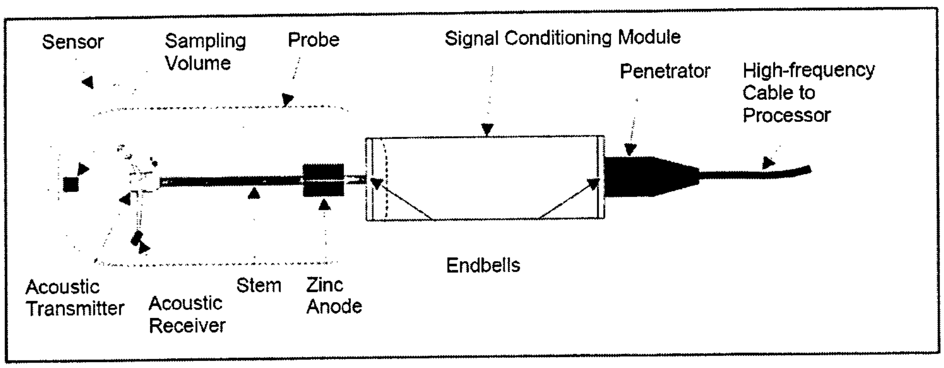


Figure 28. Sontek ADV probe assembly components (after SonTek/YSI, Inc., 1996]).

Pressure Measurement System

To record and monitor the water surface elevations and pressure head along the length of the flume, individual pressure measurement systems were installed at key locations (Table 3). Each individual system consisted of copper pipe manifold buried in the sediment inside the flume, pressure transducers, and Tygon tubing, used to connect the two ends. The manifold was fabricated from two 18-in. (45-cm) long pieces of ½-in. (1.25 cm) copper pipe that were connected by a Tee in the middle. The perpendicular leg of the Tee was inserted into taps along the centerline of the flume, perpendicular to the direction of flow (Fig. 29 and 30). Small holes were drilled in the pipe to allow water to flow into the manifold. These holes were covered with filter fabric to prevent sediment from plugging the manifold. From the tap connection on the underside of the flume, plastic Tygon tubing transmitted the water pressure to the Sensotec pressure transducers (Fig. 31). These transducers are constructed of stainless steel and utilize complete four-arm 350-Ω strain gage bridges having a range of 30 in. (76 cm) with a corresponding output of 0–10 V. The analog signals were digitized using a second NETDAQ unit (Fig. 32). Readings from each of the transducers were recorded to a comma-separated variable file at the rate of one per minute throughout the test.

Table 3. Locations of the taps for pressure measurements.

Number	Location		Purpose
	(m)	(ft)	
1	2.87	9.4	Upstream in the open water area
2	10.18	33.4	Upstream under the transition/floating cover
3	17.50	57.4	Upstream under the fixed cover
4	22.98	75.4	Upstream under the fixed cover near the velocity probe
5	26.64	87.4	Upstream under the fixed cover near the pier
6	28.16	92.4	Downstream under the fixed cover near the pier
*7	31.21	102.4	Downstream under the transition/floating cover
8	33.04	108.4	Downstream in the open water area

* The pressure transducer for #7 malfunctioned.

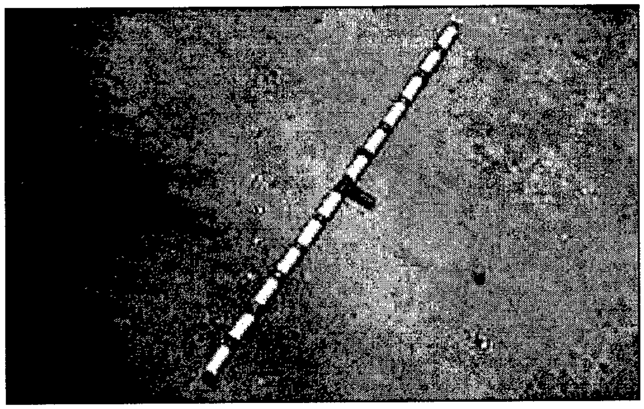


Figure 29. Copper tubing with white filter fabric covering the small holes.

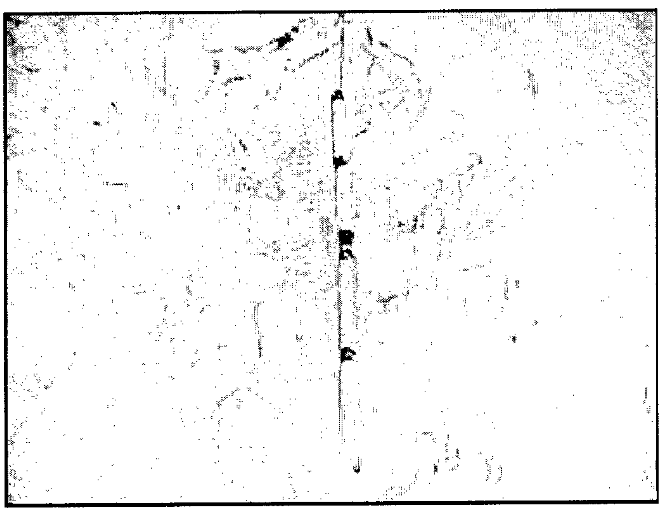


Figure 30. Copper tubing installed in the floor of the flume.

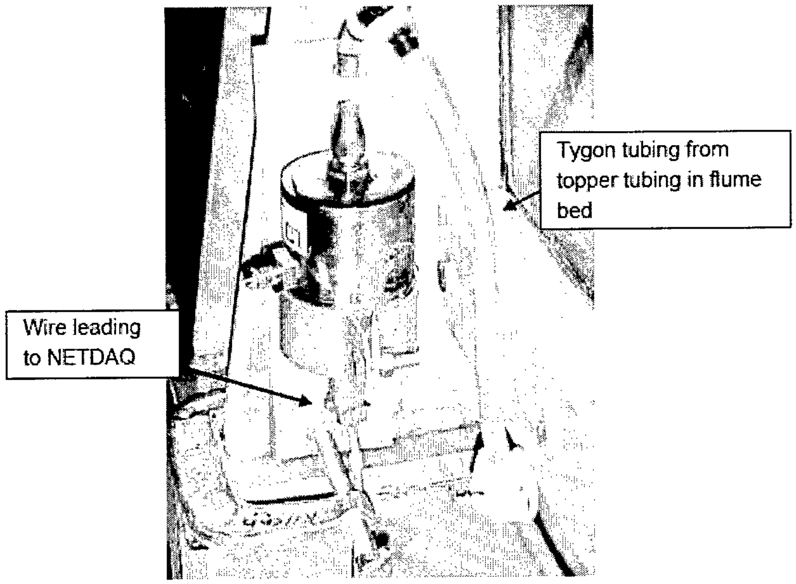


Figure 31. Pressure transducer mounted on the side of the flume.

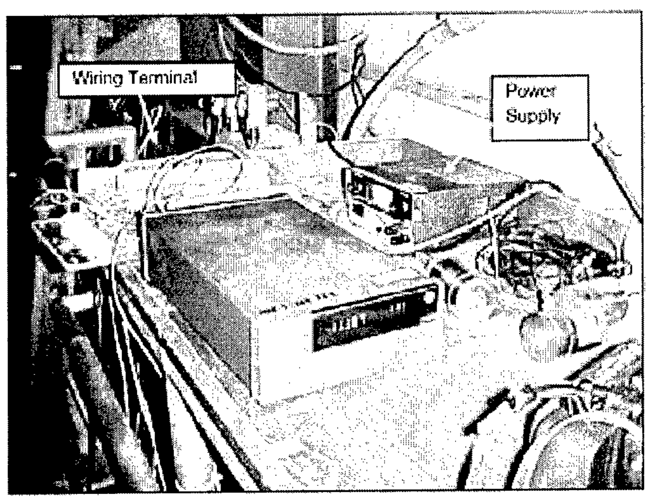


Figure 32. NETDAQ for the pressure measurement system.

Test Matrices

The test matrices were developed for a narrow range of test conditions based on the clear water scour requirement, i.e., the average velocity range from 0.5

times the critical velocity to the critical velocity. With the exception of Test A1, the average velocity range was 0.650 to 0.836 ft/s. An estimated Manning's *n* was used to calculate the slope for uniform flow. In all cases, the slope was found to be nearly horizontal and it was not significantly sensitive to varying estimates of Manning's *n*. Tables 4 and 5 list the test matrices for the open water and floating cover conditions.

Table 4. Test matrix for the open water condition.

Test	*Q*		Flow depth, Y_a		*V* (avg)		Slope
	(gpm)	(m^3/s)	(in.)	(cm)	(f/s)	(m/s)	
A1	675	0.0426	9.5	24.13	0.475	0.14478	3.23×10^{-6}
A2	925	0.0584	8	20.32	0.773	0.2356104	9.35×10^{-6}
A3	1100	0.0694	10	25.4	0.735	0.224028	7.81×10^{-6}
A4	1125	0.0710	9	22.86	0.836	0.2548128	1.05×10^{-6}
A5	875	0.0552	9	22.86	0.65	0.19812	6.35×10^{-6}
A6	890	0.0562	8.5	21.59	0.7	0.21336	7.51×10^{-6}

Table 5. Test matrix for the floating cover condition.

Test	Q		Flow depth, Y_a		V (avg)		Slope
	(gpm)	(m^3/s)	(in.)	(cm)	(f/s)	(m/s)	
B1	1100	0.0694	10	25.4	0.735	0.224028	7.81×10^{-6}
B2	925	0.0584	8	20.32	0.773	0.2356104	9.35×10^{-6}
B3	875	0.0552	9	22.86	0.65	0.19812	6.35×10^{-6}
B4	1125	0.0710	9	22.86	0.836	0.2548128	1.05×10^{-6}
B5	890	0.0562	8.5	21.59	0.7	0.21336	7.51×10^{-6}
R1*	925	0.0584	8	20.32	0.773	0.2356104	9.35×10^{-6}

** Test R1 designates the rough cover-floating test.

For the fixed cover tests, the water depth was fixed at 9 in. (22.8 cm) and the applied pressure head was 3 and 6 in. (7.6 and 15.2 cm) of water. Tests were conducted in pairs so that both pressure conditions could be applied. Consequently, a narrow velocity range was tested. Table 6 contains the fixed cover test matrix.

Table 6. Test matrix for the fixed cover condition.

Test	Q		Pressure head		V (avg)		Slope
	(gpm)	(m^3/s)	(in.)	(cm)	(f/s)	(m/s)	
C1	982.5	0.0620	3	0.0002	0.735	0.224028	8.00×10^{-6}
C2	1125	0.0710	3	0.0002	0.836	0.2548128	1.05×10^{-5}
C3	1125	0.0710	6	0.0004	0.836	0.2548128	1.05×10^{-5}
C4	982.5	0.0620	6	0.0004	0.735	0.224028	8.00×10^{-5}
C5	1041	0.0657	3	0.0002	0.773	0.2356104	8.98×10^{-6}
C6	1041	0.0657	6	0.0004	0.773	0.2356104	8.98×10^{-6}
XR1*	1041	0.0657	3	0.0002	0.773	0.2356104	8.98×10^{-6}
XR2*	1041	0.0657	6	0.0004	0.773	0.2356104	8.98×10^{-6}

* Tests XR1 and XR2 designate the rough cover fixed test.

General Procedure

Following the completion of a test, the scour hole was filled in and the bed around the pier was leveled using a radial leveling device. The radial leveling device consisted of a 22.5-in. (57.15-cm) piece of 2×6 dimensional lumber, which had a short bubble level attached to it. A wooden collar that fit over the pier was used to maintain the elevation as the 2×6 was rotated around the pier (Fig. 33). The bed was then leveled up and downstream using an aluminum blade mounted to a movable carriage (Fig. 34). An aluminum angle was also used for finish grading around the pier.

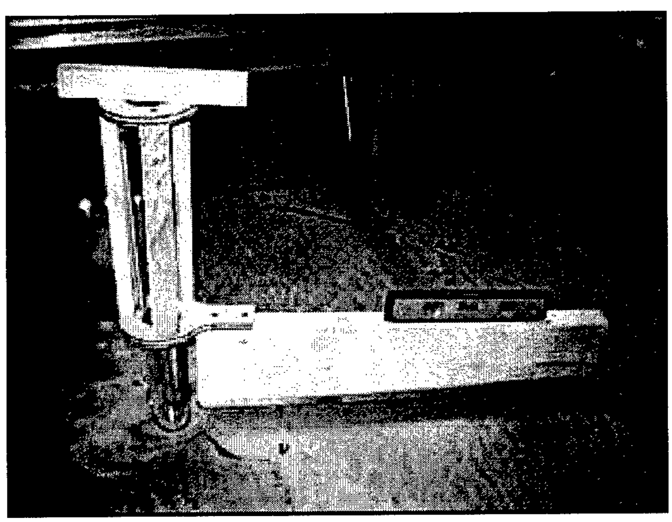


Figure 33. Device used to level the area around the pier.

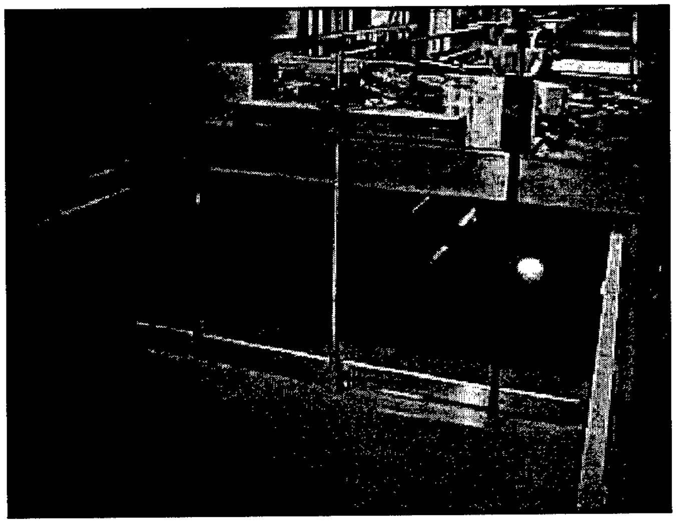


Figure 34. Bed leveling device attached to a movable carriage.

With the flow rate set to 50 gal./min (0.00315 m^3/s) and the water level set at approximately 29.21 cm (11.5 in.), the laser was calibrated using the stepped calibration block (Fig. 35). Because the flume could not be sealed, the flow rate was keep at 50 gal./min to maintain a constant water level. As noted in the discussion of the instrumentation, it was important to maintain a constant water level when using the laser as its distance measurement is sensitive to the water level. This also ensured consistency among the tests. The calibration curve was also plotted and immediately compared to previous tests to ensure consistency. Following calibration, the initial bed was characterized using both digital photographs and the laser profiling.

Next, if we were conducting a covered test, the ice cover was installed. The pier camera system was then installed and the data acquisition systems for this and for the pressure measurements were started. If a fixed cover test was being done, the ice restraint system was also installed and the data collection system documented any change in conditions as the restraints were installed. The test then began with the flow rate increased to the desired setting and the weir adjusted to attain the required depth. It generally took less than 5 minutes to achieve the correct test settings.

In addition to being recorded on the VCR and on the web server, the scour measurements were recorded manually during the test using the video monitor that displayed the view of the water/sediment interface and a scale on the pier. Approximately 1 hour after the test began, the velocity measurements were taken using the SonTek ADV.

Testing continued until there was a significant decrease in the rate of scour. With the exception of the very first test, most tests ran overnight and were from 9 to 22 hours long (Table 7).

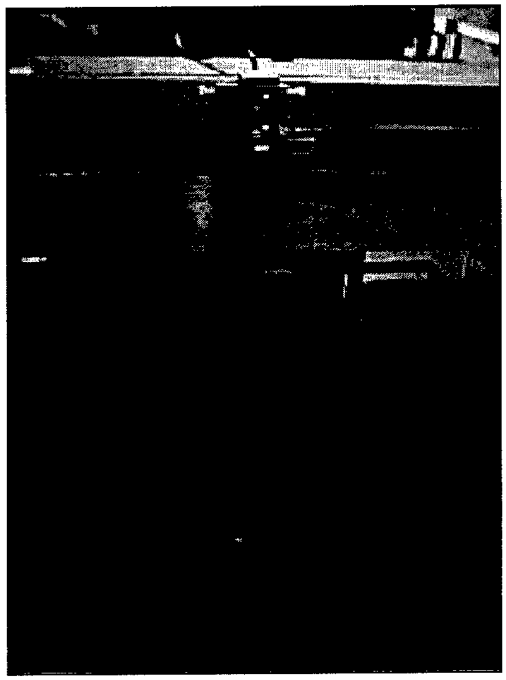


Figure 35. Calibration in progress.

At the conclusion of a test, the flow rate was lowered to 50 gal./min (0.00315 m^3/s). If the fixed cover was in place, the clamps and carriage bolts were unfastened from the flume rails and the restraint system was raised to allow for movement of the instrument carriage. The weir was gradually raised to the same level as before the test to maintain the water level at approximately 11.5 in. (29.21 cm). Before conducting the final profiling, we calibrated the laser again using the stepped calibration block. The final profiling was done at cross sections typically at 2-cm (0.78-in.) spacing up and downstream of the pier (Fig. 36). Upstream, the cross sections extended from the pier to just outside the scour hole. Downstream, the cross sections extended beyond the large mound behind the pier. Finally, numerous digital photographs characterized the resulting scour hole and dune patterns.

Table 7. Test dates, times, and durations.

Test	Start date	End date	Start time	End time	Duration (h:m)
A1	11 Feb 03	11 Feb 03	1100	1300	02:00
A2	12 Feb 03	13 Feb 03	1350	0805	18:15
A3	14 Feb 03	14 Feb 03	1037	1942	09:05
A4	06 Mar 03	07 Mar 03	1828	0855	14:27
A5	07 Mar 03	08 Mar 03	2038	1250	16:12
A6	11 Mar 03	12 Mar 03	1905	0818	13:13
B1	19 Feb 03	20 Feb 03	1354	0943	19:49
B2	21 Feb 03	22 Feb 03	1057	0905	22:08
B3	03 Mar 03	04 Mar 03	1331	0741	18:10
B4	04 Mar 03	05 Mar 03	1440	0826	17:46
B5	10 Mar 03	11 Mar 03	1713	0842	15:29
R1	08 Mar 03	09 Mar 03	1852	1305	18:13
C1	17 Mar 03	18 Mar 03	1327	0801	18:34
C2	18 Mar 03	19 Mar 03	1546	0808	16:22
C3	19 Mar 03	20 Mar 03	1646	1302	20:16
C4	07 Apr 03	08 Apr 03	1337	0832	18:55
C5	08 Apr 03	09 Apr 03	1648	0827	15:39
C6	09 Apr 03	10 Apr 03	1654	0833	15:39
XR1	15 Apr 03	16 Apr 03	1548	0905	17:17
XR2	16 Apr 03	17 Apr 03	1646	0852	16:06

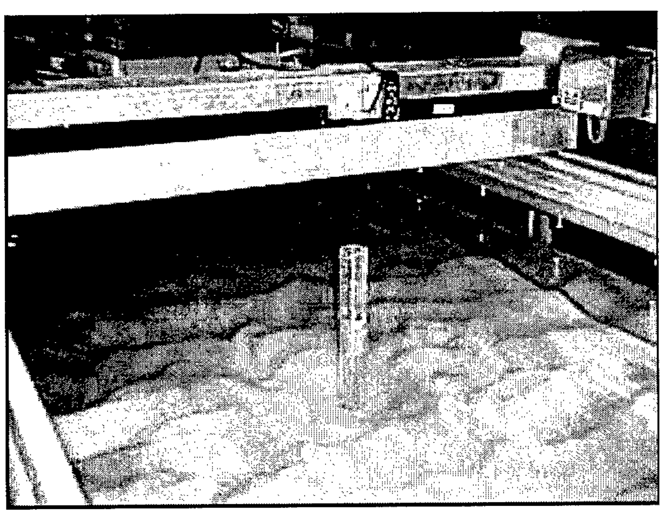


Figure 36. Final scour hole profiling for test XR2.

4 RESULTS AND DISCUSSION

Appendices A, B, and C contain the results for the open water, floating cover, and fixed cover tests, respectively. Each set of test results consists of three major components: scour depth vs. time measurements, velocity profiles, and scour hole profiling.

Scour Depth vs. Time

The camera–mirror assembly installed inside the clear cylindrical pier was used to obtain scour depth as a function of time during the tests. During the test, the depth of scour was manually recorded from the video monitors. Following the test, the pier camera images, which were recorded once per minute, were reviewed to verify existing data and to add data, e.g., scour data during the overnight hours. The only exception to this are the missing data from test R1. The resulting live-bed scour was outside of the camera range for approximately 5.5 hours. Figure 37 is an example pier camera image.

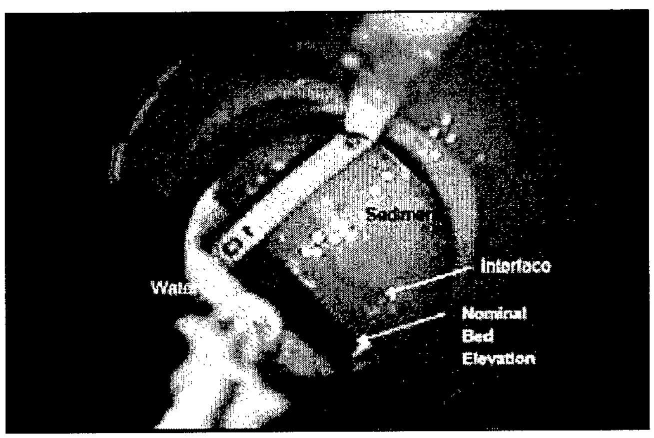


Figure 37. Example pier camera image from Test B3.

The first appendix table in each test result lists the scour vs. time data. These data are then plotted for the entire test and also for the first 3 hours of each test. The 3-hour time was chosen to examine the initial rate of scour.

Velocity Profiles

As described earlier, the average velocity, the standard deviation of the velocities, and the maximum and minimum velocities in both the *X* and *Y* directions were extracted from the velocity data file by a post-processing program. These results are tabulated in Appendices A, B, and C for each test at the three locations across the flume. The *X*-direction velocities (center, left side, and right side) are then plotted as a function of elevation.

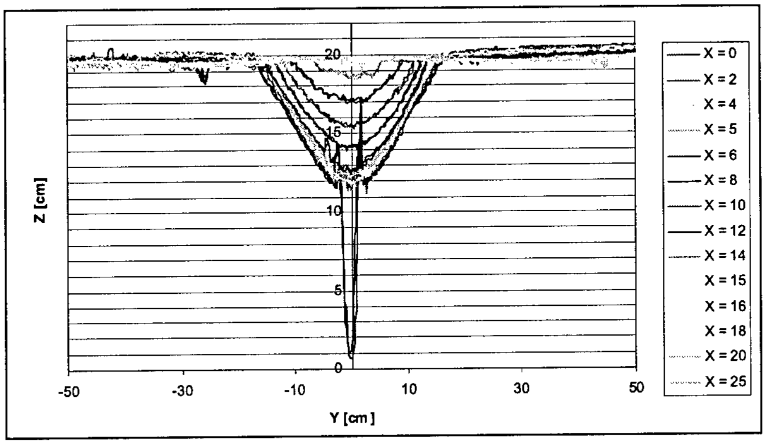
Scour Hole Profiling

Prior to the initial and final profiling, the laser was calibrated using the aluminum staircase step calibration block. Although only one initial profile and one final calibration profile are plotted on the same graph for each test, at least two initial and final calibration profiles were made for each test to ensure consistency. The initial and final calibration profiles were compared to determine an offset for the grid files used in Surfer© to produce the contour and surface plots. The offset is positive if the initial profile was greater than the final and negative if the final profile was greater than the initial. Table 8 lists the calibration offsets.

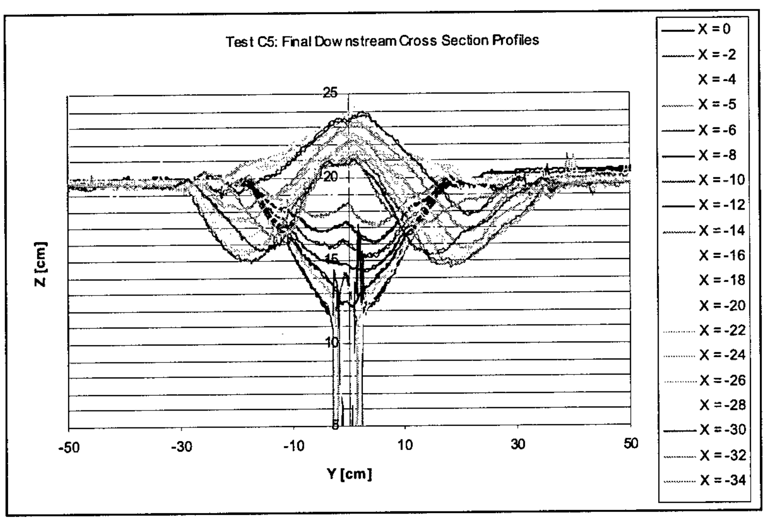
Table 8. Calibration offsets.

Test	cm	In.
A1	0	0
A2	0	0
A3	–0.7	–0.3
A4	–0.4	–0.2
A5	0	0
A6	0	0
B1	+0.3	+0.1
B2	0	0
B3	–0.5	–0.2
B4	0	0
B5	+0.3	+0.1
R1	0	0
C1	0	0
C2	+0.5	+0.2
C3	0	0
C4	0	0
C5	+0.1	0
C6	+0.4	+0.2
XR1	–0.5	–0.2
XR2	0	0

Following the calibration curves for each test, a representative photograph of each resulting scour hole is presented.



a. Upstream.



b. Downstream.

Figure 38. Cross-section profiles from Test C5. Distances in the *X*-direction are in centimeters from the center of the pier.

The contour and surface plots were developed using the three-dimensional plotting program, Surfer©. The networked data acquisition unit generates a comma-separated variable (CSV) file listing the *Y*-coordinates from the LMP and corresponding *Z*-coordinates from the laser. Following each cross section profiling, the *Y–Z* data were plotted to ensure consistency and as a cursory check the accuracy of the data. Figure 38 shows cross section profiles from test C5. Because these data are better represented by the three-dimensional surface plots, these graphs are not included in the appendices. The spikes in the data are attributable to the distance to the pier being outside the measurement range of the laser, resulting in an erroneous output signal.

A post-processing program adds the *X*-coordinate. For each test, there are two CSV files, one for the initial profile and one for the final profile. This database of *X–Y–Z* coordinates is used to generate initial and final grid files in Surfer©. Because each data file contains duplicate points from the laser moving from the near side to the far side and back, i.e., round trip, the duplicate points are averaged. The grid generation function requires that we specify the grid line geometry. A 1- by 1-cm (0.4- by 0.4-in.) grid was chosen.

A gridding method is also required by the grid generation function. The inverse distance to a power method proved to be the most appropriate for interpolating between data points, using power parameter of 1 and smoothing parameter of 0.03125. Once the initial and final grids were generated, the final grid was subtracted from the initial grid plus or minus the offset to obtain the scour hole grid. The grid node editor was then used to remove or "blank" the data from the pier area. This area is represented by the forward-slash marked areas on the contour plots. The area was usually ±4 cm (1.57 in.) from the center but often extended further downstream owing to the angle of the laser—recall it was tilted 5° forward. Occasionally, dark fine material or other debris would settle on the surface within the contour plotting area. In these cases, the erroneous data were also blanked using the grid node editor. These areas are represented by backslash marked areas on the contour plots (for example, see Test B3).

Summary Results

The experimental results are summarized in Tables 9, 10, and 11.

The results are also grouped by average velocity in Tables 12 and 13. Table 12 summarizes the grouping by average velocity using the critical velocity, V_c as 0.9 ft/s (0.27 m/s).

Table 9. Open water test results.

Test	Avg V		Y_a		Duration (h:m)	Scour depth		Notes
	(ft/s)	(m/s)	(in.)	(cm)		(in.)	(cm)	
A1	0.475	0.145	9.5	23	2:00	0.4375	1.111	
A2	0.773	0.236	8	20	17:57	3.1875	8.096	
A3	0.735	0.224	10	25	9:05	2.6875	6.826	
A4	0.836	0.255	9	22	14:27	3.3125	8.414	
A5	0.650	0.198	9	22	16:12	2.6875	6.826	
A6	0.700	0.213	8.5	21	13:13	2.8750	7.303	

Table 10. Floating cover test results.

Test	Avg V		Y_a		Duration (h:m)	Scour depth		Notes
	(ft/s)	(m/s)	(in.)	(cm)		(in.)	(cm)	
B1	0.735	0.224	10	25	19:49	3.2500	8.255	
B2	0.773	0.236	8	20	22:08	3.2500	8.255	
B3	0.650	0.198	9	22	18:10	2.7500	6.985	
B4	0.836	0.255	9	22	17:46	3.3750	8.573	
B5	0.700	0.213	8.5	21	15:29	3.2500	8.255	
R1	0.773	0.236	8	20	18:13	3.0000	7.620	Live-bed scour

Table 11. Fixed cover test results.

Test	Avg V		Y_a		Duration (h:m)	Scour depth		Notes
	(ft/s)	(m/s)	(in.)	(cm)		(in.)	(cm)	
C1	0.735	0.224	3	8	18:35	3.1250	7.938	
C2	0.836	0.255	3	8	16:22	3.2500	8.255	Live-bed scour
C3	0.836	0.255	6	15	20:16	2.8750	7.303	Live-bed scour
C4	0.735	0.224	6	15	18:55	3.1250	7.938	
C5	0.773	0.236	3	8	15:39	3.2500	8.255	
C6	0.773	0.236	6	15	15:39	3.1875	8.096	
XR1	0.773	0.236	3	8	17:17	2.8750	7.303	Live-bed scour
XR2	0.773	0.236	6	15	16:06	3.3125	8.414	Live-bed scour

Table 12. Test groups by average velocity.

Tests	V_{avg} (ft/s)	V_{avg} (cm/s)	V_{avg}/V_c
A5, B3	0.650	19.81	0.7222
A6, B5	0.700	21.34	0.7777
A3, B1, C1, C4	0.735	22.40	0.8167
A2, B2, R1, C5, C6, XR1, XR2	0.773	23.56	0.8589
A4, B4, C2, C3	0.835	25.45	0.9278

Table 13. Test results for various average velocities.

Test	Avg V		Y_a		Duration [h:m]	Scour depth (in.)	Scour depth (cm)	Notes
	(ft/s)	(m/s)	(in.)	(cm)				
A5	0.650	0.198	9	22	16:12	2.6875	6.826	
B3	0.650	0.198	9	22	18:10	2.7500	6.985	
A6	0.700	0.213	8.5	21	13:13	2.8750	7.303	
B5	0.700	0.213	8.5	21	15:29	3.2500	8.255	
A3	0.735	0.224	10	25	9:05	2.6875	6.826	
B1	0.735	0.224	10	25	19:49	3.2500	8.255	
C1	0.735	0.224	3 (12)	8 (30)	18:35	3.1250	7.938	
C4	0.735	0.224	6 (15)	15 (38)	18:55	3.1250	7.938	
A2	0.773	0.236	8	20	17:57	3.1875	8.096	
B2	0.773	0.236	8	20	22:08	3.2500	8.255	
R1	0.773	0.236	8	20	18:13	3.0000	7.620	Live-bed scour
C5	0.773	0.236	3 (12)	8 (30)	15:39	3.2500	8.255	
C6	0.773	0.236	6 (15)	15 (38)	15:39	3.1875	8.096	
XR1	0.773	0.236	3 (12)	8 (30)	17:17	2.8750	7.303	Live-bed scour
XR2	0.773	0.236	6 (15)	15 (38)	16:06	3.3125	8.414	Live-bed scour
A4	0.836	0.255	9	22	14:27	3.3125	8.414	
B4	0.836	0.255	9	22	17:46	3.3750	8.573	
C2	0.836	0.255	3	8	16:22	3.2500	8.255	Live-bed scour
C3	0.836	0.255	6	15	20:16	2.8750	7.303	Live-bed scour

Initial Analysis

The initial analysis consists of two parts. Scour depth vs. time comparisons and velocity profile comparisons are made among tests conducted for the same average velocity. For the velocity comparisons, only the center velocity profile is used. The purpose of the right and left side velocity profiles was to confirm uniform flow conditions across the channel.

Scour depth vs. time comparisons

For the lowest average velocity tested, 0.650 ft/s (19.8 cm/s), i.e., V_{avg}/V_c = 0.722, the equilibrium scour depths for both the open water (Test A5) and floating cover condition (Test B3) are essentially the same (Fig. 39). Furthermore, the scour hole appears to develop slightly faster under the open water condition (Fig. 40).

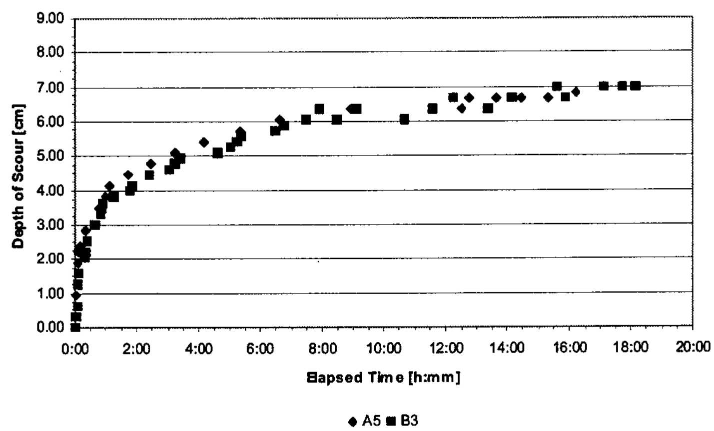


Figure 39. Scour depth vs. time for Tests A5 and B3, V_{avg} = 0.650 ft/s (19.8 cm/s).

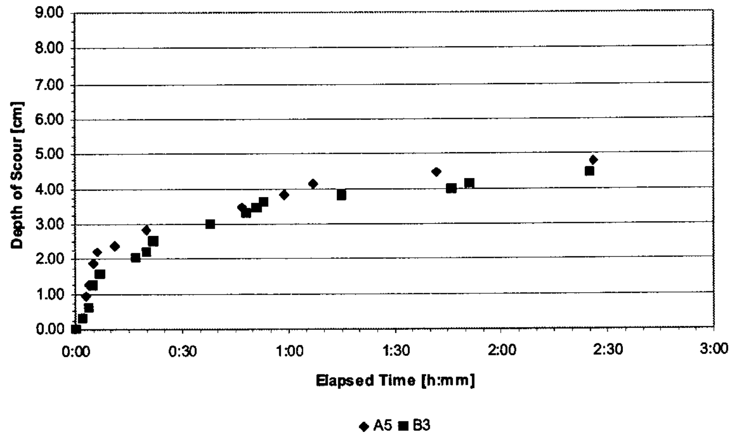


Figure 40. Scour depth vs. time (first 3 hours) for Tests A5 and B3, V_{avg} = 0.650 ft/s (19.8 cm/s).

For an average velocity of 0.700 ft/s (21.34 cm/s), i.e., $V_{avg}/V_c = 0.777$, the equilibrium scour depth for the floating cover condition (Test B5) was 0.95 cm or approximately 13.5% deeper than that for the open water condition (Test A6) (Fig. 41). Furthermore, the scour hole appears to develop slightly faster under the floating cover condition (Fig. 42).

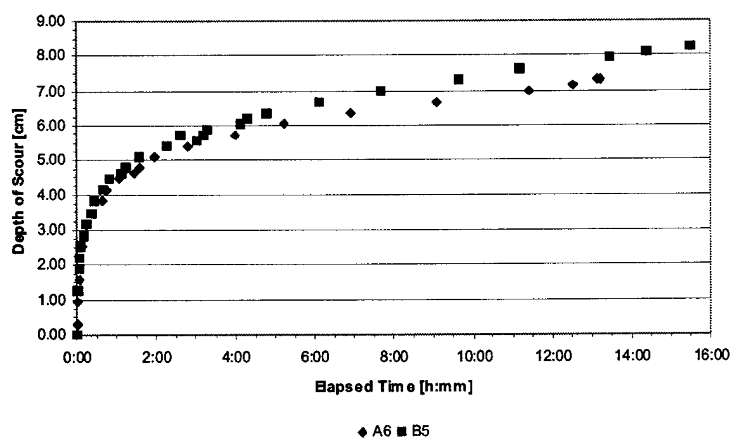


Figure 41. Scour depth vs. time for Tests A6 and B5, V_{avg} = 0.700 ft/s (21.34 cm/s).

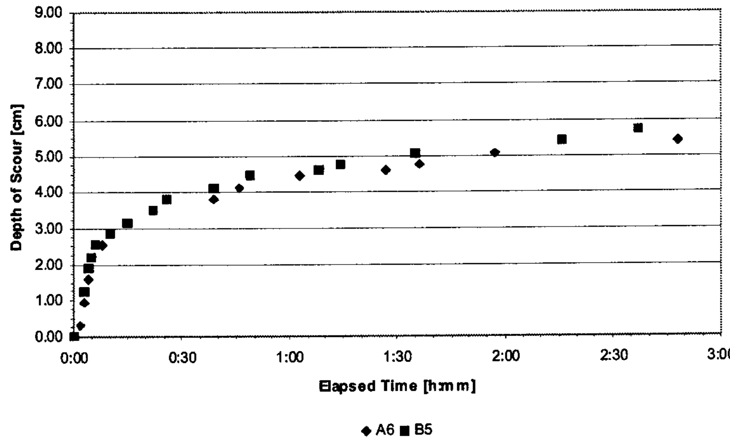


Figure 42. Scour depth vs. time (first 3 hours) for Tests A6 and B5, V_{avg} = 0.700 ft/s (21.34 cm/s).

For an average velocity of 0.735 ft/s (22.40 cm/s), $V_{avg}/V_c = 0.8167$, the equilibrium scour depth for the floating cover condition (Test B1) appears to be the greatest and approximately 21% deeper than that of the open water condition (Test A3). Under the pressure flow condition (Tests C1 and C4), the equilibrium scour depth is slightly lower (0.32 cm) than that of the floating cover condition. Nonetheless, it is still approximately 16.3% higher than that of the open water condition (Fig. 43).

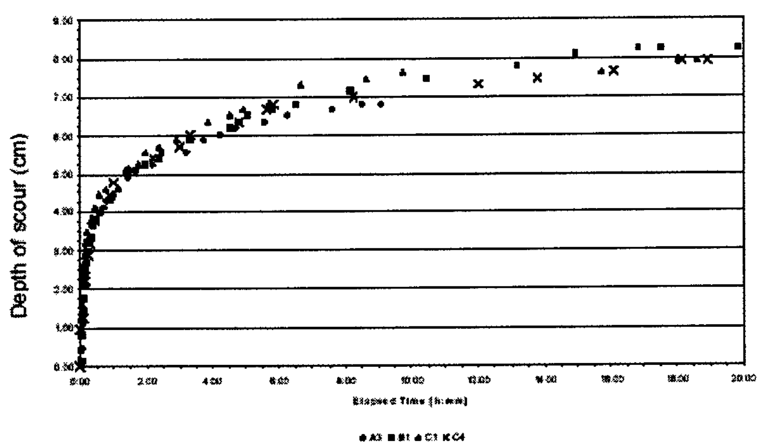


Figure 43. Scour depth vs. time for Tests A3, B1, C1 and C4, V_{avg} = 0.735 ft/s (22.4 cm/s).

Furthermore, the pressurized flow condition appears to cause a scour hole to develop more rapidly (Fig. 44). Finally, there appears to be no discernable difference between the two pressure conditions tested, i.e., 3 and 6 in. (7.6 and 15.24 cm) of pressure head at this velocity. The 6 in. maximum was a limitation imposed by the height of the flume and only represents a 66% increase in flow depth. For shallow rivers with 20-in.-thick (50-cm-thick) ice, based on the two to four-fold increase in stage, the discharge may have to increase 100 to 200% before breakup is initiated.

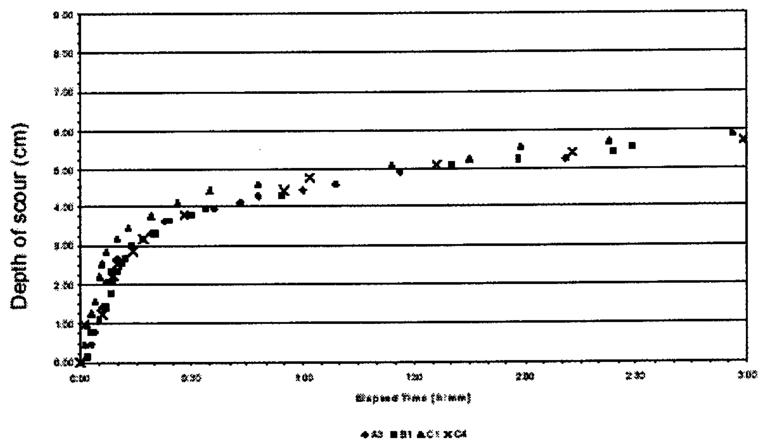


Figure 44. Scour depth vs. time (first 3 hours) for Tests A3, B1, C1, and C4, V_{avg} = 0.735 ft/s (22.4 cm/s).

For an average velocity of 0.773 ft/s (23.56 cm/s), seven different conditions were tested. This test group highlights the effects of the floating cover, roughness of the cover, and the pressure condition. In all of the rough cover tests (R1, XR1, XR2), the scour holes developed more rapidly than for the open water conditions, floating smooth cover condition, and pressurized smooth cover condition (Fig. 45). In the pressurized smooth cover tests (C5 and C6), the scour hole developed more rapidly than in the floating cover condition test. However, this effect was more pronounced for the lower pressure head condition (Test C5). The equilibrium scour depth was the largest for the higher pressure head, rough cover condition (XR2) (Fig. 46). However, the equilibrium scour depth for the lower pressure head, rough cover condition (XR1) was the least among all of the test conditions. These conclusions may be ambiguous, as the sediment transport process shifted from clear water to live-bed and the dunes may have been progressing through the scour hole at the time of the measurements.

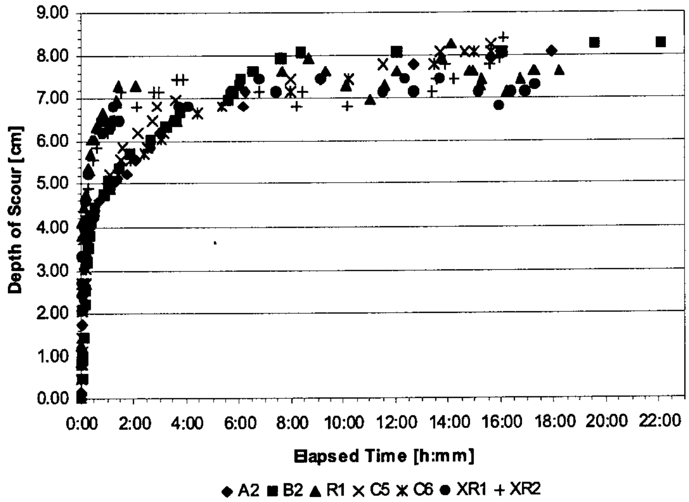


Figure 45. Scour depth vs. time for Tests A2, B2, R1, C5, C6, XR1, and XR2, V_{avg} = 0.773 ft/s (23.56 cm/s).

