Coastal and Hydraulics Laboratory

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Navigation Systems Research Program

Detection and Evaluation of Scour Protection for Navigation Dams

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Final report

Abstract: Scour occurs in the vicinity of essentially every navigation dam constructed. Scour in this report refers to the displacement of natural or engineered materials by flowing water in the vicinity of a navigation project. The severity of the scour depends on many operational and site conditions. To maintain the functional performance of the project, detection and evaluation of the scour and repair or replacement of the scour protection near these locks and dams are necessary. If severe scour exists, rehabilitation of the dam and appurtenant structures may be needed to maintain the structural integrity of the dam. Periodic inspections using hydrographic surveys and divers have typically been used to assess the condition of the need for repair. These methods do not always provide enough information to adequately assess the extent of scour and the repair and/or rehabilitation requirements. This report describes other methods to assess the condition of the existing scour protection and provides examples of reliability analyses that can be used for risk-based decision making.

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Preface

The investigation reported herein was authorized by the Headquarters, U.S. Army Corps of Engineers, and was performed during the period September 2004 to June 2007 under the Navigation Systems Research Program. Research Work Unit 31117C, Detection and Evaluation of Scour Protection for Navigation Dams, is part of the Hydrodynamics Work Area of the Inland Navigation Focus Area for the research program. The Program Manager for the Navigation Systems Research Program is James Clausner, Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC). Dr. John E. Hite, Jr., Leader, Locks Group, CHL, is the technical lead for the Inland Navigation Focus Area. Jeff Lillycrop is the ERDC Technical Director for Navigation. The research was conducted by CHL personnel, under the general supervision of Thomas Richardson, Director, CHL; William Martin, Deputy Director, CHL; Dr. Rose Kress, Chief, Navigation Division; and Dennis Webb, Chief, Navigation Branch, CHL. James Evans of the Information Technology Laboratory, ERDC, is the technical lead for the field demonstration of the acoustical camera. Dr. Hite led the experimental program and wrote this report.

COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meter
inches	0.0254	meters
knots	0.5144444	meters per second
miles (U.S. statute)	1,609.347	meters
pounds (mass)	0.45359237	kilograms
tons (force)	8,896.443	newtons
tons (2,000 pounds, mass)	907.1847	kilograms

1   Introduction

Problem statement

Scour has occurred upstream and downstream from essentially every navigation dam constructed. The severity of the scour varies greatly from project to project. Detection and evaluation of the extent of scour near these dams are necessary in order to assess repair or replacement requirements for the scour protection. If severe scour exists, rehabilitation of the dam and appurtenant structures may be needed to maintain the structural integrity of the dam. In the past, periodic inspections have been used to assess the need for repair. Often, these inspections do not provide enough information to adequately assess the extent of scour and the repair and/or rehabilitation requirements. A method to assess the condition of the existing scour protection that could be used with a risk-based analysis of the life cycle performance for the scour protection would provide valuable data for cost-effective project operation and maintenance requirements.

District input

Corps Districts were contacted to determine what issues related to scour at navigation dams were important to them. The following were concerns expressed by the U.S. Army Engineer District, St. Paul (referred to as St. Paul District hereafter):

- When will the scour actually threaten the structure?
- When or if the scour will increase enough to be a problem?
- Will the scour be worse during floods or "unusual" gate operations than when measured after the event has passed and conditions have returned to normal?

Often large scour downstream of the riprap is observed but is not considered a problem as long as the riprap has not been displaced.

Items of interest were the availability of techniques to identify riprap blanket thickness and methods that allow a real-time view of underwater rock placement. In a discussion of conditions that cause scour, it was revealed that a log jam on the upstream side of Lock and Dam No. 2 on the

Mississippi caused concentrated flows below the dam, resulting in some loss of rock used for scour protection.

A summary of the scour-related issues were identified by Corps Districts.

1. What is the horizontal position from hydrographic survey soundings?
2. Because diver reports are not always adequate to assess extent of scour, especially underneath structures, what techniques are needed?
3. When does scour start to threaten the structural integrity of the project?
4. Can excessive scour occur in one event and can maintenance be delayed to avoid costs?
5. Does rock sink or get blown away?
6. Does missing rock have to be replaced?
7. What techniques are needed to identify blanket thickness?
8. What techniques are needed to observe real-time placement of riprap?
9. Do small repairs on a frequent basis result in significant life cycle savings or not?

Objective

The objectives of this research are to (1) identify effective method(s) for determining the condition of the existing scour protection, and (2) develop a risk-based decision process to assist in developing the type and the timing of the repair and/or rehabilitation requirements needed to ensure project performance. The process will be presented in a manner that can be used by personnel responsible for project planning.

Work description

The research was divided into the following tasks to accomplish the desired objectives. Task 1 consists of performing research to identify the most effective method for assessing the condition of the existing scour protection. Field offices were contacted concerning existing techniques used to identify scour, the primary difficulties currently experienced, and what suggestions might possibly improve the current techniques. A high-resolution acoustical imaging system and a multibeam echosounder were considered for the demonstration. The two primary objectives of the demonstration were to determine if the equipment is capable of (1) identifying a scoured area underneath a structural component of the dam or lock such as the stilling basin or approach wall to define the width and depth of scour, and (2) mapping the scour protection material to a level of accuracy

that will enable changes to be identified from one inspection to the next. Task 2 is a demonstration project that will be performed to test the method(s) identified in Task 1.

Task 3 consists of establishing engineering parameters to describe the scour protection and hydraulic conditions. Examples of these parameters are size, thickness, average velocity of flow over dam end sill or apron, discharge, and stability coefficient. These parameters are used to develop equations to predict scour protection performance that will be needed in the risk-based analysis.

2   Causes of Scour

Scour at navigation projects is generally associated with displacement of the stone protection. Failure of a riprap blanket adjacent to a hydraulic structure can be caused by several factors. Failure is generally considered to be displacement of sufficient riprap to jeopardize the structural integrity of the hydraulic structure the riprap is intended to protect. Some of the more common examples of displacement are shown in Figure 1.

HYDRAULIC STRUCTURE

A.   ORIGINAL PLACEMENT

B.   DISPLACEMENT FROM SCOUR AT THE TOE

C.   DISPLACEMENT FROM FLOW

D.   DISPLACEMENT DUE TO SINKING OF RIPRAP

E.   DISPLACEMENT CAUSED BY NAVIGATION ACCIDENT
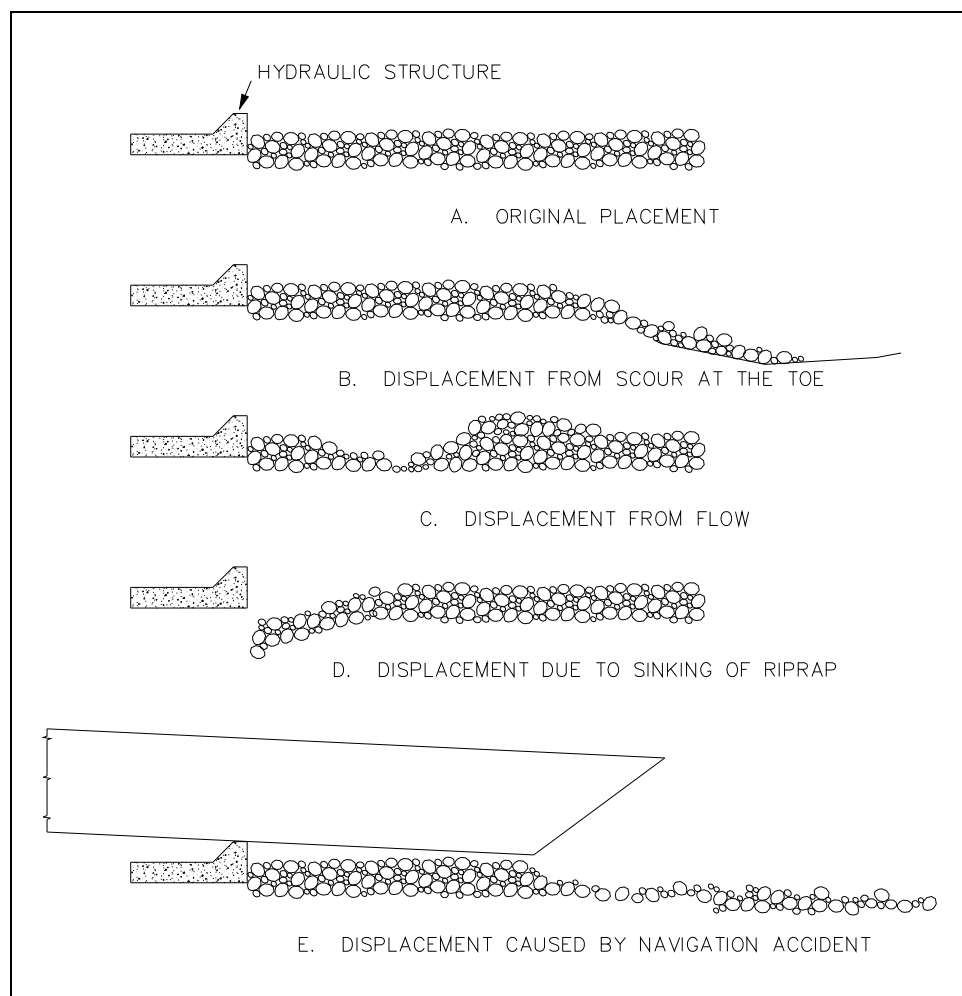
Figure 1. Examples of scour.

Scour at the toe

Wherever a riprap blanket is terminated, scour should be expected to occur. The method suggested by Corps guidance (Headquarters, U.S. Army Corps of Engineers (HQUSACE), 1987) to minimize scour at the

termination is to gradually reduce the size of the riprap blanket in the direction of the flow. This provides a transition in size from the larger riprap to the natural material. It is generally not practical or economical to provide a transition length where no scour will occur.

Scour at the termination of the riprap blanket does not always result in failure. If additional riprap is initially placed in this area, the toe can become stable in time as the riprap armors the upstream slope of the scour hole. Continual scour at the toe will result in displacement of the entire blanket and the protection to the structure will be lost.

Scour at the toe typically occurs over time and is due to the flow conditions that result from normal operations. Some normal operations such as ice and debris passage can cause the scour to be worse below the gate bays where this operation takes place. Extreme flow events such as a gate malfunction or a navigation accident can cause rapid scour at the termination of the riprap blanket. Recommended guidance for repairing scoured areas at the termination of the riprap blanket is available in Corps publications (Hite 1988a, 1988b). As a general rule, a 1 vertical and 3 horizontal downward slope at the termination is preferred.

Displacement from flow

Failure of the riprap blanket caused by displacement from flow usually occurs from inadequate riprap size. A sufficient size is required to resist the forces caused by the flowing water. The difficulty encountered in determining the appropriate riprap size results from the uncertainty in quantifying the flow parameters required for the computations. The design flow condition for riprap stability is not always clear. Figure 2 shows the scoured area downstream from the stilling basin for a project located on the Illinois Waterway that has occurred after years of operation.

In many of the older navigation projects, the riprap was designed to remain stable for the normal operating conditions. Experience has shown that these conditions are violated at times to pass ice or debris or as a result of a navigation accident. Newer guidance suggests that riprap adjacent to a low-head navigation structure should not fail as a result of the flow conditions that occur from a single gate fully open with minimum project tailwater conditions. Some damage is acceptable; however, the integrity of the structure must not be jeopardized.

Figure 2. Scour below stilling basin at navigation dam on Illinois Waterway.

Empirical relationships between flow velocity and riprap size are available in Corps guidance (HQUSACE 1987). The Ishbash equation is typically used in turbulent flow areas downstream from stilling basins. The relationship is

$$V = C \left[2g \left(\frac{\gamma_s - \gamma_w}{\gamma_w} \right) \right]^{\frac{1}{2}} D_{50\,min}^{\frac{1}{2}} \qquad (1)$$

where:

V = velocity in ft/sec
C = stone stability coefficient
g = acceleration caused by gravity
γ_s = specific weight of stone
γ_w = specific weight of water
D_{50} = stone diameter, ft, of which 50 percent is finer by weight.

For highly turbulent flow areas such as those adjacent to and downstream from stilling basins, the velocity is the average velocity computed for flow in the stilling basin and C is 0.86. The energy dissipation of the stilling basin also affects the stability of the riprap blanket. Additional research has shown that the value of C varies depending on the stilling basin design. Stilling basin designs developed from the guidance presented in EM 1110-2-1605, "Hydraulic Design of Navigation Dams" (HQUSACE 1987) suggest C is 1.12. Stilling basins designed from EM 1110-2-1605 provide good energy dissipation, which allows the riprap size to be reduced.

Previous research has shown that the following equation is more dimensionally consistent:

$$\frac{D_{50}}{D'} = C \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{\frac{1}{2}} F_{es} \right]^b \tag{2}$$

where:

D' = depth of flow over the end sill
C and b = coefficients determined from laboratory experiments
F_{es} = Froude number over end sill.

The value of C and b were determined from physical model experiments for a basin designed according to EM 1110-2-1605 for three different riprap configurations. The stability of the riprap was also evaluated for a basin designed according to EM 1110-2-1605 without baffle blocks to assist in the energy dissipation. The values of C varied between 1.3 and 1.5 and the values of b varied between 0.15 and 0.40 depending on the riprap configuration and the basin design (Hite 1988a). These equations are helpful in the initial design of the riprap protection once the design flow conditions are established.

Sinking of riprap

Movement of the filter material adjacent to a structure can cause riprap to sink. The filter material may be piped through the voids in the riprap blanket by high-velocity flow or can move through seepage. If the riprap begins to settle or sink, it may appear as if it is gone, while in fact it could still be providing protection. This problem is more noticeable where the

structure and riprap are in contact. This is generally where the velocity of the flow is the highest. Because the sunken riprap may become covered with natural material, it is difficult to determine if the riprap has sunk or has been displaced by the flow. The problem that can result from riprap movement caused by sinking would be if the riprap sinks below the bottom of the structure and then the natural material is washed away from a flow event. There would be no support under the structure and cracking or failure of the concrete structure might occur.

Navigation accident

Riprap displacement from a navigation accident can be rapid and severe. The probability of failure can be high if the vessel or barges impact the riprap protection or sink and rest on the protection. Several accidents have occurred where both loaded and unloaded barges have impacted the navigation dam with the barges either passing through the structure or becoming lodged against the structure. Several situations can result from a barge accident. The gates can be damaged and normal operations are not possible. If the head becomes greater than normal and the tailwater drops below normal from insufficient discharge through the gates, scour can occur. Barges that have sunk and lodged against the upstream side of the dam can concentrate flow and cause extreme scour locally, as illustrated in Figures 3 and 4. The accident shown in Figure 3 caused significant scour both upstream and downstream from the dam. Following the accident, a secondary stilling basin was constructed from sunken barges filled with riprap and grout to prevent loss of the dam should an accident similar to this one occur again. The accident shown in Figure 4 resulted in loss of the navigation pool, with significant economic impacts.