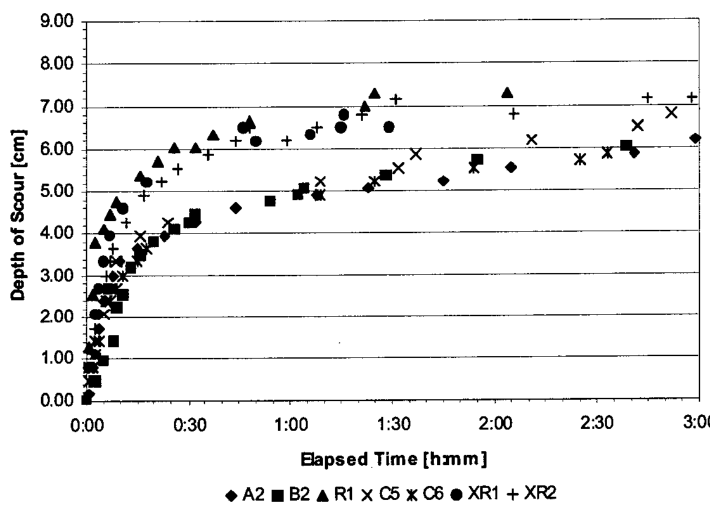


Figure 46. Scour depth vs. time (first 3 hours) for Tests A2, B2, R1, C5, C6, XR1, and XR2, V_{avg} = 0.773 ft/s (23.56 cm/s).

When the average velocity is near the critical velocity, i.e., $V_{avg}/V_c = 0.9278$, the pressure flow condition causes live-bed scour. The equilibrium scour depth for the floating cover condition (Test B4) is the greatest but only 2% greater than that for the open water condition (Test A4). As expected, the live-bed scour equilibrium depths are lower than the clear-water scour equilibrium depths. However, the larger pressure head condition (Test C3) resulted in a lower equilibrium depth compared to the smaller pressure head condition (Test C4) (Fig. 47). The pressure flow condition appears to slightly accelerate the scour process; however, the effect was not significantly different from that of the floating cover condition (Fig. 48).

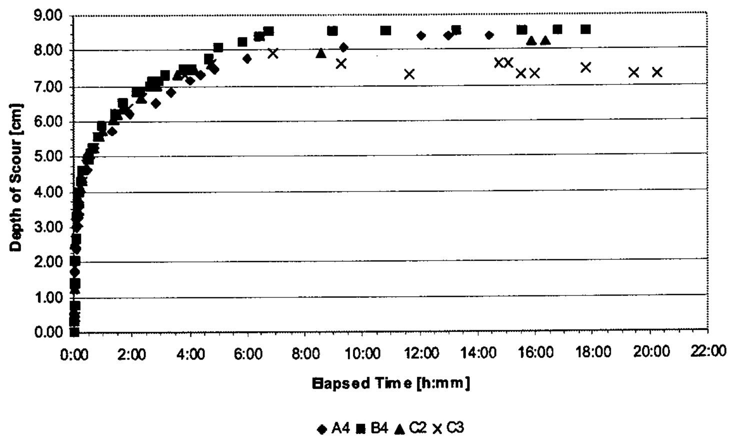


Figure 47. Scour depth vs. time for Tests A4, B4, C2, and C3, V_{avg} = 0.836 ft/s (25.48 cm/s).

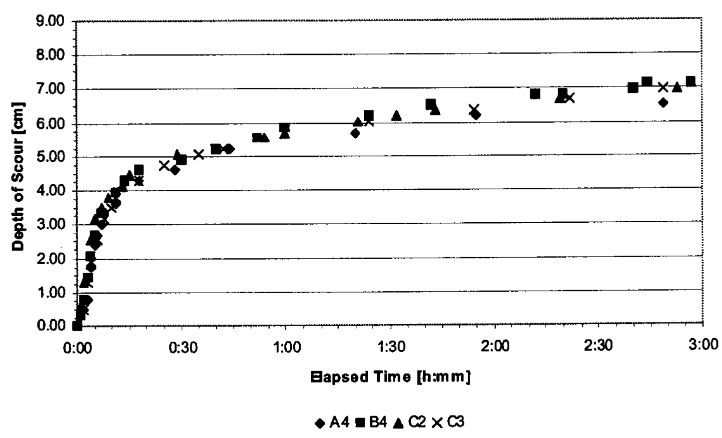


Figure 48. Scour depth vs. time (first 3 hours) for Tests A4, B4, C2, and C3, V_{avg} = 0.836 ft/s (25.48 cm/s).

Velocity profile comparisons

To further understand the scour process, we analyzed the velocity distributions. This will also provide further insight into the shear stress distribution, which is the primary mechanism responsible for scour.

As expected, the open water velocity profiles in all of the tests are logarithmic in shape. The floating cover velocity distributions appear "parabolic" in shape, with the velocity being zero at both boundaries, i.e., the no-slip condition, and a maximum in-between. The location of the maximum velocity depends on the flow depth, flow velocity, roughness of the boundaries, and the viscosity of the fluid. The maximum velocity occurs approximately at the midpoint for the floating smooth covers, indicating that the roughness of the Styrofoam and sediment are similar. The presence of the cover caused the maximum and average velocities to be located closer to the bed (Fig. 49 and 50). Consequently, larger scour depths occur for the floating cover condition.

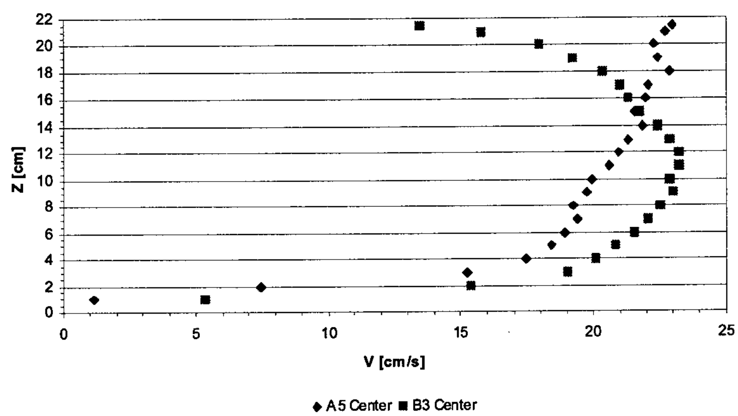


Figure 49. Velocity profiles for Tests A5 and B3, V_{avg} = 0.650 ft/s (19.8 cm/s).

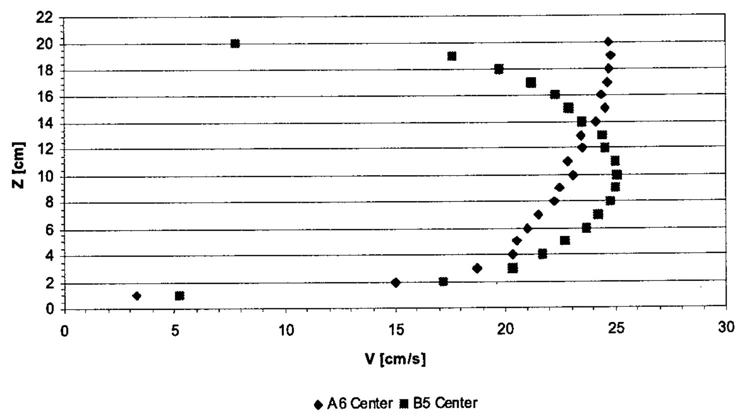


Figure 50. Velocity profiles for Tests A6 and B5, V_{avg} = 0.700 ft/s (21.34 cm/s).

For the floating rough cover, the maximum velocity also occurs near the midpoint, but it is larger (Fig. 51). This appears to contribute to the live-bed scour in this case. For the pressurized flows, the velocity profiles shifts toward the smoother boundary as the pressure head is increased. The smoother boundary is the Styrofoam ice cover. For $V_{avg}/V_c = 0.8167$ and $V_{avg}/V_c = 0.8589$, the shift is slight (Fig. 51 and 52). However, this shift is more pronounced for the tests with $V_{avg}/V_c = 0.9278$ and especially pronounced for a higher-pressure head, e.g., Test C3 (Fig. 55). Moreover, at $V_{avg}/V_c = 0.9278$, both pressure conditions contributed to the live-bed scour that occurred.

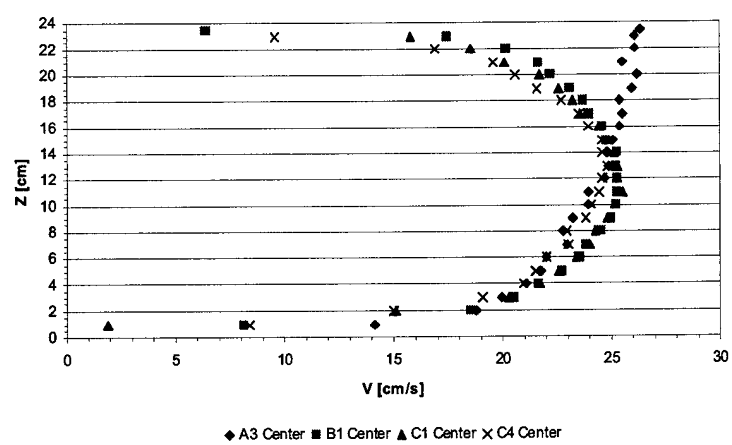


Figure 51. Velocity profiles for Tests A3, B1, C1, and C4, V_{avg} = 0.735 ft/s (23.56 cm/s).

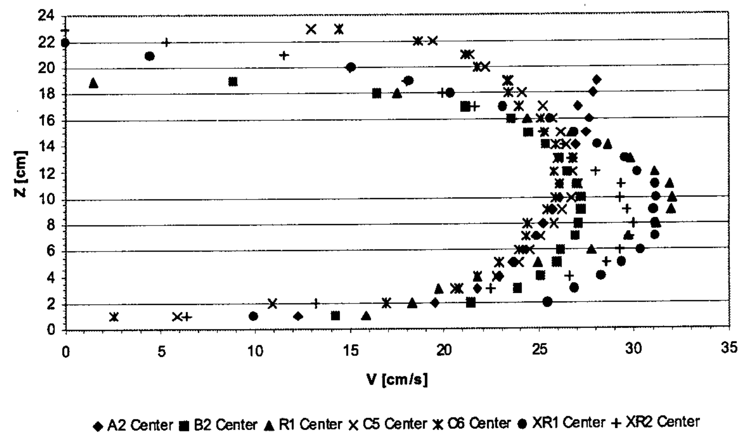


Figure 52. Velocity profiles for Tests A2, B2, R1, C5, C6, XR1, and XR2, V_{avg} = 0.773 ft/s (23.56 cm/s).

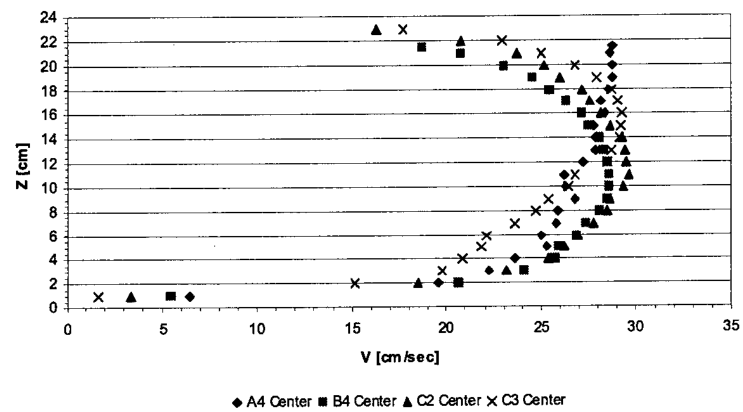


Figure 53. Velocity profiles for Tests A4, B4, C2, and C3, V_{avg} = 0.836 ft/s (22.48 cm/s).

In addition, the maximum velocity for the pressurized tests was greater than those of the floating cover tests. Theoretically, V_{avg}/V_c must be greater than 1 for live-bed scour to take place. These tests indicated that, although the average velocity may be an acceptable indicator for the type of scour (clear-water vs. live-bed) for the open water and perhaps the floating cover condition, it is not acceptable for pressurized flow conditions. In addition to being a function of the average velocity, the scour process is also a function of the velocity distribution.

For the pressurized flow under a rough cover, there is a combined effect of the pressure and roughness. In test XR1, the pressure head had a slight effect;

however, the roughness caused a definite shift of the velocity profile toward the bed, which is the smoother boundary. In Test XR2, the combined effect of the pressure head and roughness shifted the velocity profile toward the bed. And although this caused live-bed scour, the equilibrium scour depth was the largest among all conditions tested.

5 FUTURE ANALYSIS

Further analysis is planned for a follow-on report. The velocity profiles will be examined more in depth and a detailed comparison of the results from this study will be made with results from Batuca and Darghi (1986) and Olsson (2000). Also, as the shear stress distribution is the primary mechanism responsible for scour, it will be investigated.

REFERENCES

Batuca, D., and Darghi (1986) Some experimental results on local scour around cylindrical piers for open and covered flow. In *Third International Symposium on River Sedimentation, The University Of Mississippi.*

Donchenko, R.V. (1975) Conditions for ice jam formation in tailwaters. U.S. Army Cold Regions Research and Engineering Laboratory, Draft Translation 669.

Federal Highway Administration (1993) Evaluating scour at bridges. Second Ed. FHWA-IP-90-017. revised April 1993.

Maccaferri Engineering (2002) Macra 1 2002 Hydraulic Channeling Design Software—Help File.

Olsson, P. (2000) Influence of ice-covered in local scour at circular bridge piers. *Water Resource Engineering*, Lulea University of Technology, Lulea, Sweden.

SonTek/YSI, Inc. (1996) SonTek ADV Operation Manual, Firmware Version 2.1 (9 September). San Diego, California.

Wuebben, J.L. (1986) Laboratory study of flow in an ice-covered sand bed channel. In *Proceedings, Eighth IAHR Symposium on Ice, Iowa City, 18–22 August 1986*, Vol. 1, p.3–14.

Zabilansky, L.J. (1996) Ice Force and Scour Instrumentation for the White River, Vermont. USA Cold Region Research and Engineering Laboratory, Special Report 96-6.

Zabilansky, L.J. (2002) Ice cover effects on bed scour; case studies. In *ASCE 11th International Conference Cold Regions Engineering, Anchorage, Alaska, 20–22May 2002.*

Zabilansky, L.J., R. Ettema, N.E. Yankielun, and J.L. Wuebben (2002) Survey of river-ice influences on channel stability along the Fort Peck Reach of the Missouri River, Montana, winter 1998–1999. U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, ERDC/CRREL TR-02-14.

APPENDIX A: OPEN WATER

Test A1

Table A1. Scour depth vs. time data.

Initial Reading =	10.0625	in.
Start Time =	11:00	11-Feb-03
End Time =	13:00	11-Feb-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
11:00	10.0625	0:00	0.0000	0.000
11:05	10.0000	0:05	0.0625	0.159
11:07	9.8750	0:07	0.1875	0.476
11:11	9.8125	0:11	0.2500	0.635
11:17	9.7500	0:17	0.3125	0.794
11:26	9.6875	0:26	0.3750	0.953
11:58	9.6250	0:58	0.4375	1.111
12:30	9.6250	1:30	0.4375	1.111
13:00	9.6250	2:00	0.4375	1.111

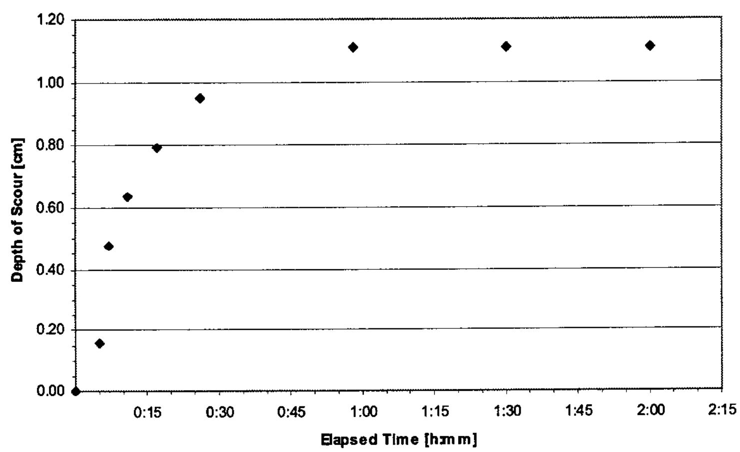


Figure A1. Scour depth vs.time.

Table A2. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	10.29	–0.09	1.04	0.41	12.84	8.28	0.99	–0.95
3	12.56	–0.50	1.30	0.44	15.62	10.13	0.44	–1.64
5	14.30	–0.60	0.78	0.48	15.68	12.37	0.68	–1.78
7	14.73	–0.55	0.95	0.44	17.04	11.45	0.41	–1.94
9	15.39	–0.56	0.84	0.40	16.81	13.26	0.22	–1.64
11	14.84	–0.48	0.91	0.41	16.34	12.29	0.36	–1.51
13	15.57	–0.63	0.94	0.35	17.45	13.42	0.58	–1.49
15	16.14	–0.58	0.67	0.34	17.51	14.40	0.39	–1.32
17	16.62	–0.66	0.56	0.39	17.95	15.70	0.26	–1.88
19	16.57	–0.66	0.66	0.35	17.62	15.05	0.19	–1.65
21	16.45	–0.71	0.57	0.31	17.62	15.22	–0.01	–1.33

Table A3. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	10.69	–0.50	1.13	0.42	12.71	7.89	0.50	–1.42
3	13.30	–0.34	0.80	0.36	14.79	11.68	0.40	–1.24
5	14.28	–0.35	0.95	0.46	16.08	12.07	0.86	–1.41
7	14.95	–0.40	0.80	0.35	16.32	13.03	0.44	–1.01
9	14.90	–0.48	0.88	0.36	16.31	12.34	0.46	–1.40
11	15.90	–0.51	0.78	0.33	17.63	14.23	0.06	–1.50
13	15.96	–0.50	0.95	0.32	20.69	14.25	0.75	–0.95
15	15.88	–0.53	0.57	0.25	16.86	14.44	0.05	–1.41
17	15.94	–0.66	0.58	0.24	16.96	14.57	–0.21	–1.32
19	15.80	–0.73	0.46	0.27	16.78	14.96	0.07	–1.40
21	15.48	–0.92	0.76	0.36	17.20	13.79	0.00	–2.17

Table A4. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	10.32	–0.17	0.94	0.43	12.12	8.43	0.90	–1.09
3	12.74	–0.32	0.97	0.42	14.29	10.18	0.46	–1.34
5	13.50	–0.48	1.18	0.38	15.89	10.57	0.42	–1.22
7	14.14	–0.40	0.68	0.44	15.53	12.38	0.79	–1.35
9	14.61	–0.64	0.99	0.39	16.86	11.68	0.27	–1.34
11	15.22	–0.63	0.72	0.31	16.38	12.80	–0.05	–1.92
13	15.20	–0.67	0.66	0.31	16.64	13.21	–0.10	–1.38
15	15.57	–0.66	0.55	0.28	16.75	14.58	0.19	–1.30
17	15.28	–0.57	0.62	0.30	17.05	14.10	0.17	–1.19
19	15.65	–0.48	0.62	0.32	17.44	14.54	0.11	–1.11
21	15.67	–0.46	0.60	0.43	17.04	13.85	0.39	–1.98

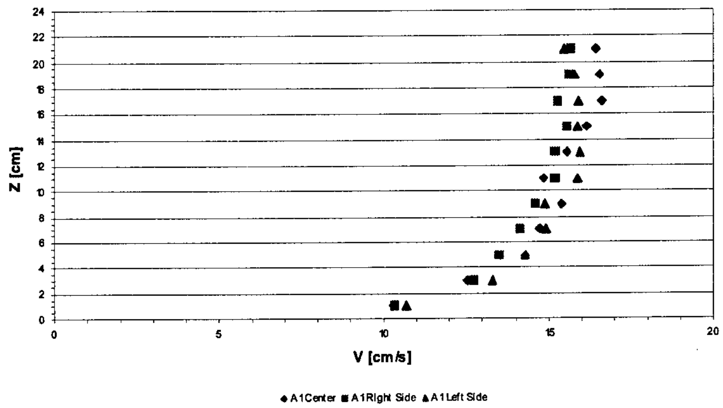


Figure A2. Velocity profiles.

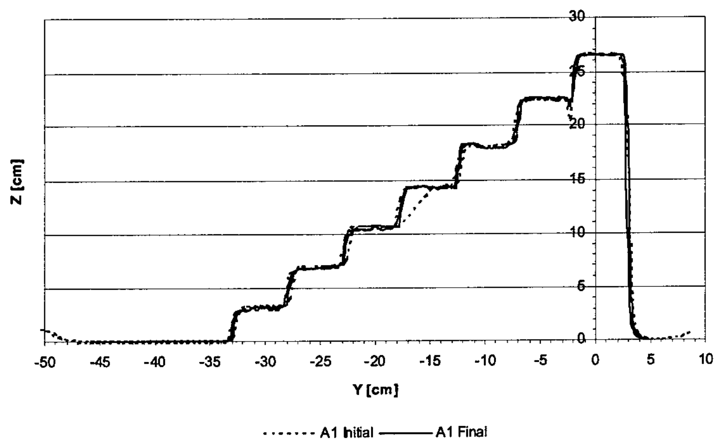


Figure A3. Calibration.

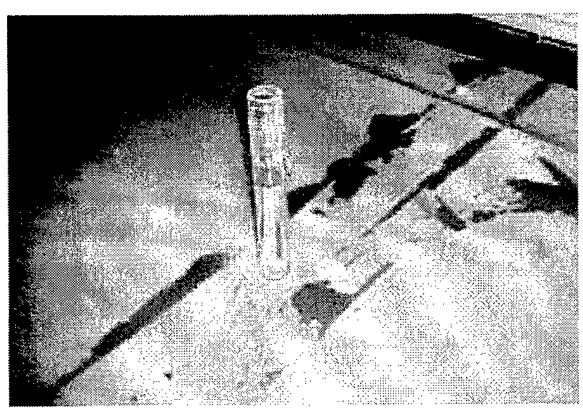


Figure A4. Final photo of scour hole; flow from right to left.

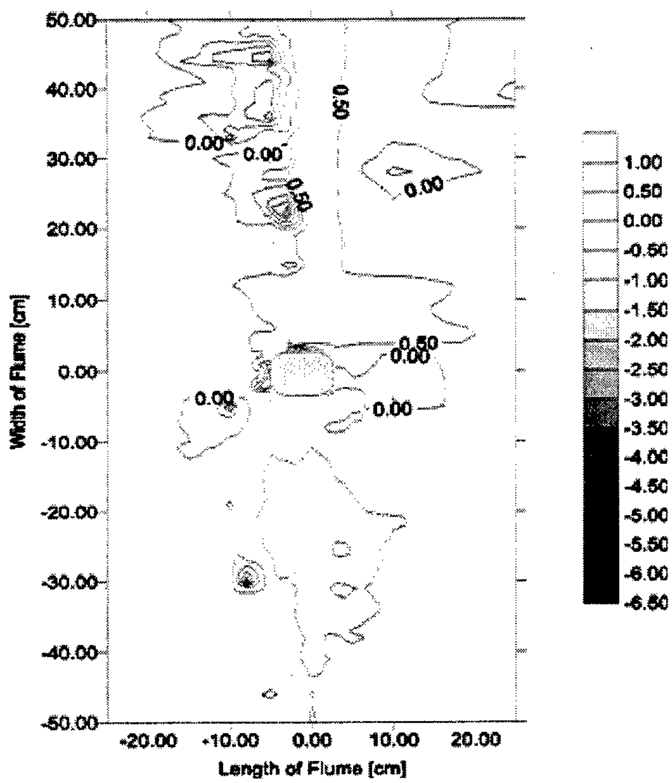


Figure A5. Contour plot; flow from right to left.

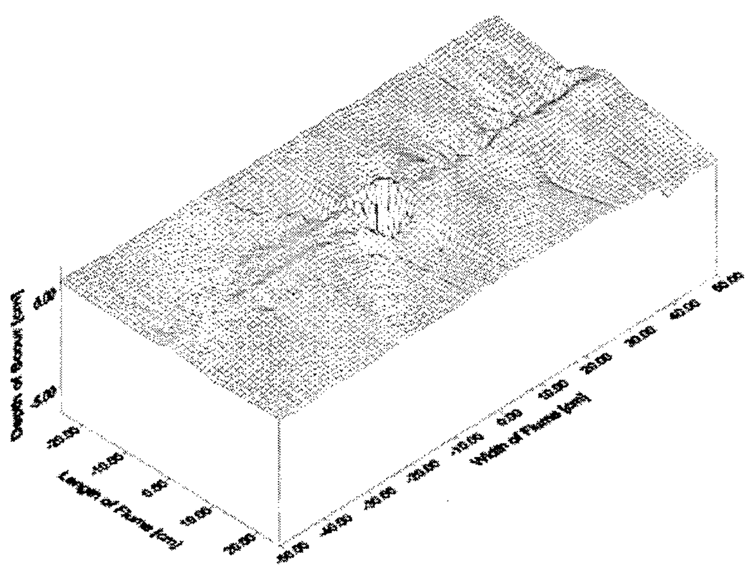


Figure A6. Surface plot; flow is from lower right to upper left.

Test A2

Table A5. Scour depth vs. time data.

Initial Reading =	10.1875	In.
Start Time =	13:50	12-Feb-03
End Time =	08:05	13-Feb-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
13:50	10.1875	0:00	0.0000	0.000
13:51	10.1250	0:01	0.0625	0.159
13:52	9.8750	0:02	0.3125	0.794
13:53	9.7500	0:03	0.4375	1.111
13:54	9.5000	0:04	0.6875	1.746
13:55	9.2500	0:05	0.9375	2.381
13:56	9.1250	0:06	1.0625	2.699
13:57	9.1250	0:07	1.0625	2.699
13:58	9.0000	0:08	1.1875	3.016
14:00	8.8750	0:10	1.3125	3.334
14:05	8.7500	0:15	1.4375	3.651
14:13	8.6250	0:23	1.5625	3.969
14:22	8.5000	0:32	1.6875	4.286
14:34	8.3750	0:44	1.8125	4.604
14:58	8.2500	1:08	1.9375	4.921
15:13	8.1875	1:23	2.0000	5.080
15:35	8.1250	1:45	2.0625	5.234
15:55	8.0000	2:05	2.1875	5.556
16:31	7.8750	2:41	2.3125	5.874
16:49	7.7500	2:59	2.4375	6.191
17:26	7.6250	3:36	2.5625	6.509
20:01	7.5000	6:11	2.6875	6.826
20:05	7.3750	6:15	2.8125	7.144
23:00	7.2500	9:10	2.9375	7.461
2:30	7.1250	12:40	3.0625	7.779
5:30	7.0625	15:40	3.1250	7.938
7:47	7.0000	17:57	3.1875	8.096

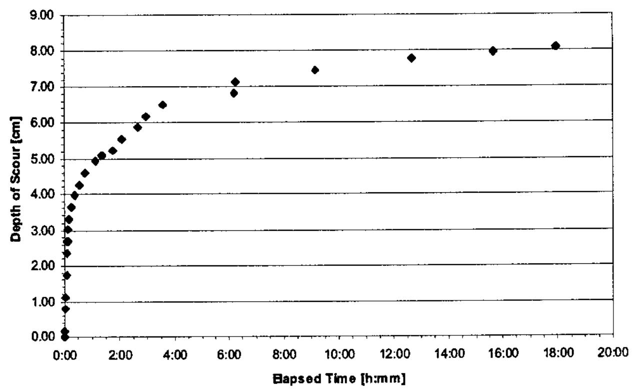


Figure A7. Scour depth vs. time.

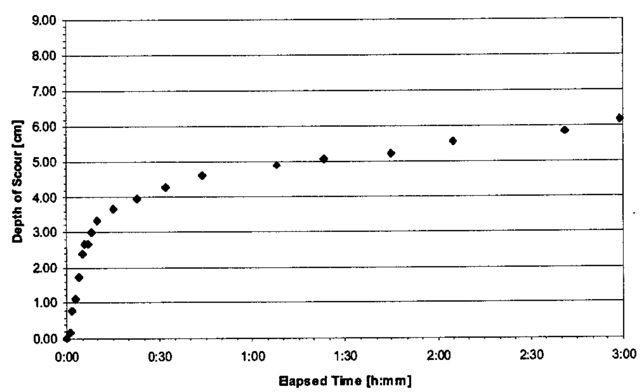


Figure A8. Scour depth vs. time for the first 3 hours.

Table A6. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	12.29	–0.12	1.59	0.58	16.09	8.68	1.21	–1.66
2	19.47	–0.62	1.66	0.68	23.32	15.80	1.17	–2.11
3	21.72	–0.77	1.58	0.65	24.89	17.97	1.35	–2.30
4	22.91	–0.87	1.85	0.60	26.35	18.94	0.40	–2.89
5	23.58	–0.93	1.62	0.60	27.10	19.56	0.30	–3.19
6	24.28	–0.96	1.40	0.64	27.59	21.46	0.91	–3.02
7	24.79	–1.04	1.29	0.61	28.41	20.59	1.17	–2.74
8	25.21	–1.05	1.55	0.59	28.49	20.56	0.52	–2.57
9	25.72	–1.04	1.39	0.52	29.32	21.68	0.65	–2.13
10	26.04	–1.13	1.56	0.51	29.43	21.88	0.52	–2.38
11	26.08	–1.01	1.17	0.57	29.36	23.44	0.71	–2.20

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
12	26.55	–1.10	1.44	0.51	29.32	22.95	0.25	–2.50
13	26.79	–1.16	1.37	0.50	29.70	23.44	0.69	–2.27
14	26.94	–1.07	1.14	0.50	29.96	23.26	0.31	–2.33
15	27.48	–1.04	1.11	0.46	30.13	24.35	–0.03	–2.22
16	27.62	–1.01	1.01	0.47	29.90	25.08	0.21	–1.95
17	27.08	–1.00	1.83	0.64	29.80	11.03	2.81	–2.37
18	27.83	–1.10	0.87	0.51	29.31	25.28	0.02	–2.56
19	28.08	–0.89	0.77	0.49	29.81	25.45	0.76	–1.90

Table A7. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	13.18	–0.25	1.33	0.55	17.64	10.46	0.89	–2.12
2	19.77	–0.54	1.83	0.67	24.28	15.48	1.95	–2.30
3	21.73	–0.79	1.78	0.59	25.47	17.19	0.79	–2.19
4	22.74	–0.89	1.63	0.57	26.14	18.76	0.58	–2.45
5	23.40	–0.89	1.51	0.64	27.22	19.80	0.92	–2.23
6	24.08	–0.95	1.71	0.53	27.71	18.96	0.59	–2.42
7	23.85	–0.97	1.47	0.49	28.05	20.19	0.69	–2.61
8	24.49	–1.05	1.67	0.62	27.92	19.66	0.37	–3.09
9	25.26	–1.14	1.36	0.54	27.66	21.79	0.01	–2.98
10	26.05	–1.20	1.09	0.43	28.16	22.88	0.03	–2.53
11	26.36	–1.23	1.21	0.48	28.64	22.89	0.17	–2.32
12	25.91	–1.22	1.08	0.44	28.32	22.54	0.39	–2.28
13	26.36	–1.20	1.05	0.45	28.84	23.62	–0.05	–2.77
14	26.65	–1.17	1.06	0.44	28.76	22.68	0.00	–2.40
15	26.74	–1.18	1.07	0.41	29.25	23.60	–0.30	–2.23
16	27.11	–0.99	0.82	0.43	29.38	24.34	0.09	–2.40
17	27.00	–1.09	0.90	0.42	28.59	23.78	–0.12	–2.27
18	27.01	–1.10	0.73	0.49	29.25	25.13	0.06	–2.52
19	27.21	–0.86	0.80	0.52	29.28	24.73	0.77	–2.48

Table A8. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	11.57	–0.21	1.37	0.39	15.94	7.70	0.61	–1.34
2	19.91	–0.60	1.88	0.59	23.60	16.07	0.58	–2.20
3	21.39	–0.69	1.59	0.60	25.04	16.99	0.95	–2.28
4	22.84	–0.81	1.49	0.52	26.72	19.49	0.21	–2.05
5	23.31	–0.82	1.48	0.51	26.54	19.68	0.55	–2.46
6	24.13	–0.81	1.55	0.56	28.36	21.22	0.59	–2.65
7	24.67	–0.92	1.18	0.45	27.32	21.04	0.20	–2.13

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
8	25.11	–0.90	1.46	0.49	28.54	21.46	0.25	–2.53
9	25.35	–0.93	1.18	0.43	27.59	21.93	0.46	–1.96
10	25.73	–0.92	1.14	0.46	28.20	22.05	0.35	–2.53
11	25.91	–0.97	1.08	0.38	27.74	23.41	–0.17	–2.37
12	25.92	–1.01	1.06	0.34	28.04	23.30	–0.12	–2.09
13	26.21	–1.02	0.94	0.37	28.58	22.59	0.30	–2.01
14	26.59	–1.06	0.78	0.32	28.59	24.18	–0.37	–1.96
15	26.44	–1.07	0.78	0.34	28.58	24.59	–0.25	–1.93
16	26.23	–1.09	0.74	0.36	27.98	24.09	0.00	–2.11
17	26.04	–1.28	0.82	0.33	28.05	23.92	–0.35	–2.13
18	25.71	–1.42	0.86	0.33	28.05	24.14	–0.50	–2.18
19	25.63	–1.49	0.80	0.39	27.36	23.85	–0.34	–2.20

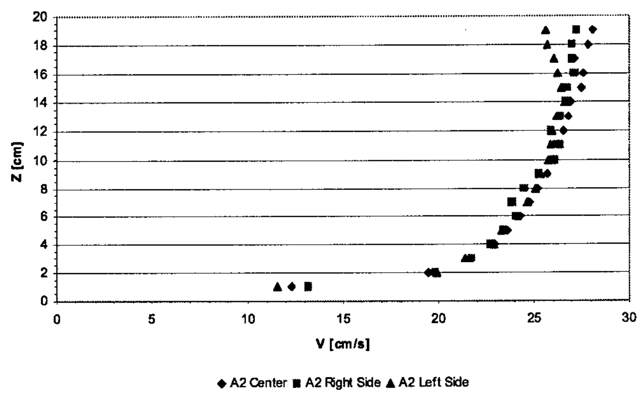


Figure A9. Velocity profiles.

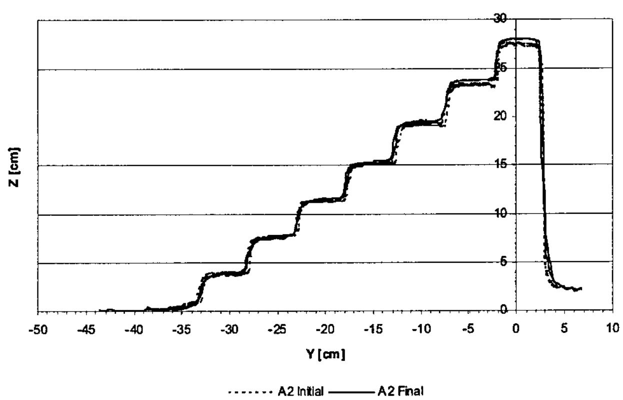


Figure A10. Calibration.

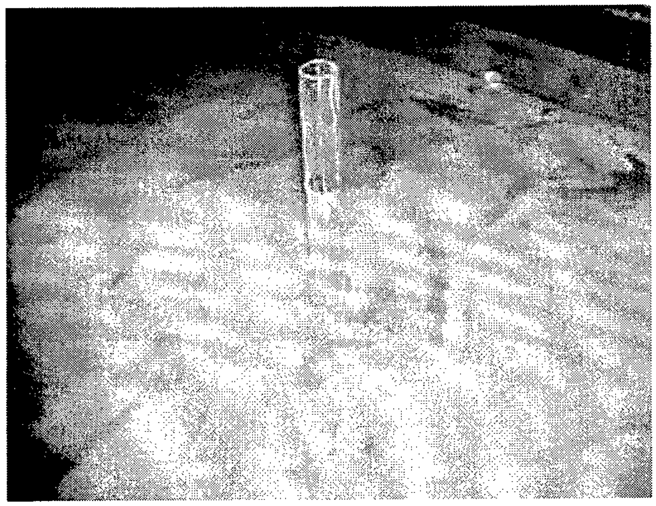


Figure A11. Final photo of scour hole; flow from right to left.

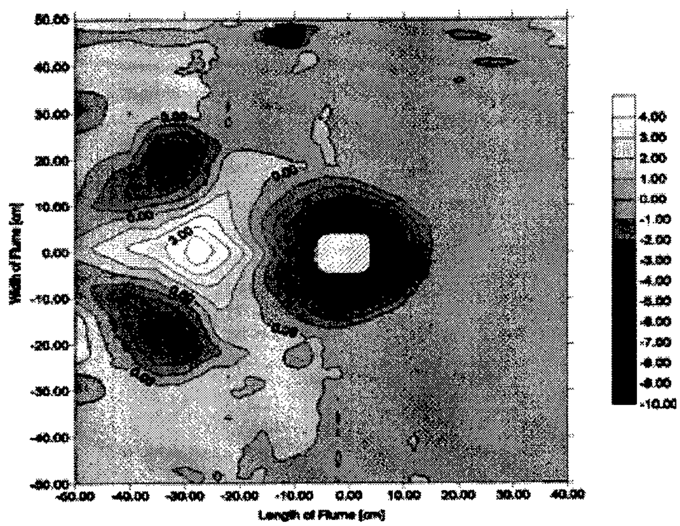


Figure A12. Contour plot; flow from right to left.

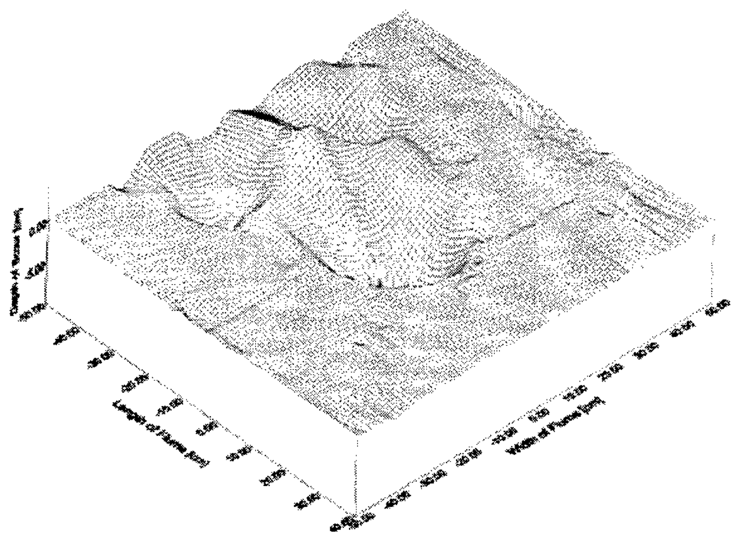


Figure A13. Surface plot; flow is from lower right to upper left.

Test A3

Table A9. Scour depth vs. time data.

Initial Reading =	10.0625	in
Start Time =	10:37	14-Feb-03
End Time =	19:42	14-Feb-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
10:37	10.0625	0:00	0.0000	0.000
10:39	10.0000	0:02	0.0625	0.159
10:40	9.8750	0:03	0.1875	0.476
10:41	9.7500	0:04	0.3125	0.794
10:43	9.5000	0:06	0.5625	1.429
10:44	9.2500	0:07	0.8125	2.064
10:45	9.1250	0:08	0.9375	2.381
10:47	9.0000	0:10	1.0625	2.699
10:51	8.8750	0:14	1.1875	3.016
10:56	8.7500	0:19	1.3125	3.334
11:00	8.6250	0:23	1.4375	3.651
11:06	8.5625	0:29	1.5000	3.810
11:13	8.5000	0:36	1.5625	3.969
11:20	8.4375	0:43	1.6250	4.128

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
11:25	8.3750	0:48	1.6875	4.286
11:37	8.3125	1:00	1.7500	4.445
11:46	8.2500	1:09	1.8125	4.604
12:03	8.1250	1:26	1.9375	4.921
12:48	8.0000	2:11	2.0625	5.239
13:50	7.8750	3:13	2.1875	5.556
14:20	7.7500	3:43	2.3125	5.874
14:50	7.6875	4:13	2.3750	6.033
15:18	7.6250	4:41	2.4375	6.191
16:09	7.5625	5:32	2.5000	6.350
16:51	7.5000	6:14	2.5625	6.509
18:12	7.4375	7:35	2.6250	6.668
19:07	7.3750	8:30	2.6875	6.826
19:42	7.3750	9:05	2.6875	6.826

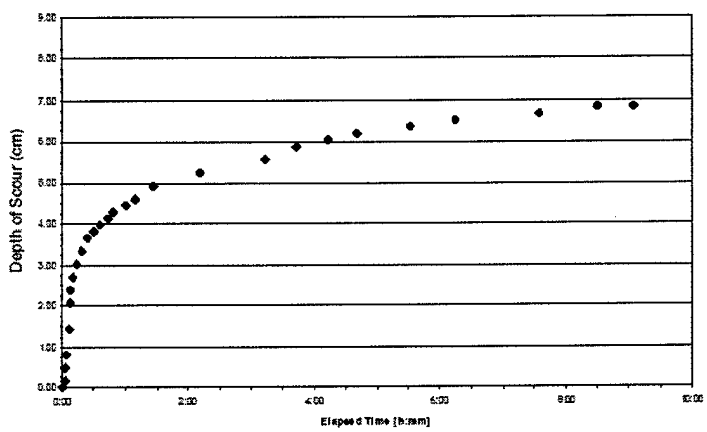


Figure A14. Scour depth vs. time.

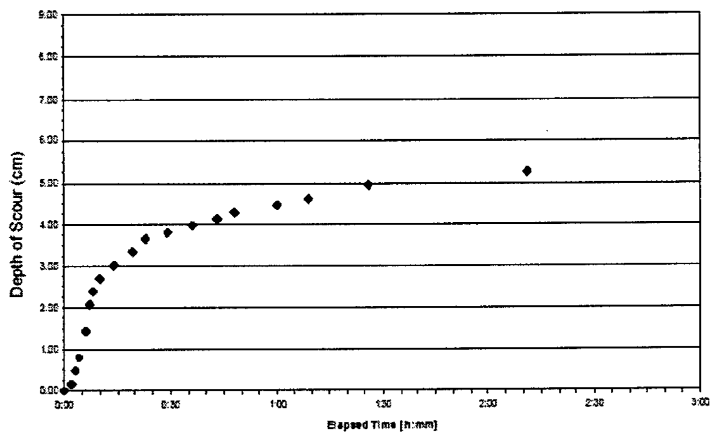


Figure A15. Scour depth vs. time for the first 3 hours.