Propeller wash

Tows entering and exiting the upper and lower approaches to locks often have to use additional horsepower to maneuver the tow and align with the guide or guard walls. Scour can result from concentrated flow generated by the propeller, especially near the lock walls. If these areas are known, additional riprap should be used to protect from propeller wash. Guidance for rock stability can be found in Maynord (1998).
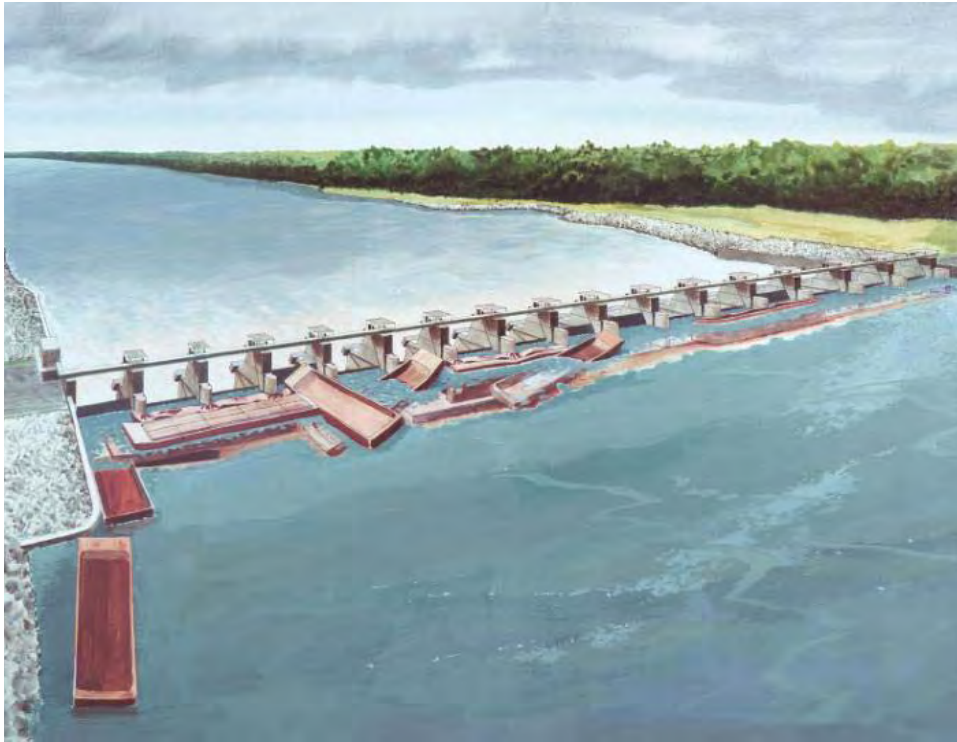
Figure 3. Artist's rendition of barge accident at the Wilbur Mills Dam, Arkansas River.

Figure 4. Barge accident at Belleville Dam, Ohio River.

3   Methods to Identify Scour

Hydrographic surveys

Personnel from the St. Paul District and the U.S. Army Engineer Research and Development Center (ERDC) met on 22 July 2003 to discuss current techniques used by St. Paul District to identify scour below navigation dams. St. Paul District uses one of their area office survey crews to perform hydrographic surveys using echosounders or multi-beam sonars of the area below the dam. These data are then used to develop cross sections and contour maps to identify areas of concern. The accumulation of these data for the river projects is referred to as the sounding program, and the reduced data and documentation are available in sounding reports. The surveys are generally performed every 1–2 years or during or immediately following events that could cause scour.

A problem encountered with the hydrographic surveys is the uncertainty of the horizontal location. If the horizontal location is not identified, then the depth data is questionable. The cross-section plots (especially the streamwise plots) often indicate deposition or erosion within the stilling basin. This data becomes suspect and appears that it should be shifted upstream or downstream sometimes 10 to 20 ft.[1] A 20-ft shift horizontally can be a dramatic vertical change greatly reducing the confidence level of the vertical location of the scour protection. Figures 5 and 6 show typical examples of scour profiles measured in the streamwise direction at Lock and Dam No. 2 on the Mississippi River. In Figure 6, the profiles show that significant scour has occurred between 30 and 60 ft downstream from the structure between 2001 and 2003. The riprap appears to have been scoured and deposited on the downslope between 80 and 110 ft downstream from the structure. This type of scoured area would need to be repaired to prevent additional scouring that would threaten the structure.

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[1] A table of factors for converting non-SI units of measure to metric (SI) units is found on page viii.
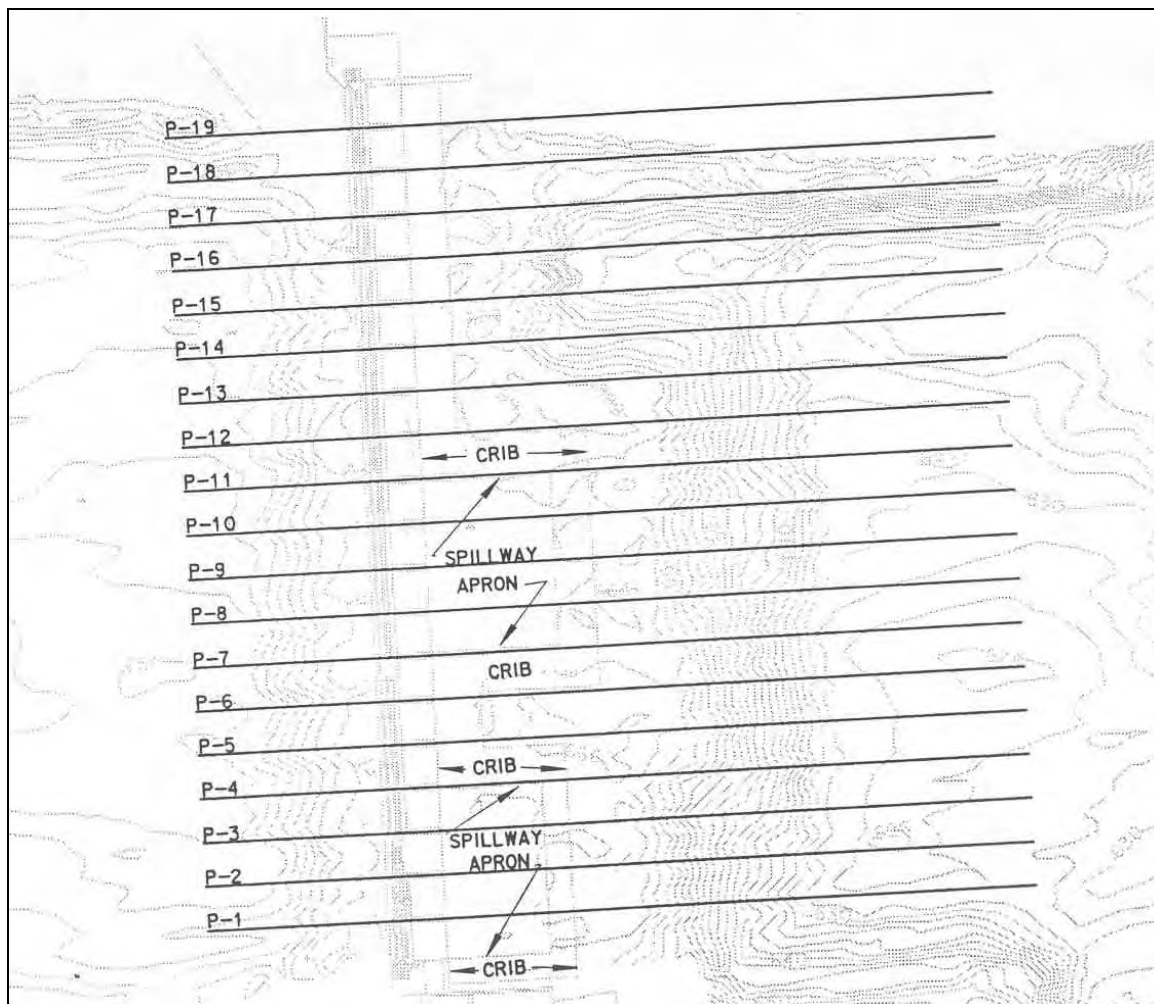
Figure 5. Example of sounding profiles taken at Lock and Dam No. 2, Mississippi River, flow is from left to right.

Diver reports

Diver inspections are used at some projects to identify scoured areas. Difficulties are often experienced from lack of visibility and knowing the precise location of the diver. Descriptions of voids underneath the stilling basin or lock walls or sills are hard to quantify, especially adjacent to large structures. Discussions with the Bureau of Reclamation personnel revealed they use a tag line to try and identify the location and extent of scour. The tag line is marked at specified intervals so the diver can report to surface personnel the intervals where scour is located, and where the line is; or record it himself. This type problem demonstrates the need for further investigation, possibly using other types of sonar equipment or an underwater camera to better assess the problem.
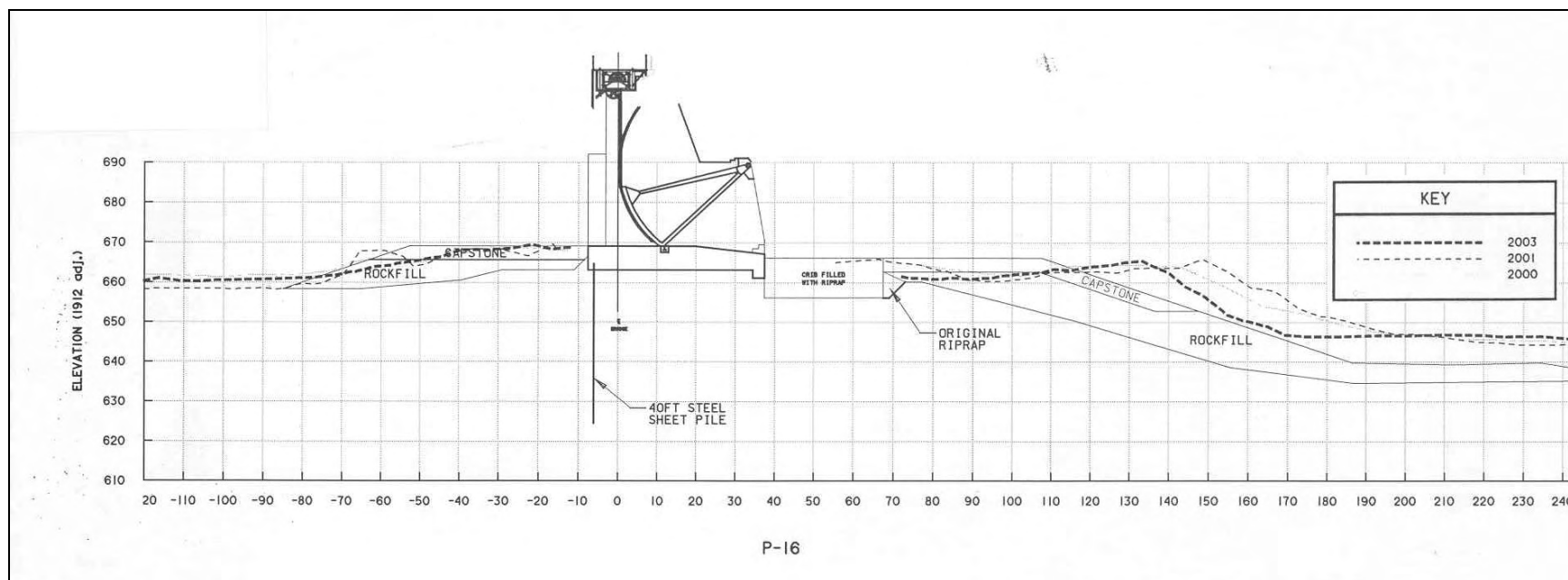
Figure 6. Example of streamwise longitudinal profile sounding data (P-16) for Dam 2 on the Mississippi River (positive distances are downstream from axis of dam)

Multi-beam sonar

Multi-beam sonar has been used to identify scour near navigation structures. In the spring of 2007, a survey boat equipped with multi-beam sonar working at Mel Price Locks and Dam on the Mississippi River recorded the images shown in Figures 7 and 8. Figure 7 shows both the upstream and downstream portions of the project. Scoured areas can be seen downstream from gate bays 2 and 4 (numbered from right to left) and upstream in front of most piers and the entire gate bay between piers 5 and 6. Figure 8 shows a close-up of the sonar image upstream from gate bay 4. The areas in front of the dam had scoured over 20 ft from the original stone placement. The scour upstream from the dam was not anticipated, and repairs will be needed to prevent further scour in this area. The depths determined from the multi-beam sonar images were verified using a boat and line sounding (Figure 9). These multi-beam images and subsequent verification demonstrate that the multi-beam sonar system can be used to determine scoured areas at navigation projects.

Acoustical camera

A Dual-frequency IDentification SONar (DIDSON) acoustical imaging system has also been used recently to help identify scour at navigation dams. The use of this method will be discussed in more detail in Chapter 6.
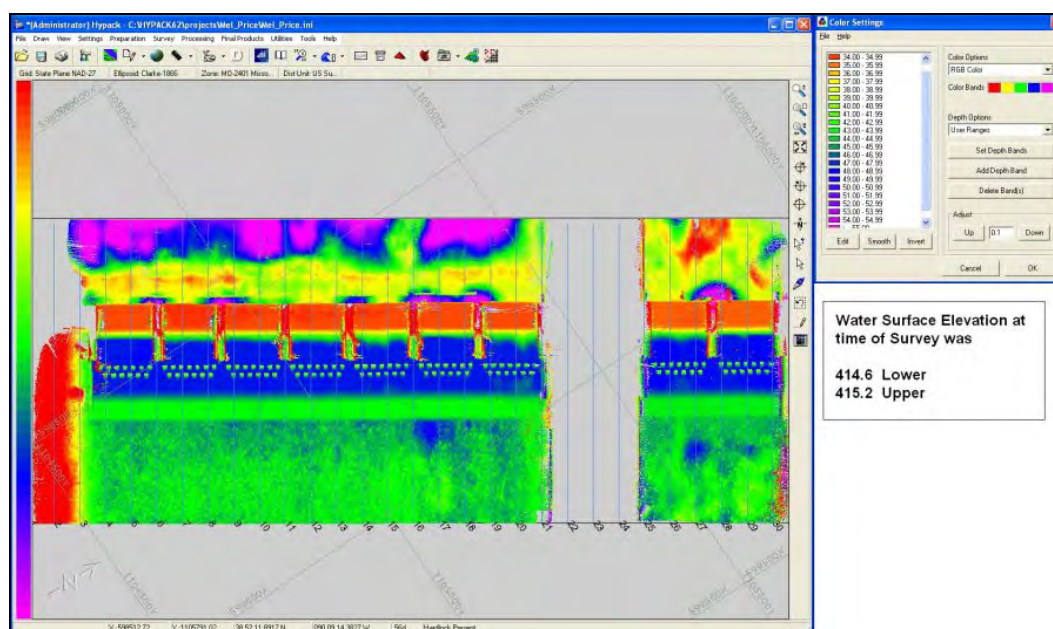
Figure 7. View of areas upstream and downstream from Mel Price Dam from multi-beam sonar (flow is from top to bottom).
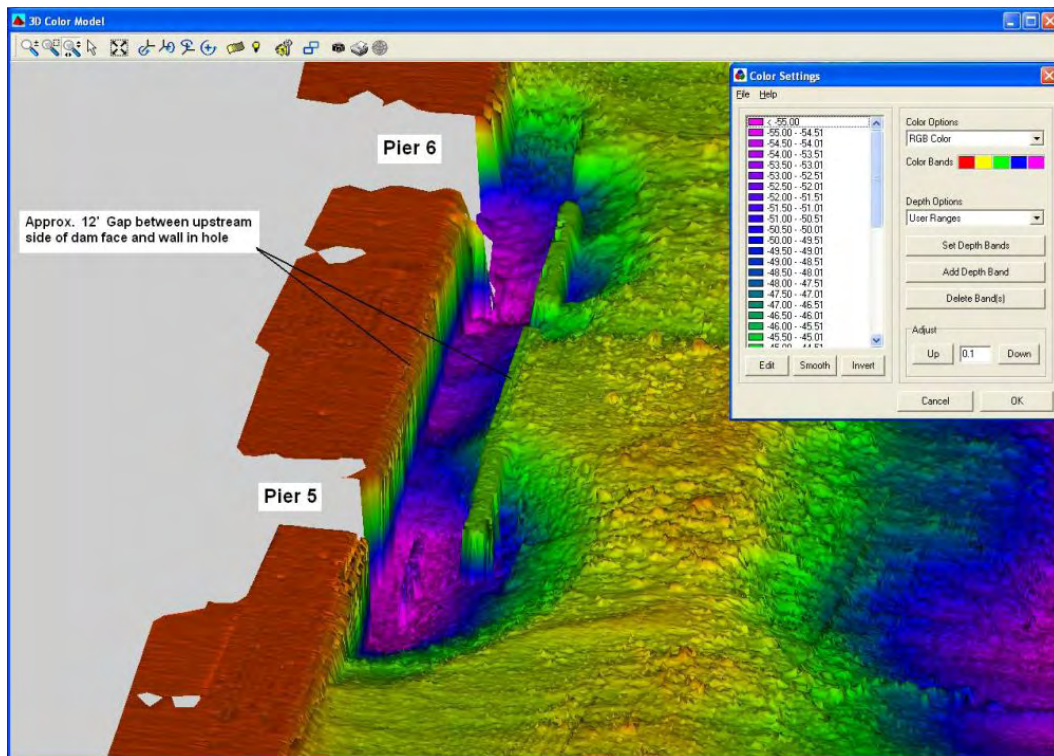
Figure 8. View of area immediately upstream from gate bay at Mel Price Dam (flow is from right to left).

Figure 9. Line sounding to verify multi-beam sonar results.

4   Scour Assessment from Sounding Data

The sounding data for Lock and Dam 2, Mississippi River, for the years 2000, 2001, and 2003 were reviewed to assess the scour at this project. The sounding data were similar to that shown in Figure 6 and were taken at the locations shown in Figure 5. The scour conditions were assessed as no damage, minimal, moderate, and significant as follows:

- No damage – survey profiles were equal to or higher than the profile of the original riprap placement
- Minimal – survey profiles were lower than the original profile, but were less than half the thickness of the capstone
- Moderate – survey profiles were lower than the original profile and were located at about half the thickness of the original capstone
- Significant – survey profiles were equal to or lower than the bottom of the original capstone

The original placement contained a capstone placed over a rockfill. The results of the damage assessment are shown below:

- Significant – 3 profiles
- Moderate – 4 profiles
- Minimal – 3 profiles
- No damage – 8 profiles

Two of the significant damage assessment profiles were adjacent to one another (P-16 and P-17). This area will need immediate reconnaissance to verify that damage exists. If the damage is verified, a decision to repair or not will need to be made. The risks of not repairing will need to be determined. The displacement of the riprap downstream from the structure appears to have been caused by the flow. There are areas downstream from where the riprap has been displaced in which the original riprap appears to have settled. This indicates the riprap has been displaced from its original placement and has been washed downstream. The riprap size appears to have been inadequate. The multi-beam sonar could be used to map the areas in need of repair.

5 Engineering Reliability

These analyses attempt to assess the reliability of scour protection material for navigation dams and establish an engineering basis for rehabilitation investment decisions.

Guidance for the analysis procedures is given in Engineering Technical Letter (ETL) 1110-2-532 (HQUSACE 1992). Reliability is computed from the probability distribution of a limit state equation. Examples of reliability assessment for breakwaters can be found in Melby and Mlakar (1997). Reliability definitions used in the analysis are provided below:

- **Reliability.** Probability that limit state equation will be greater than limit state.
- **Probability of Failure.** Probability that limit state equation will be less than limit state.
- **Limit State Equation.** Equation describing the engineering performance of interest expressed as either the difference between capacity and demand (safety margin) or ratio of capacity to demand (safety factor). Resistance and load are sometimes used for capacity and demand, respectively. The limit state equation is also known as the failure function or performance function.
- **Safety Factor.** Ratio of capacity to demand.
- **Safety Margin.** Difference between capacity and demand.
- **Limit State.** Level of performance for which capacity equals demand (safety factor = 1 and safety margin = 0).
- **Failure Surface.** Surface along the limit state described by the limit state equation.

The definitions can be illustrated by considering the riprap stability defined by Equation 1 and rearranged in Equation 3.

$$V = C(2g)^{\frac{1}{2}}\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)^{\frac{1}{2}}\left(D_{50}\right)^{\frac{1}{2}} \tag{3}$$

In hydrologic analysis, discharge, Q, is a more common representation of the flow than the velocity. The velocity, V, is equal to the discharge, Q, divided by the flow area, A,

$$V = \frac{Q}{A} \qquad (4)$$

Describing the flow entering or exiting a stilling basin is typically done in terms of the discharge per unit width of the stilling basin or q. The velocity can be computed from the unit discharge if the depth, d, of flow exiting the stilling basin is known. The velocity then becomes

$$V = \frac{q}{d} \qquad (5)$$

Substituting Equation 5 into Equation 3 gives

$$\frac{q}{d} = C(2g)^{\frac{1}{2}} \left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{\frac{1}{2}} (D_{50})^{\frac{1}{2}} \qquad (6)$$

Rearranging Equation 6 gives

$$\left(\frac{q}{d} \right) \left[\frac{1}{C(2g)^{\frac{1}{2}} \left(\dfrac{\gamma_w}{\gamma_s - \gamma_w} \right)^{\frac{1}{2}}} \right] = D_{50}^{\frac{1}{2}} \qquad (7)$$

In this equation, C is a coefficient that varies for a given level of performance. The value varies depending on the location of the riprap. For riprap placed in a low turbulence area such as in an open channel on the bank, C is usually taken as 1.2. For riprap placed in a high turbulence area such as downstream from a stilling basin, C is usually taken as 0.86. Acceptable damage to the riprap blanket refers to accepting some riprap movement for the stilling basin design flow condition. Exposure of the underlying filter or bedding material is considered failure of the riprap protection.

To perform a reliability analysis, this equation needs to be developed into the form of a safety factor, $F = C/D$, where C represents capacity and D represents demand. The level of performance where the safety factor is one will be prescribed as the limit state. Performance is satisfactory if the safety factor is greater than one and unsatisfactory when the safety factor is less than one. Using the safety factor approach, Equation 7 can be written as

$$F = \frac{D_{50}^{\frac{1}{2}} C (2g)^{\frac{1}{2}} \left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{\frac{1}{2}}}{\left(\frac{q}{d} \right)} \tag{8}$$

The limit state equation can also be expressed as a safety margin, $sm = C - D$. The condition where this margin is less than zero is unsatisfactory performance, the condition where the margin is above zero is satisfactory performance, and the condition at zero describes the limiting state of performance. Equation 8 can be written in the form of a safety margin as

$$sm = D_{50}^{\frac{1}{2}} C (2g)^{\frac{1}{2}} \left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{\frac{1}{2}} - \left(\frac{q}{d} \right) \tag{9}$$

Since some of the variables in the limit state equation are nondeterministic, the limit state equation is nondeterministic. To begin the reliability analysis, a probability density function (pdf) of these stochastic variables in the performance function must be defined. The reliability is determined from probability theory as the probability that the performance function will exceed the limit state. Using the riprap stability equation characterized by a safety factor in Equation 8, the reliability is the probability that the riprap size parameter in the numerator is large enough to withstand the velocity parameter in the denominator (the probability that F will exceed one).

To perform the reliability analysis, statistical parameters or moments such as their means, standard deviations, and correlation coefficients must be identified for the random variables (RVs). Table 1 summarizes the variable means and standard deviations for angular stone used in the reliability analysis.

Table 1. Statistics for riprap stability limit state variables.

Random Variable	Mean, μ	Standard Deviation, σ	Coefficient of Variation, c
Stone size, D_{50}	Range	Range	0.07
Riprap stability equation coefficient, C	1.11	0.28	0.25
Stone specific weight, γ_s	165 lbs/ft^3	4.9 lbs/ft^3	0.03
Unit discharge, q	Range	Range	0.07
Depth over basin, d	Range	Range	0.05

The coefficient of variation, defined as the ratio of the standard deviation to the mean, for stone size (0.07) was determined from the riprap grada-tions data presented in Table 5-3 of EM 1110-2-1605. The riprap stability coefficient, C, is a very important variable for this analysis. A C of 1.11 was selected for use in the initial analysis. This value was determined from laboratory tests conducted to determine the minimum velocity capable of causing riprap displacement that exposed the material under the riprap protection. This is a comprehensive set of data specifically collected for navigation dam stilling basins. Different levels of energy dissipation were evaluated by changing the stilling basin design. One design, based on the guidance presented in EM 1110-2-1605 for a new navigation dam stilling basin project, represents a basin with good energy dissipation for the design condition. This basin design is designated by 1 after REMR (Repair, Evaluation, Maintenance, and Rehabilitation) in Table 2. The second design was the first design with the baffle blocks removed and represented a basin with poor energy dissipation designated by 2 after REMR, in Table 2. A range of flow velocities and depths from normal to design con-ditions were evaluated. Table 2 provides the stability coefficients deter-mined from these experiments. The value of 1.11 is the average from all the experiments. The different types of riprap placement evaluated in these experiments are shown in Figure 10. The last letter shown in Table 2 for the stilling basin and riprap placement designs represents the riprap placement. "H" represents horizontal placement, "U" represents riprap placed on an upward slope in the downstream direction, and "D" repre-sents riprap placed on a downstream slope in the downstream direction. The values for the mean, standard deviation, and coefficient of variation for the stability coefficient are shown in Table 2.

Table 2. Stability coefficients, *C*, from laboratory experiments.

Stilling Basin and Riprap Placement Designs					
REMR1H	REMR2H	REMR1U	REMR2U	REMR1D	REMR2D
1.15	0.70	0.84	0.70	0.92	0.74
1.36	0.84	1.04	0.84	1.18	0.88
1.51	0.92	1.17	0.92	1.36	0.97
1.63	1.00	1.28	1.00	1.50	1.05
1.71	1.05	1.37	1.05	1.62	1.11
1.15	0.70	0.84	0.70	0.92	0.74
1.36	0.84	1.04	0.84	1.18	0.88
1.51	0.92	1.17	0.92	1.36	0.97
1.62	0.99	1.28	0.99	1.50	1.05
1.72	1.05	1.37	1.05	1.62	1.11
1.15	0.70	0.84	0.70	0.92	0.74
1.36	0.84	1.04	0.84	1.18	0.88
1.51	0.92	1.17	0.92	1.36	0.97
1.62	0.99	1.28	0.99	1.50	1.05
1.72	1.05	1.37	1.05	1.62	1.11
AVG. = 1.11 STDEV = 0.28 COEF. of VAR = 0.25 REMR = Repair, Evaluation, Maintenance, and Rehabilitation					

Point estimate method

Two RVs can be identified as significant to the determination of the demand function. These are (1) the unit discharge q and (2) the depth of flow over the end sill d. To illustrate this method, the hydraulic conditions and scour protection material for the Emsworth Locks and Dams project on the Ohio River will be used. A condition critical for scour protection is a single gate fully open with normal and below normal tailwater conditions. At the Emsworth project, the mean unit discharge for a single gate fully open with normal tailwater is 132 cfs/ft and the standard deviation (σ_q) is 9.2 cfs/ft. The mean depth over the end sill with a single gate fully open and normal tailwater is 12.2 ft and the standard deviation (σ_d) is 0.6 ft.

The integration of the demand function is approximated by performing repetitive deterministic analyses, using all possible combinations of the mean plus one standard deviation and the mean minus one standard deviation of the RVs. The values of the input values used and the results are shown in Table 3.

a. Riprap placed as a horizontal blanket.

b. Riprap placed on a 1V on 10H upward sloping blanket.

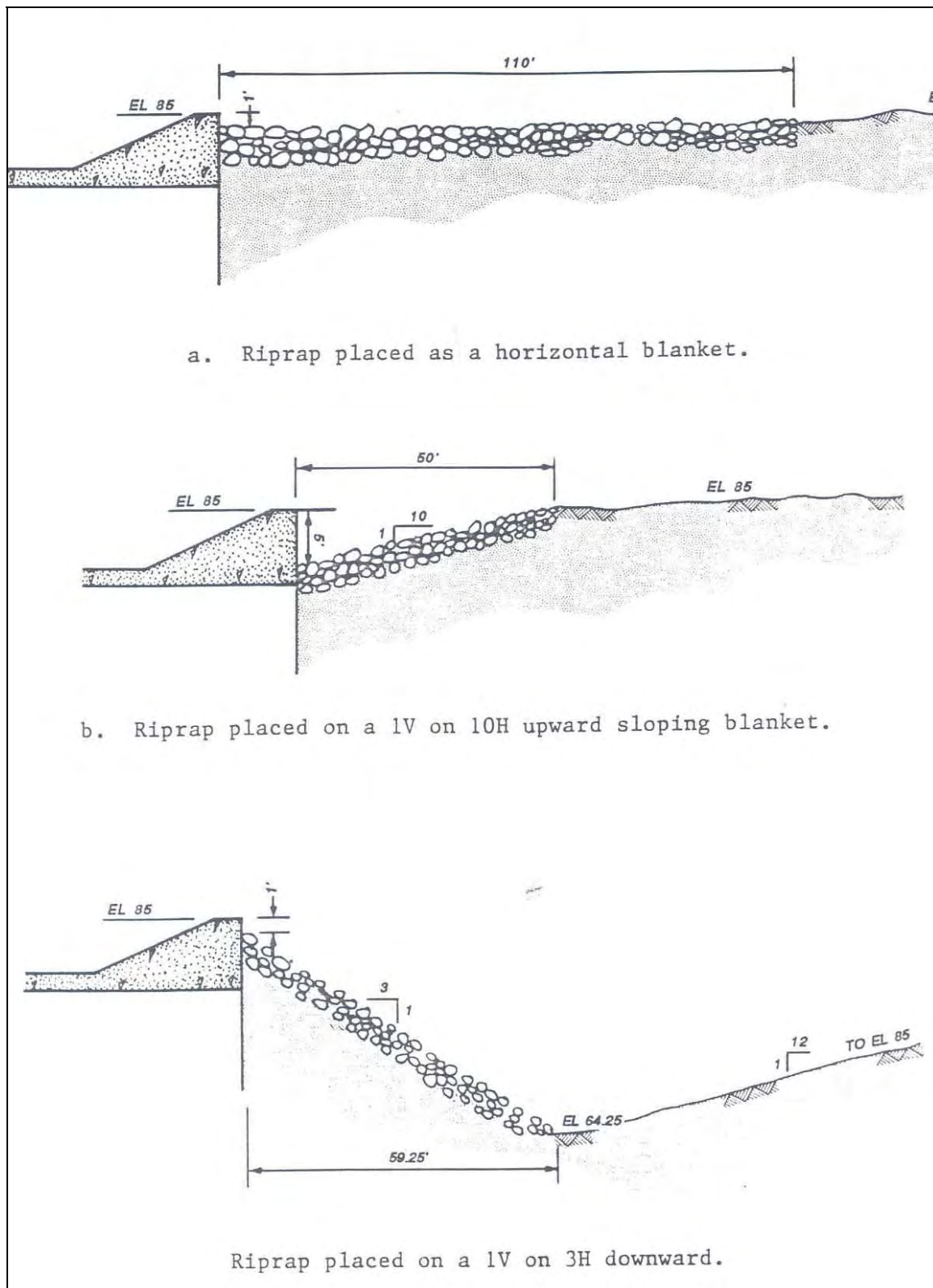Riprap placed on a 1V on 3H downward.

Figure 10. Methods of riprap placement for determination of riprap stability coefficient.

Table 3. Combinations of RVs used to approximate integration of demand function by point estimate method.

Run	RV1 q cfs	RV2 d ft	Velocity ft/sec
1	141.2	12.8	11.0
2	141.2	11.6	12.2
3	122.8	12.8	9.6
4	122.8	11.6	10.6
Mean σ_D			10.85 1.08

The mean value or expected demand, $E[D]$, of 10.85 ft/sec is the average of the calculated velocities. The standard deviation, σ_D, of 1.08 ft/sec, taken from the tabulated values, is used to calculate the coefficient of variation of demand, V_D, by the expression

$$V_D = \frac{\sigma_D}{E[D]} = \frac{1.08}{10.85} = 0.100 \qquad (10)$$

Three RVs can be identified as significant to the determination of the capacity function. These are (1) the D_{50} stone size (2) the stability coefficient, C, and (3) the stone specific weight, γ_s. At the Emsworth project, the D_{50} stone size is 4.5 ft and the standard deviation is 0.5 ft. The stability coefficient is 1.11 and the standard deviation is 0.28. The specific stone weight is 165 lb/cu ft and the standard deviation is 4.9 lb/cu ft. The values of the input variables used are shown in Table 4.

Table 4. Combinations of RVs used to approximate integration of capacity function by point estimate method.