Table A10. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	14.09	–0.66	1.59	0.56	17.91	10.35	1.00	–1.84
2	18.75	–1.07	1.98	0.59	23.72	13.84	0.49	–2.66
3	19.93	–1.21	1.66	0.65	24.81	15.73	0.12	–2.95
4	21.10	–1.26	1.95	0.55	25.2	16.90	0.04	–2.64
5	21.79	–1.27	1.52	0.53	25.65	18.14	0.05	–2.37
6	22.03	–1.38	1.68	0.59	25.51	18.59	0.72	–2.82
7	22.94	–1.43	1.44	0.61	26.13	19.13	0.19	–3.74
8	22.79	–1.41	1.53	0.65	26.38	18.63	0.11	–2.97
9	23.23	–1.46	1.26	0.61	26.43	19.77	0.83	–3.11
10	23.94	–1.45	1.24	0.56	26.32	20.07	0.04	–2.76
11	23.97	–1.47	1.33	0.61	26.88	19.89	0.27	–3.64
12	24.67	–1.48	1.36	0.53	27.9	20.98	0.44	–2.75
13	24.90	–1.53	1.12	0.46	27.19	21.80	–0.18	–2.73
14	24.85	–1.59	1.16	0.55	27.37	21.79	0.32	–2.98
15	25.08	–1.63	1.12	0.44	27.28	22.72	–0.50	–2.57
16	25.39	–1.66	1.00	0.41	27.83	22.06	–0.66	–2.58
17	25.49	–1.69	1.00	0.49	27.36	23.05	–0.20	–3.50
18	25.40	–1.63	0.86	0.42	27.27	22.84	0.23	–2.68
19	25.94	–1.67	1.00	0.50	28.21	22.78	0.05	–3.08
20	26.20	–1.65	0.73	0.44	28.08	23.80	–0.57	–2.82
21	25.54	–1.69	0.75	0.43	27.39	23.59	–0.72	–2.69
22	26.04	–1.61	0.78	0.46	27.56	23.74	–0.84	–2.79
23	26.09	–1.62	0.84	0.54	27.62	23.62	–0.31	–2.92
23.5	26.33	–1.64	0.60	0.49	28.03	24.71	–0.33	–3.35

Table A11. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	10.04	–0.46	1.58	0.52	15.50	6.25	0.90	–2.19
2	17.78	–1.06	1.71	0.59	21.91	13.84	0.65	–2.91
3	19.75	–1.18	1.67	0.66	22.96	14.93	0.48	–2.94
4	20.32	–1.16	1.77	0.69	24.35	16.14	0.64	–2.91
5	21.44	–1.35	1.54	0.62	24.08	16.16	0.65	–2.74
6	21.80	–1.40	1.46	0.59	26.53	17.74	0.39	–2.93
7	22.46	–1.43	1.49	0.55	26.00	18.50	0.04	–2.90
8	22.62	–1.50	1.22	0.55	25.27	19.73	–0.08	–2.88
9	23.06	–1.59	1.21	0.56	25.18	19.43	–0.42	–3.33
10	23.17	–1.61	1.15	0.51	26.00	20.08	–0.45	–3.15
11	23.56	–1.61	1.28	0.51	26.45	20.11	–0.18	–3.11
12	24.27	–1.70	1.20	0.50	26.81	20.41	–0.19	–3.27
13	23.88	–1.71	1.04	0.49	26.16	20.54	–0.66	–3.54
14	24.69	–1.71	1.10	0.52	27.28	20.90	0.03	–2.79
15	24.58	–1.68	1.07	0.42	26.95	21.30	–0.24	–3.15
16	24.01	–1.69	1.21	0.46	26.34	20.84	–0.53	–3.15
17	24.62	–1.68	0.72	0.45	26.36	22.84	–0.53	–3.42
18	24.79	–1.65	0.76	0.43	26.41	22.83	–0.02	–3.10
19	24.82	–1.57	0.67	0.38	26.31	22.86	–0.55	–2.59
20	25.00	–1.53	0.69	0.38	26.65	23.55	–0.71	–2.55
21	24.94	–1.48	0.76	0.43	26.69	22.89	–0.48	–2.88
22	25.07	–1.38	0.62	0.46	26.70	23.33	–0.47	–3.21
23	24.68	–1.34	0.88	0.59	27.39	22.95	0.01	–3.00
23.5	25.06	–1.29	0.72	0.55	27.36	23.57	0.62	–3.02

Table A12. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	12.03	–0.59	1.47	0.51	14.79	9.03	0.47	–2.22
2	18.46	–0.90	1.66	0.54	22.67	14.40	0.94	–3.08
3	19.68	–1.11	1.42	0.60	23.35	15.83	0.24	–3.46
4	20.01	–1.09	1.53	0.51	23.61	16.40	0.51	–2.48
5	20.74	–1.13	1.49	0.56	23.96	17.12	–0.06	–2.81
6	21.66	–1.19	1.38	0.53	24.76	17.06	0.00	–2.29
7	22.28	–1.25	1.30	0.48	25.27	19.41	0.20	–2.34
8	22.21	–1.29	1.50	0.49	25.21	18.06	0.14	–2.75
9	22.68	–1.28	1.20	0.54	25.22	19.81	0.16	–3.22
10	22.96	–1.28	1.18	0.42	24.97	19.85	–0.14	–2.31
11	23.39	–1.40	1.19	0.51	26.36	20.34	0.13	–2.61

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
12	23.72	–1.39	1.15	0.46	26.06	20.01	0.62	–2.61
13	24.12	–1.39	1.13	0.38	26.07	19.67	–0.24	–2.47
14	24.27	–1.43	1.02	0.37	26.52	21.92	–0.40	–2.37
15	24.26	–1.45	0.86	0.33	26.24	21.67	–0.50	–2.21
16	24.09	–1.52	0.85	0.42	25.86	22.01	0.12	–2.58
17	24.13	–1.62	0.84	0.33	26.34	21.04	–0.43	–2.28
18	24.06	–1.61	0.77	0.37	26.02	21.90	–0.53	–2.61
19	24.51	–1.66	0.87	0.35	26.99	21.59	–0.74	–2.46
20	24.08	–1.67	0.74	0.31	26.00	22.32	–1.01	–2.73
21	23.93	–1.86	0.73	0.31	25.37	21.90	–0.84	–2.73
22	23.48	–1.87	0.80	0.31	25.33	21.50	–0.86	–2.51
23	23.26	–2.02	0.78	0.35	24.69	21.27	–1.24	–2.88
23.5	23.44	–2.21	0.88	0.45	25.32	21.30	–0.91	–3.63

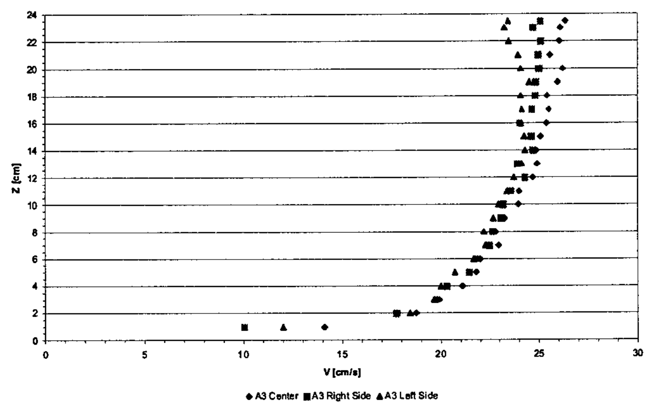


Figure A16. Velocity profiles.

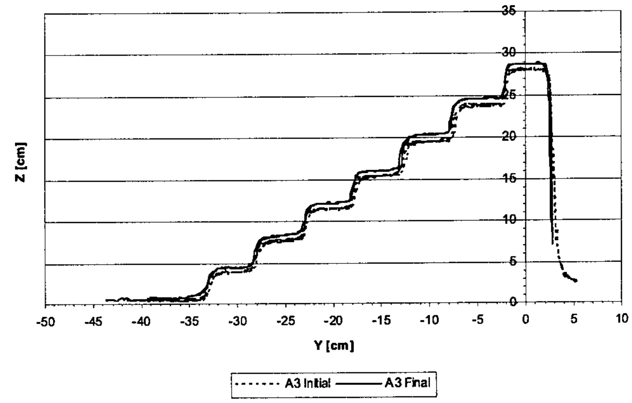


Figure A17. Calibration.

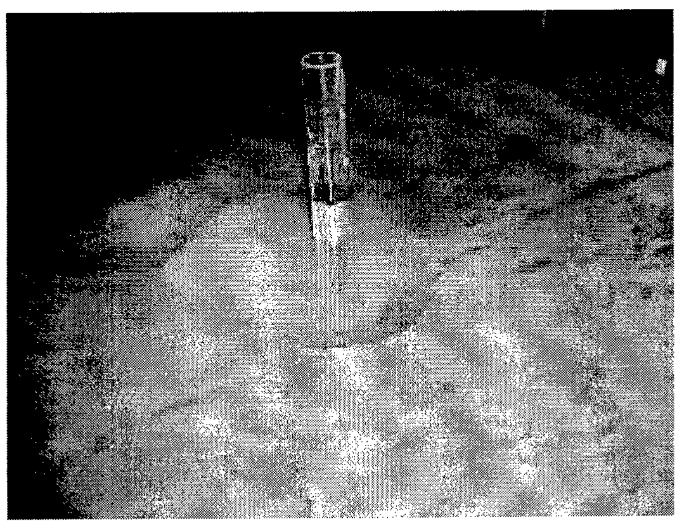


Figure A18. Final photo of scour hole; flow from right to left.

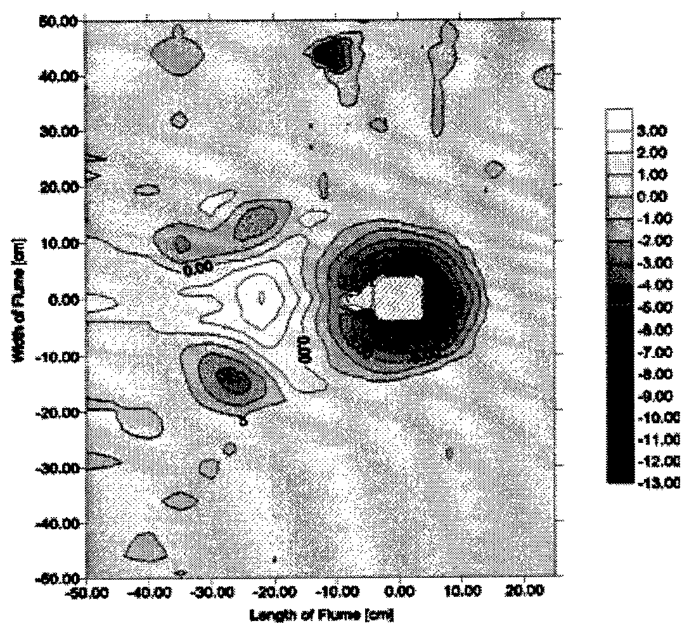


Figure A19. Contour plot; flow from right to left.

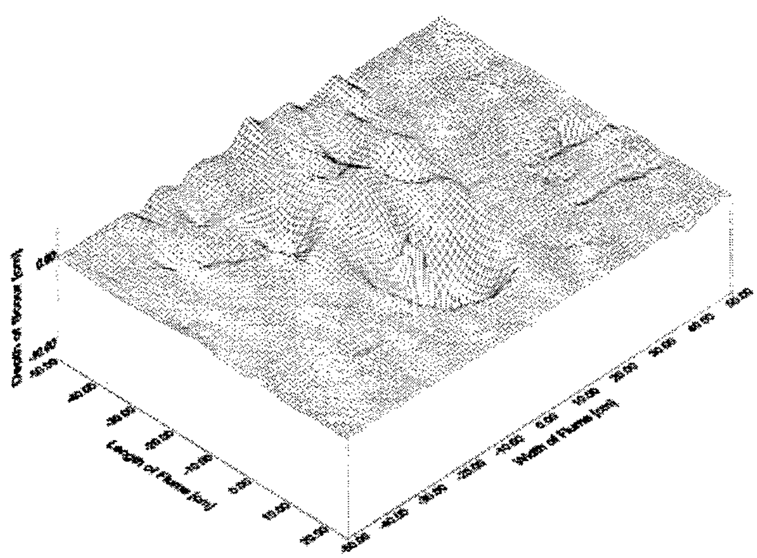


Figure A20. Surface plot; flow is from lower right to upper left.

Test A4

Table A13. Scour depth vs. time data.

Initial Reading =	10.0625	In.
Start Time =	18:28	06-Mar-03
End Time =	08:55	07-Mar-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
18:28	10.0625	0:00	0.0000	0.000
18:30	9.8750	0:02	0.1875	0.476
18:31	9.7500	0:03	0.3125	0.794
18:32	9.3750	0:04	0.6875	1.746
18:33	9.1250	0:05	0.9375	2.381
18:34	9.0000	0:06	1.0625	2.699
18:35	8.8750	0:07	1.1875	3.016
18:36	8.7500	0:08	1.3125	3.334
18:39	8.6250	0:11	1.4375	3.651
18:46	8.3750	0:18	1.6875	4.286
18:56	8.2500	0:28	1.8125	4.604
19:12	8.0000	0:44	2.0625	5.239
19:48	7.8125	1:20	2.2500	5.715
20:23	7.6250	1:55	2.4375	6.191
21:17	7.5000	2:49	2.5625	6.509
21:50	7.3750	3:22	2.6875	6.826
22:28	7.2500	4:00	2.8125	7.144
22:53	7.1875	4:25	2.8750	7.303
23:21	7.1250	4:53	2.9375	7.461
0:29	7.0000	6:01	3.0625	7.779
3:51	6.8750	9:23	3.1875	8.096
6:31	6.7500	12:03	3.3125	8.414
7:30	6.7500	13:02	3.3125	8.414
8:55	6.7500	14:27	3.3125	8.414

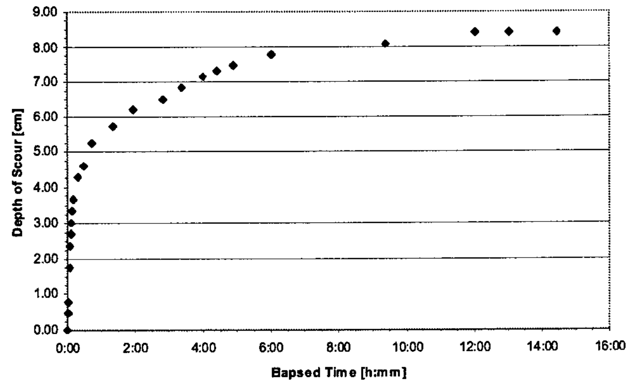


Figure A21. Scour depth vs. time.

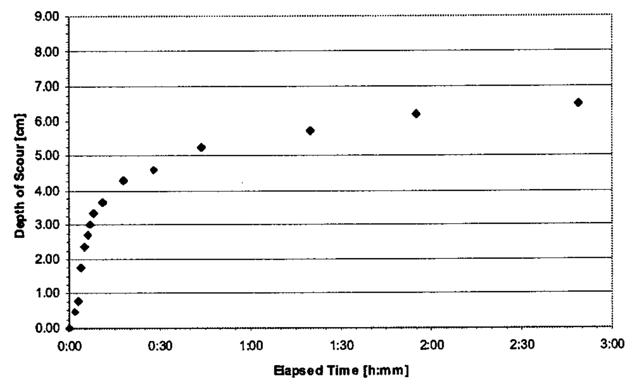


Figure A22. Scour depth vs. time for the first 3 hours.

Table A14. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	6.42	1.16	1.17	0.29	9.10	.3.90	1.98	0.37
2	19.52	0.53	1.75	0.79	23.08	15.54	2.27	–1.09
3	22.24	0.38	1.66	0.66	26.06	17.95	2.06	–1.17
4	23.56	0.31	1.76	0.68	27.51	19.18	1.93	–1.70
5	25.26	0.14	1.53	0.71	28.34	21.83	2.26	–1.30
6	24.99	0.28	1.88	0.63	28.69	19.90	1.97	–1.33
7	25.78	0.28	1.40	0.66	28.89	22.17	1.95	–1.51
8	25.88	0.31	1.46	0.61	29.55	23.00	1.54	–1.49
9	26.77	0.27	1.39	0.55	30.04	23.09	1.66	–1.21
10	26.27	0.30	1.76	0.57	29.81	21.72	1.80	–1.83
11	26.24	0.25	1.45	0.63	29.88	22.62	1.51	–1.61
12	27.23	0.29	1.53	0.53	30.41	22.90	1.71	–0.86

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
13	27.86	0.28	1.21	0.46	30.07	24.15	1.27	–0.93
14	27.84	0.25	1.24	0.56	31.05	24.33	1.84	–1.13
15	27.75	0.33	1.81	0.58	30.33	14.12	3.60	–1.08
16	28.37	0.31	1.17	0.47	31.26	24.90	1.39	–0.94
17	28.14	0.30	1.20	0.49	30.62	25.00	1.58	–1.11
18	28.52	0.37	1.05	0.48	30.63	26.05	1.94	–0.92
19	28.75	0.38	1.07	0.44	31.48	25.58	1.54	–0.65
20	28.73	0.39	0.89	0.42	30.71	26.65	1.57	–1.19
21	28.64	0.40	1.06	0.47	31.09	25.38	2.00	–0.65
21.5	28.77	0.43	1.02	0.54	30.88	25.72	2.50	–0.76

Table A15. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	5.96	1.00	1.19	0.34	9.36	2.97	1.94	0.20
2	20.43	0.44	1.59	0.75	24.29	16.28	2.08	–1.41
3	22.67	0.32	2.14	0.69	27.24	16.65	1.79	–1.68
4	24.19	0.31	1.71	0.68	28.12	18.18	2.17	–1.24
5	25.35	0.41	1.73	0.54	28.48	20.50	1.72	–0.78
6	25.27	0.23	1.84	0.60	28.61	20.47	1.92	–1.54
7	26.17	0.32	1.84	0.59	30.05	21.72	2.10	–1.29
8	26.41	0.31	1.62	0.59	29.65	22.21	2.09	–1.14
9	26.78	0.19	1.96	0.67	29.68	11.56	2.95	–1.80
10	27.19	0.25	1.44	0.57	30.13	22.94	1.89	–1.75
11	27.91	0.17	1.24	0.48	29.91	24.29	1.50	–0.93
12	27.59	0.15	1.33	0.54	30.50	24.22	1.44	–1.25
13	27.79	0.16	1.45	0.52	30.70	23.16	1.51	–0.94
14	28.08	0.17	1.01	0.42	30.07	25.34	1.39	–1.00
15	28.85	0.20	0.97	0.33	31.73	25.91	1.02	–0.61
16	28.44	0.28	1.01	0.39	31.16	25.98	1.20	–0.77
17	28.43	0.31	0.78	0.38	29.95	26.24	1.49	–0.57
18	28.77	0.38	0.80	0.40	30.61	26.18	1.30	–0.95
19	28.45	0.44	0.85	0.39	30.36	25.74	1.44	–0.89
20	28.44	0.52	0.89	0.48	30.46	26.15	1.65	–1.13
21	28.58	0.56	0.83	0.47	30.56	26.15	1.47	–0.99
21.5	28.71	0.69	0.69	0.51	30.73	27.07	1.98	–0.51

Table A16. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	1.75	0.17	0.50	0.10	3.00	0.48	0.38	–0.08
2	17.41	0.60	1.51	0.64	21.40	13.60	2.19	–1.02
3	22.53	0.31	1.72	0.59	26.64	18.46	1.72	–1.15
4	23.44	0.45	1.62	0.62	26.82	19.18	2.10	–1.20
5	24.37	0.42	1.80	0.53	27.83	18.52	1.88	–0.94
6	25.07	0.40	1.58	0.51	28.36	20.43	1.92	–1.06
7	25.90	0.52	1.36	0.46	28.50	22.44	1.72	–0.57
8	26.01	0.43	1.48	0.51	28.87	21.86	1.66	–0.82
9	26.32	0.50	1.40	0.52	29.45	23.17	2.08	–0.84
10	26.74	0.42	1.33	0.48	29.02	22.60	1.93	–0.53
11	26.93	0.53	1.17	0.42	29.45	23.97	1.51	–0.61
12	27.24	0.45	1.03	0.38	29.35	23.51	1.61	–0.53
13	27.01	0.43	1.06	0.36	29.45	22.72	1.40	–0.51
14	27.21	0.42	0.82	0.38	29.11	25.08	1.72	–0.43
15	27.40	0.38	0.77	0.32	29.70	25.40	1.28	–0.59
16	27.25	0.37	0.72	0.35	29.16	25.32	1.15	–0.52
17	27.17	0.28	0.82	0.37	29.09	24.99	1.49	–0.50
18	27.24	0.27	0.84	0.35	29.35	25.24	1.23	–0.60
19	27.16	0.22	0.77	0.39	28.86	24.85	1.25	–0.67
20	26.64	0.10	0.79	0.47	28.69	24.41	1.40	–1.11
21	26.70	0.02	0.84	0.44	28.82	24.33	1.25	–1.04
21.5	26.61	–0.04	0.95	0.50	29.08	24.42	1.46	–1.14

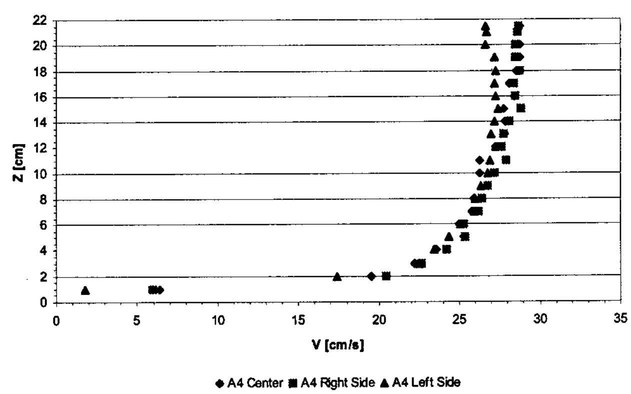


Figure A23. Velocity profiles.

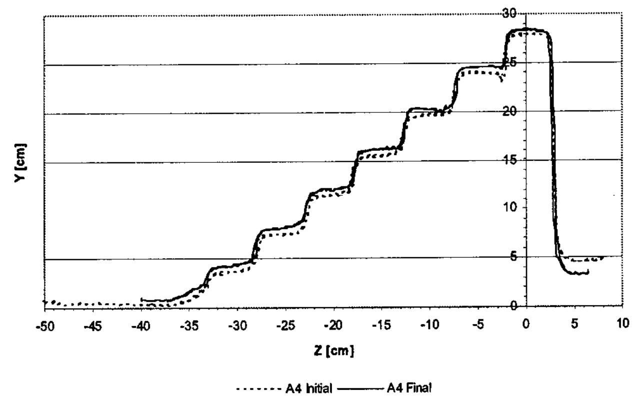


Figure A24. Calibration.

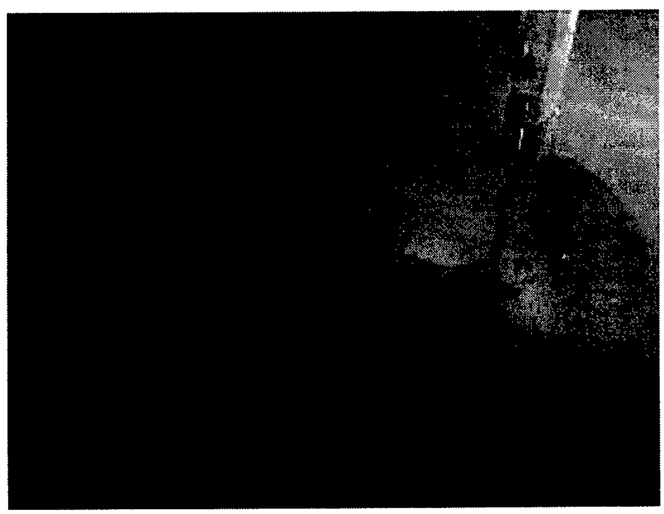


Figure A25. Final photo of scour hole; flow from right to left.

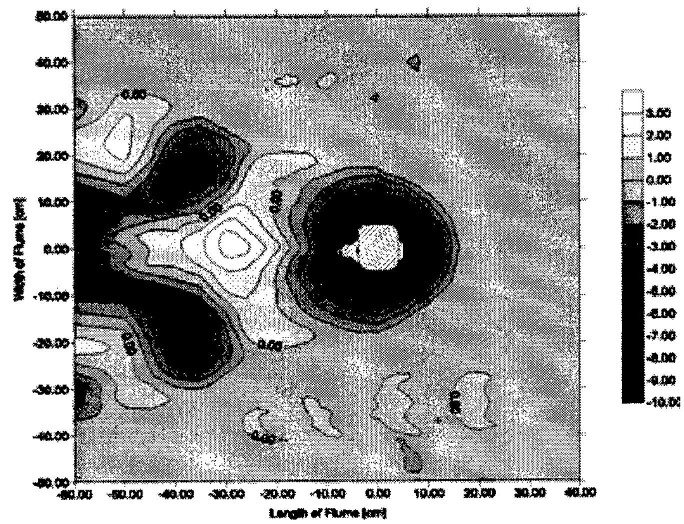


Figure A26. Contour plot; flow from right to left.

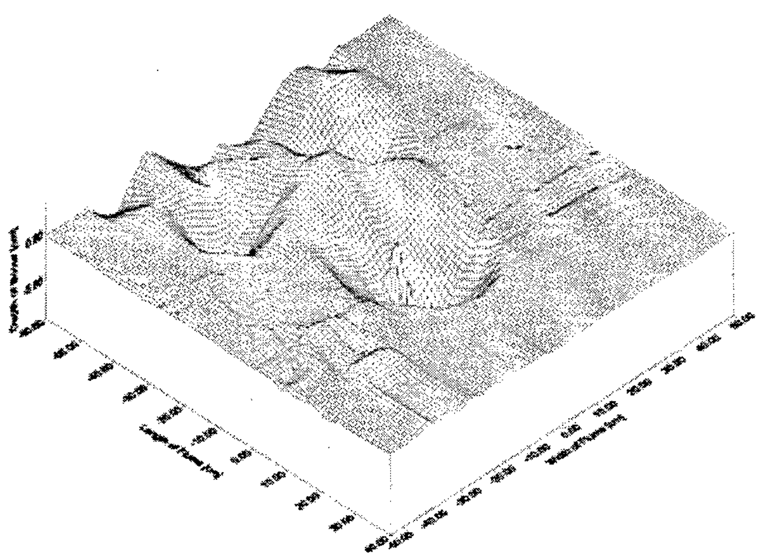


Figure A27. Surface plot; flow is from lower right to upper left.

Test A5

Table A17. Scour depth vs. time data.

Initial Reading =	10.125	In.
Start Time =	20:38	07-Mar-03
End Time =	12:50	08-Mar-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
20:38	10.1250	0:00	0.0000	0.000
20:41	9.7500	0:03	0.3750	0.953
20:42	9.6250	0:04	0.5000	1.270
20:43	9.3750	0:05	0.7500	1.905
20:44	9.2500	0:06	0.8750	2.223
20:49	9.1875	0:11	0.9375	2.381
20:58	9.0000	0:20	1.1250	2.858
21:25	8.7500	0:47	1.3750	3.493
21:37	8.6250	0:59	1.5000	3.810
21:45	8.5000	1:07	1.6250	4.128
22:20	8.3750	1:42	1.7500	4.445
23:04	8.2500	2:26	1.8750	4.763
23:52	8.1250	3:14	2.0000	5.080
0:48	8.0000	4:10	2.1250	5.398
1:57	7.8750	5:19	2.2500	5.715
3:15	7.7500	6:37	2.3750	6.033
5:36	7.6250	8:58	2.5000	6.350
9:10	7.6250	12:32	2.5000	6.350
9:24	7.5000	12:46	2.6250	6.668
10:17	7.5000	13:39	2.6250	6.668
11:05	7.5000	14:27	2.6250	6.668
11:56	7.5000	15:18	2.6250	6.668
12:50	7.4375	16:12	2.6875	6.826

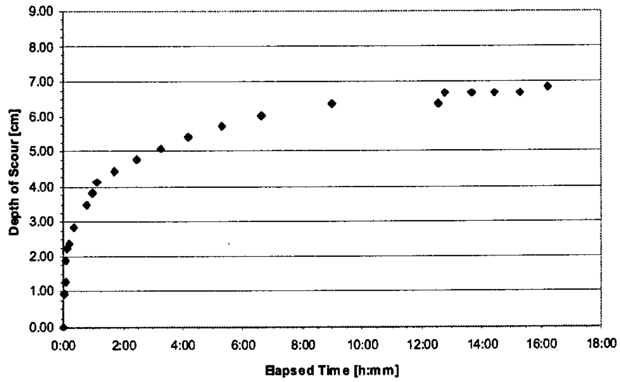


Figure A28. Scour depth vs. time.

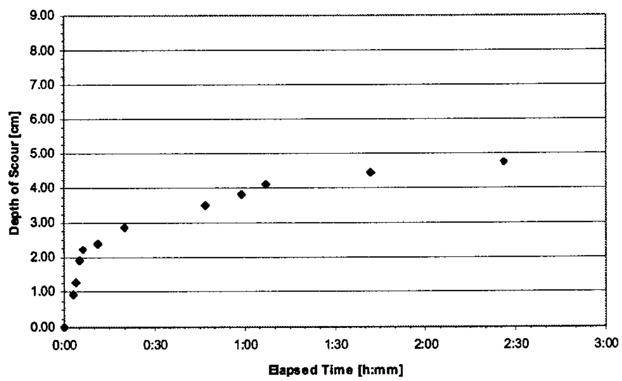


Figure A29. Scour depth vs. time for the first 3 hours.

Table A18. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	1.15	0.19	0.46	0.11	2.33	–0.04	0.58	–0.01
2	7.42	0.67	1.07	0.27	10.78	4.81	1.56	0.14
3	15.25	0.15	1.70	0.56	20.09	10.81	1.58	–1.17
4	17.48	0.10	1.61	0.56	21.18	13.47	1.55	–1.48
5	18.40	0.16	1.48	0.59	21.76	13.70	2.14	–1.64
6	18.91	0.14	1.28	0.58	22.19	16.03	1.93	–1.48
7	19.37	0.09	1.37	0.53	22.50	16.01	1.15	–1.28
8	19.21	0.15	1.41	0.63	22.09	15.69	2.33	–1.67
9	19.74	0.07	1.26	0.56	22.56	16.18	1.49	–1.37
10	19.92	0.04	1.50	0.57	23.15	15.28	1.85	–1.33
11	20.58	0.07	1.34	0.50	23.48	16.19	1.33	–1.50

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
12	20.97	0.07	1.28	0.51	23.41	16.78	1.49	–1.60
13	21.32	0.03	0.96	0.49	23.36	18.90	1.28	–1.15
14	21.87	0.03	1.21	0.51	23.98	17.95	1.65	–1.14
15	21.54	0.03	1.31	0.45	24.01	16.81	0.99	–1.03
16	21.94	0.02	0.96	0.52	23.90	18.18	1.09	–1.94
17	22.07	0.05	1.09	0.49	24.95	18.66	1.55	–1.04
18	22.87	0.08	0.73	0.38	25.25	20.49	0.93	–0.84
19	22.41	0.02	0.87	0.42	24.20	20.40	1.16	–0.90
20	22.27	0.10	1.02	0.51	23.88	18.16	1.11	–1.10
21	22.71	0.09	0.90	0.48	25.04	20.18	1.40	–1.06
21.5	22.96	0.05	0.81	0.48	24.99	21.27	1.57	–1.07

Table A19. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VxMax	VyMin
1	2.28	0.06	0.70	0.13	5.01	0.71	0.68	–0.25
2	8.38	0.29	1.17	0.30	11.80	5.44	0.93	–0.31
3	14.35	0.03	1.40	0.51	18.76	11.17	2.01	–1.45
4	17.24	0.12	1.47	0.54	20.39	13.28	1.48	–1.02
5	17.78	0.08	1.53	0.55	21.06	14.04	2.02	–1.37
6	18.02	–0.01	1.39	0.52	21.02	14.48	1.14	–1.28
7	18.56	–0.01	1.45	0.56	21.78	14.62	1.79	–1.58
8	19.06	0.01	1.57	0.48	22.09	15.20	1.22	–1.27
9	19.60	–0.11	1.09	0.48	21.98	17.04	1.24	–1.12
10	19.96	–0.07	1.20	0.46	22.57	16.18	1.32	–1.22
11	20.49	–0.10	1.16	0.45	23.69	17.55	1.49	–1.12
12	20.58	–0.14	1.19	0.45	23.92	17.35	0.88	–1.31
13	20.42	–0.07	1.07	0.47	22.78	17.93	0.98	–1.60
14	20.47	–0.14	1.17	0.47	23.36	17.29	1.24	–1.15
15	21.04	–0.04	0.86	0.39	23.28	18.62	1.00	–1.30
16	21.31	0.00	0.92	0.33	23.83	19.26	0.99	–0.82
17	21.39	0.07	0.88	0.35	23.61	18.60	1.32	–1.19
18	21.35	0.09	0.86	0.34	23.55	19.22	1.09	–0.77
19	21.26	0.22	0.86	0.34	23.58	18.92	0.99	–0.76
20	21.04	0.10	0.85	0.42	23.32	19.06	0.91	–1.07
21	20.81	0.23	0.77	0.40	22.53	18.88	1.77	–1.03
21.5	21.14	0.40	0.97	0.46	23.85	18.98	1.34	–1.07

Table A20. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	0.66	0.13	0.33	0.08	1.78	–0.01	0.39	–0.07
2	8.98	0.47	1.37	0.36	12.30	5.61	1.59	–0.43
3	14.48	0.14	1.48	0.52	17.79	11.26	1.30	–1.03
4	17.27	0.13	1.51	0.50	21.06	12.83	1.57	–1.18
5	17.40	0.20	1.34	0.55	21.89	14.35	1.76	–1.08
6	18.18	0.18	1.52	0.53	22.17	14.40	1.36	–1.21
7	18.55	0.26	1.29	0.53	21.94	15.24	1.56	–1.39
8	19.27	0.24	1.22	0.43	21.75	15.86	1.71	–0.69
9	19.38	0.22	1.33	0.43	22.32	16.01	1.53	–1.21
10	19.75	0.22	1.10	0.43	22.20	16.09	1.39	–1.01
11	20.03	0.20	1.29	0.41	22.46	16.72	1.29	–0.91
12	20.27	0.18	1.06	0.39	22.24	17.10	1.15	–1.25
13	20.35	0.16	1.12	0.36	22.81	17.19	0.96	–0.89
14	21.07	0.18	0.86	0.35	23.37	18.68	1.05	–0.71
15	20.95	0.15	0.80	0.31	22.67	18.81	0.90	–0.55
16	20.70	0.08	0.80	0.33	22.48	18.38	1.00	–1.07
17	21.08	0.02	0.65	0.32	22.88	19.50	0.64	–0.83
18	20.68	0.02	0.64	0.30	22.44	19.31	0.93	–0.55
19	20.73	–0.02	0.68	0.36	22.22	19.01	0.81	–1.03
20	20.37	–0.30	0.66	0.31	22.10	18.53	0.54	–1.09
21	20.29	–0.31	0.77	0.37	21.79	18.08	1.22	–1.35
21.5	20.25	–0.37	0.74	0.41	22.04	18.20	0.88	–1.98

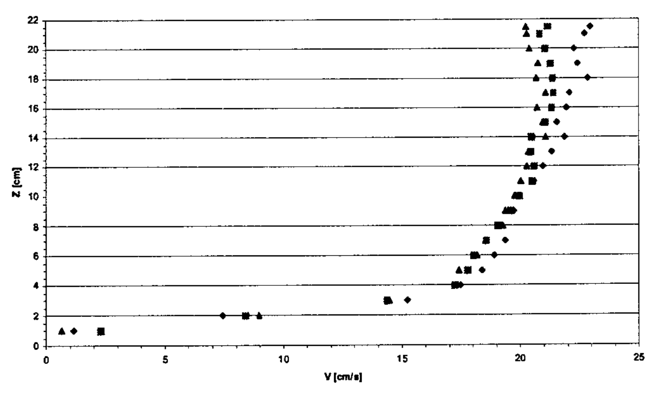


Figure A30. Velocity profiles.

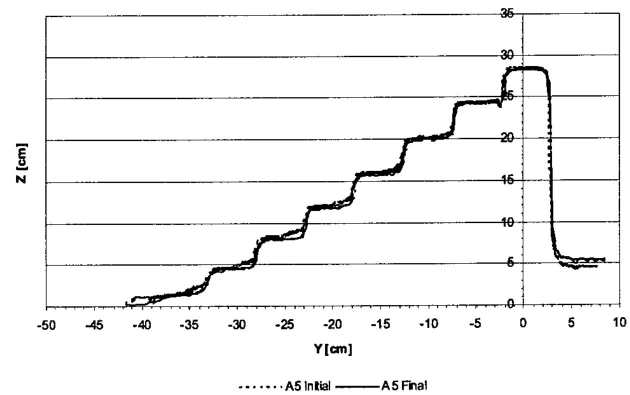


Figure A31. Calibration.

Figure A32. Final photo of scour hole; flow from right to left.

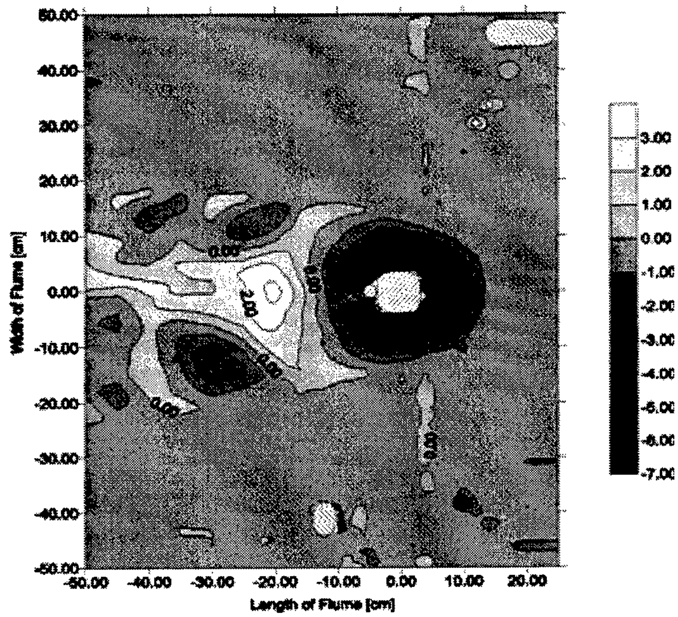


Figure A33. Contour plot; flow from right to left.

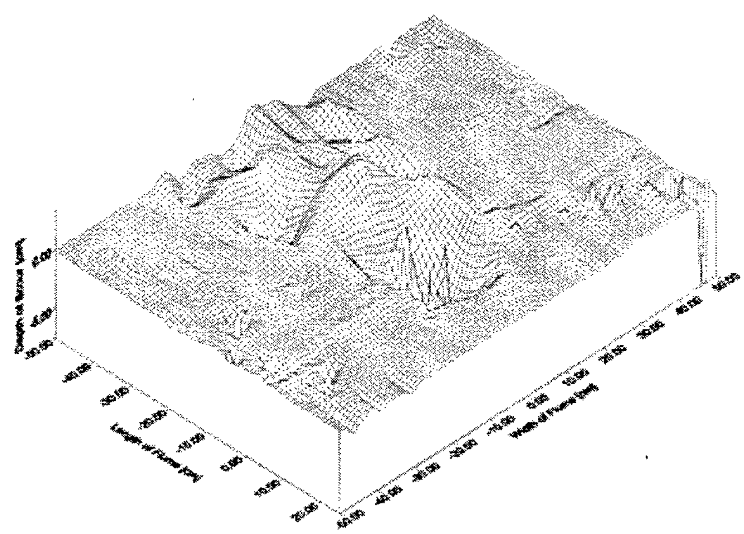


Figure A34. Surface plot; flow is from lower right to upper left.

Test A6

Table A21. Scour depth vs.time data.

Initial Reading =	10.125	in
Start Time =	19:05	11-Mar-03
End Time =	08:18	12-Mar-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
19:05	10.1250	0:00	0.0000	0.000
19:07	10.0000	0:02	0.1250	0.318
19:08	9.7500	0:03	0.3750	0.953
19:09	9.5000	0:04	0.6250	1.588
19:10	9.2500	0:05	0.8750	2.223
19:13	9.1250	0:08	1.0000	2.540
19:15	9.0000	0:10	1.1250	2.858
19:20	8.8750	0:15	1.2500	3.175
19:44	8.6250	0:39	1.5000	3.810
19:51	8.5000	0:46	1.6250	4.128
20:08	8.3750	1:03	1.7500	4.445
20:32	8.3125	1:27	1.8125	4.604
20:41	8.2500	1:36	1.8750	4.763
21:02	8.1250	1:57	2.0000	5.080
21:53	8.0000	2:48	2.1250	5.398
23:04	7.8750	3:59	2.2500	5.715
0:18	7.7500	5:13	2.3750	6.033
2:01	7.6250	6:56	2.5000	6.350
4:10	7.5000	9:05	2.6250	6.668
6:30	7.3750	11:25	2.7500	6.985
7:36	7.3125	12:31	2.8125	7.144
8:14	7.2500	13:09	2.8750	7.303
8:18	7.2500	13:13	2.8750	7.303

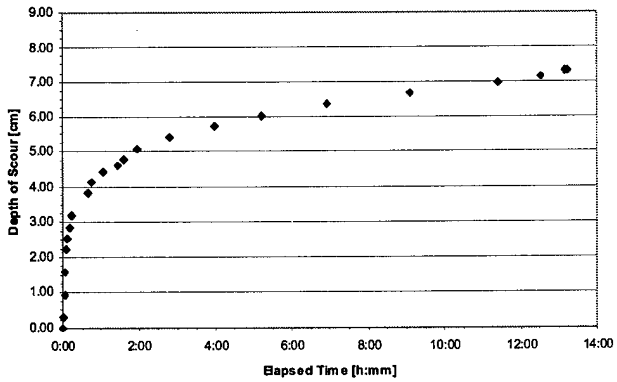


Figure A35. Scour depth vs. time.

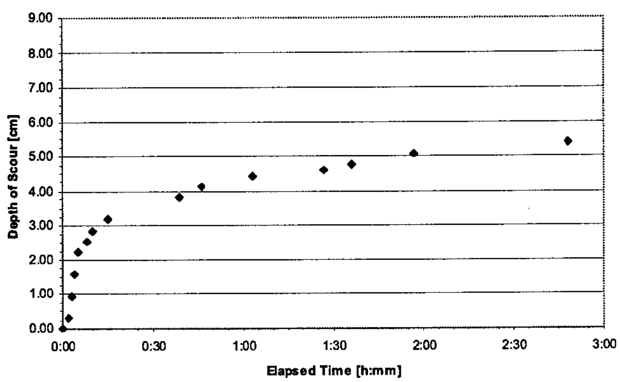


Figure A36. Scour depth vs. time for the first 3 hours.