Run	RV1 D_{50} Stone Size, ft	RV2 Stability Coefficient, C	RV3 Stone Specific Weight, γ_s	Capacity ft/sec
1	5	1.39	169.9	19.0
2	5	1.39	161.1	19.9
3	5	0.83	169.9	11.3
4	5	0.83	161.1	11.9
5	4	1.39	169.9	17.0
6	4	1.39	161.1	17.8
7	4	0.83	169.9	10.1
8	4	0.83	161.1	10.6
Mean σC				14.71 4.09

The mean value or expected capacity, $E[C]$, of 14.71 ft/sec is the average of the calculated values. The standard deviation, σ_C, of 4.09 ft/sec, taken from the tabulated values, is used to calculate the coefficient of variation of capacity, V_C, by the expression

$$V_C = \frac{\sigma_C}{E[C]} = \frac{4.09}{14.71} = 0.278 \tag{11}$$

The reliability index, β, can be calculated from Equation 2 as

$$\beta = \frac{\ln\left(E[C]/E[D]\right)}{\sqrt{V_C^2 + V_D^2}} = 1.03 \tag{12}$$

for the values of:

$$E[C] = 14.71$$
$$E[D] = 10.85$$
$$V_C = 0.278$$
$$V_D = 0.100.$$

A reliability index of 1.03 indicates a high probability of damage to the scour protection under the condition with a gate fully open and a normal tailwater condition. This preliminary analysis indicates that the scour protection material should be further evaluated to increase the reliability.

Taylor's series approximation

The integration of the performance function can be approximated by the Taylor's series method. Table 5 summarizes the analyses required for the same scour protection at Emsworth Dam. The statistics for capacity determined from the point estimate method are used in these analyses.

$$\beta = \frac{\mu_{\ln C/D}}{\sigma_{\ln C/D}} = \frac{0.291}{0.183} = 1.51 \tag{13}$$

where:

$$C = \text{Capacity}$$
$$D = \text{Demand.}$$

Table 5. Combinations of RVs used to approximate integration of performance function by Taylor's series expansion method.

Mean SD C/D-SD	RV1 q cfs	RV2 d ft	RV3 CAP ft/sec	C/D	C ft/sec	D ft/sec
	132 9.2 0.094	12.2 0.6 0.069	14.71 4.09 0.379	1.361 0.251	14.7	10.85
1	141.2	12.2	14.71	1.268	14.71	11.6
2	122.8	12.2	14.71	1.456	14.71	10.1
3	132	12.8	14.71	1.428	14.71	10.3
4	132	11.6	14.71	1.290	14.71	11.4
5	132	12.2	18.80	1.741	18.80	10.8
6	132	12.2	10.62	0.983	10.62	10.8

where:

$$\sigma_{\ln C/D} = \sqrt{\ln\left[1 + \left(\sigma_{C/D}/\mu_{C/D}\right)^2\right]} \tag{14}$$

$$\sigma_{\ln C/D} = \sqrt{\ln\left[1 + \left(0.251/1.361\right)^2\right]} \tag{15}$$

$$\sigma_{\ln C/D} = 0.183 \tag{16}$$

and

$$\mu_{\ln C/D} = \ln\mu_{C/D} - \frac{\sigma^2_{\ln C/D}}{2} \tag{17}$$

$$\mu_{\ln C/D} = \ln 1.361 - \frac{\left(0.183\right)^2}{2} \tag{18}$$

$$\mu_{\ln C/D} = 0.291 \tag{19}$$

Integration of the performance function by the Taylor series method gives a reliability index of 1.51, slightly higher than that determined from the point estimate method. This method also indicates the reliability of the scour protection is low and rehabilitation is necessary.

Reliability indices are a relative measure of the existing condition of a component and provide an estimate of the component performance. Components with high reliability indices are expected to perform their function without problems. Components with low reliability indices are expected to perform poorly and should be considered for rehabilitation. The calculations for the reliability index are examples and were patterned after the examples shown in ETL 1110-2-532 (HQUSACE 1992). Target reliability values in general are provided in Table 1-1 of ETL 1110-2-532. A β value below 2 has an unsatisfactory expected performance level and a value below 1 has a hazardous expected performance level. Since both types of analyses for the example presented in Equations 12 and 13 have reliability indices below 2, this would indicate rehabilitation would be needed. Harr (1987) provides additional information on reliability indices.

6   Acoustical Camera for Scour Detection

Demonstration project at Starved Rock Dam

A demonstration of the Dual-Frequency Identification Sonar (DIDSON) acoustical imaging system was performed at Starved Rock Dam on 19 July 2006. The system was developed by the Applied Physics Laboratory at the University of Washington and is being adapted and enhanced by the Information Technology Laboratory (ITL) at ERDC to assist with the inspection of underwater structures in turbid water. A research work effort in the Navigations Systems Research Program managed at ERDC involves detecting and evaluating scoured areas near navigation projects. Using the DIDSON to try and identify an existing scoured area was considered beneficial for both research areas. The purpose of this demonstration was to determine if a suspected scoured area underneath a stilling basin could be observed and recorded using the DIDSON.

Site selection

The U.S. Army Corps of Engineers (USACE), Mississippi Valley Division, was contacted about projects where scour was suspected underneath the dam stilling basin. The Starved Rock Project was identified as a good candidate to conduct a demonstration and evaluate the capability of the DIDSON. The project is located at mile 231 on the Illinois Waterway. A meeting was held at the project office in September 2005 to discuss project conditions and initiate planning for the demonstration. Sounding data recorded in 2000 were presented and reviewed. Three potential scoured areas were identified. The soundings showed potential scoured areas upstream and downstream from gates 9 and 10, and also down-stream from gate 1. Riprap may have been displaced from these areas. The area downstream from gate 9 appeared to have experienced the worst scour based on the soundings. There was concern that the structure may be undermined in this area. Figure 11 shows the downstream side of the dam looking from the north bank. Gate bays are numbered 1 to 10 with 10 being the southernmost gate bay. Figure 12 shows a portion of the 2005 sounding data. The area circled in red at the bottom of the figure is downstream from gate bays 8-10. Gate 10 abuts the vertical rock bluff shown in Figure 11.

Figure 11. Starved Rock Dam – looking across at downstream side of project.

Demonstration participants

The demonstration was conducted by personnel from the Coastal and Hydraulics Laboratory (CHL), ITL, and Environmental Laboratory (EL), ERDC, and the U.S. Army Engineer District, Rock Island (Rock Island District (MVR) hereafter). The following personnel participated in the demonstration.

- John Hite – CHL, ERDC
- Terry Warren – ITL, ERDC
- Dan Carr – ITL, ERDC
- Charles Hahn – EL, ERDC
- Jay Collins – EL Contractor
- Floyd Collins – Rock Island District
- Terry Hoover – Rock Island District

James Evans and Dan Eng from ITL helped plan and coordinate the field demonstration.
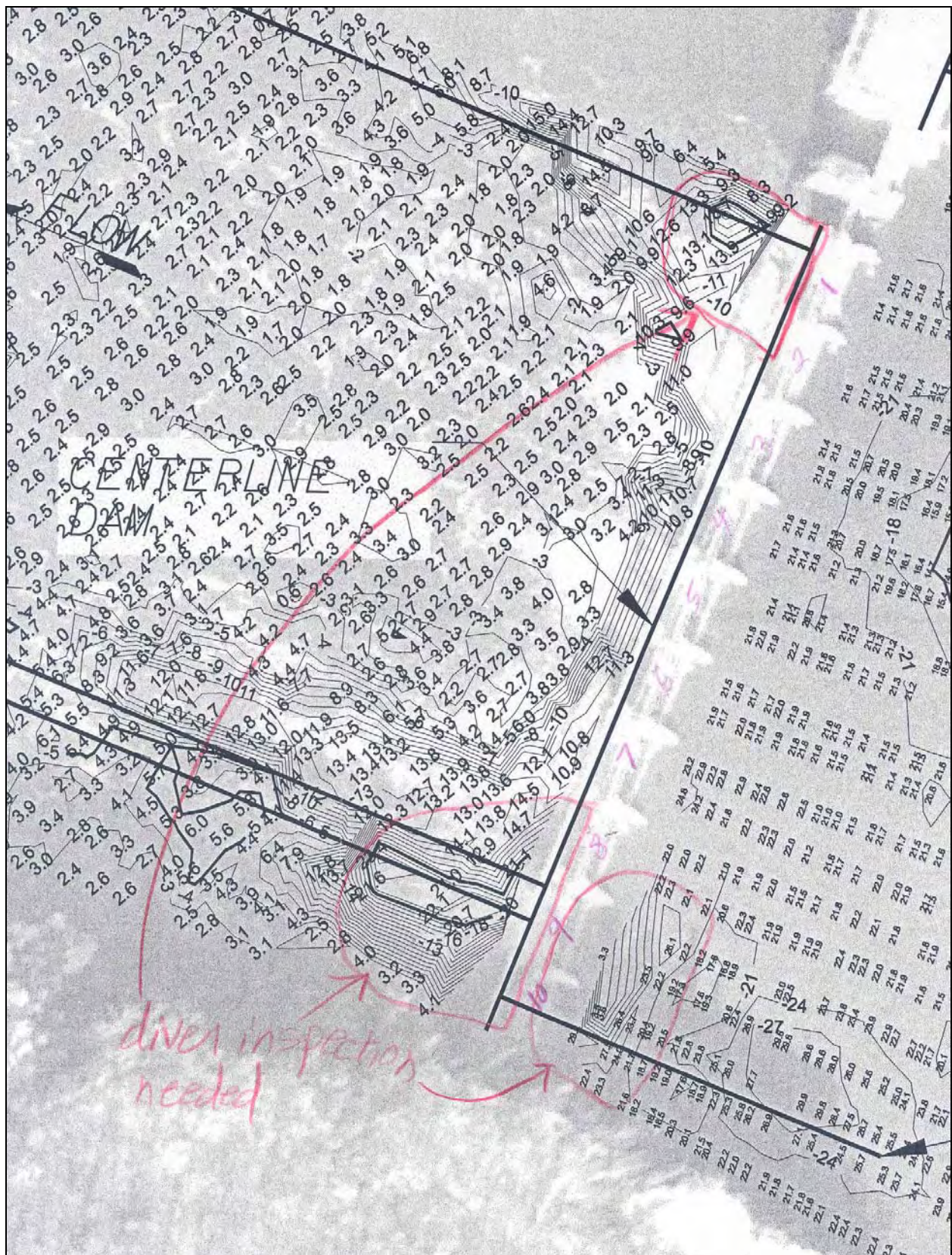
Figure 12. 2005 sounding data for Starved Rock Dam, flow is from right to left.

Accessibility

The area downstream from gate bays 9 and 10 was accessible by boat. During minimal flow the currents in this area are almost nonexistent. The boat launch was located downstream on the left bank. Terry Hoover from MVR guided the ERDC boat up the navigation channel before crossing back to the left bank. The area downstream from the stilling basin was shallow in several locations. Once on the left side, the dam could be approached without grounding. The upper pool was el 459.2,[1] the lower pool was el 441.77, and a total of 5,700 cfs was discharging through the powerhouse and dam with gate 5 open 6 in.

System components

The acoustic imaging system consists of an acoustic video camera, a personal computer, software to view and process the images, a deploying mechanism, a pan and tilt controller to position the camera, and a boat with a global position system. The boat used for the demonstration is shown in Figure 13. Figure 14 shows the mount used to position the camera underwater. A total tracking station was set up on the esplanade between the lock and dam to track the movement of the boat and can be seen in Figure 11. A target was mounted on the boat port side near the front of the cabin as shown in Figure 15. The target was located 5 ft from the bow of the boat. Figure 16 shows an example of an image on the laptop monitor during one of the tests conducted.

Test procedures

Several video recordings were made of the area downstream from gate bays 8-10 to try and determine if any scour could be observed at the end or underneath the dam apron. A total of 11 tests were conducted and several of the tests were repeated to try and make sure adequate coverage was obtained. Figure 17 shows a section view of the gate and dam. The area of interest is at the end of the dam apron (on the right side of the figure). The locations for each test are provided in Table 6.

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[1] All elevations (el) cited in this report are in feet referenced to the National Geodetic Vertical Datum (NGVD).

Figure 13. Boat used to deploy camera.

Figure 14. DIDSON acoustical camera mount.

Figure 15. Total tracking station target mounted on boat.

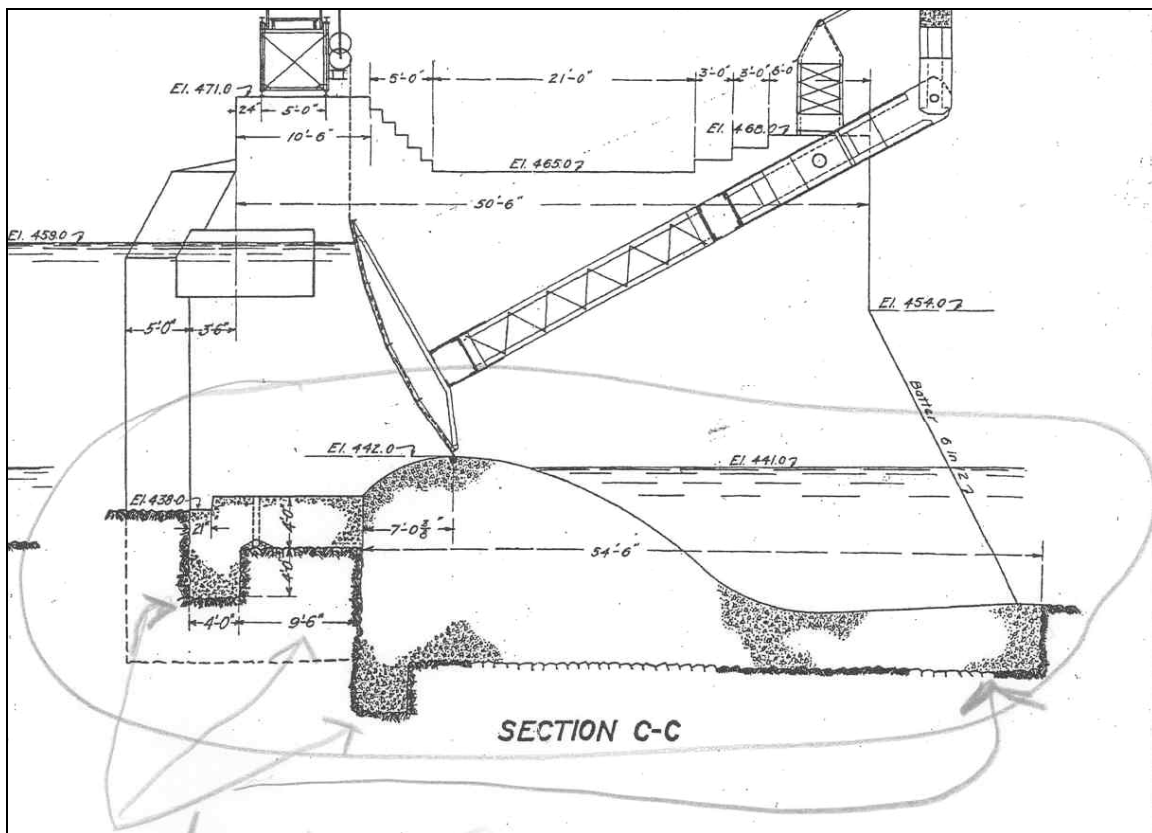

Figure 16. Underwater image on monitor.

Figure 17. Section view of gate and dam.

Table 6. Test locations.

Test No.	DIDSON Depth, ft	Location
1	12	South bank of bay 10
2	14	Pier between bays 9-10
3	14	Bay 10 side of
4	8 to14	Moving middle of bay 10 to bay 9
5	8	Pier between 8-9
6	8	Moving from bay 8 to south bank 20 ft out from pier
7	8	Moving from bay 8 to south bank 20 ft out from pier
8	8	Same as 7, did not record
9	8	Moving from bay 8 to south bank 40 ft out from pier; used trolling motor
10	8	Repeat of 9
11	8	Bays 8-10 forward movement and backing from 10 to 8

Test coordinate system

The coordinate system used to identify the camera location was based on the location of the total tracking station and does not represent dam stationing. The end of the dam apron was designated y-coordinate 1853.53 and can be seen in later figures of the boat locations during the tests. Table 7 shows the x-coordinates designated for the piers between gate

bays 7-10. For example, the x-coordinate of the center of the pier on the south side of bay 10 was 2884.54. This location is designated CL of Pier 10 in the figures that show the boat locations during the tests. The width of the gate bays is 60 ft and the piers are 8 ft wide so the center-to-center distance is 68 ft.

Table 7. X coordinates for dam piers.

Pier Location	Centerline x-coordinate
Between gate bays 7-8	2680.54
Between gate bays 8-9	2748.54
Between gate bays 9-10	2816.54
South side of gate bay 10	2884.54

Test 1

Initially, the boat was angled into the south bank approximately 17.5 ft downstream from the end of the concrete apron for the dam. The left descending bank downstream from gate bay 10 projects north into the bay. The equipment operation was verified and deployment techniques were evaluated. The boat location at different times during Test 1 is shown in Figure 18 as the yellow and magenta areas near x-coordinate 2866 and y-coordinate 1835. The horizontal line at the top of the figure represents the downstream edge of the dam apron in plan view. The vertical lines represent the center lines of the piers in plan view projected downstream from the dam apron for a distance of 40 ft. The area between the vertical lines represents gate bays 8, 9, and 10. The boat location represents the point on the boat at which the target was located. As mentioned previously, the target is on the port side of the boat, 5 ft from the bow, and the DIDSON was located 15 ft from the target or 20 ft from the bow. The DIDSON was located 15 ft north of the target during this test and was lowered 12 ft under the water surface (el 430). The area below gate bay 10 and the south bank was inspected. A rocky surface appears to be below this area and the vertical face of the dam apron appears to be in good shape with no evidence of undermining. Figure 19 shows a portion of the dam apron and area below the dam at the south side of gate bay 10. The edge at the end of the apron is the straight angled feature in the upper left side of the figure.
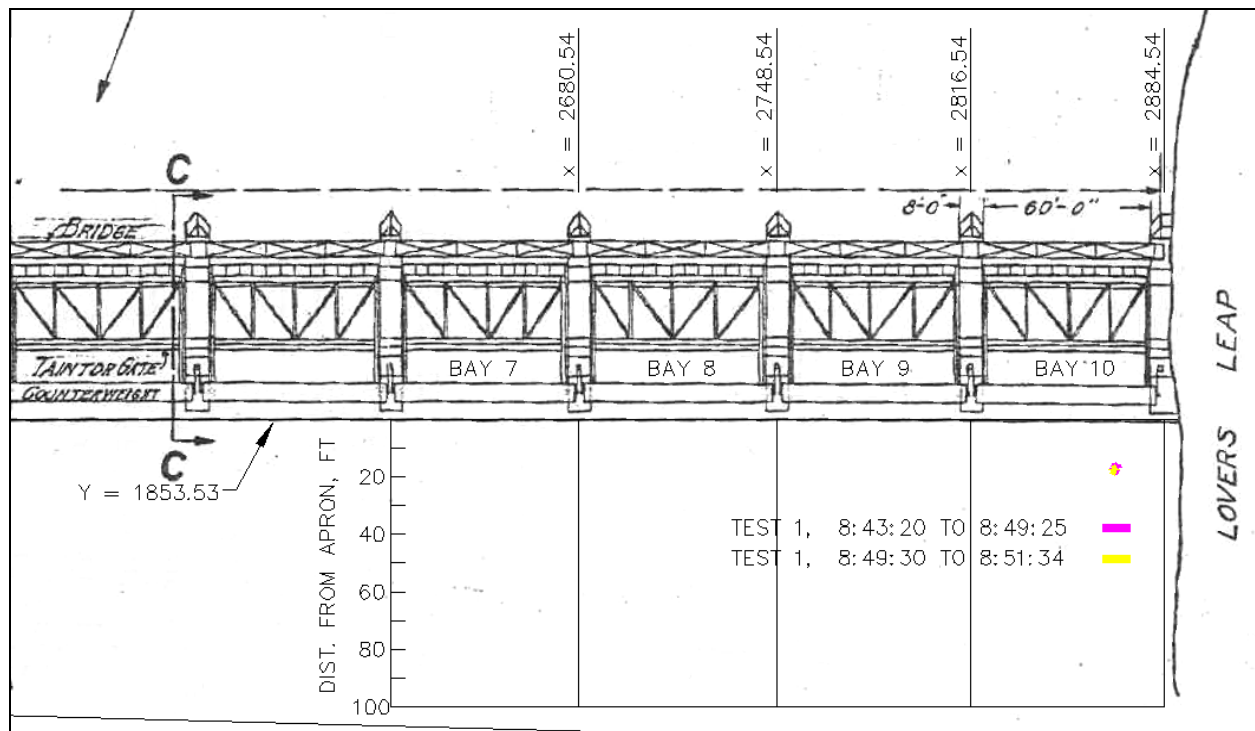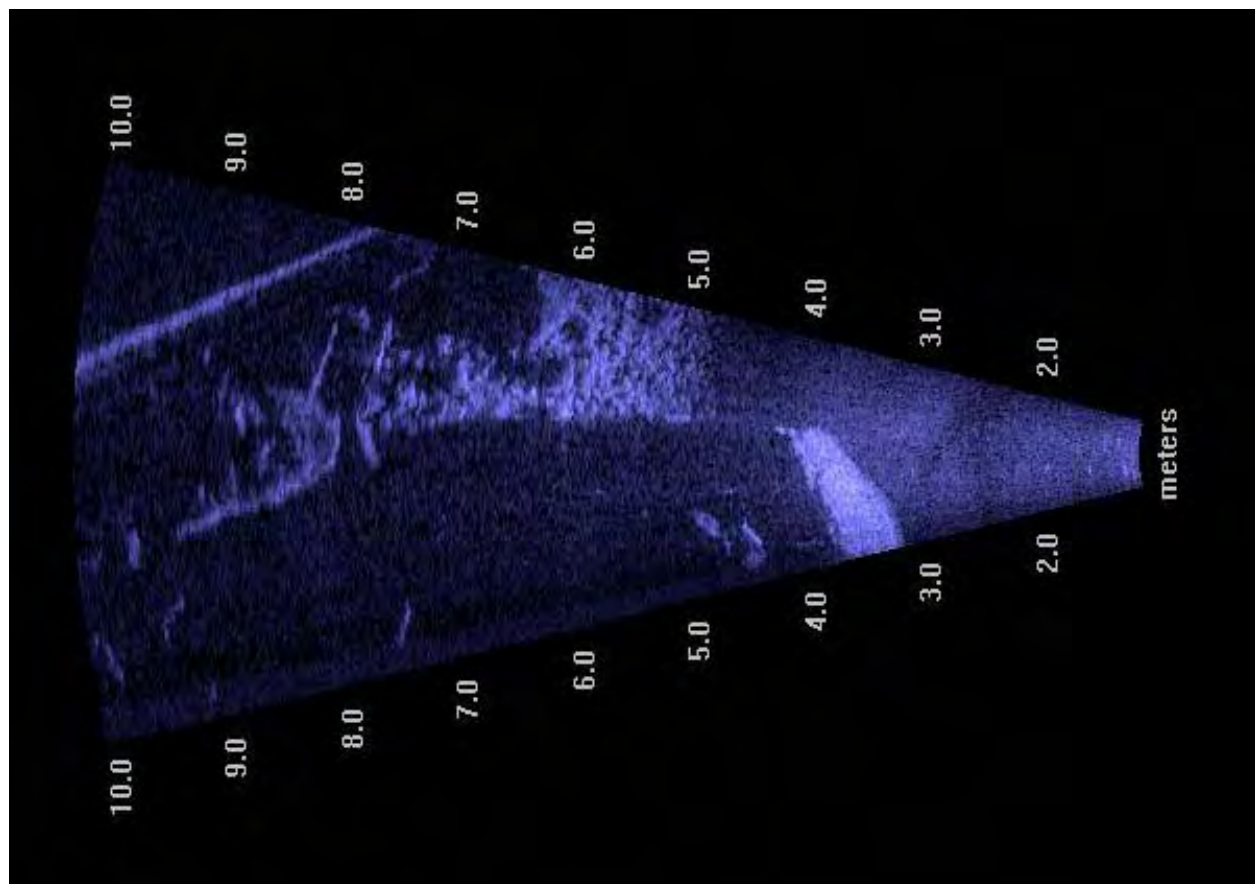
Figure 18. Boat locations during Test 1.

Figure 19. Area at middle to south side of gate bay 10 (Test 1).

The numbers are the distance in meters from the DIDSON to the feature imaged. The area on the south side of the pier between gate bays 9 and 10 (pier 9-10) is shown in Figure 20. The edge of the apron is the long slightly angled feature and the south edge of the pier 9-10 is the feature normal to this one.
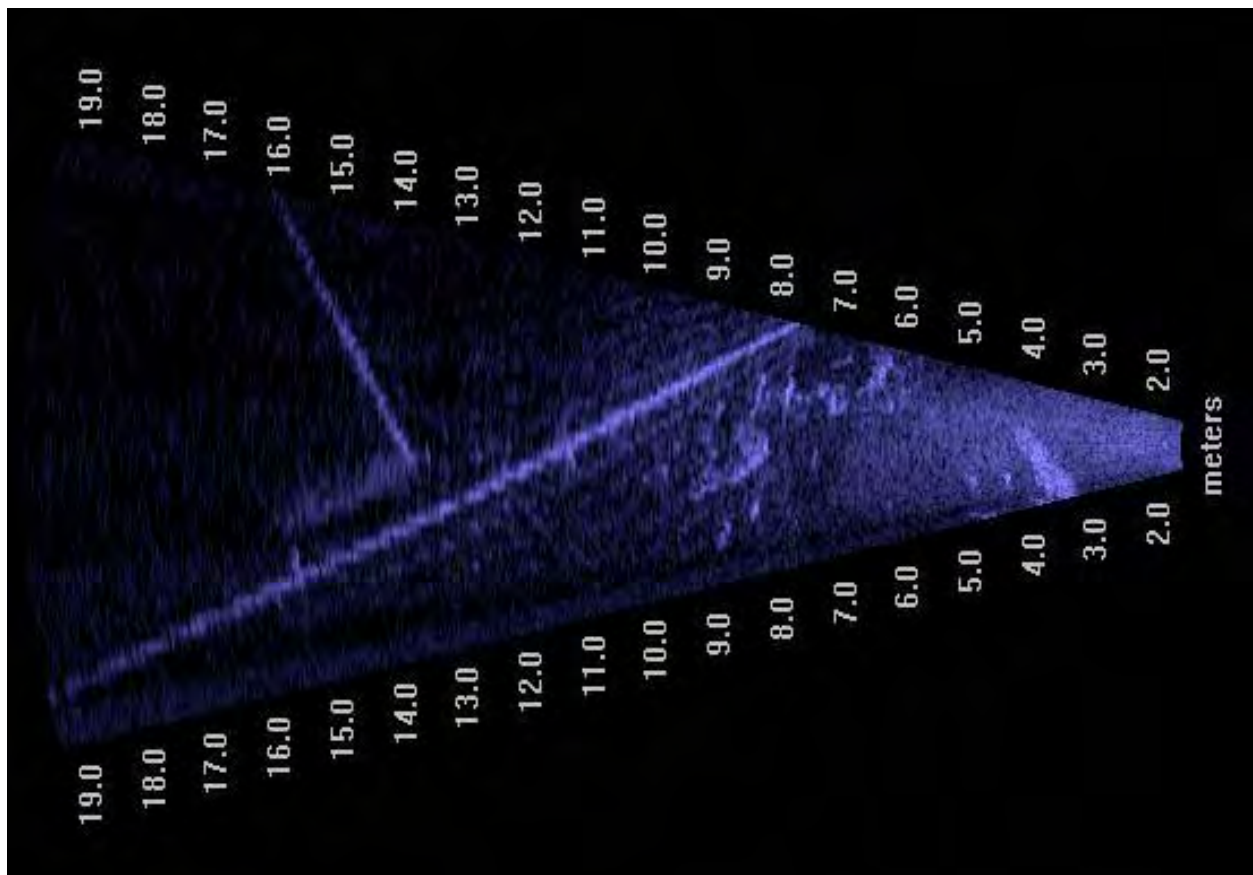

Figure 20. Area just south of the pier between gate bays 9 and 10 (Test 1).

Test 2

At the start of Test 2, the boat was nosed onto the north side of the pier between gate bays 9 and 10 and was facing upstream. The boat location during Test 2 is shown in Figure 21 as the yellow and magenta colored dots. In Figure 11, the DIDSON would be at Y-coordinate 1843, 10 ft downstream from the end of the apron. The DIDSON was lowered 14 ft below the water surface to around el 428. The area in the vicinity of the pier and the south side of gate bay 9 was inspected. The vertical face of the dam apron can be seen in the lower left of Figure 22 along with rock on the bottom. Sunken drift was observed just downstream from the end of the apron (Figure 23).
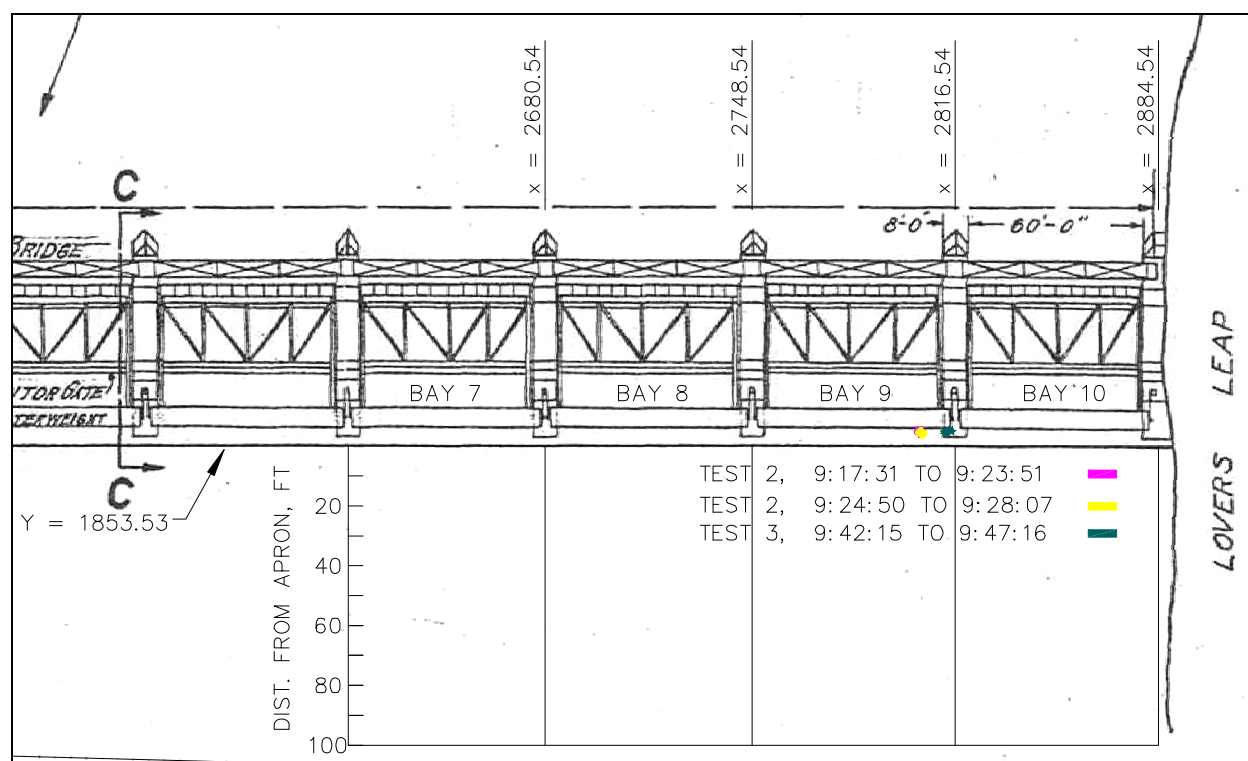
Figure 21. Boat location during Test 2 and 3.

Test 3

The boat was moved farther south on the pier between gate bays 9 and 10 (Figure 21, the teal colored area) for Test 3 to further observe this area. The DIDSON remained 14 ft below the water surface. The area from the middle to south side of gate bay 10 is shown in Figure 24.