Table A22. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	3.25	0.09	0.84	0.17	5.74	1.12	0.60	–0.41
2	15.00	–0.05	1.36	0.59	18.30	12.53	1.32	–1.43
3	18.68	–0.13	1.63	0.59	24.45	15.15	1.40	–1.80
4	20.36	–0.10	1.61	0.57	23.82	15.61	1.31	–1.44
5	20.52	–0.18	1.67	0.57	24.33	15.79	1.37	–1.52
6	21.00	–0.27	1.72	0.55	24.17	16.28	1.24	–1.62
7	21.48	–0.22	1.53	0.58	25.47	17.19	1.45	–1.93
8	22.25	–0.17	1.50	0.51	25.00	16.81	1.63	–1.41
9	22.46	–0.20	1.47	0.55	25.82	19.30	1.14	–1.78
10	23.08	–0.14	1.44	0.51	25.47	18.42	1.23	–1.72
11	22.86	–0.20	1.24	0.56	25.59	19.98	1.52	–1.89
12	23.50	–0.22	1.12	0.47	25.54	19.75	1.20	–1.31

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
13	23.42	–0.22	1.38	0.47	26.13	19.47	1.27	–1.43
14	24.08	–0.22	1.00	0.51	26.34	21.70	1.93	–1.62
15	24.53	–0.23	0.98	0.37	26.46	22.13	0.61	–1.04
16	24.36	–0.21	1.12	0.50	26.44	21.44	1.20	–1.22
17	24.64	–0.16	1.00	0.44	26.78	21.98	0.91	–1.12
18	24.71	–0.22	0.95	0.45	27.00	21.71	0.83	–1.24
19	24.76	–0.23	0.97	0.42	26.35	21.28	0.92	–1.27
20	24.69	–0.17	0.92	0.44	26.95	22.40	1.04	–1.36

Table A23. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	3.58	0.06	0.79	0.24	5.56	1.84	0.58	–0.44
2	15.17	0.12	1.44	0.51	18.49	11.67	1.72	–1.05
3	18.83	–0.10	1.40	0.56	21.75	14.20	1.46	–1.62
4	19.14	–0.16	1.55	0.59	23.82	15.48	1.83	–1.88
5	20.25	–0.20	1.56	0.55	23.85	15.91	1.36	–1.80
6	20.65	–0.23	1.62	0.54	24.26	16.41	0.99	–1.56
7	21.33	–0.24	1.50	0.51	24.28	17.80	0.98	–1.95
8	21.90	–0.28	1.32	0.48	24.41	17.92	1.29	–1.34
9	22.37	–0.30	1.15	0.43	24.93	17.94	0.67	–1.27
10	22.43	–0.29	1.38	0.47	24.83	18.70	1.00	–1.73
11	22.57	–0.30	1.29	0.48	24.90	18.60	0.88	–1.50
12	23.38	–0.31	1.01	0.44	25.55	19.72	0.91	–1.39
13	23.32	–0.31	1.29	0.44	26.24	19.83	0.68	–1.53
14	23.48	–0.37	1.10	0.51	26.12	19.91	0.77	–1.81
15	23.38	–0.26	1.16	0.43	25.78	19.13	1.02	–1.43
16	23.89	–0.32	1.13	0.43	26.55	20.23	0.74	–1.59
17	23.85	–0.25	0.83	0.43	25.90	21.93	0.75	–1.28
18	23.79	–0.16	0.81	0.43	26.06	21.65	0.65	–1.56
19	23.93	–0.18	0.86	0.52	26.95	21.78	0.98	–1.45
20	23.74	0.04	0.79	0.49	25.89	21.26	1.41	–1.57

Table A24. velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	4.05	0.46	0.80	0.20	6.29	1.78	0.92	0.07
2	13.30	0.57	1.52	0.46	17.03	9.25	1.92	–0.46
3	18.17	0.02	1.50	0.59	21.01	14.99	1.66	–1.59
4	19.17	0.11	1.48	0.49	22.57	15.66	1.45	–1.51
5	19.76	0.05	1.33	0.52	22.51	16.55	1.21	–1.27

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
6	20.68	0.03	1.44	0.56	24.10	17.82	1.48	–1.50
7	20.82	–0.03	1.36	0.52	24.78	17.46	1.46	–1.30
8	21.67	–0.02	1.26	0.55	24.25	17.92	1.66	–1.27
9	22.26	–0.06	1.03	0.41	24.23	19.44	1.04	–0.96
10	22.69	–0.06	0.99	0.42	24.98	19.94	0.93	–1.44
11	22.70	–0.07	1.01	0.44	24.86	20.61	1.47	–1.12
12	23.06	–0.04	0.94	0.42	25.37	20.58	1.32	–1.41
13	22.97	–0.13	0.86	0.40	25.28	20.83	1.07	–1.15
14	23.54	–0.08	0.74	0.33	25.63	21.68	0.83	–0.86
15	23.16	–0.18	0.89	0.37	25.08	20.09	0.95	–1.22
16	23.49	–0.22	0.69	0.33	24.91	21.83	0.62	–1.08
17	23.13	–0.21	0.81	0.31	24.66	20.79	0.64	–0.97
18	23.06	–0.37	0.73	0.33	25.09	21.43	0.47	–1.40
19	22.89	–0.52	0.66	0.34	24.73	21.11	0.38	–1.56
20	22.59	–0.68	0.80	0.33	24.33	20.18	0.12	–1.41

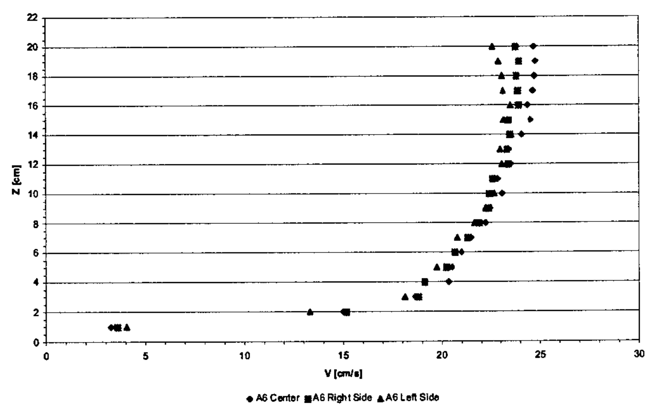


Figure A37. Velocity profile.

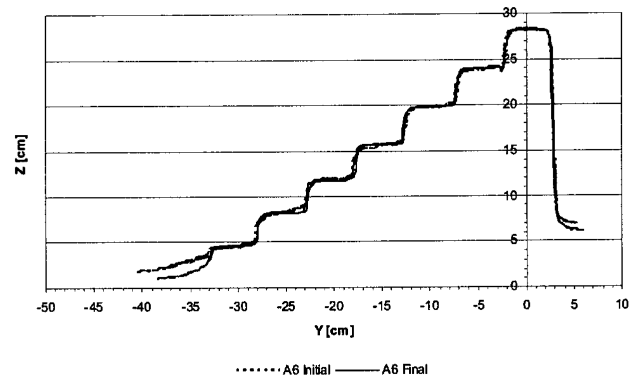


Figure A38. Calibration

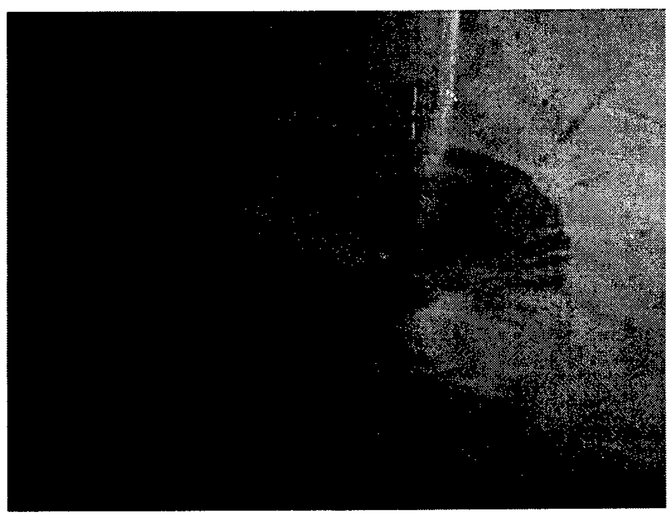


Figure A39. Final photo of scour hole; flow from right to left.

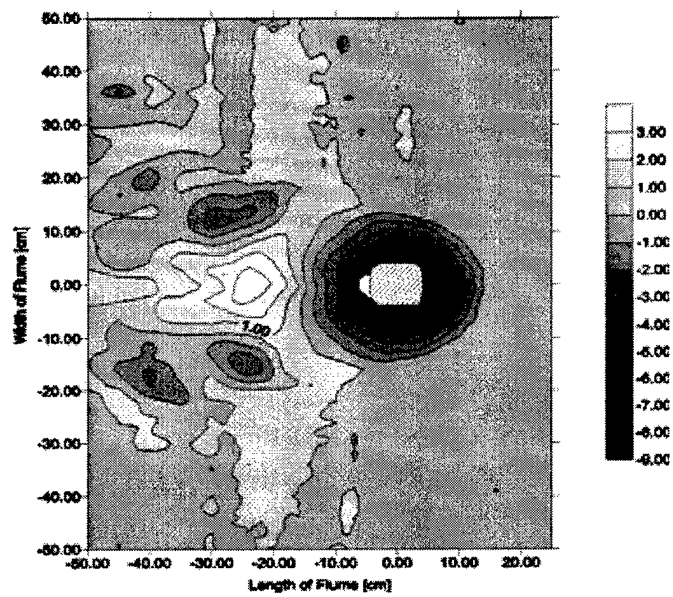


Figure A40. Contour plot; flow from right to left.

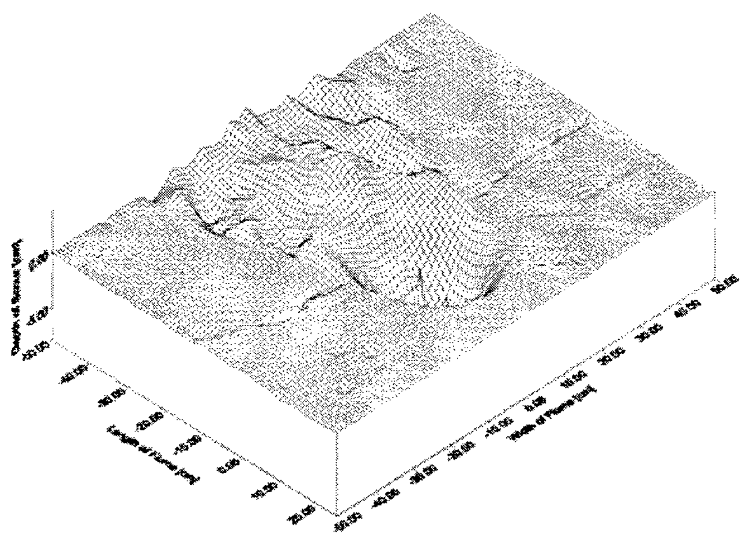


Figure A41. Surface plot; flow is from lower right to upper left.

APPENDIX B: FLOATING COVER

Test B1

Table B1. Scour depth vs. time data.

Initial Reading =	10.0625	in.
Start Time =	13:54	19-Feb-03
End Time =	09:43	20-Feb-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
13:54	10.0625	0:00	0.0000	0.000
13:56	10.0000	0:02	0.0625	0.159
13:57	9.7500	0:03	0.3125	0.794
13:59	9.6250	0:05	0.4375	1.111
14:01	9.5000	0:07	0.5625	1.429
14:02	9.3750	0:08	0.6875	1.746
14:03	9.2500	0:09	0.8125	2.064
14:04	9.1250	0:10	0.9375	2.381
14:05	9.0625	0:11	1.0000	2.540
14:06	9.0000	0:12	1.0625	2.699
14:08	8.8750	0:14	1.1875	3.016
14:11	8.8125	0:17	1.2500	3.175
14:14	8.7500	0:20	1.3125	3.334
14:18	8.6250	0:24	1.4375	3.651
14:24	8.5625	0:30	1.5000	3.810
14:28	8.5000	0:34	1.5625	3.969
14:48	8.3750	0:54	1.6875	4.286
15:34	8.0625	1:40	2.0000	5.080
15:52	8.0000	1:58	2.0625	5.239
16:18	7.9375	2:24	2.1250	5.398
16:23	7.8750	2:29	2.1875	5.556
16:56	7.8125	3:02	2.2500	5.715
17:13	7.7500	3:19	2.3125	5.874
18:08	7.6875	4:14	2.3750	6.033
18:24	7.6250	4:30	2.4375	6.191
18:43	7.5625	4:49	2.5000	6.350
18:57	7.5000	5:03	2.5625	6.509
19:44	7.4375	5:50	2.6250	6.668
20:25	7.3750	6:31	2.6875	6.826
22:05	7.2500	8:11	2.8125	7.144
0:22	7.1250	10:28	2.9375	7.461

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
3:04	7.0000	13:10	3.0625	7.779
4:50	6.8750	14:56	3.1875	8.096
6:44	6.8125	16:50	3.2500	8.255
7:25	6.8125	17:31	3.2500	8.255
9:43	6.8125	19:49	3.2500	8.255

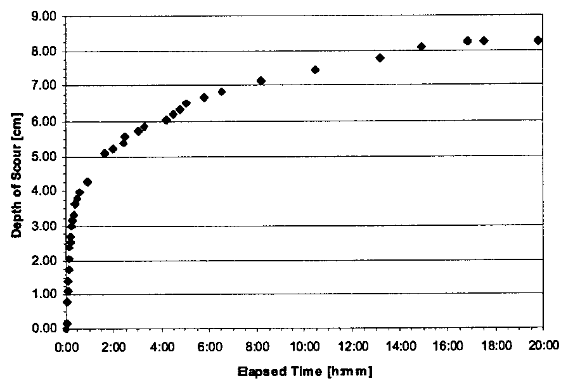


Figure B1. Scour depth vs. time.

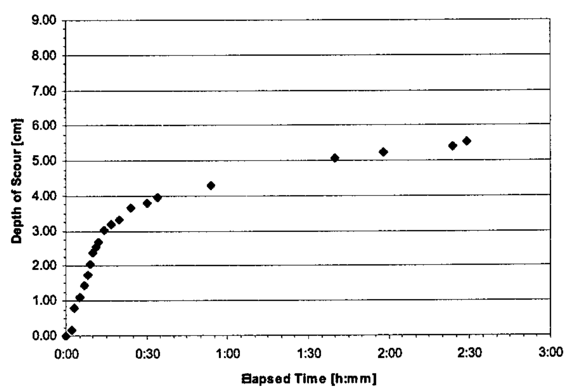


Figure B2. Scour depth vs. time for the first 3 hours.

Table B2. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	8.12	0.45	1.34	0.40	11.73	4.90	1.51	–0.48
2	18.54	0.93	1.51	0.44	21.32	13.85	2.33	–0.36
3	20.50	0.81	1.37	0.46	23.53	16.94	2.15	–0.34
4	21.65	0.83	1.20	0.45	23.99	18.45	2.09	–0.33
5	22.70	0.85	1.28	0.39	25.37	19.20	1.78	–0.05
6	23.53	0.88	1.18	0.40	25.97	20.52	1.87	–0.21
7	23.85	0.91	1.07	0.40	26.16	21.24	1.92	–0.26
8	24.51	0.91	0.98	0.33	26.57	21.86	1.59	–0.02
9	24.93	0.89	0.92	0.32	26.96	21.80	1.80	0.12
10	25.20	0.93	0.81	0.29	26.78	22.78	1.59	0.13
11	25.27	0.89	0.71	0.29	27.06	22.76	1.50	0.14
12	25.28	0.88	0.77	0.30	26.98	22.82	1.71	0.10
13	25.20	0.83	0.73	0.30	26.80	23.15	1.65	0.03
14	25.24	0.86	0.76	0.32	26.74	23.15	1.61	–0.02
15	24.76	0.78	0.91	0.37	26.93	22.12	1.87	–0.22
16	24.56	0.79	1.08	0.37	27.07	21.76	1.59	–0.43
17	23.98	0.76	1.15	0.39	26.50	20.44	1.74	–0.32
18	23.69	0.77	1.29	0.44	26.26	20.17	1.77	–0.22
19	23.08	0.75	1.37	0.48	26.26	19.37	1.91	–1.16
20	22.23	0.76	1.46	0.48	25.19	18.30	2.05	–0.45
21	21.64	0.64	1.50	0.52	25.29	17.09	2.21	–0.61
22	20.15	0.78	1.42	0.52	24.38	15.29	2.32	–1.00
23	17.48	0.92	1.65	0.50	21.48	13.65	2.02	–0.25
24	6.35	0.15	1.35	0.24	10.40	2.97	0.75	–0.32

Table B3. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	6.71	0.55	1.16	0.32	9.73	4.10	1.51	–0.42
2	14.53	0.85	1.35	0.35	18.47	10.93	1.63	–0.01
3	19.99	0.17	1.47	0.43	24.14	16.70	1.09	–0.95
4	21.51	0.04	1.40	0.44	24.82	17.34	1.09	–0.93
5	22.26	–0.03	1.24	0.38	24.58	19.05	1.00	–1.04
6	22.82	0.00	1.25	0.39	25.57	19.68	1.16	–0.91
7	23.39	–0.02	1.05	0.40	26.24	20.41	1.38	–0.93
8	24.09	–0.11	1.09	0.28	26.22	21.43	0.59	–1.16
9	24.38	–0.09	0.95	0.37	26.64	22.17	1.06	–0.98
10	24.66	–0.08	0.94	0.30	26.62	21.59	0.73	–0.71
11	24.79	–0.09	0.87	0.30	27.25	22.43	0.82	–0.74
12	24.89	–0.14	0.79	0.33	26.84	22.53	0.83	–1.21

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
13	24.96	–0.15	0.82	0.33	26.89	22.97	0.81	–1.13
14	24.55	–0.17	0.92	0.29	26.70	22.17	0.61	–1.04
15	24.42	–0.13	0.99	0.37	26.31	21.42	1.23	–1.00
16	24.08	–0.15	1.10	0.39	26.49	20.60	0.88	–1.21
17	23.68	–0.14	1.24	0.38	26.42	19.99	0.98	–1.03
18	22.85	–0.13	1.27	0.43	25.60	19.75	0.92	–1.69
19	22.44	–0.14	1.24	0.44	24.92	19.54	1.04	–1.19
20	21.34	–0.14	1.21	0.45	24.10	18.30	1.11	–1.58
21	20.68	–0.02	1.48	0.48	24.10	17.35	1.35	–1.15
22	18.86	0.14	1.61	0.52	23.30	14.32	1.33	–0.99
23	15.85	–0.01	1.45	0.55	19.82	11.51	1.30	–1.36
24	6.46	–0.01	1.54	0.28	11.22	2.94	0.79	–0.94

Table B4. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	6.51	1.18	1.22	0.29	9.84	2.77	1.92	0.54
2	16.27	1.40	1.39	0.46	20.07	13.17	2.56	0.18
3	19.86	1.53	1.47	0.48	22.73	14.88	2.62	0.47
4	20.76	1.62	1.38	0.48	24.29	17.22	2.65	0.00
5	22.05	1.66	1.21	0.41	24.35	18.13	2.74	0.50
6	22.33	1.68	1.32	0.39	24.97	18.65	2.62	0.62
7	22.83	1.72	1.03	0.40	25.34	19.43	2.63	0.42
8	23.24	1.77	0.98	0.39	25.43	20.04	2.94	0.85
9	23.71	1.90	0.92	0.41	26.11	20.44	2.82	1.00
10	24.26	1.84	0.86	0.33	26.12	21.87	2.56	0.62
11	24.37	1.87	0.83	0.29	25.98	22.17	2.90	1.12
12	24.52	1.90	0.82	0.35	26.49	22.55	2.97	1.06
13	24.51	1.91	0.76	0.31	26.80	22.41	2.75	0.89
14	24.34	1.88	0.93	0.36	26.32	21.54	2.97	0.85
15	24.18	1.80	0.83	0.36	25.97	21.90	2.62	0.41
16	24.03	1.81	0.95	0.36	26.36	21.74	3.21	0.73
17	23.33	1.72	1.17	0.38	25.73	19.78	2.50	0.74
18	23.06	1.74	1.13	0.47	25.40	19.87	3.08	0.73
19	22.35	1.62	1.28	0.45	25.43	19.10	3.03	0.48
20	21.57	1.57	1.41	0.49	24.41	18.01	2.86	–0.47
21	21.08	1.57	1.36	0.44	23.96	17.52	2.65	0.13
22	20.33	1.51	1.45	0.50	23.85	17.38	2.73	0.20
23	18.98	1.39	1.58	0.60	22.76	14.66	2.83	–0.23
24	12.95	1.20	1.77	0.50	18.02	8.78	2.82	–0.24

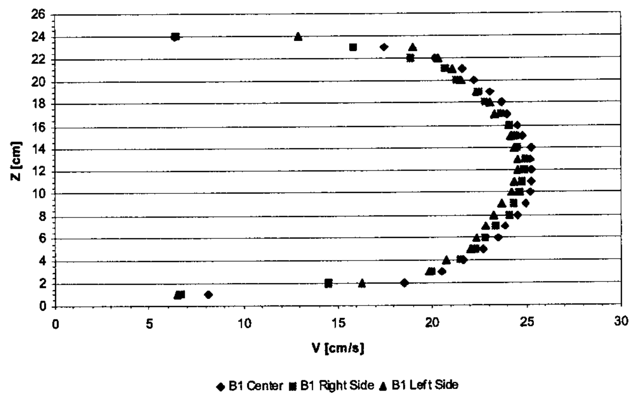


Figure B3. Velocity profiles.

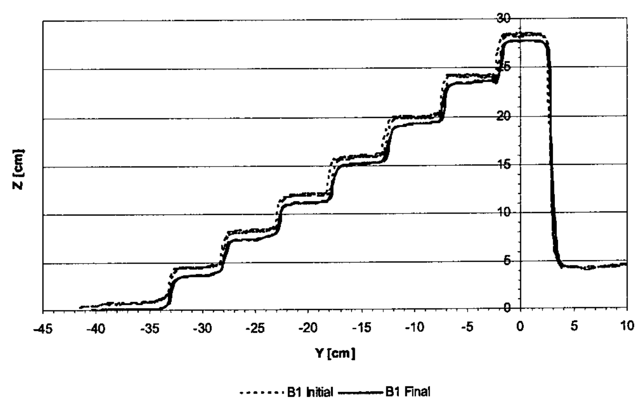


Figure B4. Calibration.

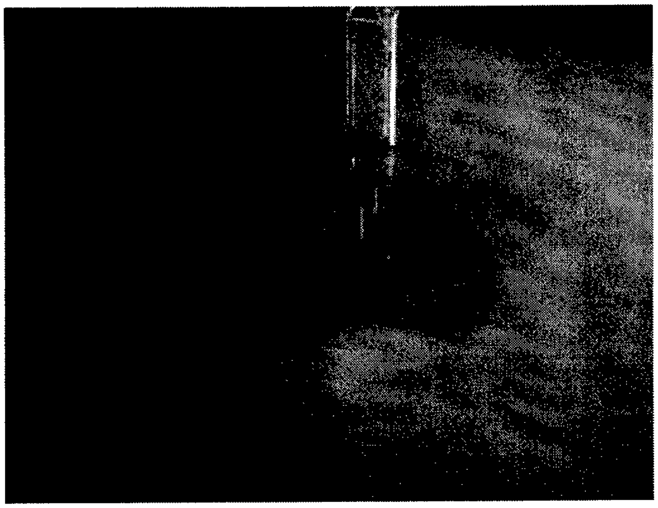


Figure B5. Final photo of scour hole; flow from right to left.

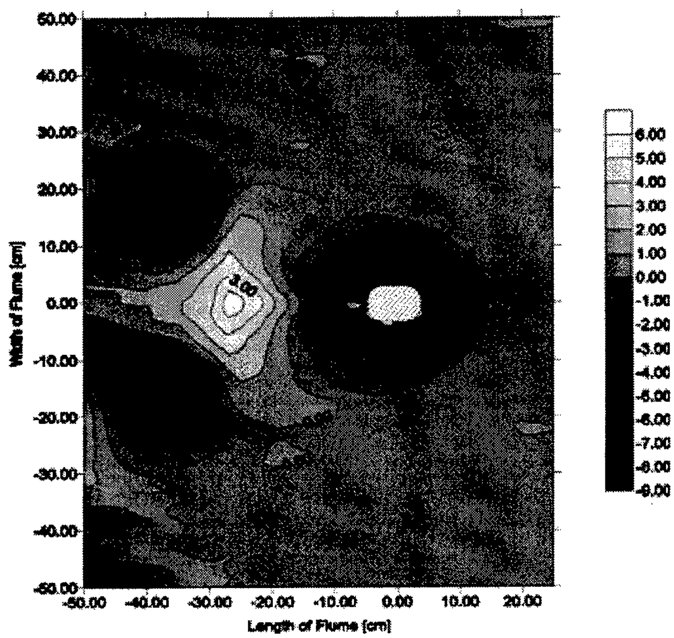


Figure B6. Contour plot; flow from right to left.

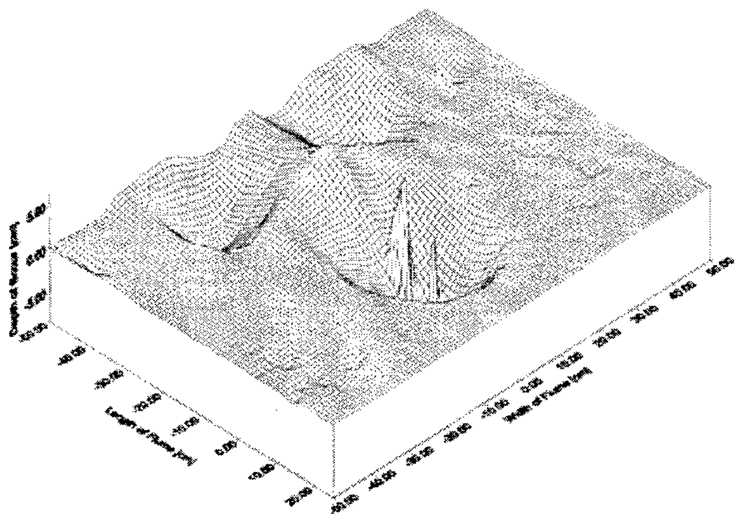


Figure B7. Surface plot; flow is from lower right to upper left.

Test B2

Table B5. Scour depth vs. time data.

Initial Reading =	10	in
Start Time =	10:57	21-Feb-03
End Time =	09:05	22-Feb-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
10:57	10.0000	0:00	0.0000	0.000
11:00	9.8125	0:03	0.1875	0.476
11:02	9.6250	0:05	0.3750	0.953
11:05	9.4375	0:08	0.5625	1.429
11:06	9.1250	0:09	0.8750	2.223
11:08	9.0000	0:11	1.0000	2.540
11:10	8.7500	0:13	1.2500	3.175
11:13	8.6250	0:16	1.3750	3.493
11:17	8.5000	0:20	1.5000	3.810
11:23	8.3750	0:26	1.6250	4.128
11:27	8.3125	0:30	1.6875	4.286
11:29	8.2500	0:32	1.7500	4.445
11:51	8.1250	0:54	1.8750	4.763
11:59	8.0625	1:02	1.9375	4.921

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
12:01	8.0000	1:04	2.0000	5.080
12:25	7.8750	1:28	2.1250	5.398
12:52	7.7500	1:55	2.2500	5.715
13:36	7.6250	2:39	2.3750	6.033
14:11	7.5000	3:14	2.5000	6.350
14:33	7.4375	3:36	2.5625	6.509
14:44	7.3750	3:47	2.6250	6.668
16:32	7.2500	5:35	2.7500	6.985
16:45	7.1875	5:48	2.8125	7.144
16:57	7.1250	6:00	2.8750	7.303
17:02	7.0625	6:05	2.9375	7.461
17:29	7.0000	6:32	3.0000	7.620
18:33	6.8750	7:36	3.1250	7.938
19:21	6.8125	8:24	3.1875	8.096
23:00	6.8125	12:03	3.1875	8.096
3:00	6.8125	16:03	3.1875	8.096
6:33	6.7500	19:36	3.2500	8.255
9:05	6.7500	22:08	3.2500	8.255

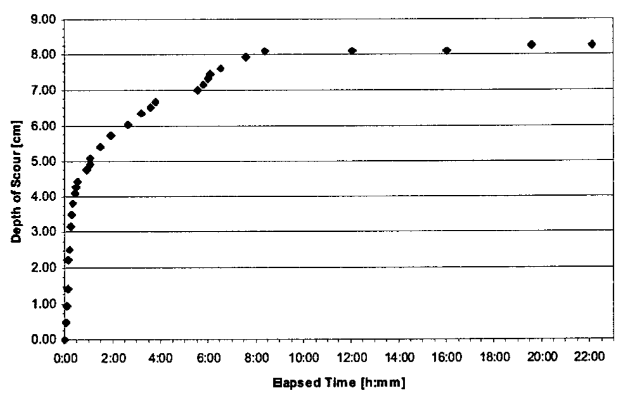


Figure B8. Scour depth vs. time.

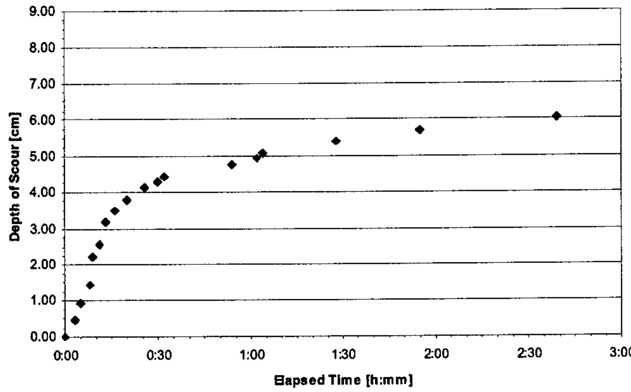


Figure B9. Scour depth vs. time for the first 3 hours.

Table B6. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	14.26	–0.25	1.75	0.42	18.39	9.43	0.80	–1.33
2	21.37	–0.75	1.64	0.48	25.73	17.41	0.29	–2.11
3	23.86	–0.89	1.27	0.43	27.40	20.28	0.46	–1.78
4	25.11	–1.00	1.06	0.36	27.72	22.63	–0.12	–2.12
5	25.92	–1.01	0.91	0.31	27.67	23.24	–0.25	–1.86
6	26.15	–1.03	0.94	0.32	28.12	23.64	–0.19	–1.90
7	26.92	–1.03	0.83	0.27	28.82	24.22	–0.36	–1.82
8	27.06	–1.08	0.82	0.25	28.90	24.58	–0.28	–1.61
9	27.22	–1.09	0.74	0.27	28.89	25.62	–0.41	–1.81
10	27.18	–1.11	0.70	0.29	28.77	25.36	–0.49	–1.96
11	27.01	–1.06	0.83	0.34	28.94	25.01	–0.04	–1.98
12	26.48	–1.08	0.95	0.28	28.41	23.77	–0.10	–1.91
13	26.05	–1.09	1.13	0.34	28.66	22.31	–0.04	–2.09
14	25.37	–1.06	1.10	0.32	28.15	22.23	–0.14	–1.83
15	24.45	–1.03	1.20	0.36	26.84	20.66	–0.08	–2.42
16	23.54	–0.98	1.34	0.44	26.74	18.63	0.03	–2.22
17	21.12	–0.73	1.58	0.50	24.70	17.41	0.91	–1.97
18	16.43	–0.84	1.97	0.47	21.61	12.07	0.34	–1.94
19	8.84	–0.35	1.15	0.33	11.95	5.81	0.43	–1.29

Table B7. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	3.75	0.33	0.85	0.14	6.37	2.05	0.83	0.01
2	18.92	–0.10	1.48	0.43	22.39	15.46	1.26	–1.09
3	22.67	–0.28	1.20	0.46	25.27	19.12	0.73	–1.49
4	24.19	–0.27	1.18	0.38	26.71	21.08	0.67	–1.41
5	24.97	–0.32	1.18	0.37	27.32	20.66	0.98	–1.29
6	25.84	–0.34	0.97	0.31	27.93	23.22	0.50	–1.17
7	26.41	–0.38	0.83	0.31	28.59	24.03	0.52	–1.10
8	26.78	–0.34	0.78	0.29	28.81	24.25	0.50	–1.10
9	26.90	–0.41	0.65	0.25	28.03	24.44	0.39	–1.20
10	26.96	–0.41	0.75	0.28	28.93	24.65	0.64	–1.06
11	26.70	–0.42	0.92	0.28	28.49	23.72	0.16	–1.22
12	26.04	–0.43	0.97	0.32	28.29	22.40	0.34	–1.32
13	25.63	–0.43	1.16	0.35	28.01	22.22	0.72	–1.27
14	25.06	–0.41	1.17	0.34	27.69	21.36	0.29	–1.23
15	24.21	–0.44	1.35	0.42	26.96	20.72	0.58	–1.48
16	23.38	–0.39	1.44	0.48	26.94	20.17	1.16	–1.54
17	22.33	–0.34	1.47	0.43	26.45	18.49	0.78	–1.41
18	19.34	–0.35	1.55	0.45	23.54	15.91	0.64	–1.58
19	3.68	–0.28	1.01	0.16	6.85	1.58	0.21	–0.70

Table B8. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	XMax	XMin	YMax	YMin
1	6.73	0.03	1.45	0.27	10.78	3.56	0.62	–0.65
2	17.72	–0.63	1.50	0.38	21.33	14.30	0.79	–1.49
3	22.22	–0.87	1.26	0.44	25.19	19.25	0.27	–1.95
4	23.69	–0.89	1.21	0.39	26.16	20.10	–0.08	–1.86
5	24.57	–0.96	1.20	0.40	27.84	21.71	0.09	–2.03
6	25.54	–0.99	1.07	0.33	28.26	21.61	–0.17	–1.73
7	25.90	–0.97	0.87	0.27	27.50	23.18	–0.39	–1.71
8	26.43	–0.99	0.79	0.28	28.15	24.34	–0.28	–2.16
9	26.64	–0.93	0.67	0.23	28.33	24.31	–0.21	–1.52
10	26.58	–0.95	0.69	0.25	28.14	24.97	–0.39	–1.78
11	26.53	–0.99	0.80	0.27	28.14	24.46	–0.27	–1.74
12	25.98	–0.99	0.84	0.30	28.05	23.76	–0.08	–2.01
13	25.60	–1.02	0.98	0.35	27.81	22.32	0.09	–1.89
14	24.68	–0.97	1.17	0.41	27.48	21.12	0.40	–2.16
15	24.08	–0.98	1.31	0.42	26.82	20.29	0.07	–2.10
16	23.22	–0.91	1.37	0.44	25.64	18.89	0.29	–1.86
17	21.42	–0.91	1.30	0.52	24.37	18.11	0.16	–2.32
18	18.76	–0.67	1.40	0.50	21.99	14.62	0.35	–1.91
19	7.60	–0.32	1.35	0.32	10.69	4.62	0.38	–1.33

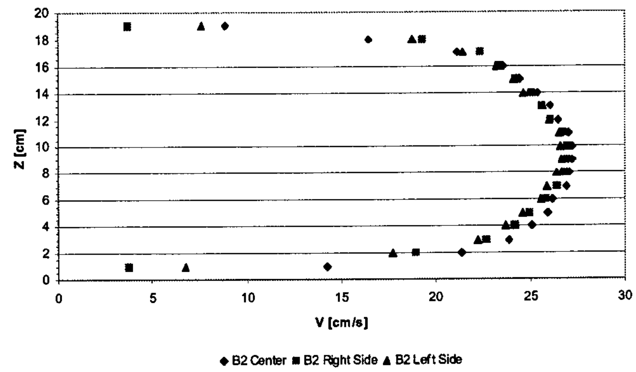


Figure B10. Velocity profiles.

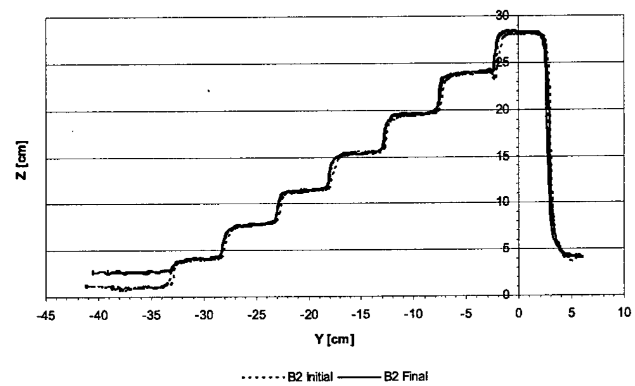


Figure B11. Calibration.

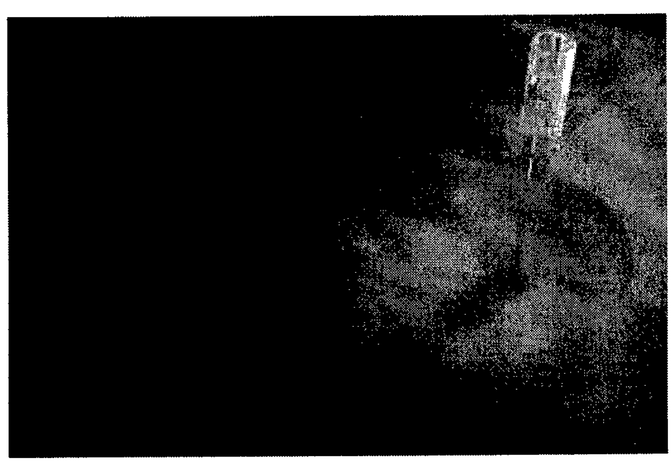


Figure B12. Final photo of scour hole; flow from right to left.

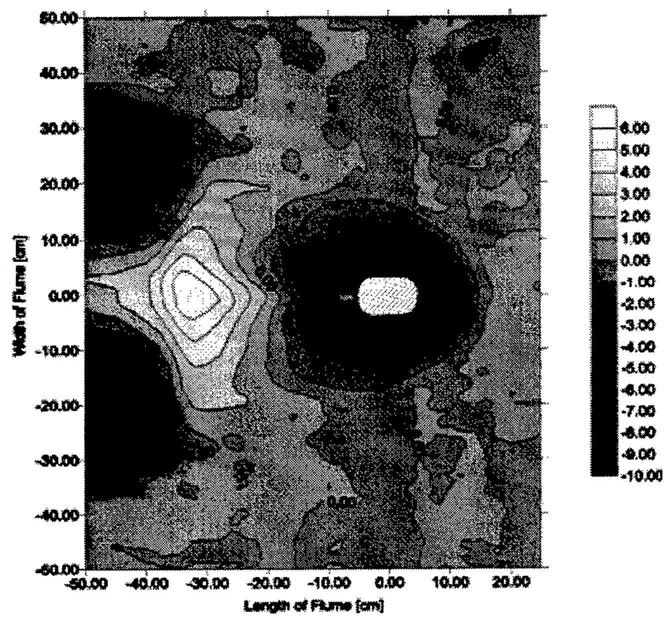


Figure B13. Contour plot; flow from right to left.

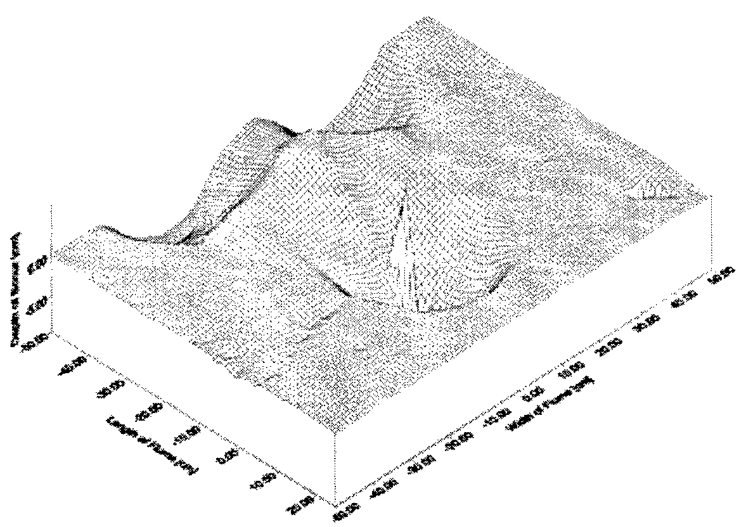


Figure B14. Surface plot; flow is from lower right to upper left.

Test B3

Table B9. Scour depth vs. time data.

Initial Reading =	10	In.
Start Time =	13:31	03-Mar-03
End Time =	07:41	04-Mar-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
13:31	10.0000	0:00	0.0000	0.000
13:33	9.8750	0:02	0.1250	0.318
13:35	9.7500	0:04	0.2500	0.635
13:36	9.5000	0:05	0.5000	1.270
13:38	9.3750	0:07	0.6250	1.588
13:48	9.1875	0:17	0.8125	2.064
13:51	9.1250	0:20	0.8750	2.223
13:53	9.0000	0:22	1.0000	2.540
14:09	8.8125	0:38	1.1875	3.016
14:19	8.6875	0:48	1.3125	3.334
14:22	8.6250	0:51	1.3750	3.493
14:24	8.5625	0:53	1.4375	3.651
14:46	8.5000	1:15	1.5000	3.810
15:17	8.4375	1:46	1.5625	3.969
15:22	8.3750	1:51	1.6250	4.128
15:56	8.2500	2:25	1.7500	4.445
16:35	8.1875	3:04	1.8125	4.604
16:45	8.1250	3:14	1.8750	4.763
16:54	8.0625	3:23	1.9375	4.921
18:08	8.0000	4:37	2.0000	5.080
18:33	7.9375	5:02	2.0625	5.239
18:46	7.8750	5:15	2.1250	5.398
18:54	7.8125	5:23	2.1875	5.556
20:00	7.7500	6:29	2.2500	5.715
20:15	7.6875	6:44	2.3125	5.874
21:00	7.6250	7:29	2.3750	6.033
21:25	7.5000	7:54	2.5000	6.350
22:00	7.6250	8:29	2.3750	6.033
22:38	7.5000	9:07	2.5000	6.350
0:12	7.6250	10:41	2.3750	6.033
1:04	7.5000	11:33	2.5000	6.350
1:46	7.3750	12:15	2.6250	6.668

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
2:54	7.5000	13:23	2.5000	6.350
3:39	7.3750	14:08	2.6250	6.668
5:08	7.2500	15:37	2.7500	6.985
5:23	7.3750	15:52	2.6250	6.668
6:39	7.2500	17:08	2.7500	6.985
7:13	7.2500	17:42	2.7500	6.985
7:41	7.2500	18:10	2.7500	6.985

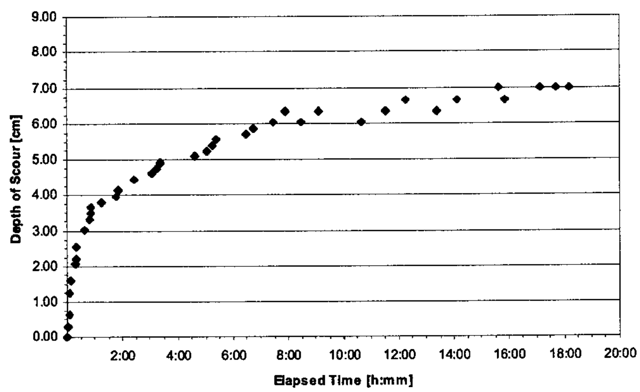


Figure B15. Scour depth vs. time.

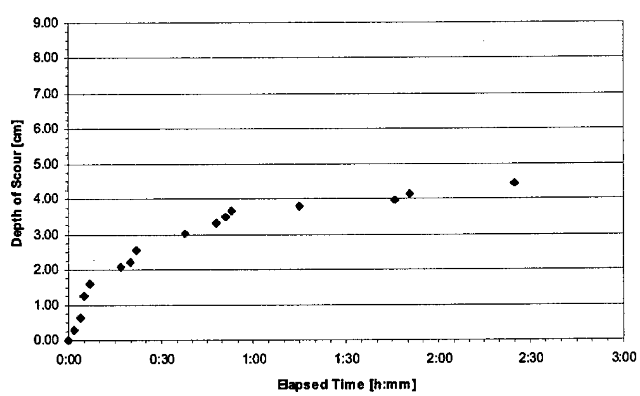


Figure B16. Scour depth vs. time for the first 3 hours.