Test 4

For Test 4, the boat began at the pier between gate bays 9 and 10 and moved downstream and upstream in this general vicinity. The boat track during Test 4 is shown in Figure 25 as the yellow track. The DIDSON was placed 8 ft below the water surface. The river bottom between the middle of gate bay 9 and gate bay 10 was observed and the downstream side of the apron from about 20 ft on either side of the pier between bays 9 and 10 was imaged. Figure 26 shows the area at the end of the apron on the gate bay 9 side (north side) of pier 9-10 and Figure 27 shows the gate bay 10 side of pier 9-10.
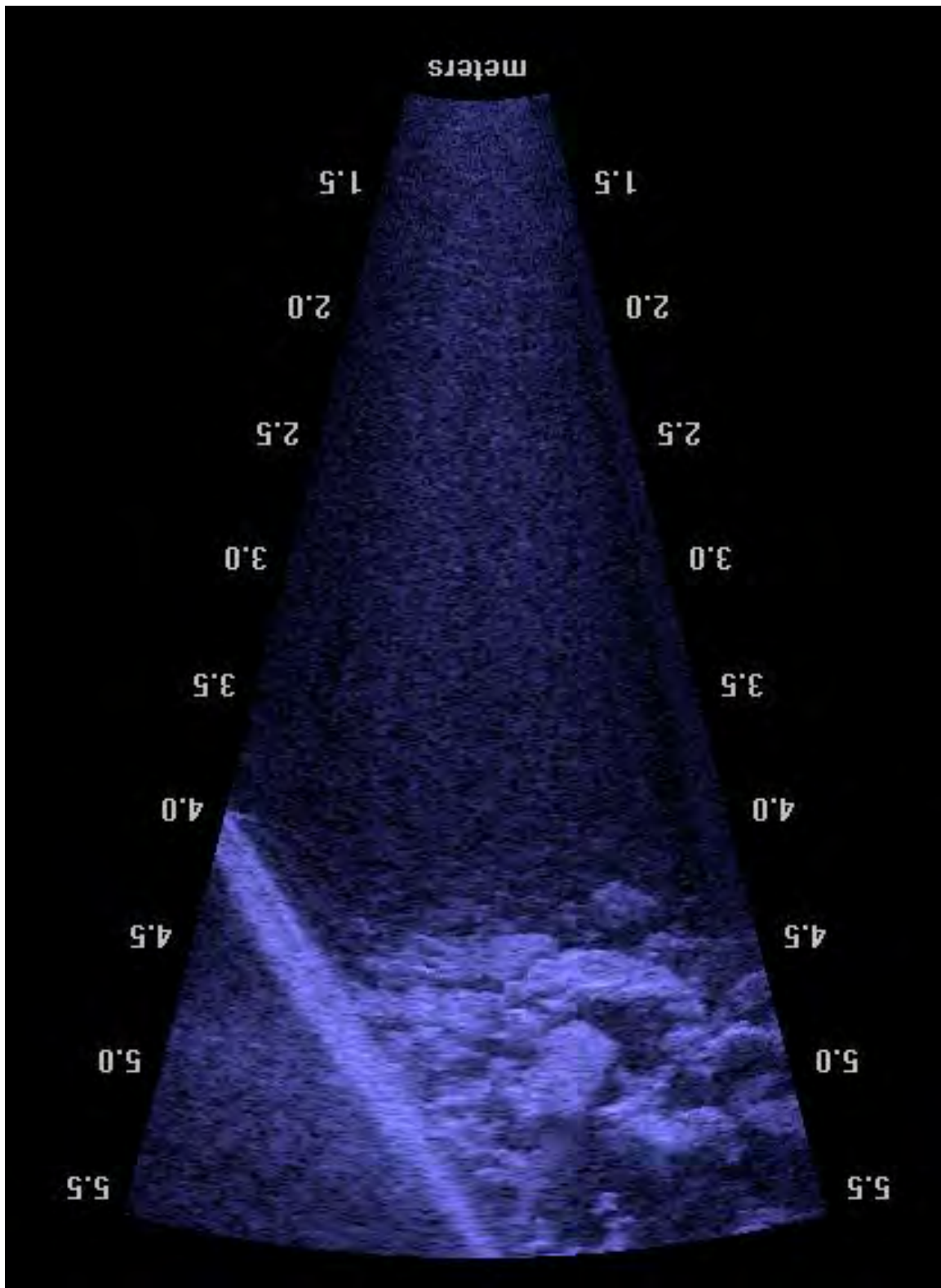
Figure 22. Area just north of pier between gate bays 9 and 10 (Test 2).
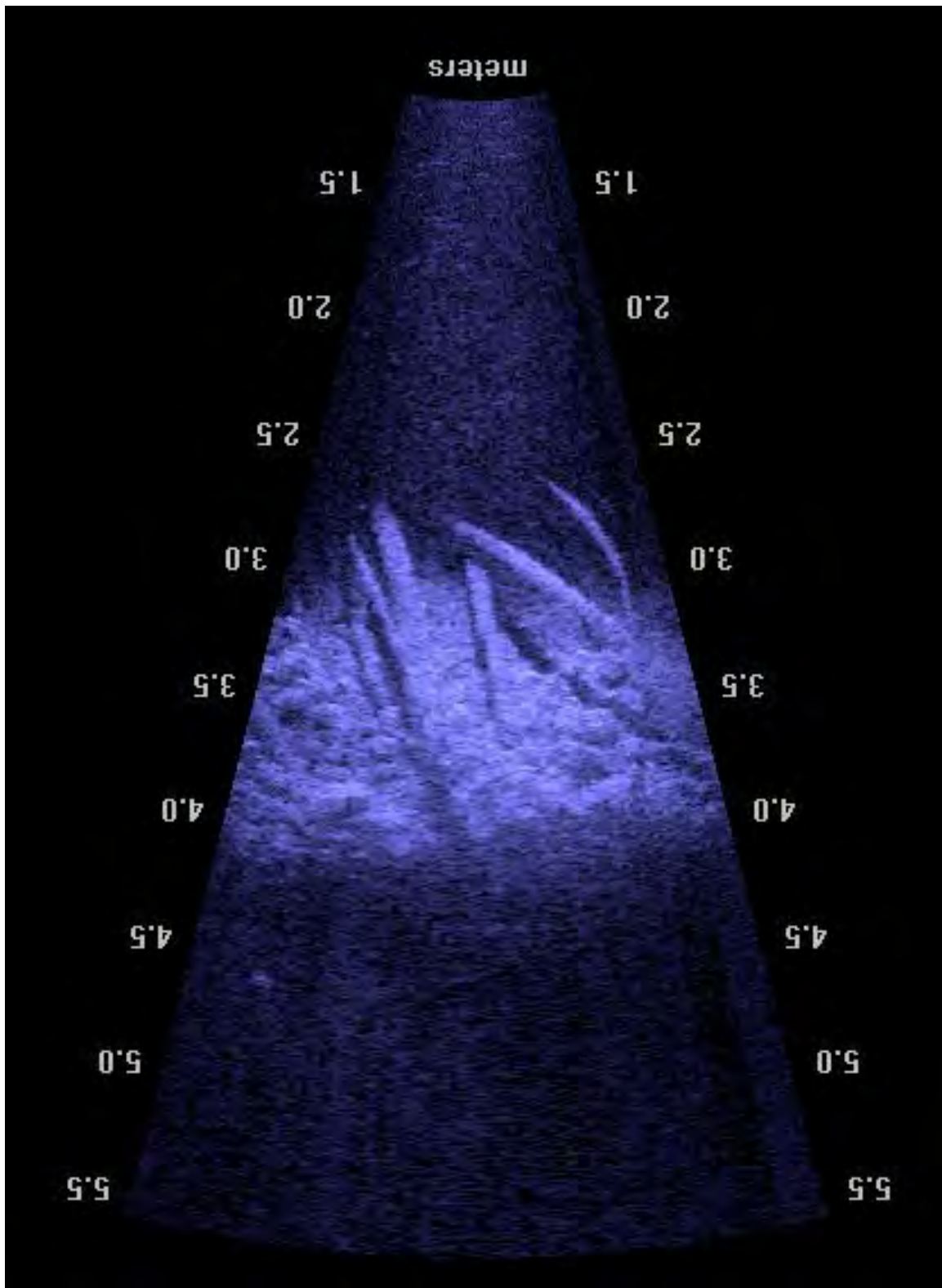
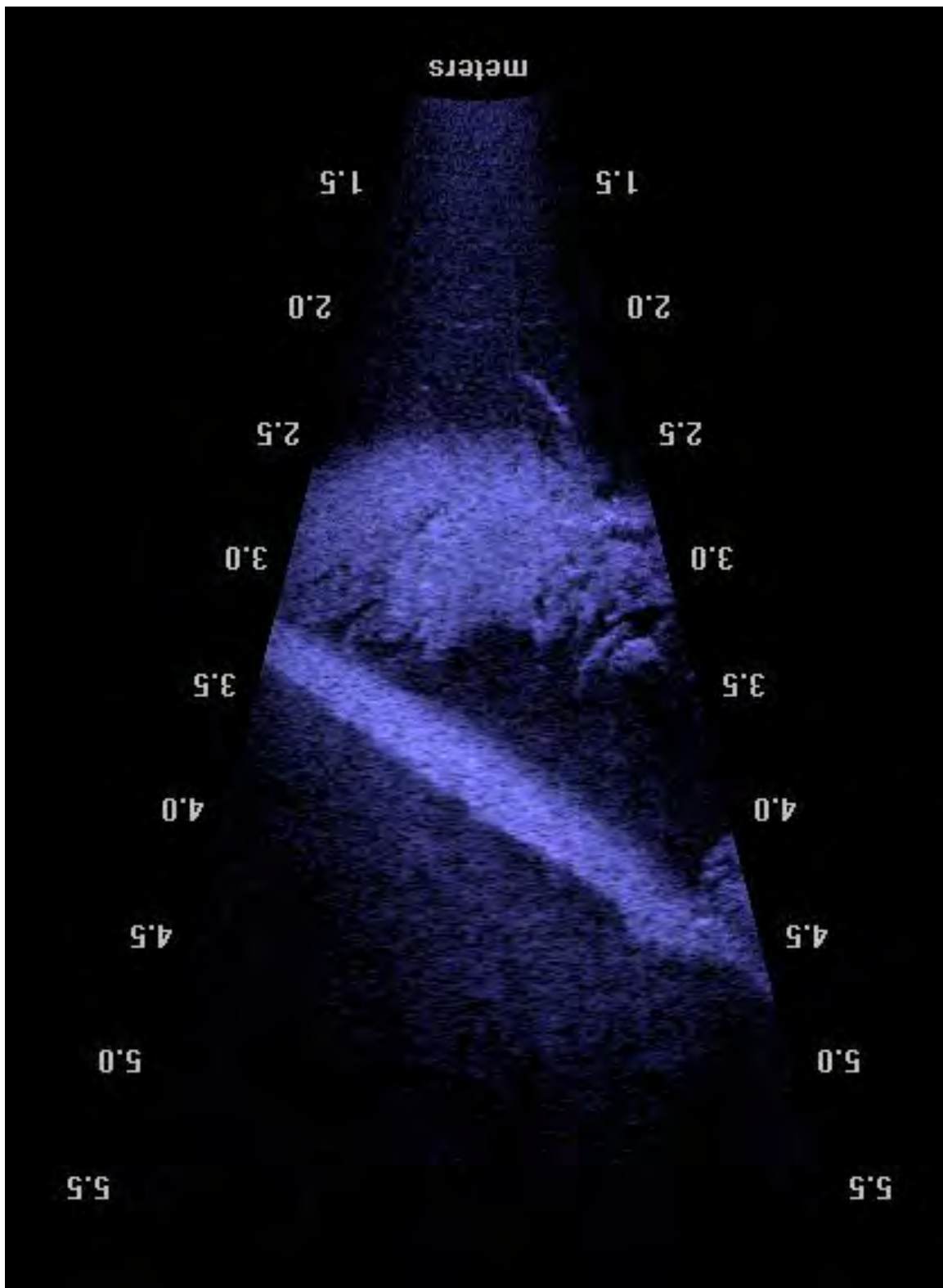Figure 23. View of sunken drift below gate bay 9 (Test 2).
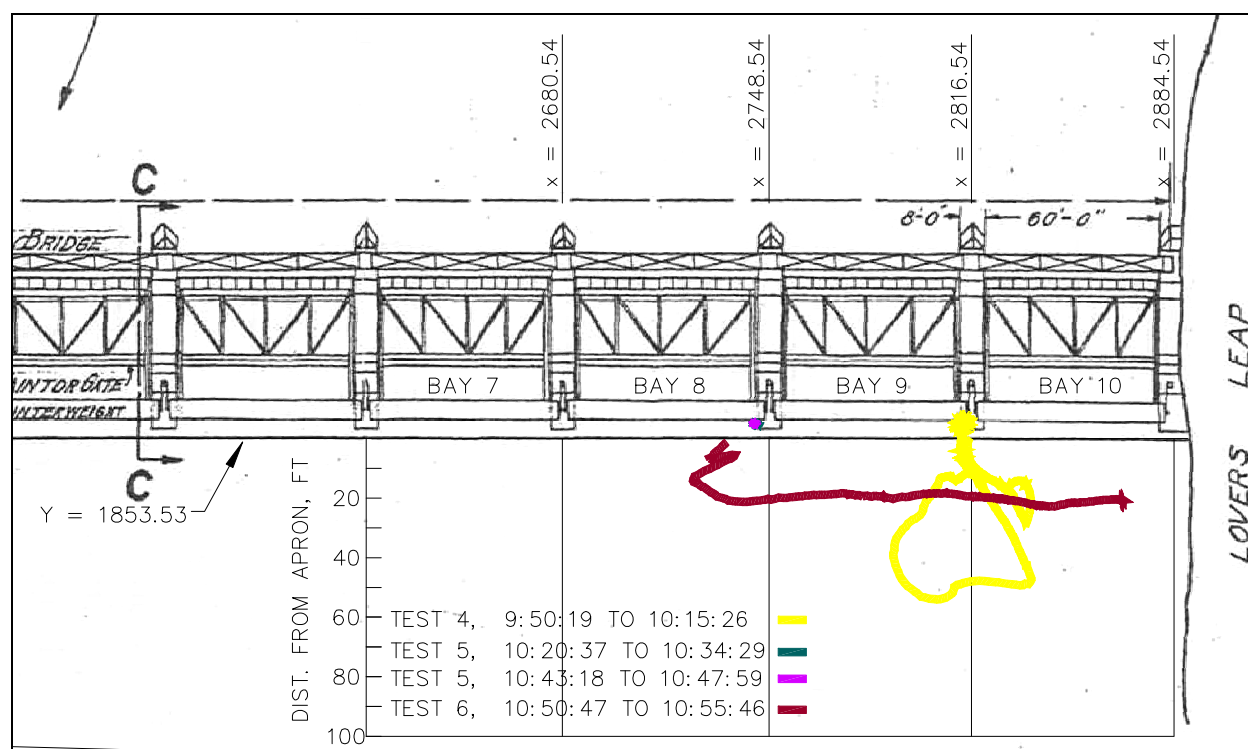
Figure 24. Area below gate bay 10.

Figure 25. Boat location during Tests 4–6.

Test 5

For Test 5, the boat was nosed on the north side of the pier between gate bays 8 and 9. The boat location is shown as the cyan colored area in Figure 25. The DIDSON remained 8 ft below the water surface. A small hole was observed on the dam apron just north (4 to 6 ft) from the pier between gate bays 8 and 9 as seen in Figure 28. This may be a former coring or possibly a weep hole. The area north of the pier between gate bays 8 and 9 is shown in Figure 29. No undermining of the apron was observed in this area. The boat position is shown in Figure 25.

Test 6

Test 6 was conducted to determine if the DIDSON could be used success-fully moving along parallel to the dam. The test was started just north of pier 8-9 and then the boat moved about 20 ft downstream from the end of the apron with the DIDSON at 8 ft below the water surface. The boat track for Test 6 is shown in Figure 25 as the brown colored track. Figure 30 shows an image that was recorded below gate bay 10 about 30 ft south of pier 9-10 and 22 ft from the dam apron.
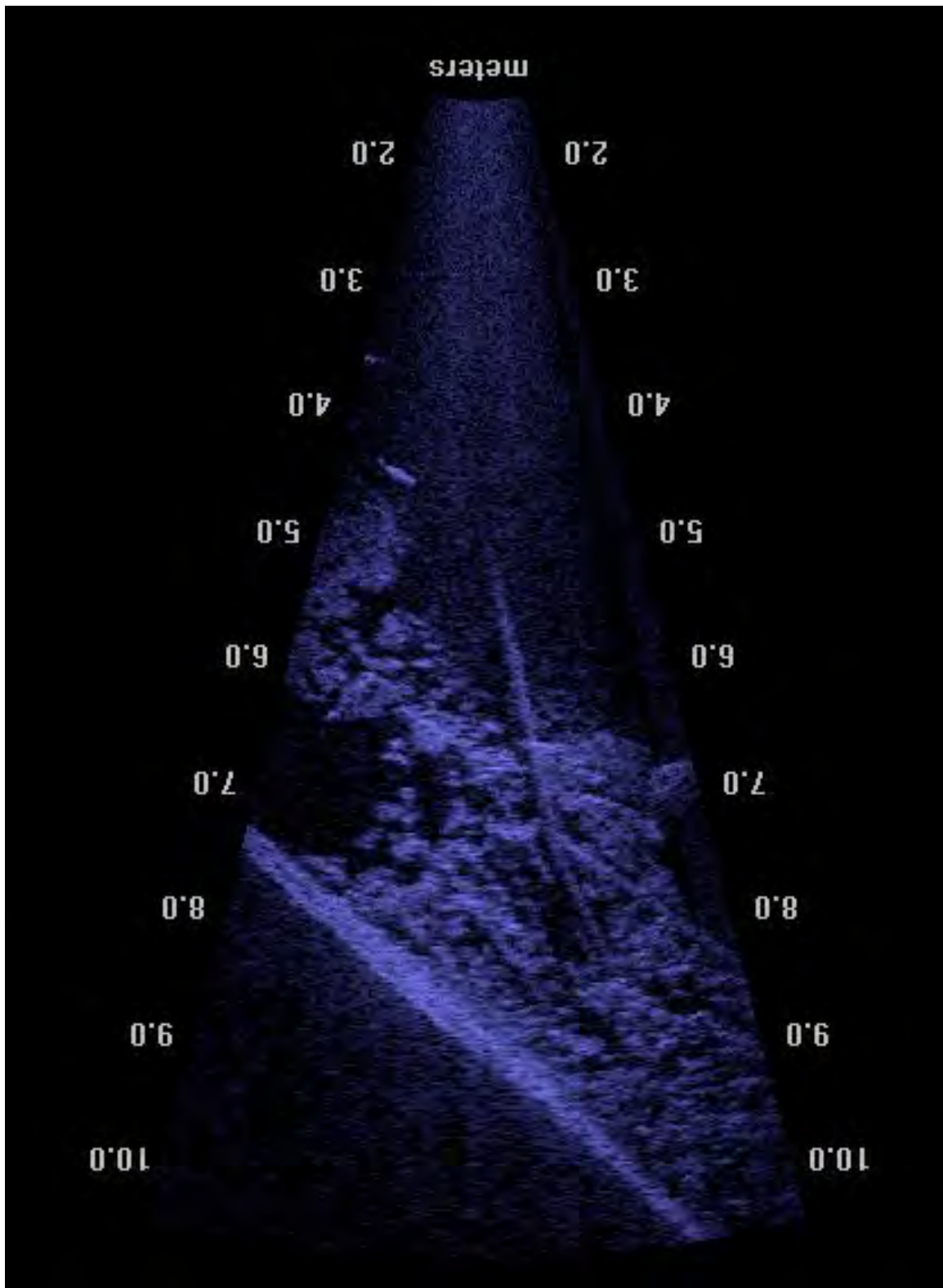
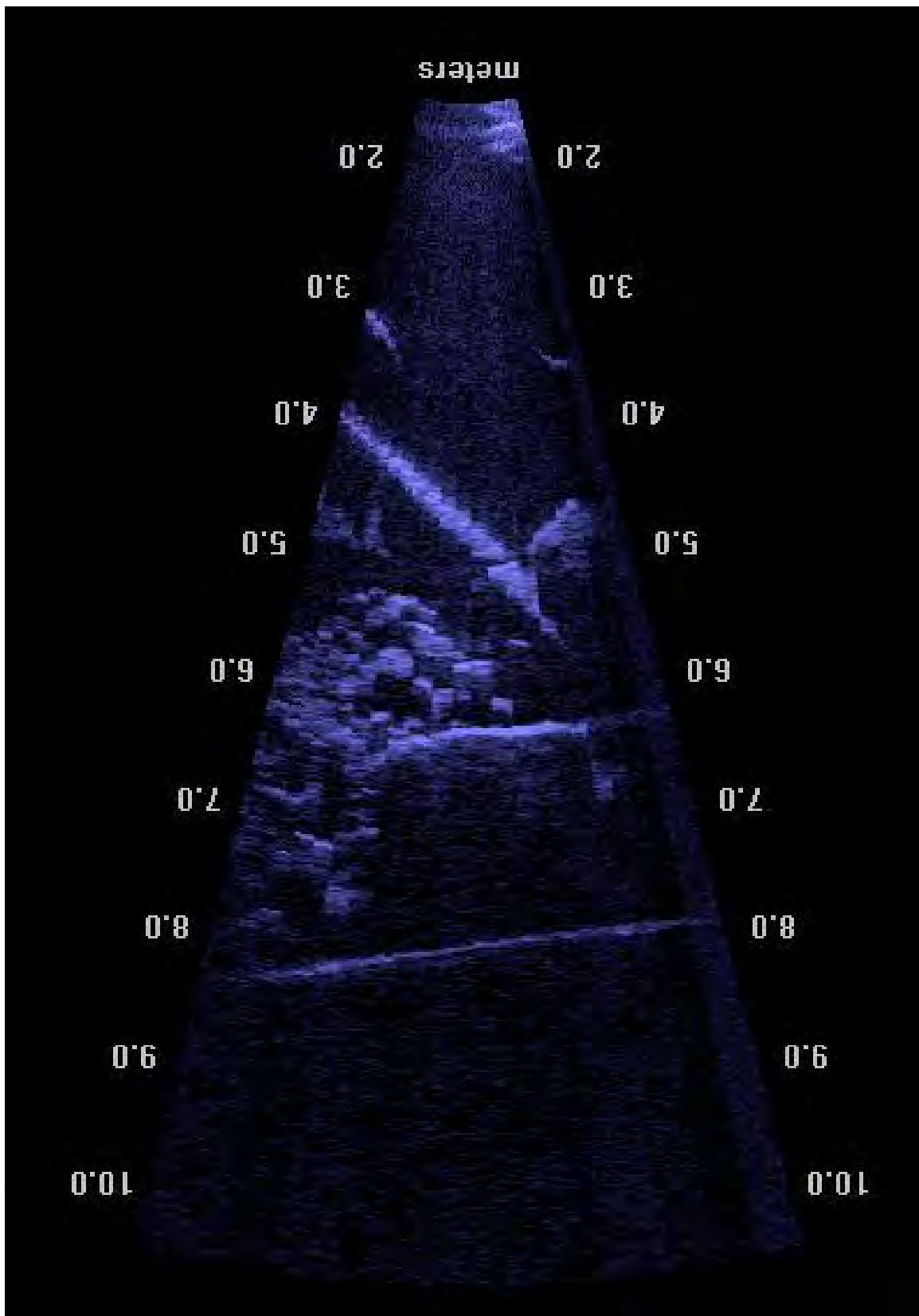Figure 26. Dam apron on north side of pier 9-10 (Test 4).

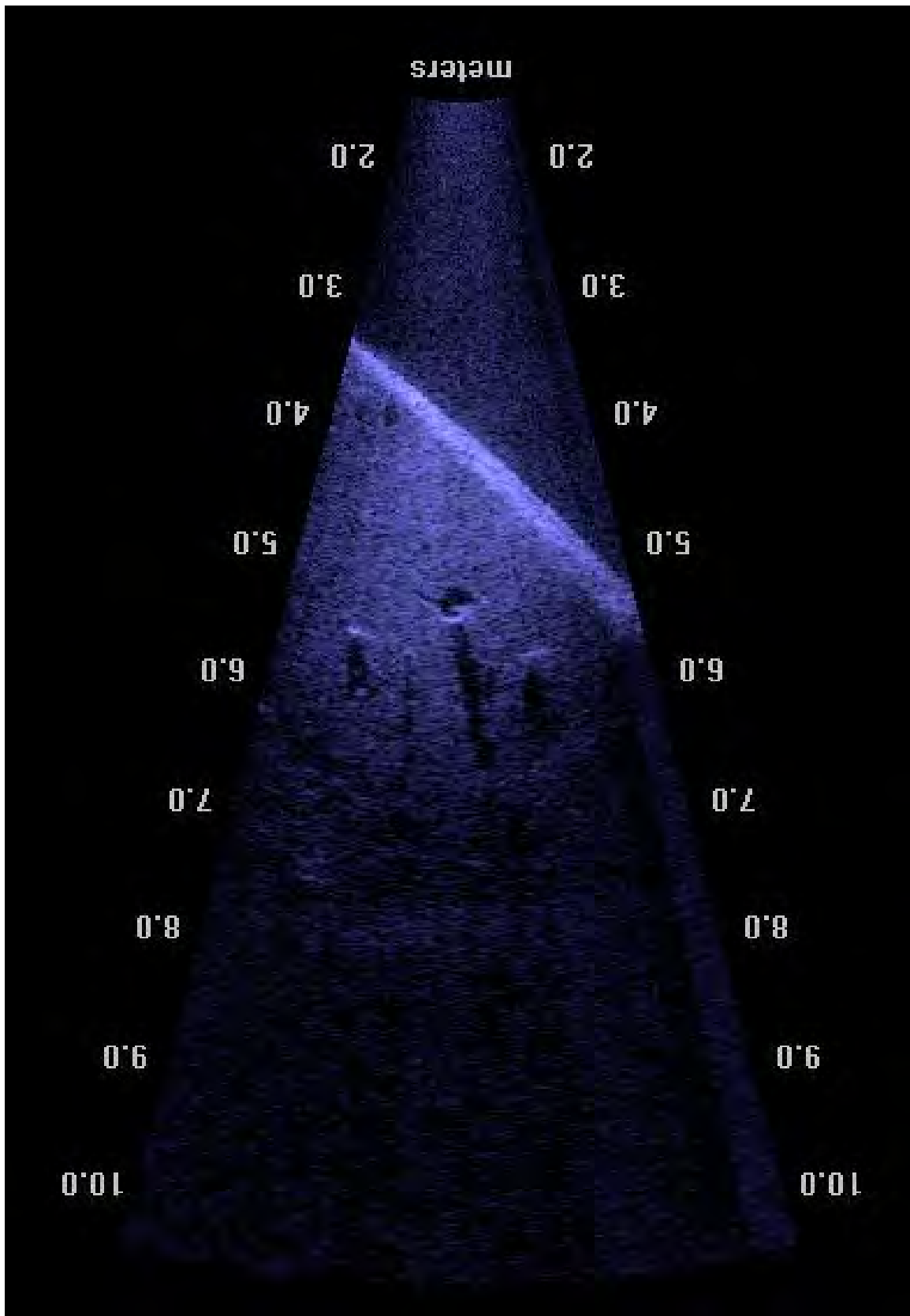Figure 27. Area on south side of pier 9-10 (Test 4).

Figure 28. Small hole on dam apron on north side of pier 8-9 (Test 5).
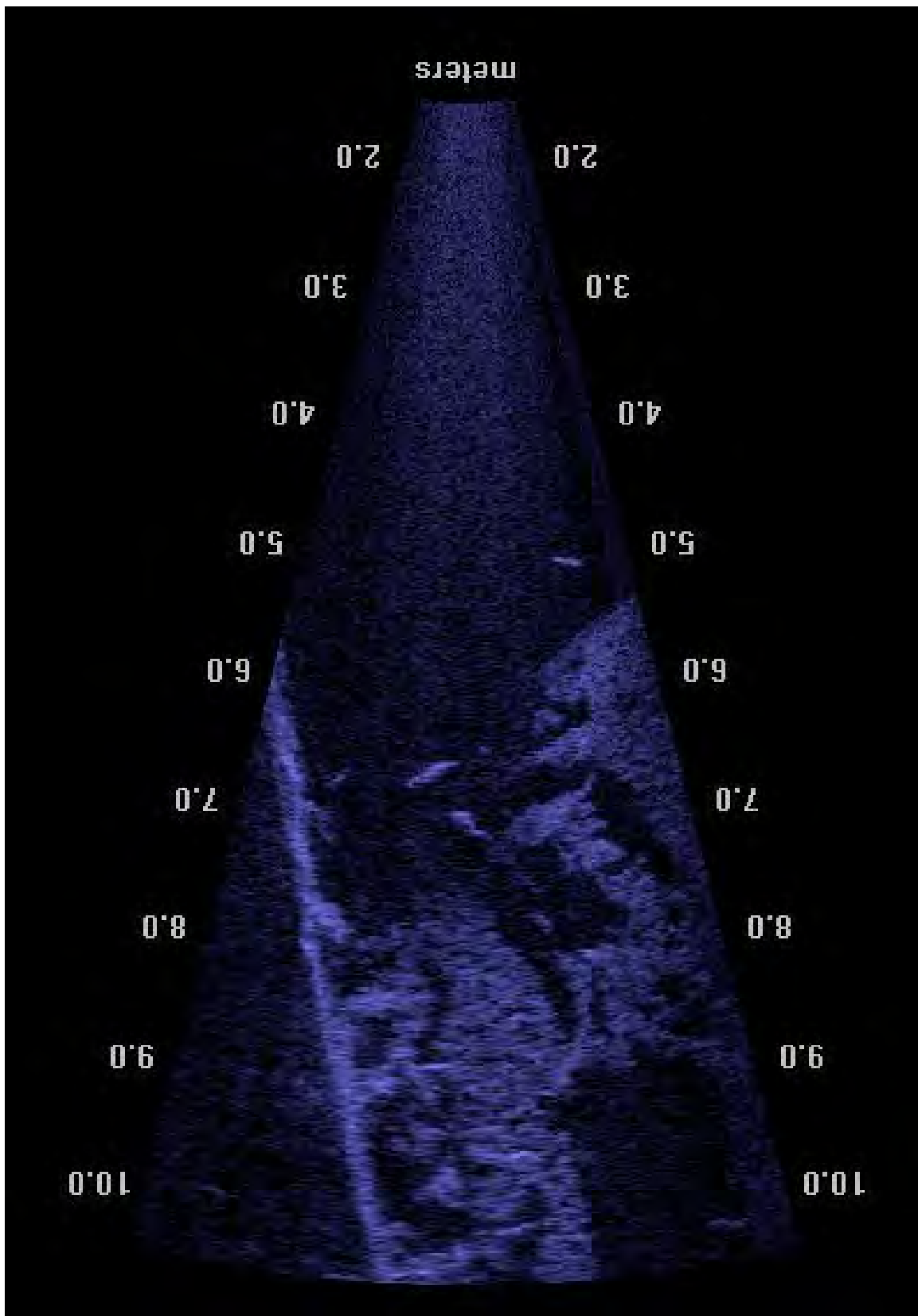
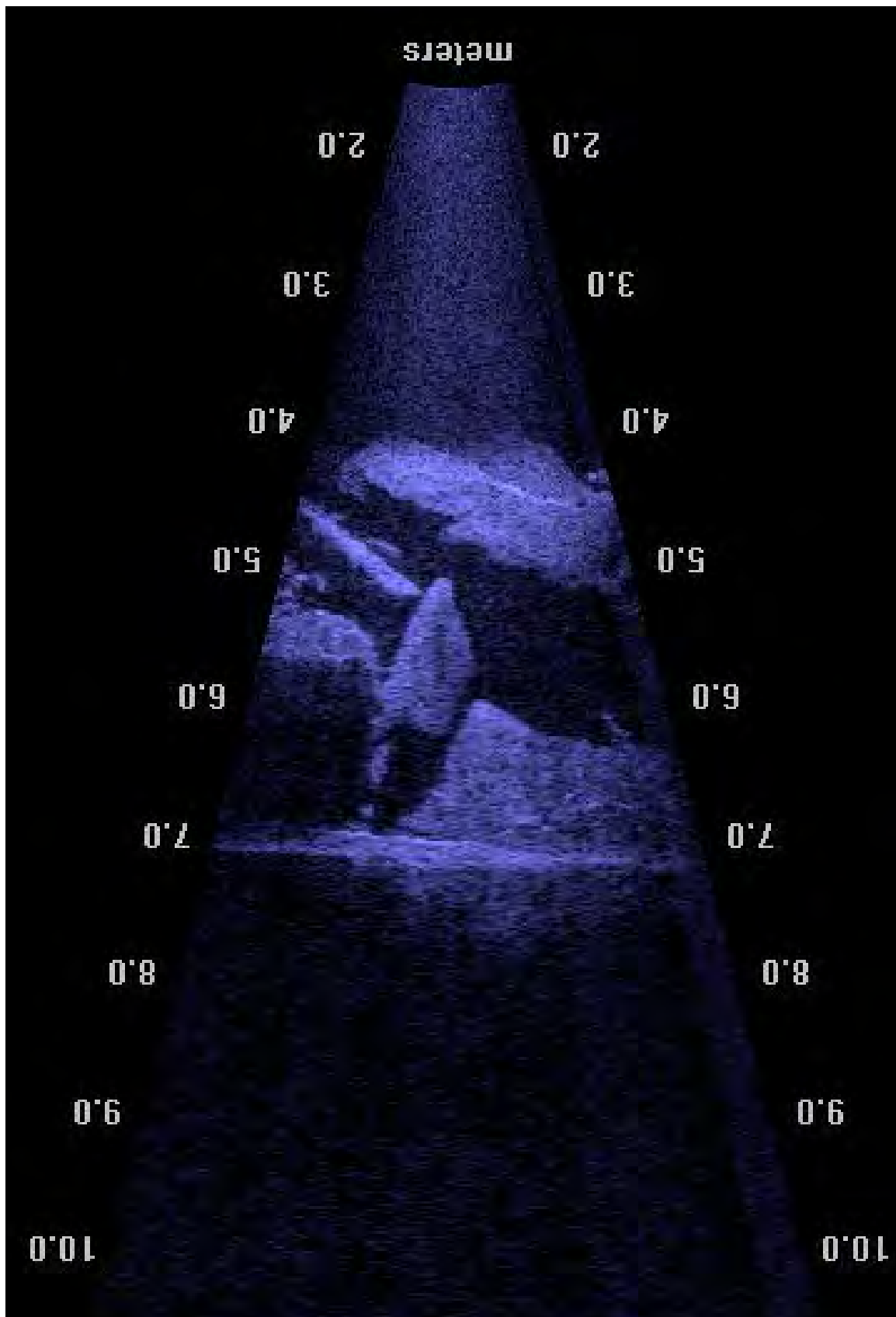Figure 29. Area north of pier 8-9 (Test 5).