Table B10. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	5.34	0.55	0.95	0.27	7.91	3.23	1.16	–0.21
2	15.36	0.12	1.26	0.38	18.24	12.21	1.05	–1.01
3	19.04	0.07	1.39	0.42	21.76	15.34	1.60	–0.98
4	20.10	0.03	1.24	0.42	22.35	16.61	1.22	–1.06
5	20.85	0.07	1.11	0.43	23.36	17.81	0.93	–1.19
6	21.57	0.04	0.96	0.37	23.84	19.45	0.81	–1.04
7	22.04	0.01	0.96	0.37	24.15	19.49	0.86	–1.26
8	22.51	0.05	0.90	0.31	24.58	20.11	1.09	–0.71
9	23.05	0.02	0.88	0.28	25.30	20.99	0.79	–0.76
10	22.88	–0.02	0.74	0.30	24.49	20.87	0.97	–0.75
11	23.21	0.00	0.66	0.27	25.15	21.69	0.99	–0.59
12	23.23	0.00	0.63	0.25	24.51	21.36	0.61	–0.74
13	22.87	–0.05	0.70	0.32	24.33	20.66	0.77	–0.92
14	22.43	–0.05	1.01	0.34	24.62	19.78	0.83	–1.30
15	21.77	–0.03	1.04	0.37	23.79	18.87	1.04	–0.82
16	21.33	–0.03	1.11	0.39	23.67	17.59	1.31	–1.14
17	20.98	–0.01	1.10	0.36	23.46	18.36	0.95	–1.07
18	20.33	–0.06	1.18	0.40	23.03	16.98	1.09	–1.23
19	19.23	–0.04	1.67	0.41	22.51	15.32	1.32	–1.03
20	17.97	–0.01	1.32	0.45	20.54	14.94	1.10	–1.45
21	15.78	0.08	1.53	0.50	19.09	12.27	1.38	–1.08
21.5	13.45	0.18	1.29	0.47	16.30	10.48	1.56	–1.22

Table B11. velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	3.29	0.36	0.67	0.14	5.36	1.82	0.79	0.00
2	12.33	0.76	1.04	0.40	15.15	9.42	1.73	–0.10
3	18.56	–0.16	1.26	0.40	21.02	15.46	0.88	–1.68
4	19.49	–0.18	1.13	0.39	22.68	16.35	0.78	–1.20
5	20.43	–0.27	1.17	0.42	23.35	17.12	0.67	–1.83
6	21.04	–0.31	1.10	0.41	23.51	17.87	0.68	–1.37
7	21.52	–0.32	0.96	0.34	23.43	18.83	0.50	–1.20
8	22.27	–0.39	0.85	0.32	24.10	20.00	0.53	–1.49
9	22.49	–0.42	0.79	0.28	24.19	19.85	0.32	–0.97
10	22.52	–0.37	0.71	0.26	24.00	20.78	0.38	–0.99
11	22.80	–0.41	0.72	0.25	24.37	20.54	0.35	–0.96
12	22.51	–0.36	0.86	0.29	24.20	20.05	0.46	–1.00
13	22.61	–0.36	0.71	0.27	24.67	20.25	0.21	–0.98
14	22.22	–0.41	0.82	0.32	23.83	20.30	0.96	–1.15

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
15	21.65	–0.40	1.07	0.36	24.00	18.28	0.41	–1.35
16	21.28	–0.36	1.03	0.35	23.66	18.69	0.67	–1.17
17	20.45	–0.36	1.17	0.41	22.88	17.62	0.77	–1.44
18	19.47	–0.34	1.26	0.38	22.12	16.46	0.56	–1.31
19	18.67	–0.29	1.27	0.42	21.48	14.60	1.49	–1.31
20	17.53	–0.34	1.13	0.46	20.01	14.97	0.89	–1.55
21	13.49	0.03	1.34	0.44	16.48	10.10	1.31	–0.90
21.5	6.91	0.39	2.37	0.27	14.59	3.14	1.20	–0.61

Table B12. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VyMin	VyMax	VyMin
1	12.60	0.53	1.05	0.45	14.97	10.43	1.82	–0.68
2	14.77	0.52	1.37	0.45	19.18	11.54	1.59	–0.72
3	17.35	0.19	1.37	0.40	20.34	14.14	1.37	–0.71
4	18.95	0.10	1.16	0.42	21.44	16.53	1.33	–0.89
5	19.82	0.19	1.16	0.39	22.68	16.26	1.31	–0.72
6	20.51	0.05	1.04	0.39	22.72	17.57	1.08	–0.85
7	21.15	0.09	0.99	0.35	23.29	18.56	1.06	–0.82
8	21.64	0.11	0.99	0.30	23.60	19.46	0.95	–0.84
9	22.04	0.11	0.92	0.33	23.96	18.99	1.10	–0.75
10	22.36	0.12	0.64	0.33	23.99	20.97	0.96	–0.84
11	22.28	0.14	0.76	0.28	23.92	20.01	0.79	–0.75
12	22.45	0.08	0.76	0.30	23.83	20.33	1.05	–0.78
13	22.26	0.08	0.84	0.32	23.89	18.78	0.71	–1.02
14	22.18	0.06	0.80	0.31	24.13	19.72	1.08	–0.67
15	21.41	0.06	1.06	0.33	24.03	18.71	0.88	–0.90
16	20.70	0.08	0.99	0.36	22.99	18.22	1.14	–1.06
17	20.52	0.02	1.23	0.39	22.92	17.11	1.15	–1.09
18	19.38	–0.02	1.37	0.38	22.58	15.11	1.01	–1.00
19	18.81	0.09	1.19	0.40	21.63	15.97	0.93	–0.99
20	17.82	–0.03	1.29	0.43	21.04	14.71	1.25	–1.06
21	11.27	0.08	1.32	0.38	14.49	7.14	1.00	–0.94
21.5	9.39	0.09	1.37	0.41	13.82	6.84	1.30	–0.79

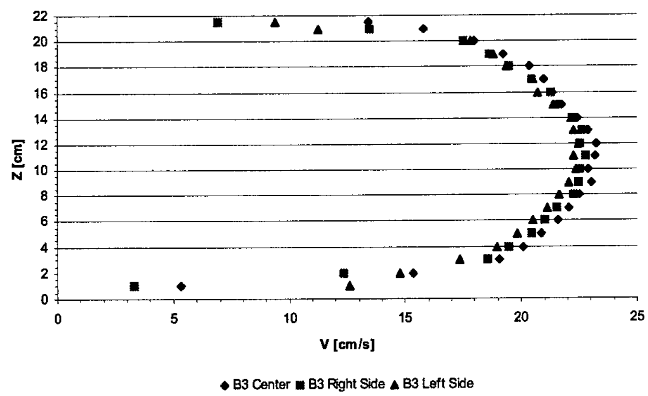


Figure B17. Velocity profiles.

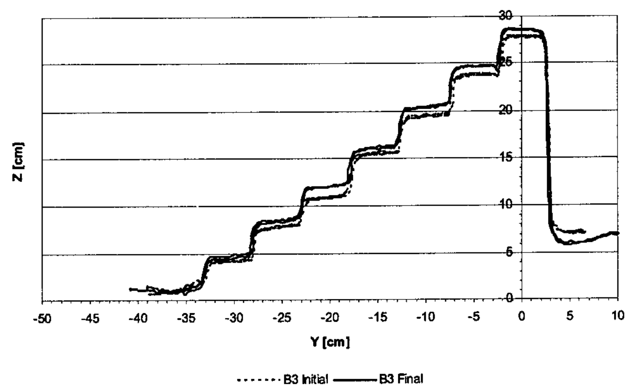


Figure B18. Calibration.

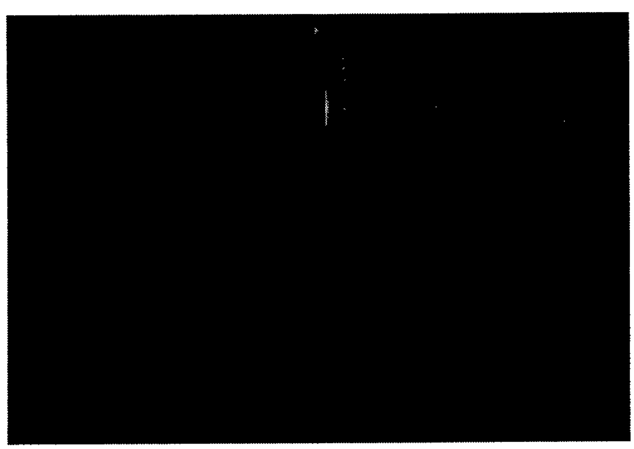


Figure B19. Final photo of scour hole; flow from right to left.

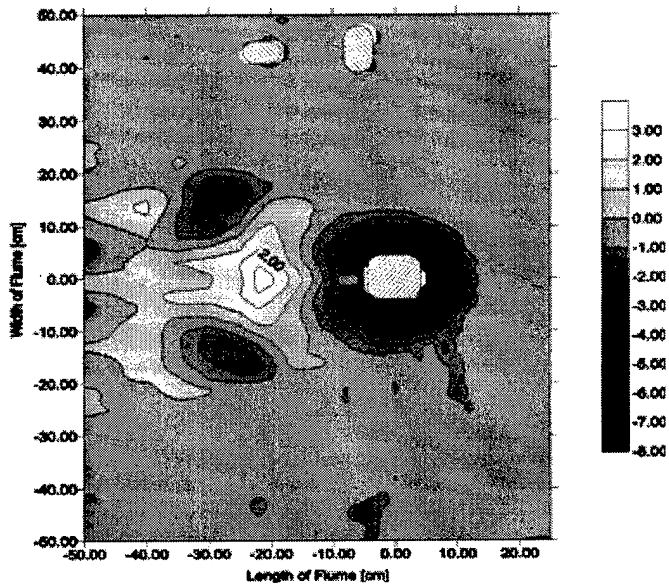


Figure B20. Contour plot; flow from right to left.

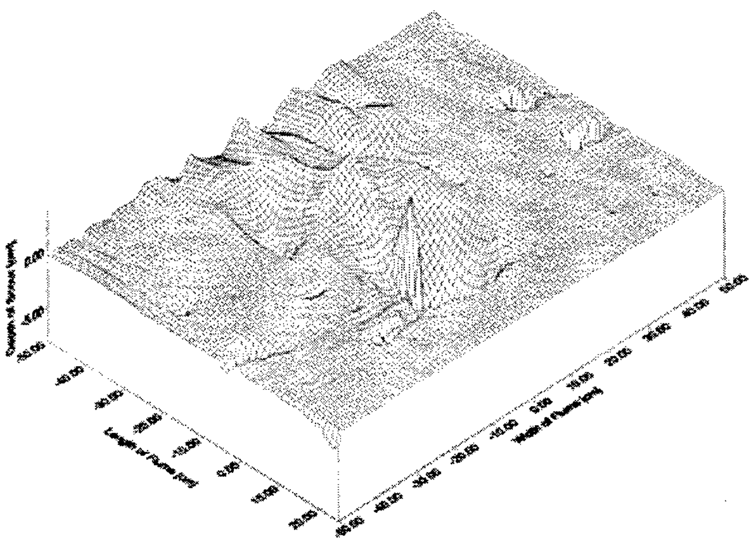


Figure B21. Surface plot; flow is from lower right to upper left.

Test B4

Table B13. Scour depth vs. time data.

Initial Reading =	10.0625	In.
Start Time =	14:40	04-Mar-03
End Time =	08:26	05-Mar-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour Depth [cm]
14:40	10.0625	0:00	0.0000	0.000
14:41	9.9375	0:01	0.1250	0.318
14:42	9.7500	0:02	0.3125	0.794
14:43	9.5000	0:03	0.5625	1.429
14:44	9.2500	0:04	0.8125	2.064
14:45	9.0000	0:05	1.0625	2.699
14:47	8.7500	0:07	1.3125	3.334
14:51	8.5000	0:11	1.5625	3.969
14:54	8.3750	0:14	1.6875	4.286
14:58	8.2500	0:18	1.8125	4.604
15:10	8.1250	0:30	1.9375	4.921
15:20	8.0000	0:40	2.0625	5.239
15:32	7.8750	0:52	2.1875	5.556
15:40	7.7500	1:00	2.3125	5.874
16:04	7.6250	1:24	2.4375	6.191
16:22	7.5000	1:42	2.5625	6.509
16:52	7.3750	2:12	2.6875	6.826
17:00	7.3750	2:20	2.6875	6.826
17:20	7.3125	2:40	2.7500	6.985
17:24	7.2500	2:44	2.8125	7.144
17:37	7.2500	2:57	2.8125	7.144
17:49	7.1875	3:09	2.8750	7.303
18:26	7.1250	3:46	2.9375	7.461
18:45	7.1250	4:05	2.9375	7.461
19:22	7.0000	4:42	3.0625	7.779
19:40	6.8750	5:00	3.1875	8.096
20:32	6.8125	5:52	3.2500	8.255
21:05	6.7500	6:25	3.3125	8.414
21:26	6.6875	6:46	3.3750	8.573
23:38	6.6875	8:58	3.3750	8.573
1:31	6.6875	10:51	3.3750	8.573
3:58	6.6875	13:18	3.3750	8.573
6:14	6.6875	15:34	3.3750	8.573

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour Depth [cm]
7:27	6.6875	16:47	3.3750	8.573
8:26	6.6875	17:46	3.3750	8.573

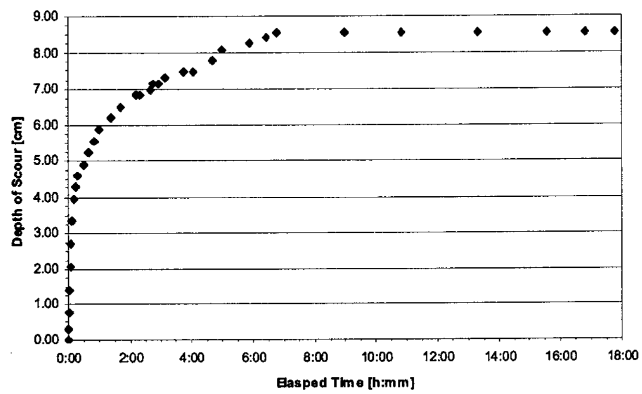


Figure B22. Scour depth vs. time.

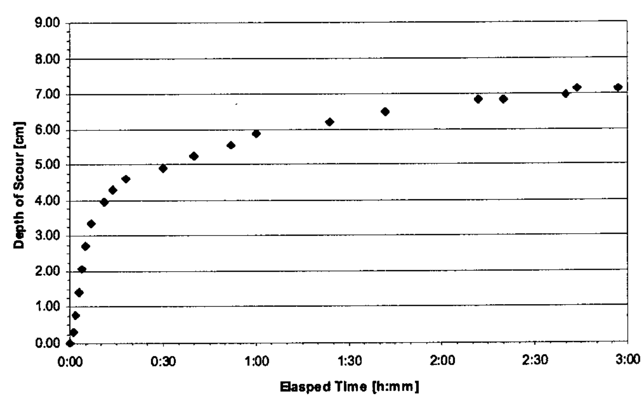


Figure B23. Scour depth vs. time for the first 3 hours.

Table B14. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	5.47	0.13	0.89	0.23	7.78	3.18	0.62	–0.46
2	20.61	–0.72	1.51	0.49	23.99	16.18	0.23	–2.24
3	24.10	–0.85	1.37	0.42	27.23	21.20	0.11	–1.74
4	25.75	–0.97	1.19	0.40	28.66	21.55	0.03	–1.97

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
5	25.96	–0.96	1.37	0.40	28.96	22.71	0.30	–2.06
6	26.83	–0.93	1.37	0.37	29.60	21.76	0.08	–2.08
7	27.36	–0.96	1.26	0.36	30.05	23.56	0.20	–1.98
8	28.03	–0.92	1.07	0.35	30.67	25.44	–0.03	–2.23
9	28.46	–0.93	0.95	0.30	30.99	25.63	–0.16	–1.73
10	28.55	–0.96	0.78	0.32	30.10	26.63	–0.04	–1.73
11	28.52	–0.98	0.83	0.30	30.49	26.53	–0.33	–1.70
12	28.50	–0.96	0.81	0.33	30.57	26.52	–0.09	–1.85
13	28.29	–0.98	0.91	0.30	30.43	25.48	–0.23	–1.68
14	28.09	–1.01	1.00	0.35	30.28	24.95	–0.04	–2.02
15	27.48	–1.06	1.06	0.32	29.95	24.60	–0.32	–2.05
16	27.11	–0.97	1.09	0.38	29.62	23.16	–0.19	–2.07
17	26.28	–0.91	1.27	0.43	28.82	22.82	0.51	–1.99
18	25.46	–0.89	1.44	0.40	28.12	22.19	0.19	–1.89
19	24.52	–0.78	1.30	0.45	26.84	19.98	0.33	–1.89
20	23.05	–0.66	1.72	0.47	25.89	17.38	0.42	–1.69
21	20.75	–0.58	1.49	0.50	24.10	17.00	0.74	–1.81
21.5	18.67	–0.48	1.83	0.54	22.97	13.54	0.66	–2.12

Table B15. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	5.47	0.45	1.26	0.26	9.39	2.45	1.12	–0.25
2	18.42	–0.24	1.84	0.50	22.41	14.30	0.89	–1.79
3	24.34	–0.54	1.26	0.45	28.00	20.33	0.44	–1.84
4	26.04	–0.54	1.43	0.44	28.73	21.55	0.70	–1.67
5	26.65	–0.58	1.23	0.41	29.28	23.36	0.46	–1.68
6	27.37	–0.54	1.34	0.31	31.11	24.18	0.50	–1.21
7	28.20	–0.61	1.03	0.37	30.15	25.33	0.88	–1.78
8	28.73	–0.56	0.93	0.33	30.62	25.93	0.27	–1.48
9	29.34	–0.57	0.87	0.32	31.60	26.86	0.31	–1.40
10	29.58	–0.56	0.75	0.32	31.45	28.03	0.14	–1.49
11	29.36	–0.60	0.86	0.29	31.28	27.23	0.23	–1.29
12	29.46	–0.62	0.83	0.30	31.06	27.16	0.56	–1.32
13	28.78	–0.56	1.61	0.52	31.00	15.05	3.83	–1.53
14	28.47	–0.62	0.90	0.32	30.54	25.99	0.21	–1.28
15	27.97	–0.64	1.16	0.34	30.89	25.21	0.09	–1.48
16	26.98	–0.60	1.30	0.41	29.89	23.57	0.41	–1.44
17	26.48	–0.60	1.47	0.34	29.16	22.94	0.34	–1.56
18	25.92	–0.55	1.75	0.45	29.47	20.79	0.51	–1.48
19	24.32	–0.61	1.56	0.45	28.48	20.91	0.68	–1.69

20	23.57	–0.49	1.57	0.49	27.15	19.41	1.04	–1.72
21	19.50	–0.60	1.63	0.56	23.29	15.62	0.69	–2.40
21.5	10.36	–0.08	1.21	0.36	12.91	7.15	0.89	–0.92

Table B16. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	0.77	–0.09	0.37	0.08	2.14	–0.02	0.13	–0.34
2	18.04	0.42	1.59	0.43	21.51	13.85	1.54	–0.51
3	23.08	–0.05	1.65	0.51	26.27	19.04	1.17	–1.38
4	24.26	–0.05	1.50	0.44	27.29	21.25	0.99	–1.22
5	25.68	–0.04	1.58	0.42	28.82	21.86	1.24	–1.12
6	26.10	–0.03	1.53	0.42	28.85	22.21	0.91	–1.15
7	26.89	–0.06	1.33	0.35	29.39	23.48	0.95	–0.95
8	27.47	–0.06	1.12	0.31	29.55	24.59	0.74	–0.94
9	27.87	–0.11	0.97	0.30	29.56	24.25	0.59	–0.91
10	27.89	–0.12	0.83	0.28	29.73	24.90	0.68	–1.13
11	27.96	–0.12	0.79	0.28	29.74	25.72	0.57	–0.88
12	28.00	–0.12	0.75	0.29	29.97	25.89	0.74	–0.88
13	27.75	–0.10	0.82	0.32	29.63	25.90	0.81	–1.00
14	27.57	–0.11	0.91	0.31	29.46	25.34	0.54	–0.88
15	27.16	–0.12	1.07	0.38	29.53	24.47	0.87	–0.97
16	26.73	–0.21	1.07	0.37	29.39	23.70	0.73	–0.99
17	26.16	–0.19	1.23	0.40	29.25	22.21	0.96	–1.16
18	24.62	–0.20	1.45	0.49	27.89	20.44	0.97	–1.40
19	23.89	–0.22	1.40	0.46	26.72	20.25	1.12	–1.36
20	22.41	–0.20	1.38	0.47	25.47	18.51	1.04	–1.41
21	20.25	0.00	1.63	0.55	24.26	15.69	1.28	–1.49
21.5	18.93	–0.21	1.45	0.53	22.32	14.71	0.99	–1.45

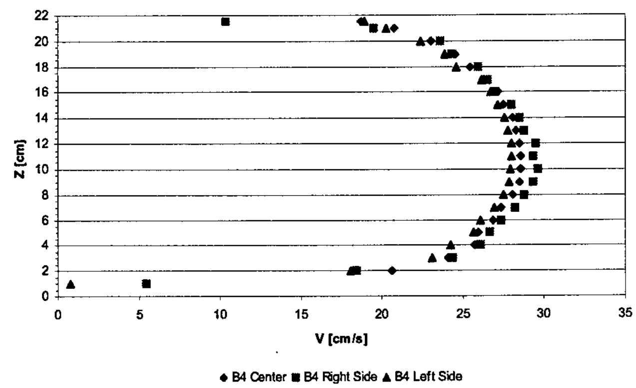


Figure B24. Velocity profiles.

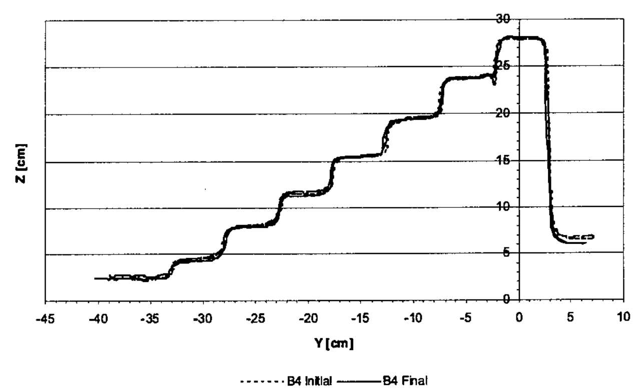


Figure B25. Calibration.

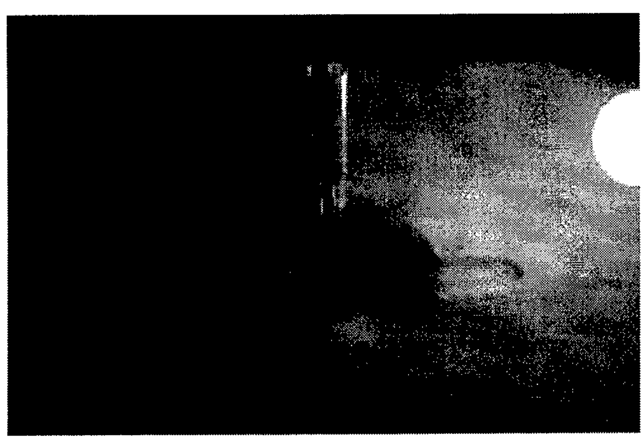


Figure B26. Final photo of scour hole; flow from right to left.

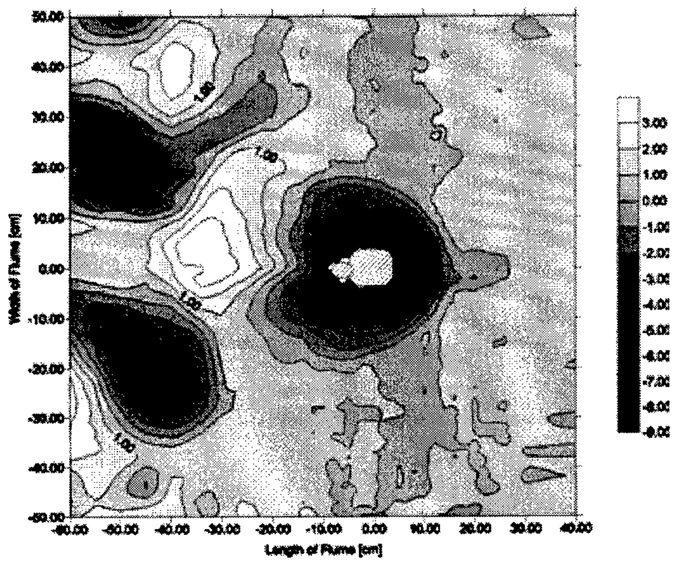


Figure B27. Contour plot; flow from right to left.

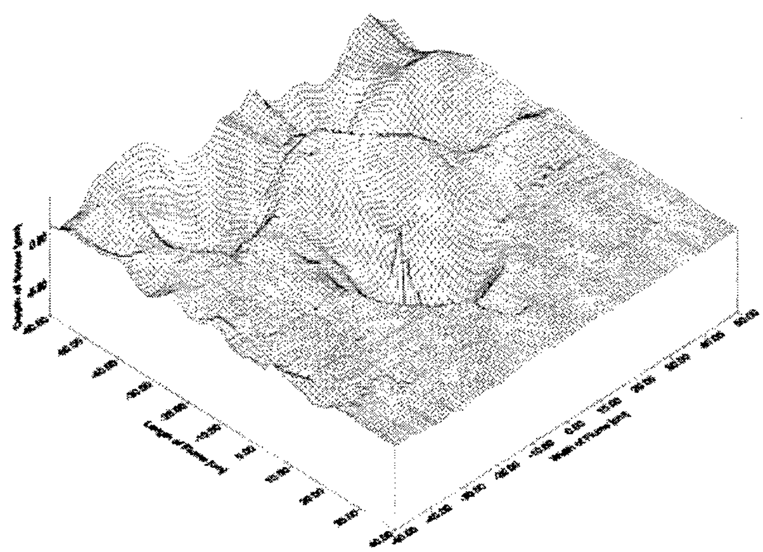


Figure B28. Surface plot; flow is from lower right to upper left.

Test B5

Table B17. Scour depth vs. time data.

Initial Reading =	10	In.
Start Time =	17:13	10-Mar-03
End Time =	08:42	11-Mar-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
17:13	10.0000	0:00	0.0000	0.000
17:16	9.5000	0:03	0.5000	1.270
17:17	9.2500	0:04	0.7500	1.905
17:18	9.1250	0:05	0.8750	2.223
17:19	9.0000	0:06	1.0000	2.540
17:23	8.8750	0:10	1.1250	2.858
17:28	8.7500	0:15	1.2500	3.175
17:35	8.6250	0:22	1.3750	3.493
17:39	8.5000	0:26	1.5000	3.810
17:52	8.3750	0:39	1.6250	4.128
18:02	8.2500	0:49	1.7500	4.445
18:21	8.1875	1:08	1.8125	4.604
18:27	8.1250	1:14	1.8750	4.763
18:48	8.0000	1:35	2.0000	5.080
19:29	7.8750	2:16	2.1250	5.398
19:50	7.7500	2:37	2.2500	5.715
20:15	7.8125	3:02	2.1875	5.556
20:25	7.7500	3:12	2.2500	5.715
20:31	7.6875	3:18	2.3125	5.874
21:20	7.6250	4:07	2.3750	6.033
21:31	7.5625	4:18	2.4375	6.191
22:00	7.5000	4:47	2.5000	6.350
23:21	7.3750	6:08	2.6250	6.668
0:53	7.2500	7:40	2.7500	6.985
2:51	7.1250	9:38	2.8750	7.303
4:24	7.0000	11:11	3.0000	7.620
6:41	6.8750	13:28	3.1250	7.938
7:35	6.8125	14:22	3.1875	8.096
8:42	6.7500	15:29	3.2500	8.255

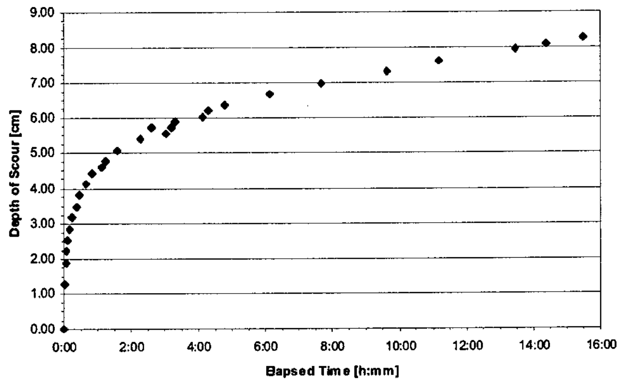


Figure B29. Scour depth vs. time.

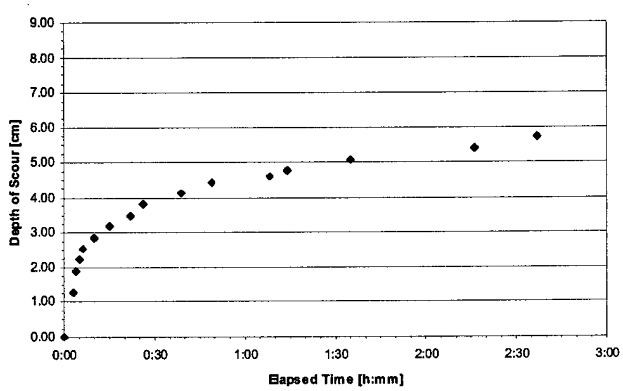


Figure B30. Scour depth vs. time for the first 3 hours.

Table B18. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	5.23	0.28	0.93	0.17	7.78	3.04	0.66	–0.17
2	17.18	0.14	1.35	0.43	20.21	13.61	1.16	–0.78
3	20.36	–0.13	1.20	0.47	23.86	16.92	1.28	–1.22
4	21.65	–0.18	1.25	0.42	24.42	17.97	1.22	–1.10
5	22.69	–0.22	1.18	0.36	25.46	19.90	0.99	–1.24
6	23.69	–0.24	1.09	0.32	25.79	20.68	0.64	–1.17
7	24.24	–0.23	0.88	0.33	26.14	21.28	0.60	–1.24
8	24.76	–0.21	0.75	0.28	26.56	22.23	0.66	–0.85
9	25.00	–0.28	0.81	0.27	26.96	22.89	0.36	–0.96
10	25.11	–0.31	0.68	0.26	26.67	23.34	0.33	–1.06
11	25.02	–0.27	0.70	0.29	26.42	22.95	0.66	–1.02

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
12	24.56	–0.29	0.87	0.34	26.36	22.11	0.93	–1.11
13	24.42	–0.29	0.95	0.26	26.45	22.10	0.29	–1.18
14	23.50	–0.28	1.15	0.38	26.45	20.38	0.73	–1.31
15	22.90	–0.25	1.10	0.41	25.02	19.72	0.68	–1.23
16	22.26	–0.22	1.31	0.40	24.86	18.54	0.74	–1.07
17	21.18	–0.19	1.28	0.48	24.02	18.05	0.85	–1.37
18	19.72	–0.13	1.29	0.42	22.97	17.07	1.02	–1.06
19	17.59	–0.12	1.47	0.44	21.38	14.09	1.15	–1.20
20	7.78	–0.15	1.10	0.33	10.66	5.47	0.66	–1.35

Table B19. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	7.02	0.18	1.08	0.27	9.55	4.59	0.75	–0.71
2	16.90	0.47	1.32	0.42	20.45	13.56	1.63	–0.49
3	20.98	0.06	1.29	0.45	23.77	17.51	1.13	–1.11
4	22.51	0.07	1.33	0.38	25.17	18.77	0.85	–0.80
5	22.95	0.04	1.16	0.37	25.34	19.60	1.05	–0.78
6	24.02	0.03	1.06	0.37	26.39	20.88	1.05	–0.70
7	24.33	–0.01	0.89	0.29	26.06	21.80	0.64	–0.69
8	24.92	0.03	0.80	0.34	26.72	22.46	0.94	–0.96
9	25.13	–0.02	0.68	0.28	26.73	23.60	0.93	–0.93
10	25.19	–0.01	0.60	0.30	26.55	23.50	0.76	–0.77
11	25.22	–0.06	0.70	0.31	26.96	23.37	0.65	–0.93
12	24.79	–0.03	0.81	0.28	26.33	22.43	0.75	–0.67
13	24.38	–0.01	0.93	0.34	26.15	21.47	1.12	–0.83
14	24.10	0.01	1.03	0.32	26.08	20.05	1.21	–0.82
15	23.54	–0.02	1.10	0.38	25.95	20.44	0.60	–1.37
16	22.84	0.02	1.22	0.38	25.15	19.63	1.09	–1.00
17	21.74	0.00	1.38	0.43	24.78	18.19	1.25	–1.19
18	20.44	0.06	1.29	0.46	23.28	17.10	1.41	–1.29
19	19.39	0.09	1.31	0.49	22.28	16.03	1.43	–1.12
20	15.13	0.11	1.38	0.60	19.45	11.15	1.61	–1.31

Table B20. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	5.52	0.05	1.00	0.18	8.12	3.55	0.55	–0.41
2	17.16	0.61	1.38	0.45	20.57	14.40	1.71	–0.54
3	20.01	0.55	1.34	0.47	23.26	16.89	1.83	–0.46
4	21.48	0.62	1.29	0.46	24.42	17.89	1.87	–0.62

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
5	22.72	0.67	1.14	0.40	25.05	19.92	1.74	–0.32
6	23.32	0.70	0.93	0.31	25.41	20.61	1.55	–0.16
7	23.83	0.63	0.96	0.33	25.76	21.08	1.45	–0.30
8	24.22	0.70	0.90	0.32	26.21	22.15	1.59	–0.08
9	24.63	0.71	0.76	0.28	26.16	22.69	1.36	–0.37
10	24.92	0.74	0.66	0.28	26.29	23.53	1.47	–0.15
11	24.77	0.67	0.71	0.28	26.30	22.50	1.24	–0.07
12	24.59	0.66	0.79	0.28	26.21	21.98	1.24	–0.29
13	24.17	0.62	0.93	0.32	26.19	21.37	1.53	–0.32
14	23.82	0.61	0.97	0.32	25.72	21.05	1.30	–0.32
15	23.27	0.62	1.12	0.39	25.69	20.46	1.78	–0.60
16	22.55	0.50	1.20	0.43	25.37	18.92	1.63	–0.56
17	21.45	0.51	1.32	0.44	24.18	17.32	1.56	–0.63
18	20.14	0.39	1.35	0.47	23.36	17.00	1.98	–0.95
19	17.53	0.39	1.70	0.48	20.96	13.56	1.89	–0.59
20	14.28	0.42	1.33	0.55	17.25	10.78	1.46	–0.98

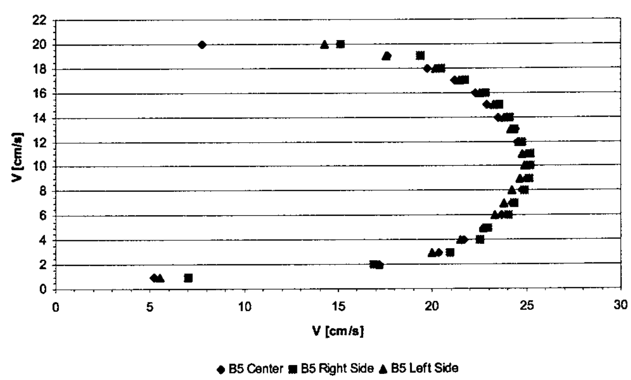


Figure B31. Velocity profiles.

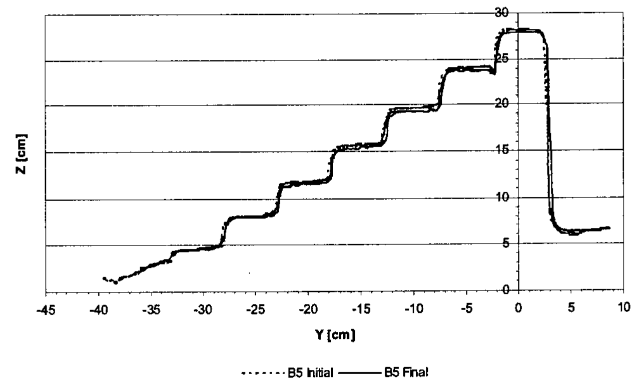


Figure B32. Calibration.

Figure B33. Final photo of scour hole; flow from right to left.

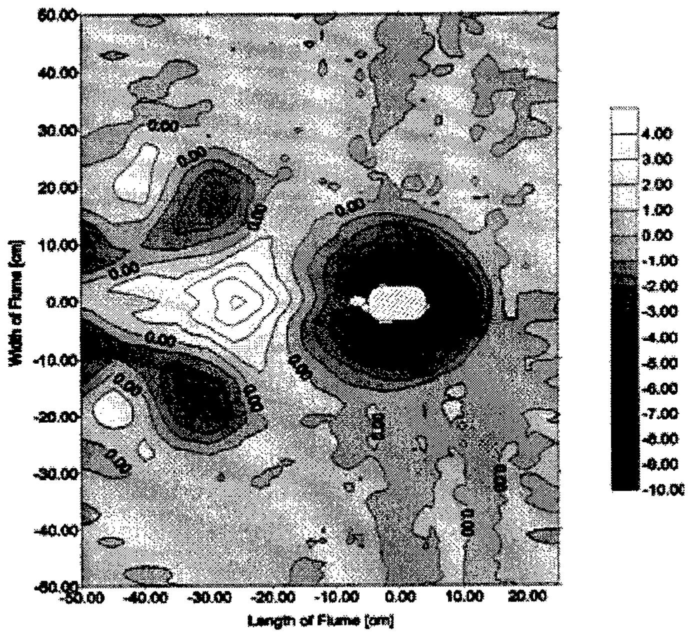


Figure B34. Contour plot; flow from right to left.

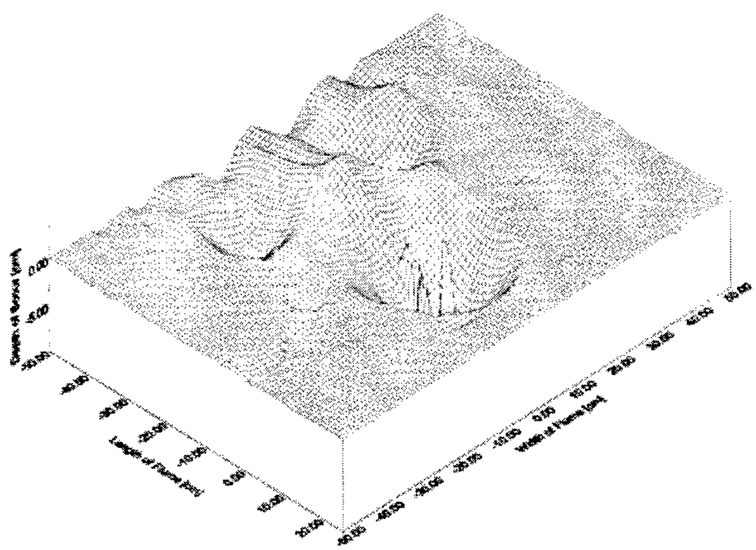


Figure B35. Surface plot; flow is from lower right to upper left.

Test R1

Table B21. Scour depth vs. time data.

Initial Reading =	10	In.
Start Time =	18:52	08-Mar-03
End Time =	13:05	09-Mar-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
18:52	10.0000	0:00	0.0000	0.000
18:53	9.5000	0:01	0.5000	1.270
18:54	9.0000	0:02	1.0000	2.540
18:55	8.5000	0:03	1.5000	3.810
18:57	8.3750	0:05	1.6250	4.128
18:59	8.2500	0:07	1.7500	4.445
19:01	8.1250	0:09	1.8750	4.763
19:08	7.8750	0:16	2.1250	5.398
19:13	7.7500	0:21	2.2500	5.715
19:18	7.6250	0:26	2.3750	6.033
19:24	7.6250	0:32	2.3750	6.033
19:29	7.5000	0:37	2.5000	6.350
19:40	7.3750	0:48	2.6250	6.668
20:14	7.2500	1:22	2.7500	6.985
20:17	7.1250	1:25	2.8750	7.303
20:56	7.1250	2:04	2.8750	7.303
2:32	7.0000	7:40	3.0000	7.620
3:34	6.8750	8:42	3.1250	7.938
4:10	7.0000	9:18	3.0000	7.620
4:56	7.1250	10:04	2.8750	7.303
5:55	7.2500	11:03	2.7500	6.985
6:25	7.1250	11:33	2.8750	7.303
6:56	7.0000	12:04	3.0000	7.620
8:38	6.8750	13:46	3.1250	7.938
8:58	6.7500	14:06	3.2500	8.255
9:39	7.0000	14:47	3.0000	7.620
9:47	7.0000	14:55	3.0000	7.620
10:06	7.1250	15:14	2.8750	7.303
10:10	7.0625	15:18	2.9375	7.461
11:05	7.1875	16:13	2.8125	7.144
11:36	7.0625	16:44	2.9375	7.461
12:05	7.0000	17:13	3.0000	7.620
12:11	7.0000	17:19	3.0000	7.620
13:05	7.0000	18:13	3.0000	7.620

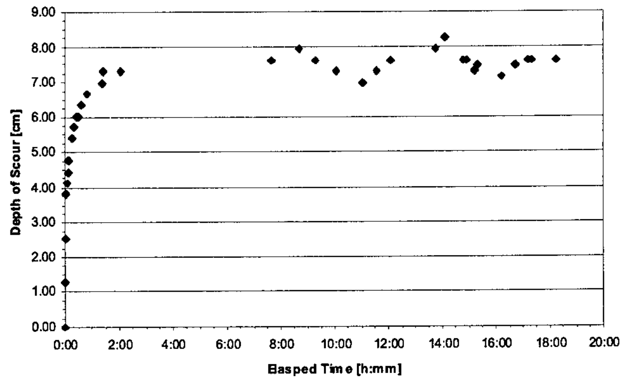


Figure B36. Scour depth vs. time.

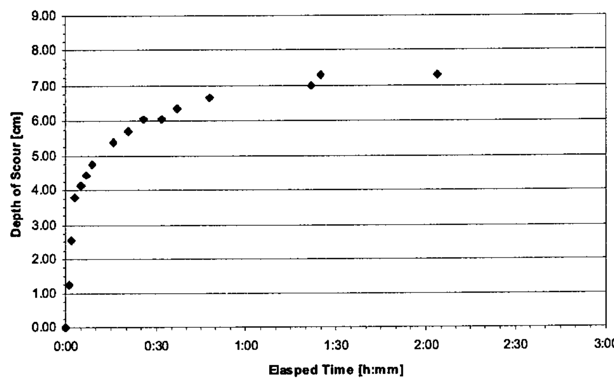


Figure B37. Scour depth vs. time for the first 3 hours.

Table B22. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	15.87	–3.87	1.68	1.24	20.16	13.08	–0.86	–7.06
2	18.28	–1.17	1.68	1.09	22.23	14.33	1.60	–3.78
3	19.70	–0.93	1.85	1.07	25.31	16.04	1.95	–3.97
4	21.75	–1.38	2.24	0.82	27.58	17.25	0.67	–3.39
5	24.93	–1.44	2.43	0.87	29.56	17.93	1.63	–3.52
6	27.79	–0.95	2.06	0.73	31.88	21.66	1.23	–3.19
7	29.67	–0.66	1.82	0.55	32.81	25.10	1.00	–2.07
8	31.14	–0.49	1.40	0.53	34.37	27.65	0.79	–2.02
9	31.92	–0.45	1.15	0.53	34.25	27.99	0.65	–2.02

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
10	32.03	–0.38	0.88	0.47	34.40	29.49	0.85	–1.49
11	31.88	–0.41	1.02	0.47	33.92	28.77	0.64	–1.70
12	31.13	–0.36	1.24	0.58	34.13	27.29	1.14	–1.94
13	29.86	–0.25	1.63	0.68	33.79	24.94	2.16	–2.37
14	28.65	–0.30	1.99	0.66	32.17	23.60	1.07	–2.35
15	26.71	–0.31	2.14	0.75	31.94	18.97	1.61	–2.44
16	24.34	–0.26	2.63	0.87	29.23	17.44	2.58	–2.72
17	21.11	0.02	2.43	1.06	26.07	15.17	3.26	–2.58
18	17.53	0.27	2.47	1.01	22.46	11.74	3.28	–2.38
19	1.50	0.09	0.59	0.15	3.12	0.34	0.60	–0.28

Table B23. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	14.08	–2.45	2.44	1.84	19.79	8.42	2.80	–7.11
2	21.33	–0.01	2.60	0.97	28.92	14.73	2.15	–2.29
3	24.86	–0.08	2.13	0.74	29.40	18.26	1.64	–1.84
4	26.39	–0.25	1.87	0.70	30.27	19.38	1.48	–1.75
5	27.72	–0.83	1.89	0.67	32.17	23.80	1.22	–2.81
6	28.71	–0.93	1.84	0.66	32.44	22.02	0.66	–2.64
7	29.41	–0.90	1.70	0.71	33.46	24.96	0.79	–2.95
8	30.21	–0.93	1.66	0.60	33.56	24.54	0.66	–2.22
9	30.97	–0.94	1.35	0.51	33.46	27.05	0.46	–2.22
10	31.26	–0.97	1.13	0.53	33.86	28.49	0.43	–2.67
11	31.00	–0.82	1.16	0.57	33.30	27.87	0.79	–2.16
12	30.73	–0.80	1.28	0.54	33.49	26.74	0.64	–2.20
13	29.29	–0.79	1.53	0.67	32.53	25.37	0.58	–3.03
14	27.87	–0.69	1.99	0.67	31.84	22.17	1.53	–2.13
15	25.65	–0.60	2.33	0.86	30.84	18.97	1.48	–2.89
16	23.32	–0.44	2.39	0.93	28.26	17.42	1.93	–2.53
17	20.18	–0.47	2.94	0.98	27.47	12.18	2.33	–2.41
18	14.73	–0.29	2.81	1.02	21.81	7.44	2.34	–2.61
19	5.24	–0.32	1.52	0.51	9.66	2.37	0.82	–1.76

Table B.24. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	11.17	3.21	1.94	1.50	16.40	5.44	7.29	–0.12
2	14.43	1.85	2.26	0.96	19.62	9.03	4.27	–0.64
3	18.43	1.24	2.40	1.05	24.62	13.47	4.76	–1.72
4	20.72	0.90	2.48	0.79	28.17	14.97	3.19	–1.50
5	22.59	0.69	2.46	0.97	29.50	15.74	3.74	–1.65

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
6	23.96	0.76	2.22	0.75	30.75	18.95	3.01	–0.71
7	25.21	0.79	2.15	0.84	31.32	20.61	2.58	–1.51
8	27.49	0.82	1.86	0.70	32.37	21.76	2.23	–0.73
9	29.37	0.75	1.52	0.68	33.15	24.17	2.46	–0.94
10	30.83	0.71	1.24	0.53	33.32	26.78	2.17	–0.32
11	30.96	0.58	1.03	0.52	32.93	28.01	2.06	–0.56
12	30.59	0.53	1.27	0.51	33.52	27.58	2.41	–0.87
13	29.84	0.49	1.77	0.64	33.18	24.61	2.05	–1.68
14	28.54	0.52	1.89	0.66	32.51	22.66	2.39	–1.32
15	26.67	0.41	2.09	0.82	31.81	20.65	2.84	–2.40
16	23.99	0.24	2.62	0.87	29.27	16.98	2.17	–2.02
17	19.54	0.31	2.78	0.98	25.62	13.63	2.55	–3.09
18	13.48	–0.17	2.82	0.79	20.20	6.23	2.12	–2.32
19	2.41	–0.15	0.78	0.25	4.52	0.54	0.48	–0.78

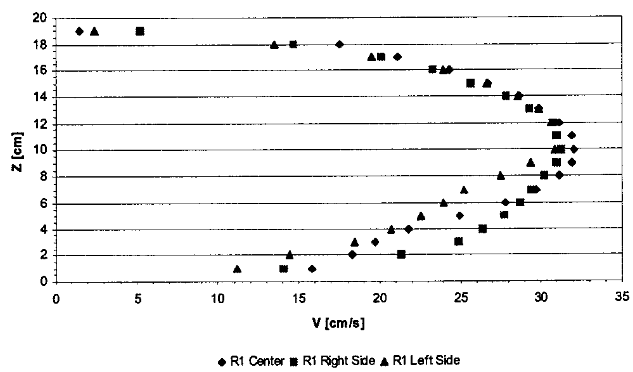


Figure B38. Velocity profiles.

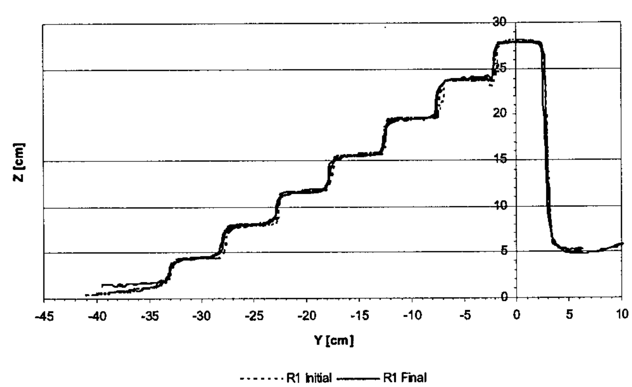


Figure B39. Calibration.

Figure B40. Final photo of scour hole; flow from right to left.

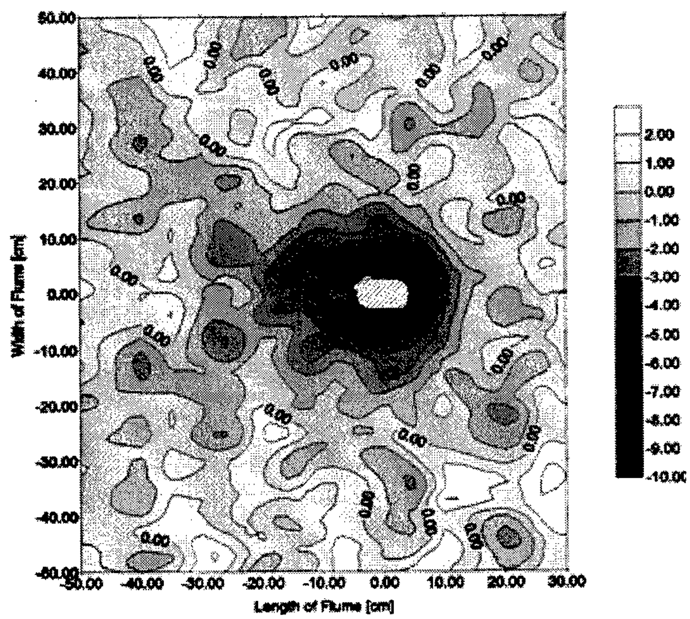


Figure B41. Contour plot; flow from right to left.

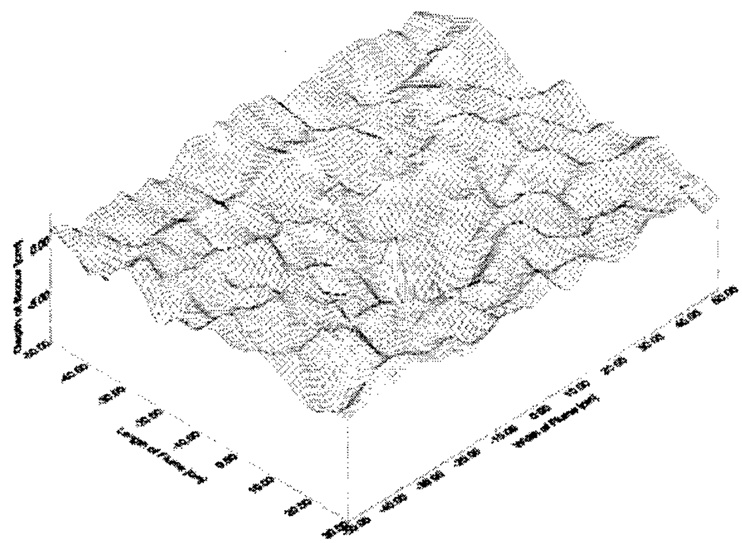


Figure B42. Surface plot; flow is from lower right to upper left.

APPENDIX C: FIXED COVER

Test C1

Table C1. Scour depth vs. time data.

Initial Reading =	10	In.
Start Time =	13:26	17-Mar-03
End Time =	08:01	18-Mar-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in]	Scour depth [cm]
13:26	10.0000	0:00	0.0000	0.000
13:27	9.8125	0:01	0.1875	0.476
13:28	9.6250	0:02	0.3750	0.953
13:29	9.5000	0:03	0.5000	1.270
13:30	9.3750	0:04	0.6250	1.588
13:31	9.1250	0:05	0.8750	2.223
13:32	9.0000	0:06	1.0000	2.540
13:33	8.8750	0:07	1.1250	2.858
13:36	8.7500	0:10	1.2500	3.175
13:39	8.6250	0:13	1.3750	3.493
13:45	8.5000	0:19	1.5000	3.810
13:52	8.3750	0:26	1.6250	4.128
14:01	8.2500	0:35	1.7500	4.445
14:14	8.1875	0:48	1.8125	4.604
14:50	8.0000	1:24	2.0000	5.080
15:11	7.9375	1:45	2.0625	5.239
15:25	7.8125	1:59	2.1875	5.556
15:49	7.7500	2:23	2.2500	5.715
16:22	7.6875	2:56	2.3125	5.874
17:17	7.5000	3:51	2.5000	6.350
17:58	7.4375	4:32	2.5625	6.509
18:21	7.3750	4:55	2.6250	6.668
19:09	7.3125	5:43	2.6875	6.826
20:05	7.1250	6:39	2.8750	7.303
22:03	7.0625	8:37	2.9375	7.461
23:11	7.0000	9:45	3.0000	7.620
5:10	7.0000	15:44	3.0000	7.620
7:28	6.8750	18:02	3.1250	7.938
8:01	6.8750	18:35	3.1250	7.938

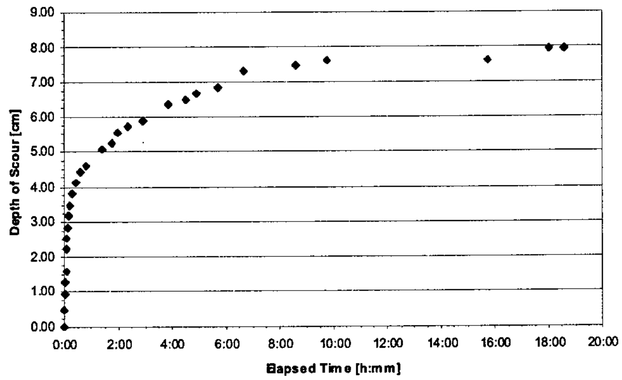


Figure C1. Scour depth vs. time.

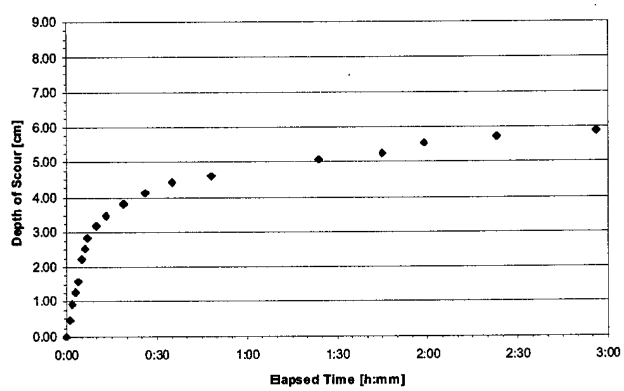


Figure C2. Scour depth vs. time for the first 3 hours.

Table C2. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	1.86	0.37	0.52	0.12	3.21	0.88	0.71	0.09
2	15.12	–0.03	1.25	0.40	18.23	12.55	1.00	–1.02
3	20.25	–0.17	1.45	0.40	23.91	16.42	0.90	–1.05
4	21.72	–0.25	1.34	0.39	24.78	18.03	0.66	–1.23
5	22.55	–0.31	1.20	0.42	25.95	19.47	0.66	–1.67
6	23.39	–0.28	1.29	0.39	25.85	18.64	0.91	–1.23
7	24.01	–0.38	1.19	0.36	26.45	20.18	0.54	–1.17
8	24.24	–0.33	1.09	0.35	26.41	21.36	0.54	–1.05
9	24.82	–0.38	0.97	0.32	26.46	21.08	0.73	–1.31
10	25.16	–0.39	0.80	0.31	27.00	21.79	0.29	–1.27
11	25.49	–0.38	0.75	0.30	27.24	23.50	0.34	–1.10

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
12	25.23	–0.37	0.83	0.26	27.05	23.27	0.19	–1.00
13	25.29	–0.38	0.74	0.28	27.08	23.40	0.34	–1.03
14	25.12	–0.45	0.75	0.31	26.50	22.72	0.30	–1.18
15	24.88	–0.44	0.87	0.29	26.76	22.15	0.36	–1.41
16	24.48	–0.42	0.97	0.34	26.39	21.80	0.34	–1.44
17	23.55	–0.38	1.12	0.40	26.20	20.62	0.61	–1.41
18	23.22	–0.39	1.12	0.38	25.67	19.53	0.60	–1.43
19	22.59	–0.36	1.19	0.40	24.96	19.48	0.80	–1.36
20	21.70	–0.33	1.32	0.48	24.76	17.91	0.84	–1.52
21	20.08	–0.24	1.46	0.41	23.44	16.64	0.92	–1.39
22	18.53	–0.12	1.51	0.52	23.34	14.92	0.97	–1.75
23	15.79	–0.18	1.53	0.60	18.86	11.66	1.47	–2.09

Table C3. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	3.89	0.89	0.86	0.22	6.06	2.20	1.46	0.44
2	10.89	0.61	1.21	0.31	14.04	7.62	1.32	–0.22
3	18.97	0.40	1.35	0.45	21.86	15.28	1.40	–0.57
4	21.26	0.19	1.33	0.47	24.51	17.99	1.35	–1.34
5	22.08	0.24	1.22	0.42	25.19	18.83	1.27	–0.76
6	23.06	0.22	1.22	0.37	25.51	20.09	1.17	–0.64
7	23.34	0.21	1.24	0.41	25.87	19.50	1.42	–0.98
8	24.32	0.16	1.17	0.34	26.49	20.59	0.92	–0.84
9	24.94	0.15	0.84	0.30	26.57	22.17	1.06	–0.45
10	24.87	0.18	1.18	0.31	27.19	20.99	1.14	–0.51
11	25.44	0.15	0.79	0.30	27.00	22.74	0.83	–0.76
12	25.27	0.17	0.82	0.28	27.22	22.83	0.81	–0.60
13	25.18	0.12	0.71	0.30	26.72	23.65	0.94	–1.01
14	24.91	0.15	0.89	0.28	26.83	22.22	0.93	–0.47
15	24.76	0.14	0.80	0.33	26.44	22.37	0.92	–1.00
16	24.15	0.15	0.96	0.38	26.33	21.79	1.14	–0.70
17	23.69	0.16	1.29	0.34	26.07	20.01	0.99	–0.76
18	22.91	0.11	1.21	0.37	25.51	19.08	0.95	–0.85
19	22.39	0.15	1.16	0.42	24.58	19.73	1.34	–1.17
20	21.30	0.18	1.37	0.49	24.64	18.20	1.73	–1.09
21	20.17	0.10	1.55	0.48	23.81	15.42	1.45	–0.86
22	18.52	0.10	1.50	0.49	21.79	15.02	1.15	–1.32
23	15.38	–0.28	1.38	0.56	18.70	11.88	1.21	–1.58

Table C4. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	1.76	0.29	0.78	0.17	4.25	0.03	0.70	–0.16
2	5.78	0.20	0.99	0.20	8.32	3.50	0.78	–0.31
3	17.93	0.46	1.35	0.46	20.95	14.87	1.61	–0.74
4	20.34	0.27	1.15	0.47	23.10	16.99	1.38	–1.32
5	21.32	0.21	1.37	0.43	24.49	17.36	1.51	–1.11
6	22.60	0.20	1.21	0.37	25.48	20.11	1.22	–0.88
7	23.45	0.23	1.19	0.38	25.79	19.17	1.21	–0.64
8	24.06	0.20	0.87	0.34	25.89	21.38	0.97	–0.67
9	24.33	0.22	0.86	0.31	26.18	21.34	1.15	–0.59
10	24.68	0.22	0.68	0.29	26.43	22.86	1.15	–0.63
11	24.64	0.22	0.86	0.26	26.55	22.10	0.95	–0.39
12	24.93	0.23	0.74	0.26	26.68	22.92	0.96	–0.36
13	24.72	0.21	0.90	0.30	26.91	21.21	0.91	–0.77
14	24.23	0.24	0.95	0.33	25.98	21.74	1.82	–0.64
15	23.91	0.18	1.02	0.35	26.28	20.77	1.05	–0.74
16	23.78	0.17	1.17	0.43	26.37	20.19	1.23	–0.86
17	22.83	0.17	1.19	0.40	25.97	19.86	1.30	–0.87
18	22.13	0.08	1.45	0.40	24.80	18.60	1.06	–1.00
19	21.10	0.12	1.50	0.49	24.41	17.16	1.31	–0.92
20	20.71	0.15	1.60	0.42	24.14	16.88	1.22	–0.87
21	19.83	0.19	1.45	0.45	24.16	16.16	1.86	–0.86
22	16.53	0.18	1.31	0.51	19.46	12.79	1.34	–1.08
23	3.76	–0.19	0.94	0.26	7.21	1.29	0.58	–0.86

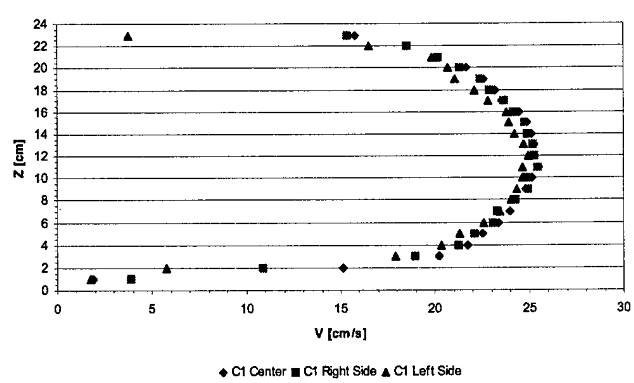


Figure C3. Velocity profiles.

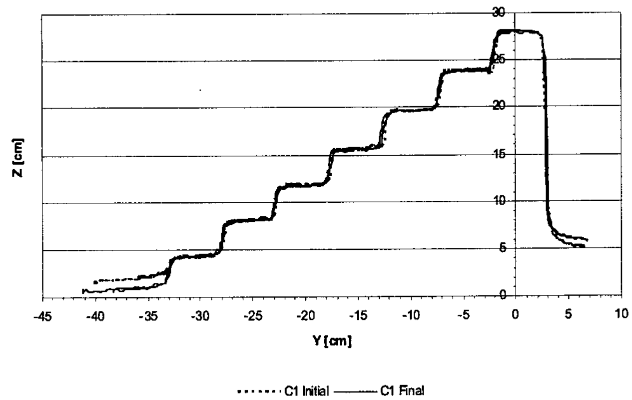


Figure C4. Calibration.

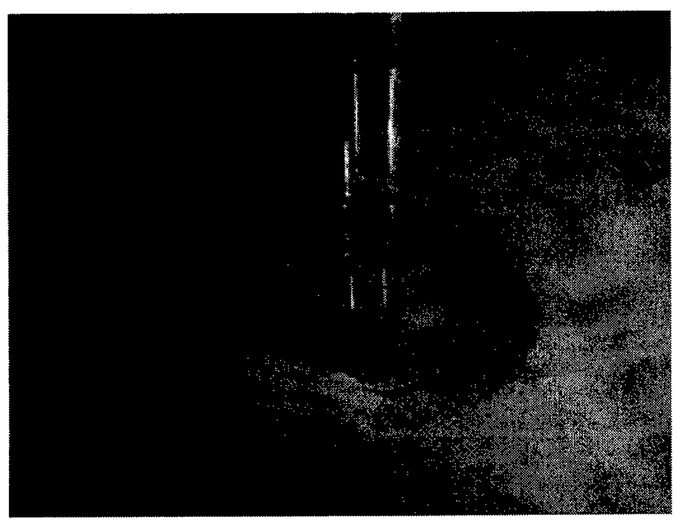


Figure C5. Final photo of scour hole; flow from right to left.

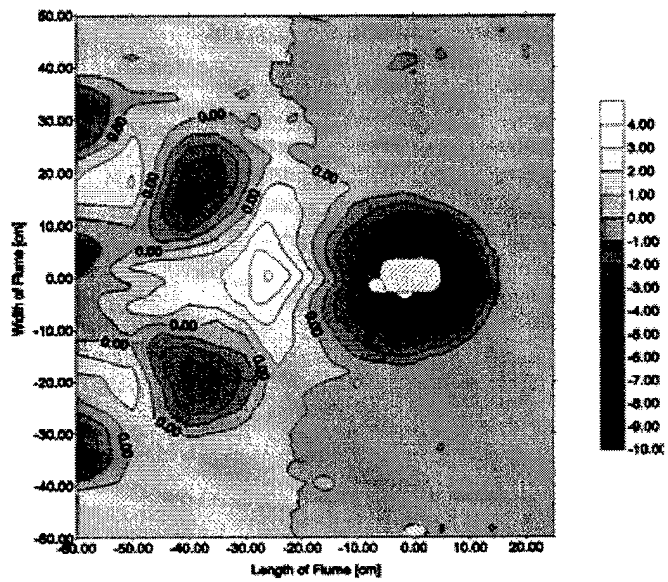


Figure C6. Contour plot; flow from right to left.

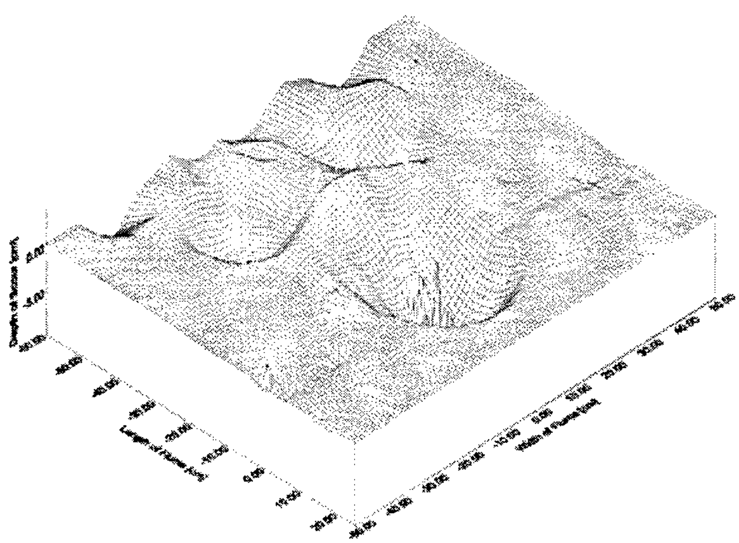


Figure C7. Surface plot; flow is from lower right to upper left.

Test C2

Table C5. Scour depth vs. time data.

Initial Reading =	10	In.
Start Time =	15:46	18-Mar-03
End Time =	08:08	19-Mar-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
15:46	10.0000	0:00	0.0000	0.000
15:47	9.7500	0:01	0.2500	0.635
15:48	9.5000	0:02	0.5000	1.270
15:50	9.0000	0:04	1.0000	2.540
15:51	8.7500	0:05	1.2500	3.175
15:53	8.6250	0:07	1.3750	3.493
15:55	8.5000	0:09	1.5000	3.810
15:59	8.3750	0:13	1.6250	4.128
16:01	8.2500	0:15	1.7500	4.445
16:15	8.0000	0:29	2.0000	5.080
16:26	7.9375	0:40	2.0625	5.239
16:40	7.8125	0:54	2.1875	5.556
16:46	7.7500	1:00	2.2500	5.715
17:07	7.6250	1:21	2.3750	6.033
17:18	7.5625	1:32	2.4375	6.191
17:29	7.5000	1:43	2.5000	6.350
18:05	7.3750	2:19	2.6250	6.668
18:39	7.2500	2:53	2.7500	6.985
18:43	7.1875	2:57	2.8125	7.144
19:21	7.1250	3:35	2.8750	7.303
19:55	7.0625	4:09	2.9375	7.461
20:34	7.0000	4:48	3.0000	7.620
0:20	6.8750	8:34	3.1250	7.938
7:39	6.7500	15:53	3.2500	8.255
8:08	6.7500	16:22	3.2500	8.255

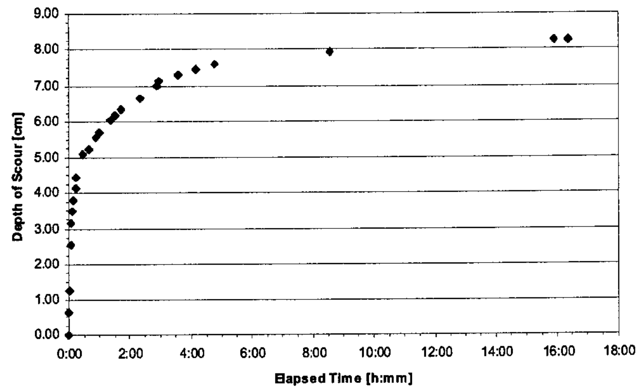


Figure C8. Scour depth vs. time.

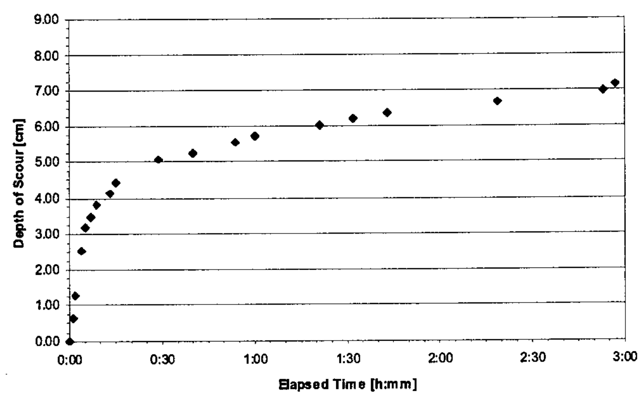


Figure C9. Scour depth vs. time for the first 3 hours.

Table C6. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	3.33	0.36	0.87	0.20	6.10	0.92	1.02	–0.02
2	18.50	0.72	1.71	0.50	23.15	14.35	1.98	–0.55
3	23.18	0.70	1.36	0.51	26.38	19.62	2.17	–0.67
4	25.37	0.78	1.46	0.46	29.03	21.50	2.08	–0.57
5	26.21	0.71	1.41	0.42	29.23	23.03	1.58	–0.64
6	26.94	0.77	1.27	0.38	30.09	23.79	1.69	–0.22
7	27.76	0.71	1.24	0.34	30.74	24.39	1.48	–0.02
8	28.49	0.77	1.11	0.29	30.90	25.82	1.73	0.14
9	28.62	0.79	1.21	0.37	31.16	25.98	1.84	–0.24
10	29.31	0.77	0.90	0.30	31.46	26.65	1.60	–0.02

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
11	29.61	0.79	0.93	0.28	31.84	26.22	1.63	0.04
12	29.48	0.77	0.80	0.28	30.91	27.55	1.44	–0.08
13	29.39	0.75	0.86	0.28	31.47	27.19	1.40	–0.01
14	29.29	0.74	0.84	0.34	31.22	27.51	2.46	–0.04
15	28.64	0.73	0.97	0.39	30.73	25.55	1.65	–0.27
16	28.15	0.71	1.67	0.53	30.67	13.74	1.59	–3.44
17	27.59	0.73	1.28	0.40	30.25	24.53	1.91	–0.47
18	27.17	0.70	1.30	0.41	30.07	22.63	1.71	–0.38
19	25.99	0.72	1.31	0.43	28.96	23.15	1.67	–0.45
20	25.18	0.81	1.70	0.40	28.66	20.22	1.84	–0.40
21	23.77	0.83	1.64	0.52	27.05	19.46	2.34	–0.47
22	20.73	0.73	1.73	0.52	24.51	15.91	1.93	–0.43
23	16.27	0.61	1.70	0.56	20.83	12.80	2.07	–1.04

Table C7. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	8.81	1.56	1.44	0.33	12.52	5.62	2.50	0.70
2	19.72	0.65	1.82	0.50	23.88	15.34	2.11	–0.53
3	23.67	0.67	1.62	0.48	28.05	20.04	2.14	–0.37
4	25.25	0.73	1.52	0.39	29.05	21.30	1.77	–0.48
5	26.60	0.73	1.36	0.38	29.39	23.73	1.80	–0.41
6	27.46	0.67	1.07	0.33	30.26	24.44	1.46	–0.20
7	28.35	0.65	1.32	0.35	30.73	23.30	1.76	–0.18
8	28.62	0.62	1.02	0.35	30.87	25.98	1.45	–0.47
9	29.04	0.65	1.06	0.33	31.36	24.24	1.89	–0.53
10	29.52	0.62	0.80	0.30	31.38	27.14	1.28	–0.11
11	29.68	0.61	0.75	0.28	31.59	27.74	1.38	–0.13
12	29.61	0.60	0.76	0.29	31.29	26.67	1.24	–0.22
13	29.37	0.61	0.90	0.28	31.07	26.23	1.32	–0.03
14	28.81	0.58	0.93	0.35	30.41	26.67	1.40	–0.22
15	28.49	0.56	1.01	0.35	30.31	25.58	1.31	–0.34
16	28.20	0.54	1.14	0.38	30.78	24.59	1.53	–0.18
17	27.73	0.54	1.16	0.36	30.15	24.18	1.66	–0.57
18	27.21	0.48	1.17	0.39	30.11	24.64	1.67	–0.42
19	25.42	0.45	1.64	0.43	28.87	19.74	1.63	–0.71
20	24.41	0.46	1.62	0.51	27.68	20.12	1.65	–0.73
21	22.23	0.35	1.60	0.59	26.14	18.36	1.96	–0.85
22	20.33	0.32	1.76	0.62	23.91	15.67	2.14	–1.11
23	13.38	–0.45	1.67	0.57	17.81	9.19	1.60	–2.22

Table C8. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	1.37	0.19	0.53	0.12	2.86	0.23	0.57	–0.10
2	10.52	0.05	1.64	0.35	14.39	6.40	0.95	–0.82
3	21.14	0.46	1.94	0.51	25.58	16.98	2.08	–1.00
4	24.28	0.47	1.46	0.50	27.27	20.80	1.66	–0.77
5	25.75	0.55	1.27	0.41	28.24	22.90	1.77	–0.49
6	26.81	0.51	1.15	0.42	29.74	23.82	1.57	–0.40
7	27.45	0.58	1.18	0.35	29.76	23.50	1.38	–0.71
8	27.96	0.53	1.04	0.34	30.80	24.88	1.88	–0.68
9	28.64	0.51	0.91	0.30	30.75	25.50	1.52	–0.20
10	28.62	0.51	0.77	0.31	30.25	26.48	1.27	–0.19
11	28.84	0.51	0.75	0.26	30.47	26.89	0.97	–0.18
12	28.97	0.55	0.74	0.30	30.91	26.27	1.53	–0.33
13	28.66	0.50	0.86	0.36	30.65	26.50	1.47	–0.42
14	28.51	0.47	1.07	0.37	30.83	25.12	1.49	–0.57
15	28.24	0.47	1.12	0.34	30.13	24.74	1.41	–0.40
16	27.68	0.49	1.09	0.35	29.76	24.76	1.53	–0.41
17	26.97	0.47	1.13	0.40	29.78	23.59	1.37	–0.57
18	26.33	0.45	1.32	0.43	28.96	23.48	1.49	–0.74
19	25.72	0.35	1.53	0.47	29.01	21.22	1.57	–0.90
20	24.05	0.40	1.67	0.52	28.23	19.88	1.67	–0.96
21	22.72	0.40	1.73	0.55	26.70	18.16	1.65	–0.78
22	17.22	0.27	1.59	0.53	22.07	14.24	1.61	–1.15
23	0.81	–0.09	0.34	0.07	1.79	0.06	0.07	–0.28

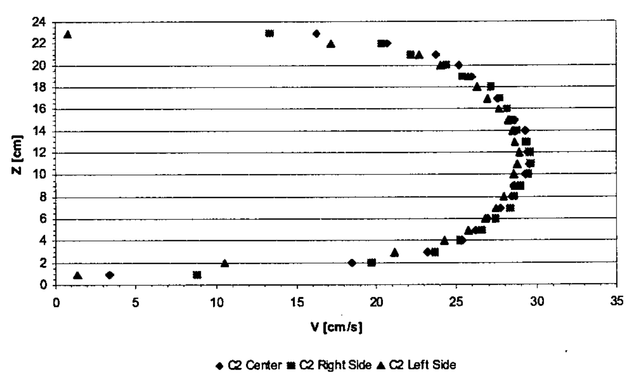


Figure C10. Velocity profiles.

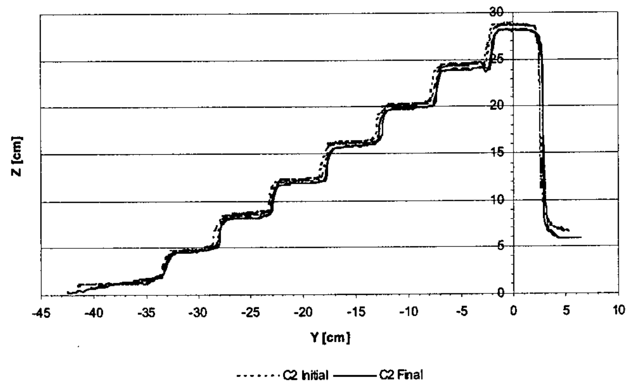


Figure C11. Calibration.

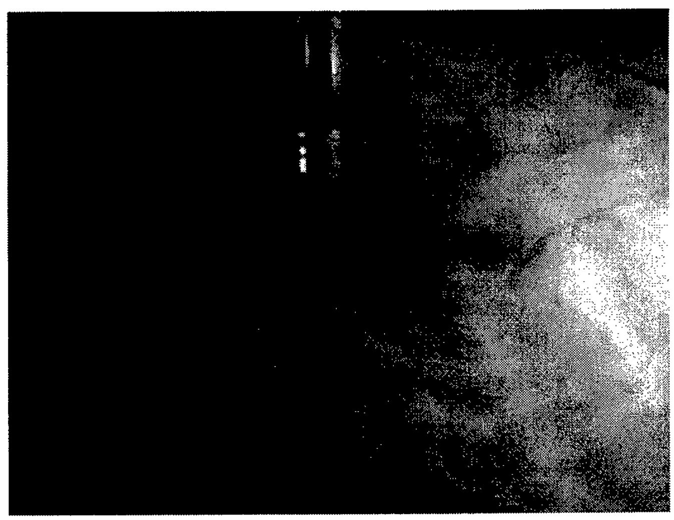


Figure C12. Final photo of scour hole; flow from right to left.

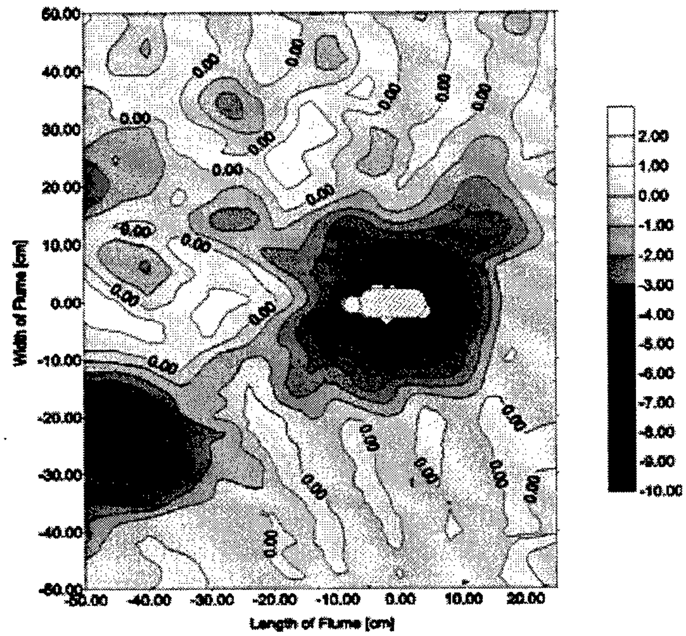


Figure C13. Contour plot; flow from right to left.

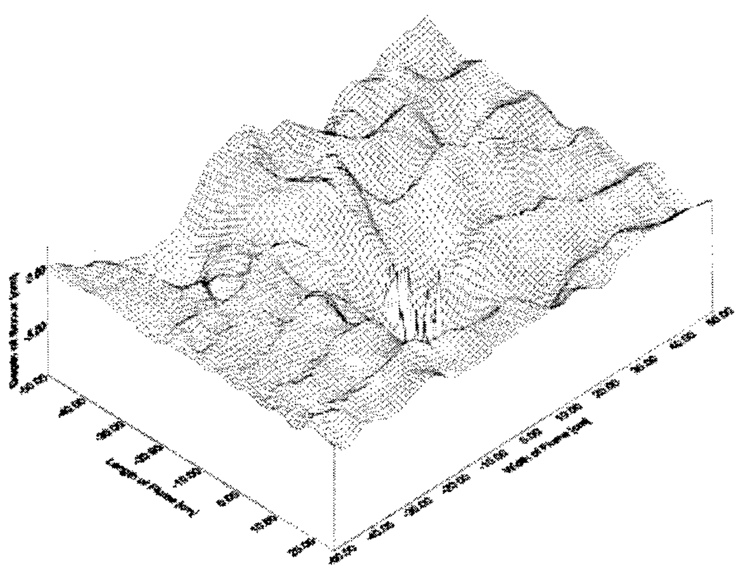


Figure C14. Surface plot; flow is from lower right to upper left.

Test C3

Table C9. Scour depth vs. time data.

Initial Reading =	10	In.
Start Time =	16:46	19-Mar-03
End Time =	13:02	20-Mar-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
16:46	10.0000	0:00	0.0000	0.000
16:48	9.8125	0:02	0.1875	0.476
16:49	9.5000	0:03	0.5000	1.270
16:50	9.2500	0:04	0.7500	1.905
16:52	9.0000	0:06	1.0000	2.540
16:54	8.7500	0:08	1.2500	3.175
16:56	8.6250	0:10	1.3750	3.493
16:57	8.5000	0:11	1.5000	3.810
17:04	8.3125	0:18	1.6875	4.286
17:11	8.1250	0:25	1.8750	4.763
17:21	8.0000	0:35	2.0000	5.080
17:28	7.9375	0:42	2.0625	5.239
18:10	7.6250	1:24	2.3750	6.033
18:40	7.5000	1:54	2.5000	6.350
19:08	7.3750	2:22	2.6250	6.668
19:35	7.2500	2:49	2.7500	6.985
20:36	7.1250	3:50	2.8750	7.303
21:34	7.0000	4:48	3.0000	7.620
23:41	6.8750	6:55	3.1250	7.938
2:03	7.0000	9:17	3.0000	7.620
4:23	7.1250	11:37	2.8750	7.303
7:32	7.0000	14:46	3.0000	7.620
7:52	7.0000	15:06	3.0000	7.620
8:16	7.1250	15:30	2.8750	7.303
8:45	7.1250	15:59	2.8750	7.303
10:34	7.0625	17:48	2.9375	7.461
12:12	7.1250	19:26	2.8750	7.303
13:02	7.1250	20:16	2.8750	7.303

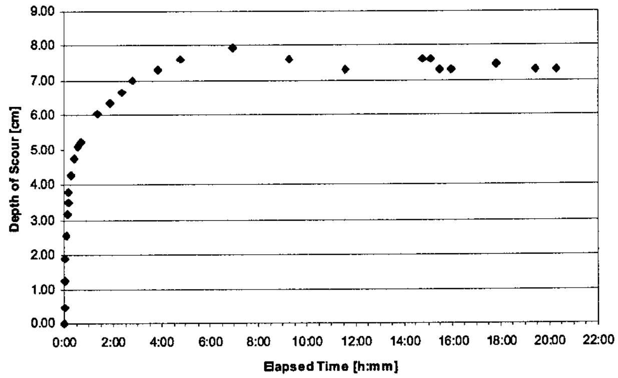


Figure C15. Scour depth vs. time.

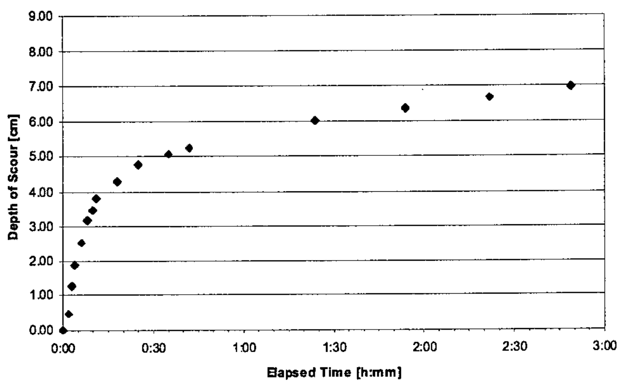


Figure C16. Scour depth vs. time for the first 3 hours.

Table C10. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	1.66	–0.18	0.56	0.14	3.25	0.51	0.14	–0.56
2	15.14	0.41	2.05	0.86	19.73	10.93	2.56	–1.81
3	19.75	0.53	1.94	0.91	25.83	15.86	2.52	–1.70
4	20.81	0.54	1.69	0.86	24.78	17.37	3.32	–1.35
5	21.84	0.66	2.07	0.87	26.93	17.11	2.61	–1.51
6	22.13	0.55	2.17	0.83	27.36	17.12	2.76	–1.34
7	23.58	0.64	2.32	0.88	28.26	17.84	3.54	–1.97
8	24.72	0.59	2.10	0.81	29.99	19.00	2.92	–2.15
9	25.38	0.69	2.27	0.81	30.81	19.51	2.66	–1.46
10	26.46	0.67	1.94	0.67	30.02	20.43	2.56	–0.96
11	26.76	0.74	1.80	0.66	30.71	21.55	3.98	–1.24

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
12	28.45	0.73	1.79	0.58	32.14	22.76	2.12	–1.74
13	28.69	0.79	1.52	0.56	32.72	24.52	2.69	–0.52
14	29.15	0.75	1.39	0.52	31.80	23.89	1.96	–0.62
15	29.21	0.70	1.37	0.45	31.74	23.86	2.10	–0.27
16	29.28	0.69	0.89	0.49	31.47	26.84	2.08	–0.56
17	29.07	0.66	1.18	0.46	31.72	26.25	1.87	–0.59
18	28.72	0.61	1.07	0.45	31.52	25.58	2.39	–0.30
19	27.93	0.69	1.30	0.41	30.46	23.59	1.81	–0.32
20	26.80	0.69	1.52	0.46	30.98	23.43	1.83	–0.64
21	24.99	0.67	1.47	0.51	28.46	20.62	2.20	–0.68
22	22.95	0.75	1.52	0.54	26.02	18.24	2.08	–1.04
23	17.70	0.53	1.58	0.53	21.33	14.41	1.86	–0.66

Table C11. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	5.40	0.75	1.47	0.39	9.61	1.94	2.03	–0.06
2	12.13	0.11	1.93	0.63	17.30	8.52	1.58	–1.58
3	19.34	0.95	2.13	0.95	24.29	14.28	3.42	–1.09
4	20.87	0.98	2.12	0.86	26.40	16.26	3.14	–1.66
5	21.57	1.11	2.23	0.84	26.69	14.29	3.09	–1.60
6	23.06	1.19	2.27	0.78	28.83	16.01	3.18	–1.07
7	23.53	1.14	2.23	0.76	28.87	19.04	2.85	–1.06
8	24.36	1.26	2.23	0.73	30.08	19.44	3.09	–0.57
9	25.42	1.37	2.02	0.77	29.79	18.70	3.26	–0.76
10	26.25	1.44	1.72	0.64	30.08	21.92	3.11	–0.12
11	27.03	1.47	1.70	0.67	32.12	22.52	2.91	–0.16
12	28.20	1.51	1.65	0.58	31.27	23.29	3.04	–0.94
13	28.79	1.45	1.68	0.50	32.02	24.19	2.47	0.14
14	29.59	1.49	1.23	0.46	31.79	26.57	2.93	0.39
15	29.41	1.50	1.18	0.49	32.25	25.91	2.68	–0.13
16	29.73	1.45	1.03	0.36	31.89	26.69	2.27	0.56
17	29.53	1.38	1.22	0.34	31.94	25.64	2.22	0.27
18	29.02	1.35	1.21	0.45	31.57	25.58	2.43	0.19
19	27.97	1.25	1.26	0.49	30.23	24.40	2.34	0.22
20	27.45	1.22	1.48	0.44	31.17	23.34	2.66	0.23
21	25.22	1.12	2.04	0.62	28.96	11.07	2.34	–2.77
22	23.34	0.95	1.90	0.53	27.97	18.26	2.35	–0.29
23	17.69	0.83	1.58	0.56	21.47	13.44	2.36	–0.83

Table C12. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	2.54	–0.20	0.64	0.14	4.29	0.91	0.11	–0.59
2	16.07	–0.10	2.03	0.75	22.04	10.31	1.92	–1.91
3	20.92	–0.27	1.92	0.74	26.84	16.82	1.43	–2.34
4	21.50	–0.05	1.88	0.70	25.64	17.24	1.67	–1.87
5	23.09	–0.06	2.18	0.74	27.07	17.09	1.92	–1.92
6	23.62	0.07	1.98	0.77	27.88	18.56	2.01	–2.13
7	24.07	0.04	1.94	0.70	28.15	19.46	1.85	–1.73
8	24.54	0.10	2.02	0.65	28.51	19.75	1.48	–1.65
9	25.01	0.10	2.66	0.76	29.19	9.53	2.43	–2.16
10	25.34	0.08	1.92	0.72	29.35	19.64	2.08	–1.66
11	26.44	0.30	1.50	0.56	29.62	22.69	2.42	–1.13
12	27.17	0.25	1.66	0.54	30.44	23.30	1.90	–1.03
13	26.96	0.27	1.81	0.52	29.93	21.36	1.61	–1.28
14	27.91	0.25	1.48	0.51	31.04	22.04	1.90	–0.75
15	27.89	0.33	1.24	0.42	30.18	22.06	1.32	–0.74
16	28.19	0.22	1.13	0.38	30.57	25.05	0.88	–0.86
17	27.65	0.18	0.96	0.43	29.66	24.75	1.23	–1.09
18	27.51	0.19	0.99	0.42	30.01	24.82	1.40	–0.74
19	26.69	0.15	1.12	0.45	29.00	23.61	1.25	–0.94
20	25.44	0.23	1.35	0.45	28.79	21.42	1.10	–1.02
21	23.59	0.14	1.61	0.57	26.82	18.50	1.28	–1.15
22	20.62	0.12	1.52	0.49	24.26	16.97	1.71	–1.39
23	8.42	0.24	1.05	0.32	12.21	6.28	1.10	–0.63

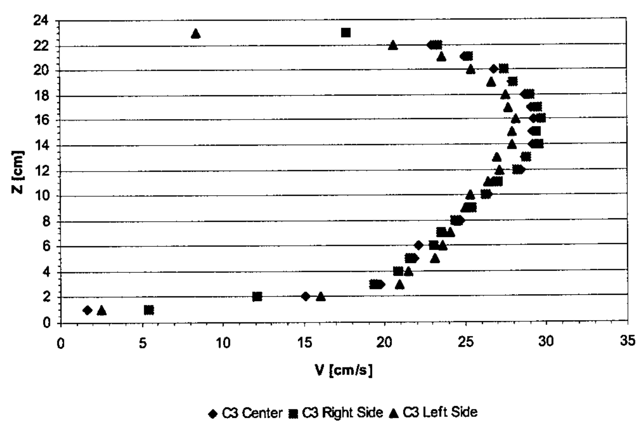


Figure C17. Velocity profiles.

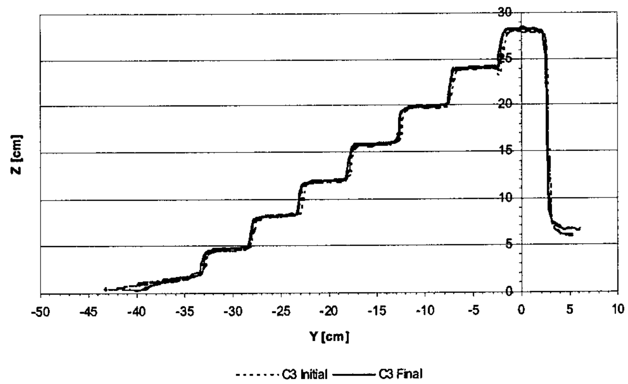


Figure C18. Calibration.

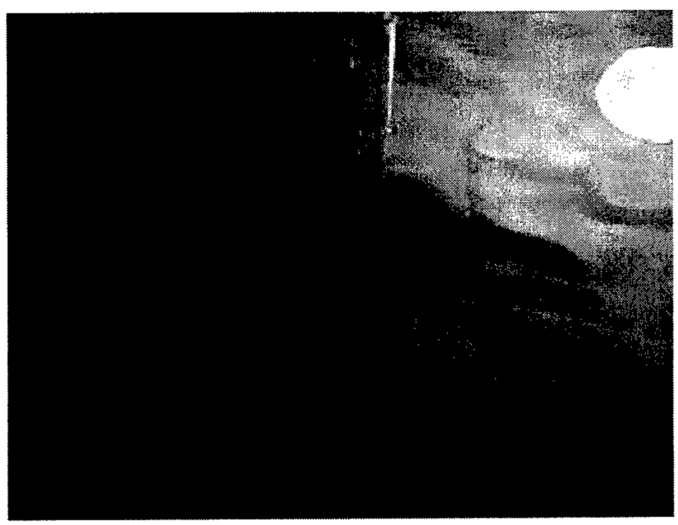


Figure C19. Final photo of scour hole; flow from right to left.

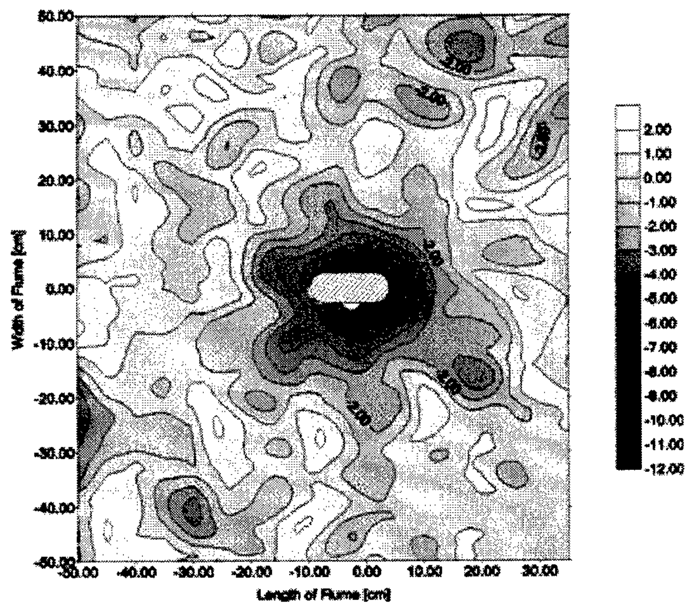


Figure C20. Contour plot; flow from right to left.

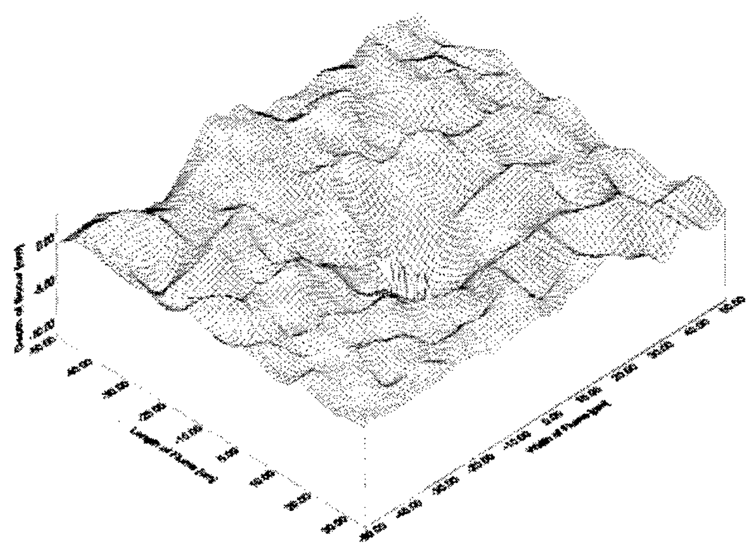


Figure C21. Surface plot; flow is from lower right to upper left.

Test C4

Table C13. Scour depth vs. time data.

Initial Reading =	10	In.
Start Time =	13:37	07-Apr-03
End Time =	08:32	08-Apr-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
13:37	10.000	0:00	0.0000	0.000
13:38	9.625	0:01	0.3750	0.953
13:43	9.500	0:06	0.5000	1.270
13:46	9.125	0:09	0.8750	2.223
13:47	9.000	0:10	1.0000	2.540
13:51	8.875	0:14	1.1250	2.858
13:54	8.750	0:17	1.2500	3.175
14:05	8.500	0:28	1.5000	3.810
14:32	8.250	0:55	1.7500	4.445
14:39	8.125	1:02	1.8750	4.763
15:13	8.000	1:36	2.0000	5.080
15:50	7.875	2:13	2.1250	5.398
16:36	7.750	2:59	2.2500	5.715
16:56	7.625	3:19	2.3750	6.033
18:26	7.500	4:49	2.5000	6.350
19:15	7.375	5:38	2.6250	6.668
19:26	7.313	5:49	2.6875	6.826
21:53	7.250	8:16	2.7500	6.985
1:39	7.125	12:02	2.8750	7.303
3:24	7.063	13:47	2.9375	7.461
5:43	7.000	16:06	3.0000	7.620
7:45	6.875	18:08	3.1250	7.938
8:32	6.875	18:55	3.1250	7.938

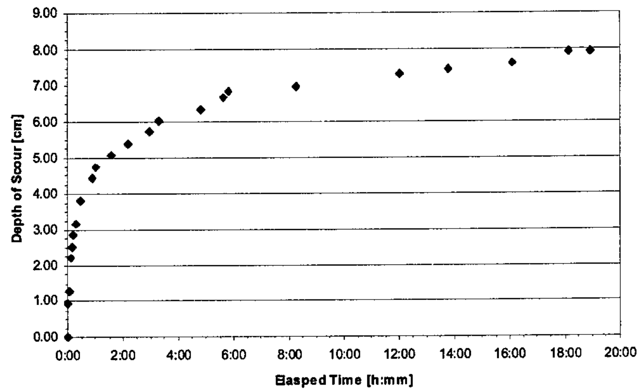


Figure C22. Scour depth vs. time.

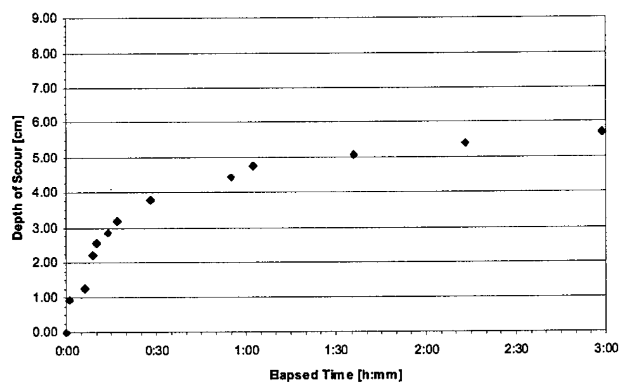


Figure C23. Scour depth vs. time for the first 3 hours.

Table C14. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	8.37	0.94	1.42	0.35	12.83	5.41	2.02	0.20
2	14.96	0.30	1.55	0.41	20.26	11.22	1.22	–0.53
3	19.11	0.07	1.57	0.51	22.11	15.24	1.58	–1.04
4	20.93	0.03	1.37	0.46	23.80	17.58	1.60	–1.06
5	21.49	–0.04	1.68	0.44	24.84	16.94	1.14	–1.56
6	22.02	–0.02	1.32	0.44	24.93	17.98	1.29	–1.25
7	23.00	0.02	1.40	0.32	25.48	19.02	1.06	–0.74
8	22.97	–0.06	1.39	0.41	25.78	18.95	1.05	–1.11
9	23.82	–0.05	0.92	0.32	25.90	21.43	0.71	–0.82
10	24.06	0.00	1.18	0.33	26.23	20.14	0.74	–1.11

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
11	24.46	–0.09	1.03	0.35	26.35	20.83	0.77	–1.03
12	24.55	–0.11	0.78	0.27	26.42	22.57	0.88	–0.85
13	24.82	–0.11	0.70	0.27	26.74	22.81	0.47	–0.94
14	24.55	–0.10	0.65	0.31	26.09	22.38	0.93	–0.93
15	24.55	–0.13	0.81	0.29	26.24	21.89	0.62	–0.91
16	23.95	–0.16	0.97	0.33	26.01	20.87	0.62	–1.00
17	23.53	–0.16	1.01	0.36	25.71	20.70	0.87	–1.11
18	22.71	–0.18	1.11	0.38	24.96	19.39	0.84	–1.19
19	21.56	–0.21	1.16	0.41	23.85	18.64	0.90	–1.21
20	20.60	–0.12	1.47	0.47	24.02	16.93	1.72	–1.14
21	19.59	–0.09	1.38	0.46	22.27	16.23	1.14	–1.28
22	16.92	–0.13	1.55	0.49	20.46	13.02	0.95	–1.31
23	9.53	–0.35	1.27	0.40	12.93	6.80	0.81	–1.37

Table C15. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	1.05	0.15	0.37	0.09	1.93	0.06	0.41	–0.05
2	15.65	–0.55	1.43	0.45	19.14	11.90	0.58	–1.31
3	18.69	–0.72	1.27	0.48	22.04	15.29	0.36	–1.85
4	20.46	–1.00	1.31	0.50	23.35	17.00	0.29	–1.90
5	22.04	–1.09	1.10	0.40	24.74	19.44	–0.08	–1.93
6	22.67	–1.15	1.06	0.36	24.97	20.19	–0.22	–1.99
7	23.40	–1.20	0.96	0.34	25.41	21.17	–0.10	–2.11
8	24.01	–1.24	0.83	0.29	25.98	21.07	–0.29	–2.38
9	24.15	–1.29	0.80	0.33	26.20	22.07	–0.47	–2.03
10	24.32	–1.35	0.71	0.25	25.92	22.41	–0.74	–2.14
11	24.63	–1.35	0.64	0.28	26.18	22.46	–0.40	–2.07
12	24.57	–1.39	0.87	0.26	26.20	21.94	–0.63	–1.97
13	24.31	–1.42	0.87	0.29	25.94	21.94	–0.52	–2.32
14	24.14	–1.41	0.85	0.31	26.44	22.31	–0.46	–2.24
15	23.76	–1.41	1.16	0.31	25.72	20.07	–0.06	–2.17
16	23.20	–1.40	1.39	0.39	25.35	19.14	–0.36	–2.53
17	22.86	–1.39	1.20	0.48	25.47	19.35	–0.03	–2.49
18	21.90	–1.33	1.34	0.46	24.61	17.59	–0.06	–2.34
19	21.36	–1.22	1.57	0.41	24.79	17.51	0.06	–2.13
20	20.13	–1.19	1.74	0.51	23.87	16.14	–0.11	–2.61
21	19.07	–1.11	1.57	0.45	22.29	14.70	0.38	–2.42
22	17.33	–1.01	1.66	0.51	21.70	13.15	0.08	–2.62
23	10.23	–0.02	1.27	0.43	13.54	7.48	0.85	–1.66

Table C16. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	1.09	–0.06	0.41	0.09	2.25	0.38	0.17	–0.32
2	14.69	–0.12	1.37	0.48	17.46	11.12	0.99	–1.16
3	19.35	–0.71	1.60	0.41	23.96	15.06	0.44	–1.58
4	20.34	–0.67	1.51	0.41	22.93	16.41	0.37	–1.78
5	21.29	–0.76	1.67	0.42	24.92	16.55	0.66	–2.05
6	21.62	–0.77	1.50	0.42	24.49	17.33	0.32	–2.02
7	22.91	–0.78	1.09	0.38	24.68	20.01	0.32	–1.75
8	23.28	–0.76	1.33	0.34	25.95	19.02	0.35	–1.68
9	23.91	–0.77	1.23	0.31	26.09	20.28	0.01	–1.62
10	24.07	–0.75	1.13	0.31	26.07	20.23	0.14	–1.48
11	24.38	–0.74	0.92	0.27	26.16	21.80	0.16	–1.39
12	24.26	–0.72	0.72	0.31	25.94	22.52	–0.02	–1.63
13	24.08	–0.68	0.85	0.26	25.81	21.78	–0.01	–1.32
14	23.86	–0.77	0.76	0.32	25.42	21.56	0.01	–1.50
15	23.45	–0.70	0.85	0.34	25.16	20.87	0.08	–1.48
16	23.21	–0.72	0.81	0.26	25.11	20.66	–0.15	–1.29
17	22.59	–0.68	1.15	0.36	25.42	19.33	0.18	–1.55
18	21.93	–0.72	1.29	0.39	24.43	18.49	0.26	–1.57
19	21.56	–0.69	1.17	0.41	23.97	18.26	0.39	–2.07
20	20.02	–0.60	1.27	0.47	23.56	16.74	0.40	–2.00
21	18.28	–0.53	1.27	0.47	21.51	15.10	0.93	–1.90
22	15.49	–0.54	1.14	0.48	18.40	12.83	0.81	–1.82
23	5.96	–0.26	1.06	0.28	8.67	3.67	0.37	–1.12

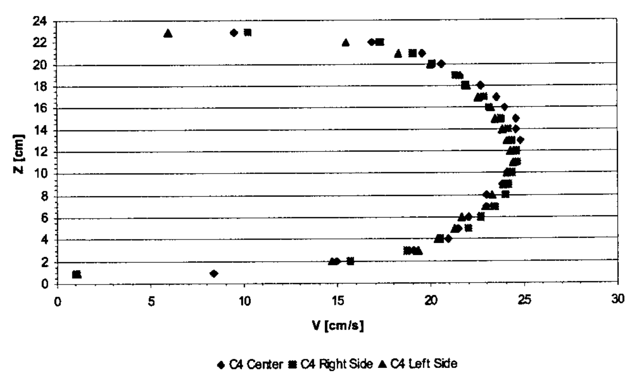


Figure C24. Velocity profiles.

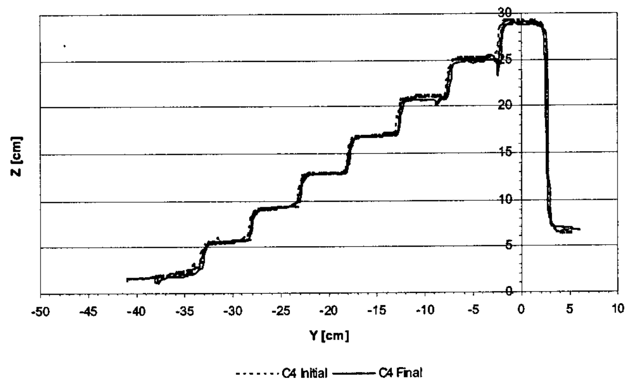


Figure C25. Calibration.

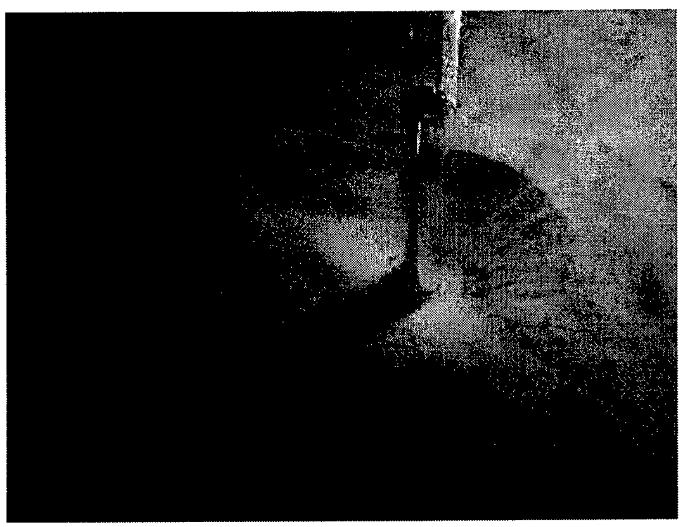


Figure C26. Final photo of scour hole; flow from right to left.

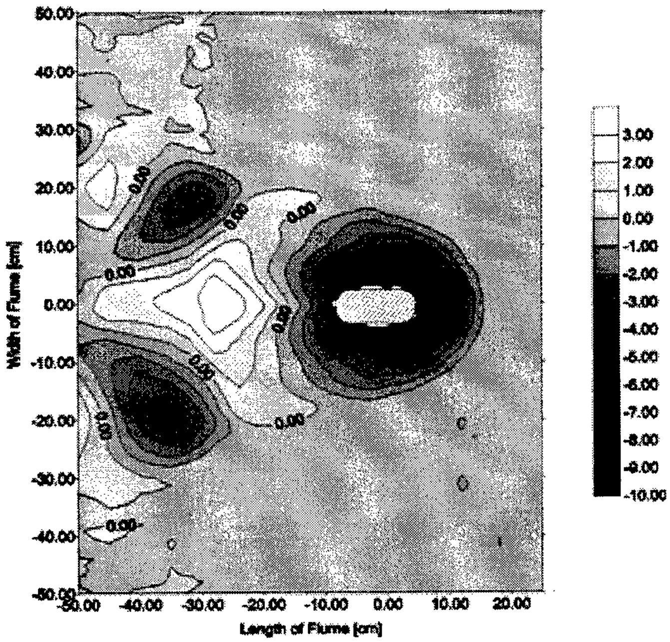


Figure C27. Contour plot; flow from right to left.

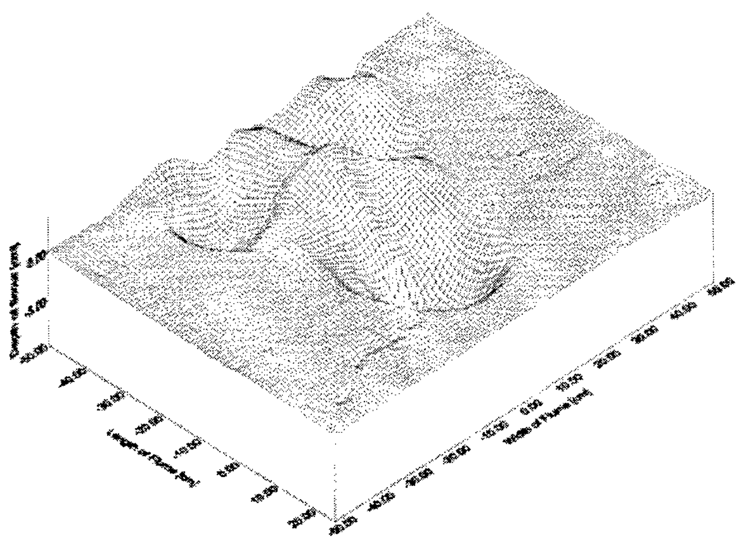


Figure C28. Surface plot; flow is from lower right to upper left.

Test C5

Table C17. Scour depth vs. time data.

Initial Reading =	10.0625	In.
Start Time =	16:48	08-Apr-03
End Time =	08:27	09-Apr-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
16:48	10.0625	0:00	0.0000	0.000
16:49	9.7500	0:01	0.3125	0.794
16:51	9.5000	0:03	0.5625	1.429
16:53	9.2500	0:05	0.8125	2.064
16:54	9.1250	0:06	0.9375	2.381
16:55	9.0000	0:07	1.0625	2.699
16:57	8.7500	0:09	1.3125	3.334
17:04	8.5000	0:16	1.5625	3.969
17:12	8.3750	0:24	1.6875	4.286
17:57	8.0000	1:09	2.0625	5.239
18:20	7.8750	1:32	2.1875	5.556
18:25	7.7500	1:37	2.3125	5.874
18:59	7.6250	2:11	2.4375	6.191
19:30	7.5000	2:42	2.5625	6.509
19:40	7.3750	2:52	2.6875	6.826
20:23	7.3125	3:35	2.7500	6.985
22:36	7.2500	5:48	2.8125	7.144
0:46	7.1250	7:58	2.9375	7.461
4:18	7.0000	11:30	3.0625	7.779
6:28	6.8750	13:40	3.1875	8.096
7:27	6.8750	14:39	3.1875	8.096
8:27	6.8125	15:39	3.2500	8.255

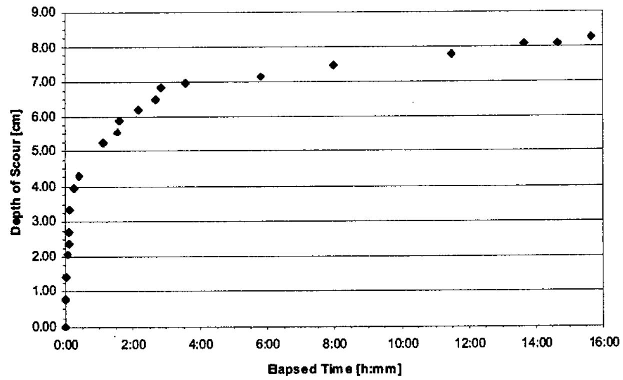


Figure C29. Scour depth vs. time.

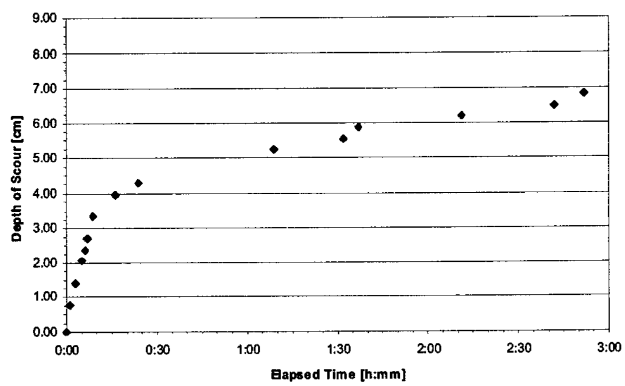


Figure C30. Scour depth vs. time for the first 3 hours.

Table C18. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	5.86	1.17	1.45	0.33	10.19	3.00	2.12	0.52
2	10.94	0.92	1.67	0.33	16.05	7.27	1.75	0.14
3	20.55	0.66	1.66	0.44	24.26	16.10	1.61	–0.45
4	22.76	0.64	1.36	0.42	25.89	19.43	1.50	–0.38
5	23.94	0.76	1.38	0.43	27.11	19.69	1.75	–0.43
6	24.50	0.78	1.33	0.43	26.70	20.58	2.02	–0.69
7	25.05	0.72	1.41	0.36	27.75	20.58	1.69	–0.37
8	25.81	0.76	1.05	0.31	27.65	22.76	1.44	–0.30
9	26.23	0.76	0.91	0.32	28.36	24.04	1.55	–0.18
10	26.70	0.77	0.79	0.30	28.72	24.69	1.56	0.09
11	27.05	0.73	0.70	0.25	28.68	24.88	1.36	–0.04

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
12	26.77	0.76	0.69	0.26	28.36	24.83	1.56	0.19
13	26.77	0.75	0.77	0.32	28.53	24.09	1.85	–0.10
14	26.41	0.77	0.84	0.32	27.99	22.44	1.81	0.01
15	26.13	0.69	0.80	0.35	27.70	23.78	1.99	–0.18
16	25.70	0.67	1.11	0.38	28.13	22.67	1.69	–0.23
17	25.23	0.67	1.13	0.44	27.81	22.19	1.53	–0.64
18	24.10	0.65	1.33	0.45	27.85	20.99	1.73	–0.43
19	23.35	0.71	1.32	0.45	26.12	19.62	1.80	–0.72
20	22.15	0.79	1.49	0.47	25.98	18.15	2.06	–0.24
21	21.35	0.78	1.40	0.47	24.28	17.44	2.44	–0.78
22	19.40	0.74	1.57	0.55	23.61	15.02	2.18	–0.70
23	13.00	0.64	1.48	0.52	17.08	9.44	2.25	–0.80

Table C19. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	5.29	0.72	1.34	0.31	8.64	1.90	1.60	0.15
2	18.38	0.18	1.45	0.47	21.85	15.04	1.28	–1.17
3	20.93	–0.12	1.34	0.43	24.25	16.81	1.01	–1.44
4	22.14	–0.25	1.58	0.43	26.00	17.99	1.15	–1.24
5	23.97	–0.26	1.23	0.40	26.80	19.31	0.49	–1.40
6	24.65	–0.35	1.34	0.41	26.98	19.49	0.92	–1.18
7	25.29	–0.38	1.06	0.38	27.14	22.05	0.59	–1.51
8	25.70	–0.33	1.05	0.37	27.93	22.80	0.85	–1.14
9	26.75	–0.34	0.93	0.28	28.35	24.25	0.33	–1.19
10	26.80	–0.39	0.99	0.30	29.53	23.49	0.32	–1.14
11	27.03	–0.35	0.76	0.30	28.87	24.84	0.36	–1.27
12	27.05	–0.37	0.76	0.31	28.56	24.87	0.43	–1.19
13	27.07	–0.35	0.75	0.22	28.79	24.80	0.20	–0.83
14	26.79	–0.32	0.84	0.27	28.26	24.37	0.51	–0.89
15	26.66	–0.36	0.84	0.29	28.33	24.55	0.57	–1.05
16	26.16	–0.35	0.91	0.36	28.18	23.45	0.51	–1.10
17	25.69	–0.38	0.99	0.33	27.79	23.07	0.44	–1.23
18	24.56	–0.38	1.23	0.43	26.94	20.99	0.59	–1.46
19	23.75	–0.45	1.26	0.48	27.33	20.81	0.77	–1.66
20	22.49	–0.50	1.53	0.50	25.50	19.01	0.72	–1.60
21	21.56	–0.59	1.35	0.52	25.57	18.05	0.66	–1.83
22	17.75	–0.55	1.67	0.51	21.94	14.04	1.01	–1.79
23	11.27	–0.85	1.31	0.61	14.70	8.65	1.06	–2.35

Table C20. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	6.16	0.80	1.16	0.25	9.39	3.39	1.65	0.22
2	16.30	–0.23	1.84	0.48	20.08	11.26	1.06	–1.29
3	20.55	–0.32	1.49	0.44	23.65	17.01	0.75	–1.39
4	22.35	–0.29	1.46	0.44	25.65	18.21	0.85	–1.39
5	23.32	–0.22	1.32	0.44	26.02	20.54	1.18	–1.17
6	24.14	–0.25	1.28	0.40	27.28	20.17	0.57	–1.25
7	25.10	–0.29	1.14	0.32	27.03	21.20	0.93	–1.00
8	25.25	–0.24	0.94	0.34	27.55	23.55	0.48	–1.04
9	25.70	–0.25	1.06	0.33	28.05	22.28	0.52	–0.92
10	26.06	–0.31	0.75	0.31	27.70	23.70	0.55	–1.00
11	26.16	–0.21	0.69	0.31	28.23	23.92	0.62	–1.04
12	26.12	–0.25	0.71	0.29	27.99	23.62	0.56	–1.11
13	26.23	–0.28	0.80	0.34	27.74	23.48	0.61	–1.09
14	25.84	–0.23	0.85	0.34	27.41	23.03	1.16	–1.04
15	25.42	–0.34	1.10	0.33	27.97	22.58	0.55	–1.04
16	24.91	–0.34	1.01	0.41	27.28	22.55	1.03	–1.55
17	24.34	–0.33	1.08	0.44	26.49	20.73	1.30	–1.36
18	23.60	–0.34	1.31	0.41	26.77	20.05	0.89	–1.41
19	22.66	–0.36	1.54	0.48	26.35	19.00	0.78	–1.44
20	22.21	–0.32	1.43	0.46	26.13	18.07	0.58	–1.82
21	19.75	–0.22	1.58	0.52	22.99	15.77	0.95	–1.48
22	15.86	–0.17	1.35	0.56	19.47	12.50	1.07	–1.54
23	3.95	0.55	0.85	0.22	6.49	1.80	1.14	0.15

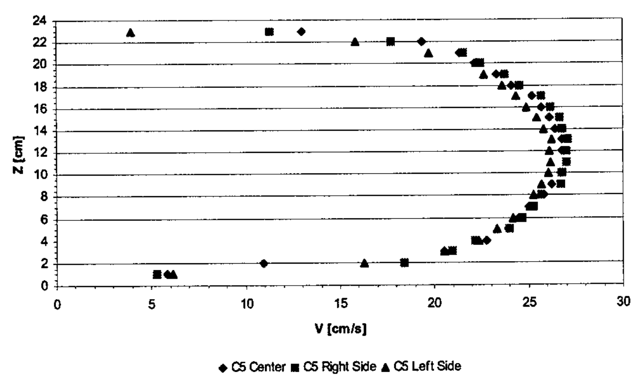


Figure C31. Velocity profiles.

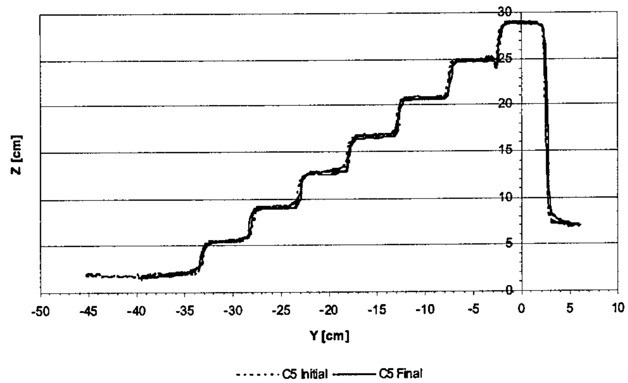


Figure C32. Calibration.

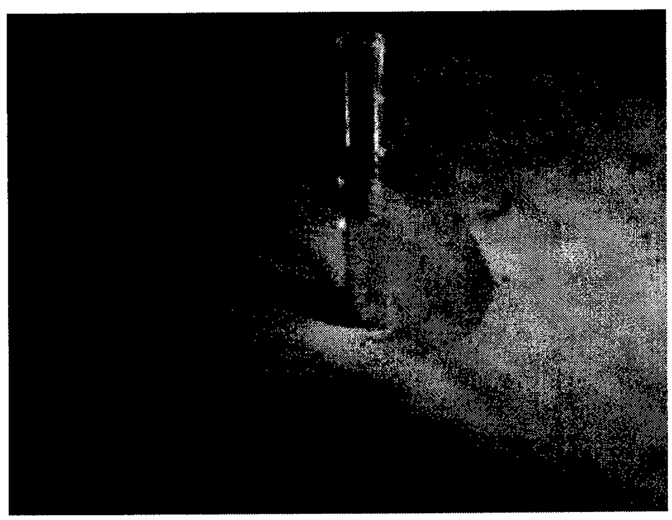


Figure C33. Final photo of scour hole; flow from right to left.

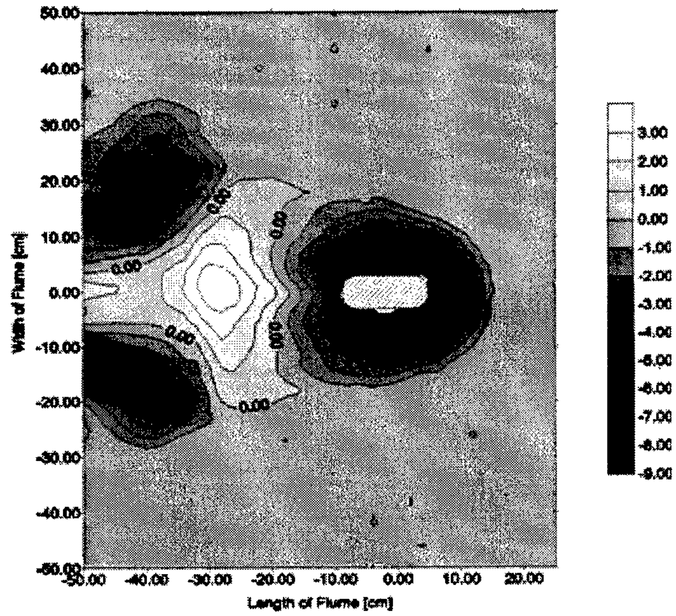


Figure C34. Contour plot; flow from right to left.

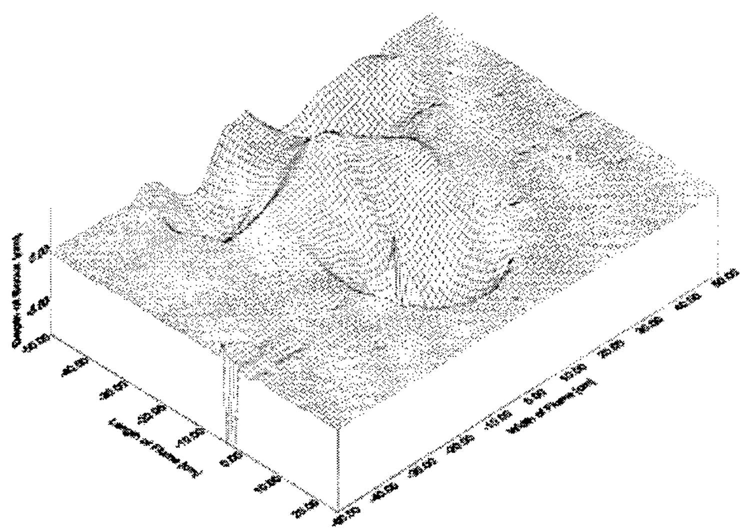


Figure C35. Surface plot; flow is from lower right to upper left.

Test C6

Table C21. Scour depth vs. time data.

Initial Reading =	10.0625	In.
Start Time =	16:54	09-Apr-03
End Time =	08:33	10-Apr-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
16:54	10.0625	0:00	0.0000	0.000
16:55	9.8750	0:01	0.1875	0.476
16:56	9.7500	0:02	0.3125	0.794
16:57	9.6250	0:03	0.4375	1.111
16:58	9.5000	0:04	0.5625	1.429
16:59	9.0000	0:05	1.0625	2.699
17:01	9.1250	0:07	0.9375	2.381
17:03	9.0000	0:09	1.0625	2.699
17:05	8.8750	0:11	1.1875	3.016
17:09	8.7500	0:15	1.3125	3.334
17:12	8.6250	0:18	1.4375	3.651
18:03	8.1250	1:09	1.9375	4.921
18:19	8.0000	1:25	2.0625	5.239
18:48	7.8750	1:54	2.1875	5.556
19:19	7.8125	2:25	2.2500	5.715
19:27	7.7500	2:33	2.3125	5.874
19:57	7.6875	3:03	2.3750	6.033
20:03	7.6250	3:09	2.4375	6.191
20:33	7.5000	3:39	2.5625	6.509
21:18	7.4375	4:24	2.6250	6.668
22:15	7.3750	5:21	2.6875	6.826
0:52	7.2500	7:58	2.8125	7.144
3:06	7.1250	10:12	2.9375	7.461
6:23	7.0000	13:29	3.0625	7.779
7:54	6.8750	15:00	3.1875	8.096
8:33	6.8750	15:39	3.1875	8.096

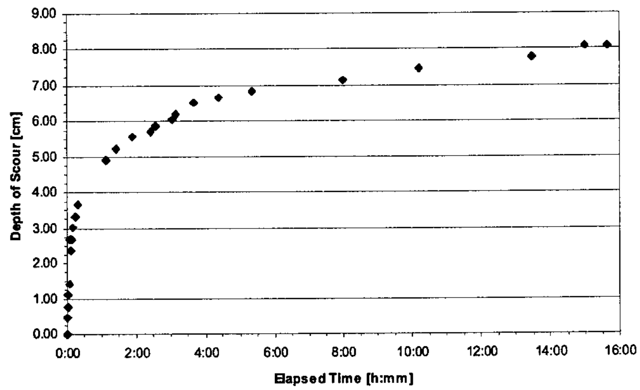


Figure C36. Scour depth vs. time.

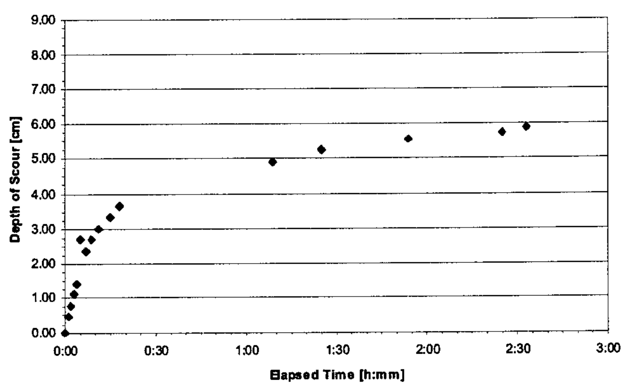


Figure C37. Scour depth vs. time for the first 3 hours.

Table C22. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	2.58	0:48	0.93	0.21	5.31	0.54	1.02	0.05
2	16.95	0.56	1.88	0.44	21.22	13.59	1.94	–0.48
3	20.76	0.30	1.63	0.44	24.38	16.54	1.52	–0.85
4	21.73	0.27	1.43	0.51	24.68	17.95	1.43	–1.01
5	22.89	0.38	1.40	0.41	25.75	19.09	1.59	–0.71
6	23.98	0.33	1.20	0.40	26.30	20.81	1.11	–0.81
7	24.30	0.34	1.13	0.40	26.62	21.71	1.26	–0.53
8	24.39	0.30	1.22	0.38	27.38	20.89	1.28	–0.78
9	25.40	0.35	1.04	0.33	27.55	22.26	1.19	–0.52
10	25.87	0.27	0.76	0.31	27.25	23.39	1.26	–0.29

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
11	26.07	0.23	1.00	0.33	27.91	22.68	0.91	–0.91
12	25.78	0.24	0.90	0.32	27.51	23.16	1.04	–0.68
13	25.98	0.24	0.80	0.29	27.97	23.77	0.87	–0.58
14	25.83	0.16	0.90	0.34	27.97	22.65	1.24	–0.76
15	25.32	0.17	1.11	0.34	27.36	21.41	1.42	–0.59
16	25.09	0.19	1.22	0.35	27.56	21.27	1.13	–0.88
17	23.97	0.17	1.36	0.38	26.57	19.37	1.17	–1.14
18	23.39	0.13	1.55	0.48	26.98	20.00	1.62	–1.17
19	23.31	0.11	1.18	0.41	25.65	19.72	1.28	–0.88
20	21.75	0.11	1.47	0.48	24.63	16.88	1.51	–0.97
21	21.09	0.17	1.37	0.47	23.70	17.29	1.22	–1.20
22	18.66	0.19	1.31	0.51	22.62	15.35	1.48	–1.31
23	14.45	0.54	1.58	0.52	18.43	10.97	1.79	–0.67

Table C23. Velocity profile data at right side

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	0.44	–0.01	0.31	0.07	1.58	–0.24	0.14	–0.20
2	14.42	–0.15	1.59	0.42	19.86	10.63	0.75	–1.25
3	20.40	–0.58	1.53	0.45	24.34	15.81	0.65	–1.71
4	22.21	–0.63	1.43	0.44	25.70	18.51	0.52	–1.60
5	23.14	–0.74	1.29	0.48	26.06	18.47	0.48	–2.12
6	23.98	–0.76	1.34	0.32	27.33	19.33	0.00	–1.72
7	24.84	–0.85	0.97	0.34	27.06	22.32	0.23	–1.52
8	25.40	–0.89	1.05	0.33	28.41	22.38	0.01	–1.56
9	25.65	–0.87	0.70	0.25	27.09	23.83	–0.22	–1.52
10	25.77	–0.85	0.87	0.31	28.21	23.03	–0.07	–1.74
11	25.82	–0.91	0.95	0.26	27.86	22.54	–0.08	–1.60
12	25.89	–0.88	0.99	0.28	27.96	21.86	–0.12	–1.55
13	25.77	–0.96	0.97	0.31	27.92	22.29	0.39	–1.87
14	25.19	–0.97	1.23	0.30	28.13	22.17	–0.19	–1.70
15	25.27	–0.91	1.14	0.35	27.59	22.23	0.17	–1.87
16	25.00	–0.97	1.08	0.33	27.26	22.09	0.02	–1.73
17	24.45	–0.96	1.12	0.40	26.67	21.50	0.19	–2.14
18	23.16	–0.94	1.42	0.45	26.29	18.84	0.25	–2.08
19	22.70	–1.03	1.45	0.47	25.97	19.04	0.52	–2.21
20	21.63	–0.94	1.62	0.49	24.87	17.84	0.06	–2.03
21	19.90	–1.05	1.66	0.52	24.01	15.31	0.01	–2.45
22	18.17	–1.01	1.62	0.54	22.06	14.47	0.28	–2.41
23	9.23	–1.11	1.56	0.39	13.09	5.34	–0.37	–2.21

Table C24. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	0.85	0.10	0.39	0.07	2.12	–0.13	0.29	–0.06
2	13.55	0.07	1.31	0.44	16.86	10.57	1.01	–1.25
3	18.62	0.07	1.76	0.52	22.61	14.82	1.58	–1.26
4	20.38	0.11	1.78	0.48	23.85	15.80	1.66	–0.92
5	21.40	0.07	1.38	0.44	25.02	18.12	1.29	–1.23
6	23.09	0.12	1.32	0.42	26.41	19.36	1.13	–0.74
7	23.31	0.18	1.26	0.35	25.89	19.10	1.27	–0.84
8	23.78	0.22	1.36	0.36	26.30	20.18	1.28	–1.00
9	24.50	0.19	1.24	0.33	27.11	20.68	1.05	–0.72
10	24.79	0.20	1.31	0.34	27.20	21.74	1.27	–1.06
11	25.01	0.21	0.97	0.29	27.16	22.06	0.99	–0.62
12	25.08	0.18	0.76	0.27	26.64	22.63	0.88	–0.49
13	24.86	0.23	0.93	0.29	27.19	22.16	1.13	–0.52
14	24.88	0.19	0.84	0.30	26.94	22.27	1.10	–0.44
15	24.54	0.19	1.01	0.32	26.92	21.61	1.10	–0.43
16	24.26	0.21	0.99	0.31	26.27	21.28	1.11	–0.43
17	23.88	0.12	1.17	0.33	25.85	19.78	0.91	–0.76
18	23.46	0.14	1.10	0.39	25.77	20.17	1.16	–0.98
19	22.51	0.06	1.22	0.42	25.42	19.91	1.08	–1.67
20	21.13	–0.03	1.43	0.51	24.90	18.18	1.40	–1.39
21	20.14	0.07	1.25	0.49	23.42	17.57	1.48	–1.26
22	17.11	–0.14	1.60	0.46	20.81	12.19	1.11	–1.29
23	3.64	–0.10	1.09	0.33	7.43	1.75	0.95	–0.69

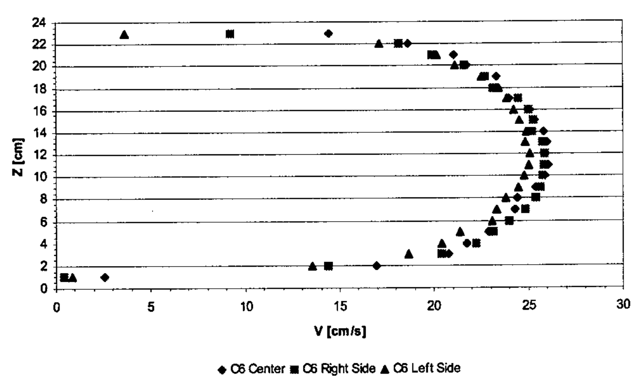


Figure C38. Velocity profiles.

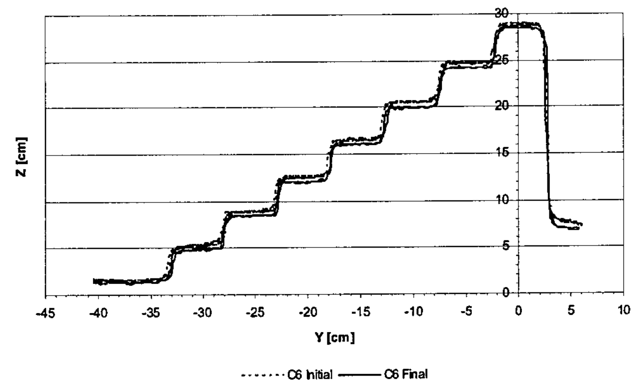


Figure C39. Calibration.

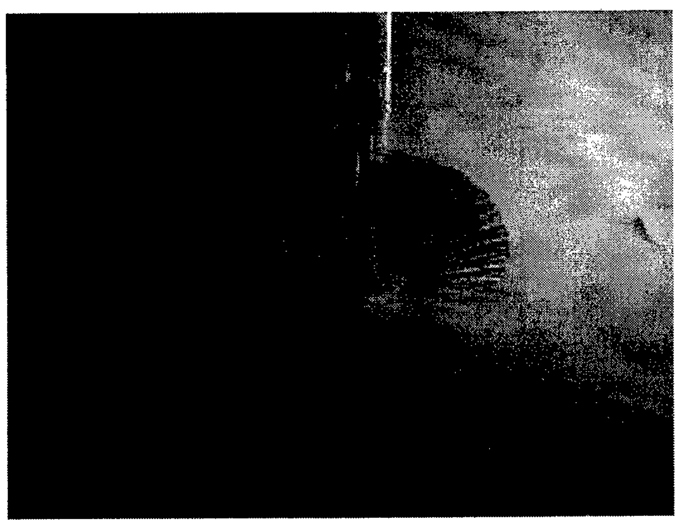


Figure C40. Final photo of scour hole; flow from right to left.

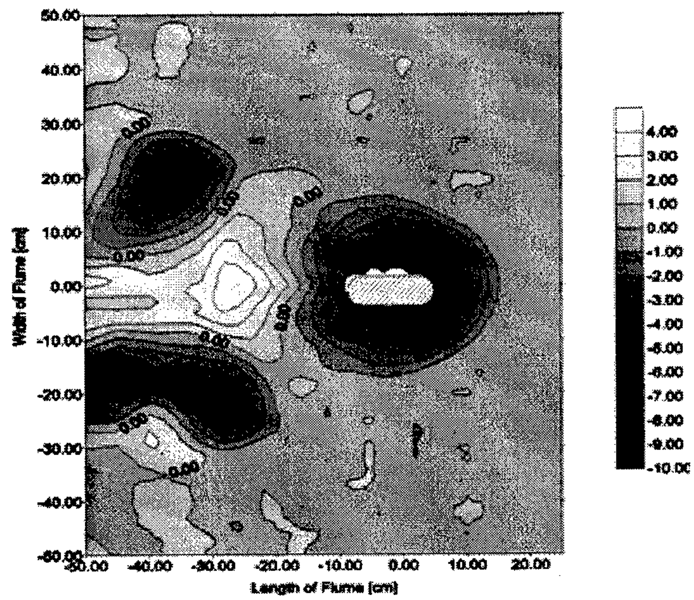


Figure C41. Contour plot; flow from right to left.

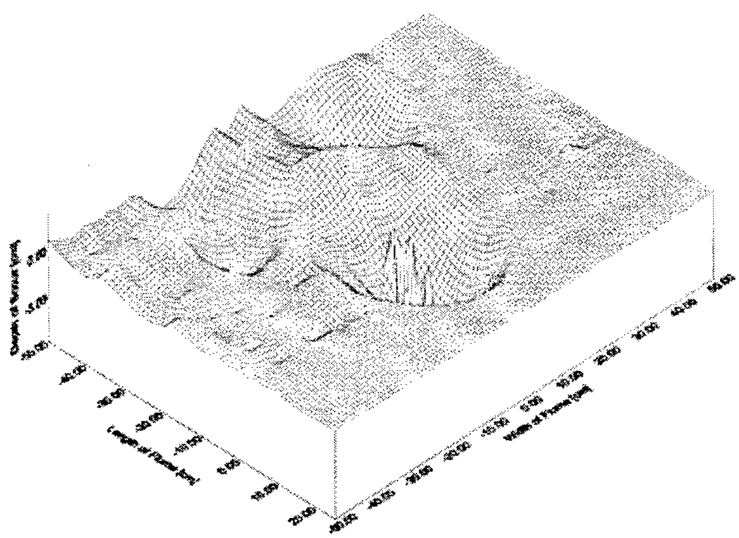


Figure C42. Surface plot; flow is from lower right to upper left.

Test XR1

Table C.25. Scour depth vs. time data.

Initial Reading =	10.0625	In.
Start Time =	15:48	15-Apr-03
End Time =	09:05	16-Apr-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
15:48	10.0625	0:00	0.0000	0.000
15:49	9.7500	0:01	0.3125	0.794
15:51	9.2500	0:03	0.8125	2.064
15:52	9.0000	0:04	1.0625	2.699
15:53	8.7500	0:05	1.3125	3.334
15:55	8.5000	0:07	1.5625	3.969
15:59	8.2500	0:11	1.8125	4.604
16:06	8.0000	0:18	2.0625	5.239
16:34	7.5000	0:46	2.5625	6.509
16:38	7.6250	0:50	2.4375	6.191
16:54	7.5625	1:06	2.5000	6.350
17:03	7.5000	1:15	2.5625	6.509
17:04	7.3750	1:16	2.6875	6.826
17:17	7.5000	1:29	2.5625	6.509
19:20	7.5000	3:32	2.5625	6.509
19:30	7.3750	3:42	2.6875	6.826
19:51	7.3750	4:03	2.6875	6.826
21:33	7.2500	5:45	2.8125	7.144
22:36	7.1250	6:48	2.9375	7.461
23:15	7.2500	7:27	2.8125	7.144
0:58	7.1250	9:10	2.9375	7.461
3:18	7.2500	11:30	2.8125	7.144
4:09	7.1250	12:21	2.9375	7.461
4:28	7.2500	12:40	2.8125	7.144
5:30	7.1250	13:42	2.9375	7.461
6:58	7.2500	15:10	2.8125	7.144
7:43	7.3750	15:55	2.6875	6.826
8:13	7.2500	16:25	2.8125	7.144
8:43	7.2500	16:55	2.8125	7.144
9:05	7.1875	17:17	2.8750	7.303

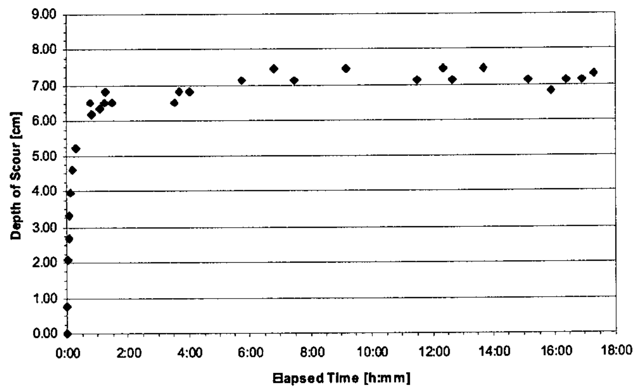


Figure C43. Scour depth vs. time.

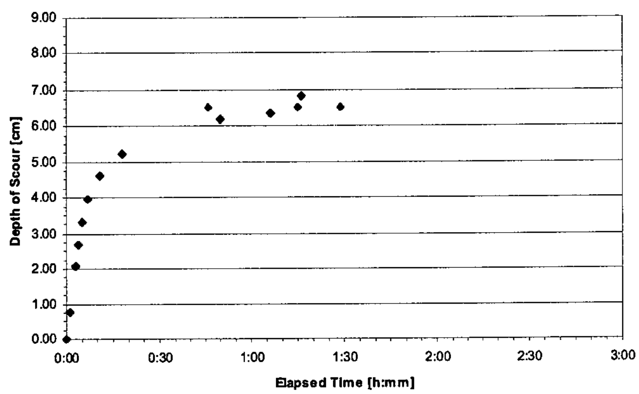


Figure C44. Scour depth vs. time for the first 3 hours.

Table C26. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	9.93	–0.91	2.87	1.26	18.15	3.65	2.13	–4.30
2	25.40	2.80	1.79	0.77	29.95	19.82	5.04	0.71
3	26.85	2.74	1.86	0.73	31.43	21.48	4.68	1.10
4	28.25	2.20	1.91	0.66	32.16	21.96	4.00	0.33
5	29.36	2.00	1.64	0.66	32.45	24.70	3.34	0.37
6	30.31	1.63	1.33	0.51	33.50	26.67	2.73	0.27
7	31.11	1.60	1.43	0.60	34.31	27.37	3.11	0.22
8	31.07	1.43	1.48	0.49	35.13	27.33	3.09	0.28
9	31.06	1.41	1.29	0.45	33.90	27.60	2.57	0.38
10	31.15	1.36	1.48	0.54	34.80	26.29	2.74	0.12

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
11	31.13	1.40	1.38	0.55	33.74	27.21	2.71	0.22
12	30.20	1.18	1.46	0.56	33.19	26.33	2.59	0.01
13	29.57	1.17	1.82	0.69	33.44	23.71	3.52	–0.36
14	28.07	1.06	1.96	0.65	32.99	23.42	3.71	–0.41
15	26.87	1.03	2.21	0.75	31.35	19.94	3.37	–0.78
16	25.61	0.96	2.31	0.93	30.01	18.07	3.45	–2.03
17	23.09	0.70	2.56	0.93	28.16	16.49	3.31	–1.74
18	20.35	0.80	2.79	0.98	26.40	14.35	3.11	–3.17
19	18.11	0.67	2.83	1.19	23.89	11.42	3.25	–2.89
20	15.10	0.48	2.92	1.13	22.55	5.49	2.98	–2.05
21	4.45	0.17	1.42	0.54	8.46	1.18	1.45	–1.52

Table C27. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VxMax	VxMin
1	7.07	1.51	1.35	0.42	10.81	3.32	2.47	0.52
2	17.64	0.42	1.42	0.63	21.86	14.91	1.58	–1.29
3	20.32	0.33	1.55	0.69	24.80	16.47	2.17	–1.37
4	22.74	–0.02	1.62	0.71	26.41	18.89	1.38	–1.63
5	23.88	0.00	1.74	0.70	28.72	19.29	1.64	–1.93
6	25.29	–0.03	1.83	0.66	29.00	20.81	1.72	–1.49
7	26.44	–0.08	1.48	0.59	30.35	22.46	1.43	–1.65
8	27.67	0.03	1.53	0.62	30.70	23.36	1.55	–1.51
9	27.75	–0.07	1.42	0.57	31.26	24.13	1.19	–1.75
10	28.27	–0.05	1.20	0.57	31.24	25.29	1.53	–1.54
11	28.75	–0.01	1.14	0.52	30.95	25.76	1.35	–1.30
12	28.20	0.03	1.33	0.59	31.38	24.31	2.07	–1.68
13	28.02	0.01	1.42	0.61	31.14	23.37	1.55	–1.77
14	27.26	–0.08	1.63	0.62	30.98	22.49	1.43	–2.10
15	26.13	0.00	2.07	0.71	30.79	20.81	2.08	–2.01
16	25.41	–0.05	2.59	0.81	30.64	18.04	2.50	–2.53
17	23.14	–0.05	2.41	0.90	28.59	17.58	1.82	–2.32
18	21.47	–0.03	3.07	0.99	26.79	13.01	2.91	–2.57
19	18.94	0.04	2.88	0.91	26.67	12.58	2.73	–2.11
20	15.85	–0.27	2.79	1.05	21.71	9.10	2.49	–3.55
21	9.76	–0.11	2.10	0.84	15.01	4.78	2.48	–2.34
22	0.17	–0.03	0.36	0.09	0.97	–0.96	0.27	–0.25
23	–0.06	0.00	0.26	0.07	0.55	–0.62	0.17	–0.16

Table C28. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	0.17	0.05	0.22	0.07	0.72	–0.30	0.30	–0.13
2	2.96	0.32	0.84	0.23	5.10	1.00	0.85	–0.20
3	20.81	0.85	1.95	0.88	24.76	16.09	2.73	–1.44
4	23.91	0.85	1.76	0.67	27.53	19.48	2.76	–0.94
5	25.09	0.84	2.05	0.68	29.44	19.17	3.14	–0.77
6	26.78	0.84	1.74	0.61	30.56	21.28	2.52	–0.59
7	27.50	0.92	2.00	0.64	32.11	22.51	2.77	–0.44
8	29.19	1.07	1.59	0.70	32.91	25.05	3.19	–0.76
9	29.99	1.12	1.45	0.57	33.01	25.97	3.66	–0.20
10	30.30	1.13	1.24	0.61	33.10	27.60	2.99	–0.25
11	30.77	1.17	0.98	0.52	33.21	27.55	2.41	–0.13
12	31.08	1.08	1.08	0.51	33.47	28.24	2.43	–0.23
13	30.84	1.09	1.33	0.51	33.64	26.69	2.50	–0.06
14	30.62	1.04	1.49	0.50	33.57	25.33	2.30	–0.16
15	28.98	0.99	1.73	0.69	32.25	23.75	3.19	–1.08
16	28.48	1.03	1.92	0.67	31.87	21.32	2.64	–0.64
17	26.78	0.93	2.07	0.78	30.92	22.07	3.33	–0.93
18	24.88	0.67	2.24	0.95	29.83	18.84	3.37	–1.70
19	22.83	0.77	2.74	0.99	29.56	13.11	4.49	–1.58
20	20.81	0.90	2.71	0.98	28.15	13.56	3.08	–1.40
21	15.78	0.48	2.99	1.06	24.00	9.88	3.10	–1.78
22	10.28	0.32	2.31	0.84	15.20	4.39	3.77	–1.85
23	0.06	0.00	0.31	0.08	0.95	–0.72	0.21	–0.21
24	–0.01	0.01	0.59	0.17	1.52	–1.96	0.37	–0.62

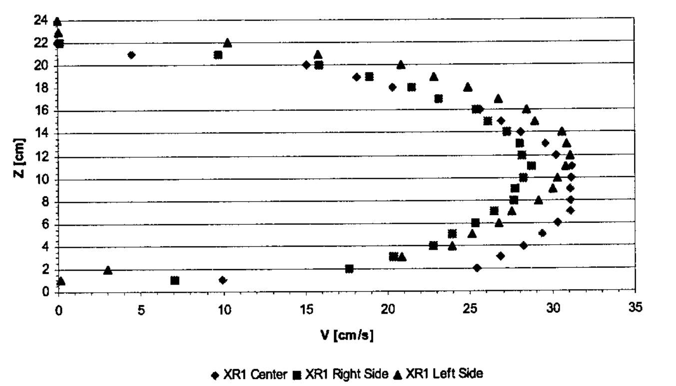


Figure C45. Velocity profiles.

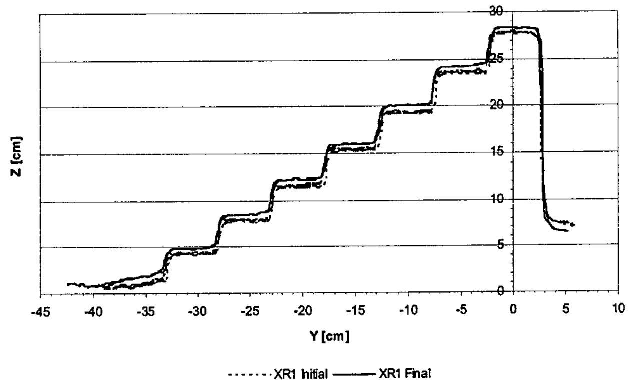


Figure C46. Calibration.

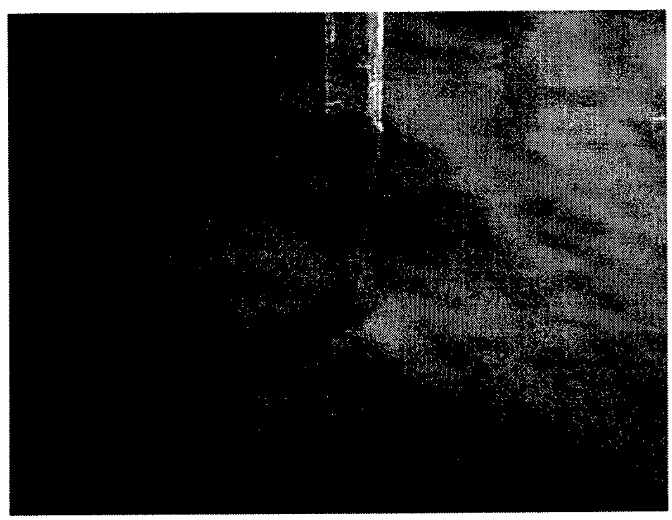


Figure C47. Final photo of scour hole; flow from right to left.

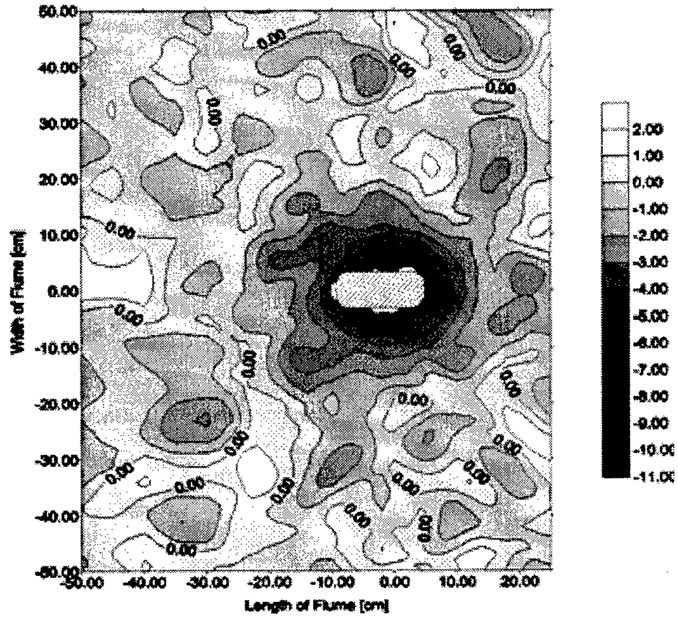


Figure C48. Contour plot; flow from right to left.

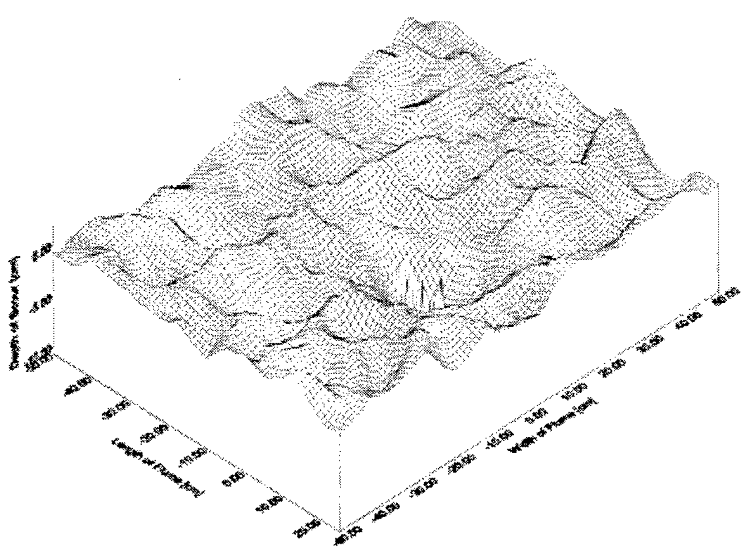


Figure C49. Surface plot; flow is from lower right to upper left.

Test XR2

Table C29. Scour depth vs. time data.

Initial Reading =	10.1875	In.
Start Time =	16:46	16-Apr-03
End Time =	08:52	17-Apr-03

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
16:46	10.1875	0:00	0.0000	0.000
16:47	9.8750	0:01	0.3125	0.794
16:48	9.7500	0:02	0.4375	1.111
16:49	9.5000	0:03	0.6875	1.746
16:51	9.1250	0:05	1.0625	2.699
16:52	9.0000	0:06	1.1875	3.016
16:53	8.8750	0:07	1.3125	3.334
16:54	8.7500	0:08	1.4375	3.651
16:58	8.5000	0:12	1.6875	4.286
17:03	8.2500	0:17	1.9375	4.921
17:08	8.1250	0:22	2.0625	5.239
17:13	8.0000	0:27	2.1875	5.556
17:22	7.8750	0:36	2.3125	5.874
17:30	7.7500	0:44	2.4375	6.191
17:34	7.6250	0:48	2.5625	6.509
17:45	7.7500	0:59	2.4375	6.191
17:54	7.6250	1:08	2.5625	6.509
18:07	7.5000	1:21	2.6875	6.826
18:17	7.3750	1:31	2.8125	7.144
18:52	7.5000	2:06	2.6875	6.826
19:31	7.3750	2:45	2.8125	7.144
19:44	7.3750	2:58	2.8125	7.144
20:25	7.2500	3:39	2.9375	7.461
20:41	7.2500	3:55	2.9375	7.461
23:34	7.3750	6:48	2.8125	7.144
0:58	7.5000	8:12	2.6875	6.826
1:12	7.3750	8:26	2.8125	7.144
2:54	7.5000	10:08	2.6875	6.826
6:10	7.3750	13:24	2.8125	7.144
6:21	7.2500	13:35	2.9375	7.461
6:38	7.1250	13:52	3.0625	7.779
6:59	7.2500	14:13	2.9375	7.461
8:20	7.1250	15:34	3.0625	7.779

Time	Reading [in.]	Elapsed time [h:m]	Scour depth [in.]	Scour depth [cm]
8:42	7.0625	15:56	3.1250	7.938
8:44	7.0000	15:58	3.1875	8.096
8:52	6.8750	16:06	3.3125	8.414

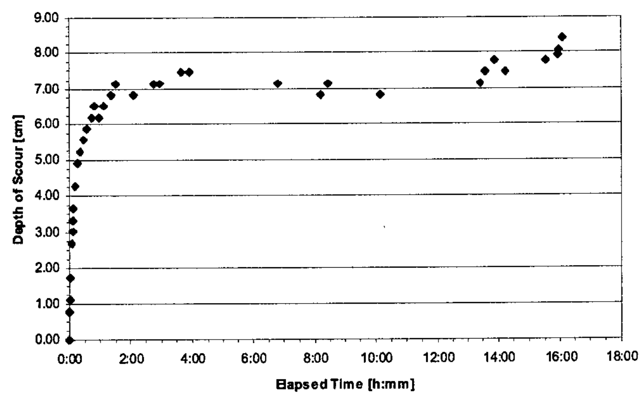


Figure C50. Scour depth vs. time.

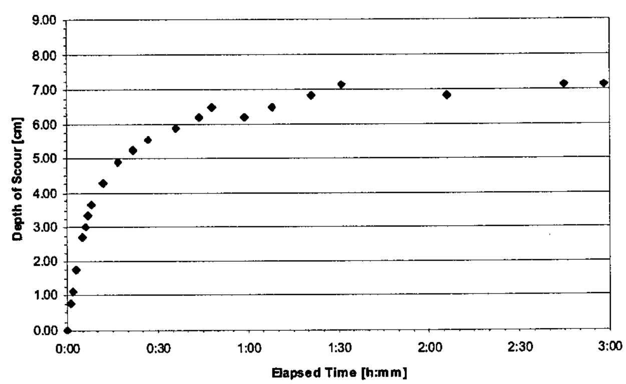


Figure C51. Scour depth vs. time for the first 3 hours.

Table C30. Velocity profile data at center.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	6.36	2.20	1.52	0.95	9.49	2.38	4.32	0.14
2	13.16	1.14	2.05	0.96	18.36	8.15	3.90	–1.07
3	22.45	0.82	1.66	0.62	26.45	16.14	2.31	–0.48

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
4	26.60	0.93	1.16	0.56	29.43	23.52	2.56	–0.41
5	28.52	0.89	1.15	0.47	31.05	25.17	2.02	–0.25
6	29.23	0.88	1.01	0.48	31.37	26.61	2.25	–0.67
7	29.73	0.87	0.92	0.43	31.61	26.79	1.81	–0.08
8	29.94	0.81	1.14	0.47	32.71	26.49	1.97	–0.35
9	29.60	0.92	1.45	0.46	32.58	25.87	2.39	–0.27
10	29.23	0.94	1.47	0.56	32.28	24.79	2.27	–0.34
11	29.35	0.79	1.47	0.55	32.40	25.33	2.31	–0.44
12	28.02	0.72	2.03	0.66	32.12	22.78	2.39	–0.70
13	26.69	0.66	2.30	0.78	30.90	20.41	2.81	–1.85
14	26.27	0.55	2.05	0.78	30.67	19.59	2.24	–1.39
15	25.22	0.60	2.69	0.86	30.09	19.04	2.48	–2.12
16	23.62	0.43	2.71	0.97	28.52	16.20	2.82	–2.15
17	21.60	0.38	2.82	1.00	27.58	13.64	2.65	–2.03
18	19.91	0.42	3.07	1.05	27.42	12.63	3.63	–2.87
19	18.02	0.58	3.33	1.23	25.68	10.05	4.39	–2.75
20	15.02	0.37	2.63	1.01	21.32	8.48	3.22	–2.54
21	11.54	0.34	2.69	1.02	17.92	4.71	3.36	–2.20
22	5.32	0.19	1.58	0.64	9.46	1.26	1.90	–1.26
23	0.02	0.01	0.33	0.08	0.85	–1.04	0.30	–0.23

Table C31. Velocity profile data at right side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	2.03	0.29	0.67	0.15	3.74	0.66	0.89	0.01
2	14.94	–0.08	2.21	0.55	19.67	8.96	1.18	–1.36
3	26.16	–0.91	1.29	0.53	28.69	21.21	0.54	–2.10
4	27.82	–1.01	1.21	0.45	30.87	24.57	0.07	–2.37
5	28.78	–1.12	1.08	0.52	30.97	25.32	0.11	–2.63
6	29.34	–1.05	1.10	0.50	31.59	24.97	0.80	–2.96
7	29.06	–1.15	1.36	0.56	32.20	25.05	0.11	–2.72
8	29.73	–1.27	1.07	0.52	31.62	26.55	0.09	–2.42
9	29.55	–1.26	1.32	0.51	32.49	25.25	0.00	–2.99
10	28.46	–1.23	1.66	0.61	31.61	23.69	0.23	–3.50
11	27.61	–1.24	2.38	0.72	31.31	20.56	0.38	–2.77
12	26.47	–1.17	2.36	0.82	30.95	19.46	0.93	–2.72
13	25.92	–1.26	2.73	0.86	31.16	18.39	1.66	–4.49
14	25.85	–1.21	2.36	0.91	31.32	20.03	2.39	–3.57
15	24.72	–1.11	2.60	0.80	30.63	15.69	0.99	–3.12
16	22.37	–1.11	3.18	1.03	29.47	14.39	1.38	–3.19
17	20.32	–1.10	2.87	1.13	27.58	12.42	1.46	–4.56
18	19.71	–1.11	3.12	1.12	27.81	12.71	2.11	–3.65

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
19	16.33	–0.61	3.18	1.28	24.19	8.85	2.82	–3.67
20	14.25	–0.87	2.83	1.31	21.84	8.74	2.88	–4.17
21	8.20	–0.49	2.43	0.94	15.40	3.87	1.56	–3.57
22	0.52	0.00	0.46	0.13	1.57	–0.71	0.34	–0.30
23	0.05	0.00	0.24	0.07	0.64	–0.57	0.14	–0.25

Table C32. Velocity profile data at left side.

Z-Elevation	VxMean	VyMean	VxSD	VySD	VxMax	VxMin	VyMax	VyMin
1	0.66	–2.47	2.38	0.98	8.85	–5.11	–0.79	–5.41
2	16.70	0.68	1.95	1.06	21.78	10.40	3.05	–1.91
3	21.91	1.71	2.09	0.89	28.23	16.01	3.89	–0.51
4	25.99	0.53	1.44	0.56	28.91	21.87	1.90	–0.74
5	27.12	0.06	1.17	0.55	29.53	24.35	1.22	–1.35
6	27.68	–0.22	1.15	0.50	30.34	25.33	0.94	–1.53
7	28.24	–0.44	1.04	0.48	31.04	25.33	0.70	–1.54
8	28.35	–0.67	1.08	0.47	30.16	25.87	0.21	–2.09
9	28.11	–0.80	1.29	0.59	31.53	22.89	0.87	–2.41
10	27.55	–0.85	1.39	0.59	30.76	22.56	0.88	–2.71
11	26.97	–0.99	1.52	0.53	30.38	22.38	1.11	–2.17
12	26.25	–0.90	1.89	0.70	30.29	22.21	0.78	–2.80
13	25.86	–0.97	1.88	0.67	29.78	20.32	0.75	–3.39
14	25.17	–1.01	2.27	0.75	29.74	17.40	0.89	–3.14
15	23.79	–1.06	2.14	0.71	28.95	17.52	0.59	–3.38
16	22.62	–0.92	2.02	0.87	27.04	17.19	0.95	–3.45
17	20.71	–0.86	2.44	0.93	27.51	14.22	0.96	–2.92
18	18.81	–0.74	2.97	1.04	25.97	11.83	2.08	–3.06
19	17.12	–0.88	2.64	1.07	22.25	9.47	1.82	–3.78
20	13.33	–0.73	2.62	1.21	20.81	6.09	2.50	–3.88
21	4.79	–0.18	1.55	0.54	8.82	1.36	1.21	–1.58
22	0.35	–0.04	0.59	0.13	2.14	–0.50	0.46	–0.60
23	0.04	–0.01	0.43	0.10	1.34	–1.44	0.22	–0.28

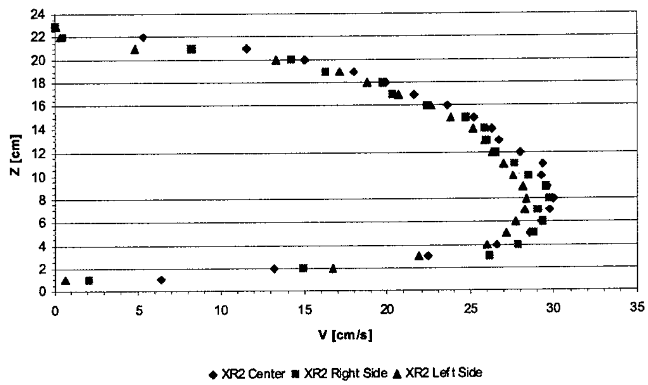


Figure C52. Velocity profiles.

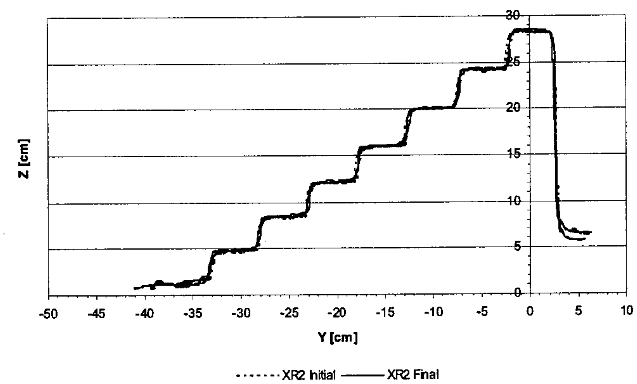


Figure C53. Calibration.

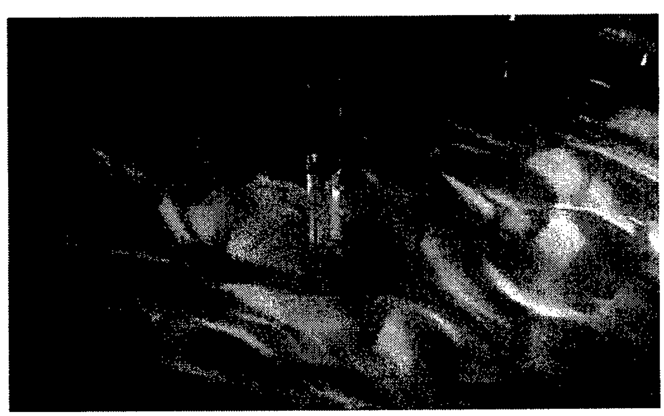


Figure C54. Final photo of scour hole; flow from right to left.

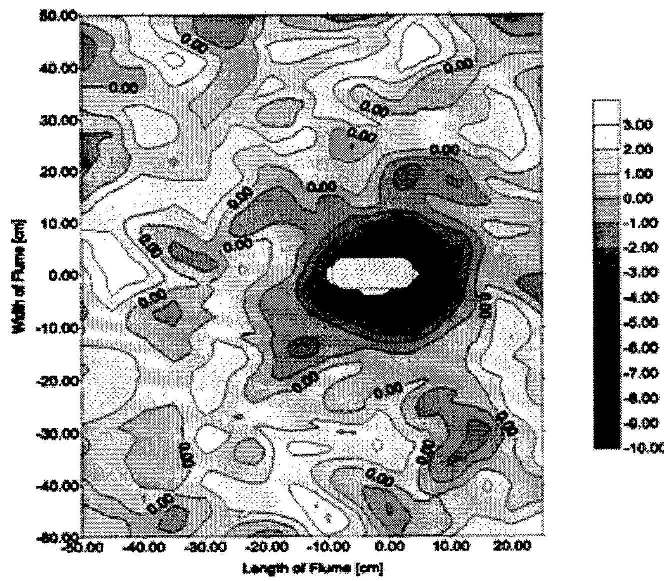


Figure C55. Contour plot; flow from right to left.

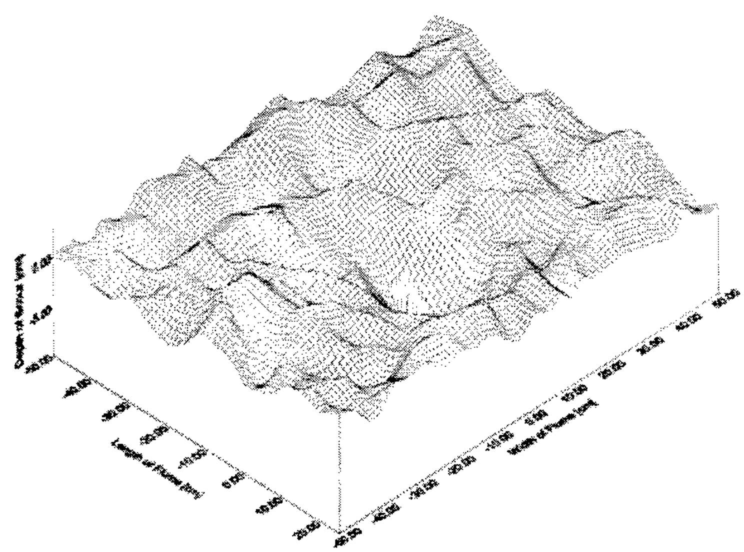


Figure C56. Surface plot; flow is from lower right to upper left.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
April 2004	Technical Report	

4. TITLE AND SUBTITLE

Laboratory Test of Scour Under Ice:
Data and Preliminary Results

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Decker Hains and Leonard Zabilansky

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S Army Engineer Research and Development Center
Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CRREL TR-04-9

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited. Available from NTIS, Springfield, Virginia 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT

An ice cover may be a major factor determining how alluvial channel morphology evolves in rivers, and a significant influence on bridge pier scour. This was confirmed with real-time monitoring of the bed elevation and extensive bathometry measurements made in the Mississippi River, the Missouri River, and the White River in Vermont. In all cases, the sediment process was significantly different from what existing sediment equations would predict. This laboratory study examined the sensitivity of various parameters affecting sediment transport under ice. Twenty tests were conducted in CRREL's refrigerated flume using mean flow velocities in the clear-water scour range. Three surface conditions were modeled: open water, a floating cover, and a fixed cover, simulating ice frozen to the river banks and a bridge pier, with a superimposed hydrostatic head that could be created by an upstream ice jam. The ice cover was simulated using Styrofoam with both smooth and rough surfaces. Under clear-water scour, the equilibrium scour depths for the fixed and floating covers were similar, but up to 21% higher than those found for open water. The cover roughness altered the velocity distribution and caused live-bed scour even when the mean flow velocity was 0.86 times the critical velocity for bed movement. When the average velocity was 0.93 times critical velocity, the pressure flow caused live-bed scour. A combination of increased cover roughness and pressure flow resulted in the largest equilibrium scour depth.

15. SUBJECT TERMS

Ice
Scour
Bridge scour
Hydraulic instrumentation
Sediment transport

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
U	U	U	U	180	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18