Figure 30. Image 30 ft south from pier 9-10 looking back toward apron (Test 6).

Test 7

Test 7 was conducted similarly to Test 6, this time trying to keep the DIDSON aimed at the dam apron. The test started below gate bay 8, moved toward the middle of gate bay 9, back to the middle of 8, and then toward the middle of gate bay 10. The magenta color represents the track during Test 7 as shown in Figure 31. The end of the apron was observed closely all the way across gate bay 9 and to the middle of gate bay 10. No evidence of cracking was observed. The pier between gate bays 9 and 10 and the area below the pier is shown in Figure 32.
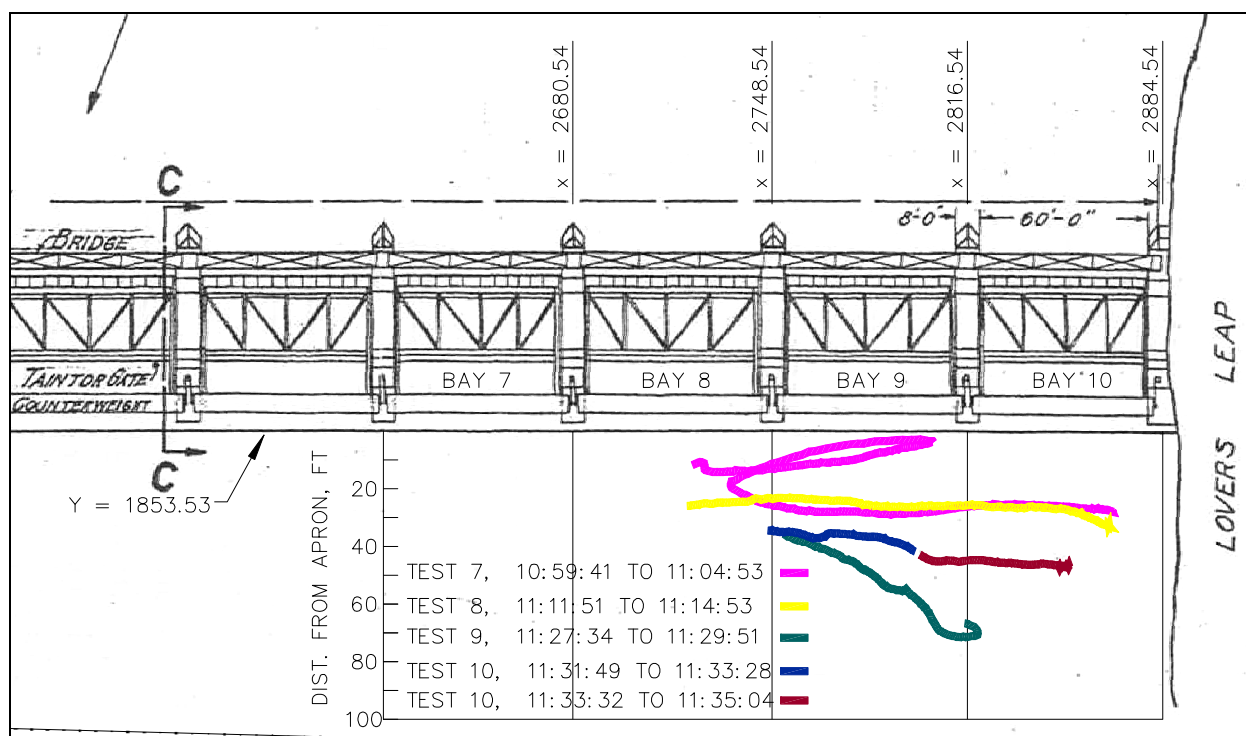

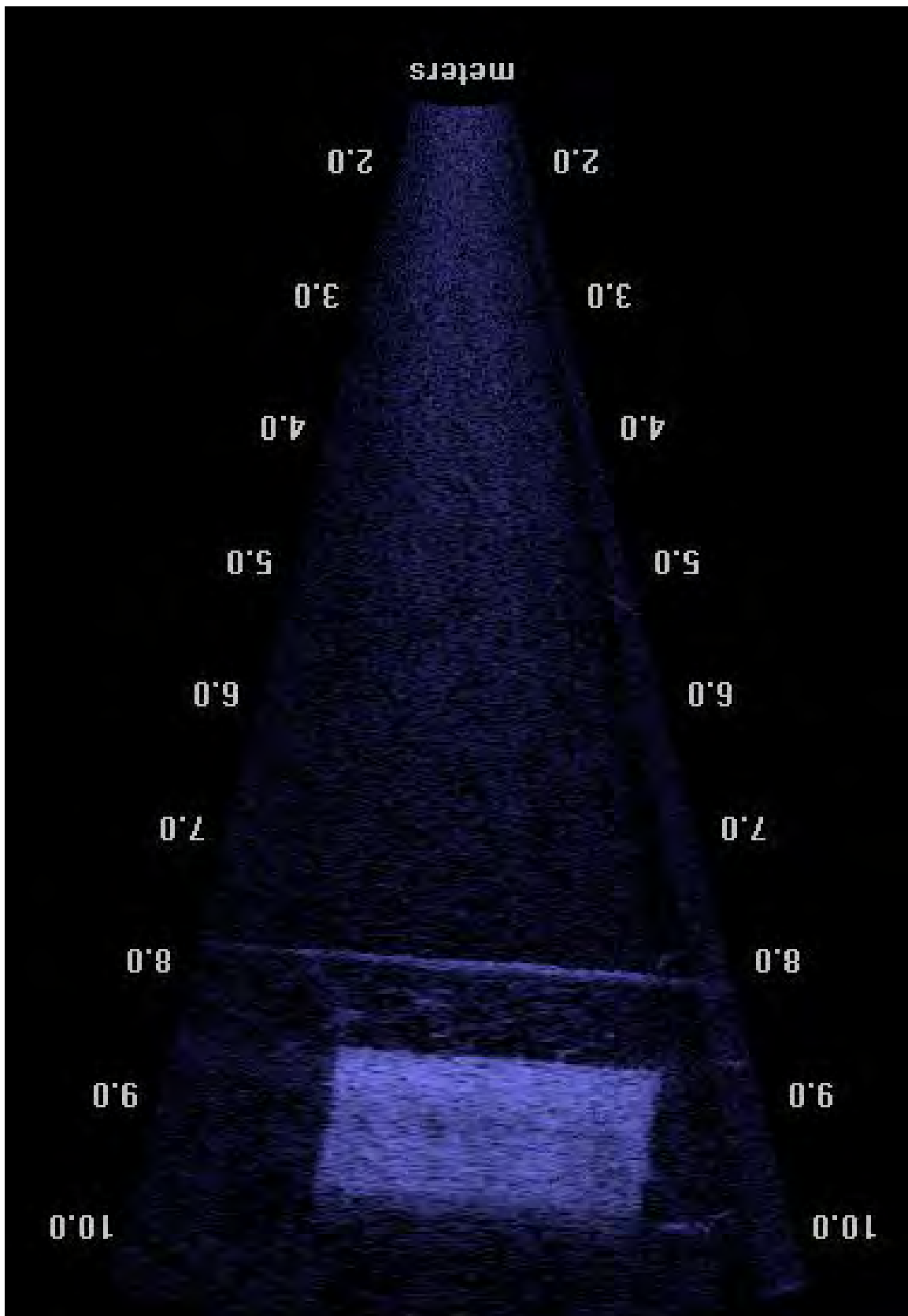Figure 31. Boat locations during Tests 7–10.

Figure 32. Pier 9-10 and area below apron.

Tests 8–10

Test 8 began behind gate bay 8 and moved toward gate 10 as seen in Figure 31. The DIDSON was aimed at the area below the apron for this test. The bottom was more than 20 ft from the DIDSON behind gate bay 8 and through gate bay 9 and started to rise as gate bay 10 was approached. Figure 33 is an image of the bottom about 26 ft downstream from the dam apron and near the middle of gate bay 9. For Test 9, the boat was moved farther downstream below gate bay 9 and the bottom in this area was observed. The trolling motor was used to guide the boat during this test to see if a track more parallel to the dam could be accomplished. It was difficult to determine the location of the image real time without seeing a portion of the dam. The boat also tended to move downstream as the track was run. The boat was moved closer to the dam and the area behind gate bays 9 and 10 was observed again during Test 10. Figure 34 shows the area out from pier 9-10 toward the dam apron. The dam apron is the horizontal feature at the bottom of the figure.

Test 11

The DIDSON was rotated to get different image coverage and placed back at 8 ft below the water surface. The boat track during this test is shown in Figure 35. The test was initiated at the pier between gate bays 9 and 10 and then the boat moved toward gate bay 8 and then toward gate bay 10. A view of the pier between gate bays 8 and 9 is shown in Figure 36. This figure is a good reference for Figure 37, which shows where the downstream face of the dam apron intersects the bottom of the river. This view was observed on the DIDSON from the pier between 8 and 9 all the way to the south edge of bay 10. Figure 38 shows the downstream face of the apron toward the south side of gate bay 10 where the apron starts getting close to the bank. There was no evidence of significant undermining of the dam apron or apron cracking. The track was repeated and the images were verified.
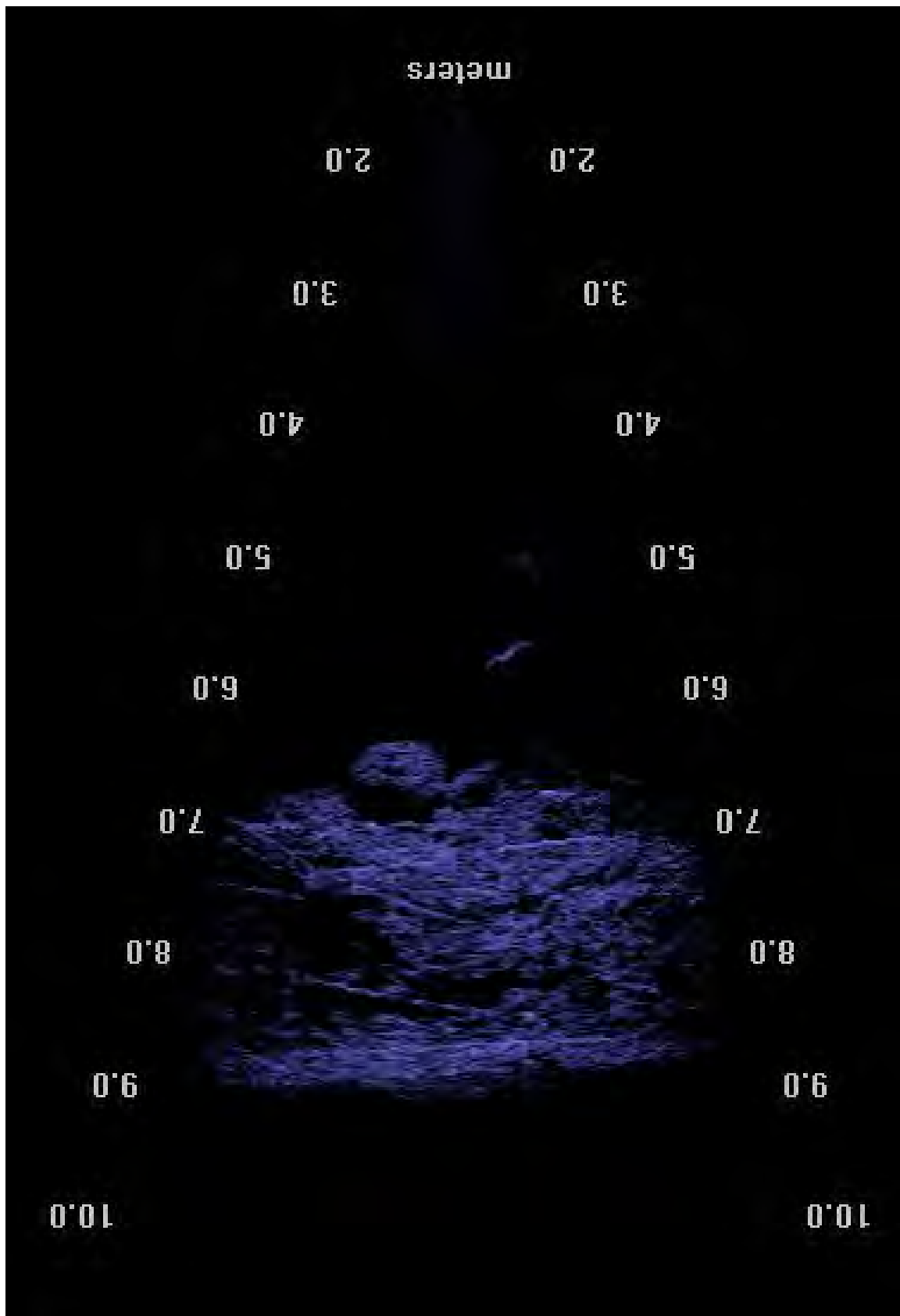
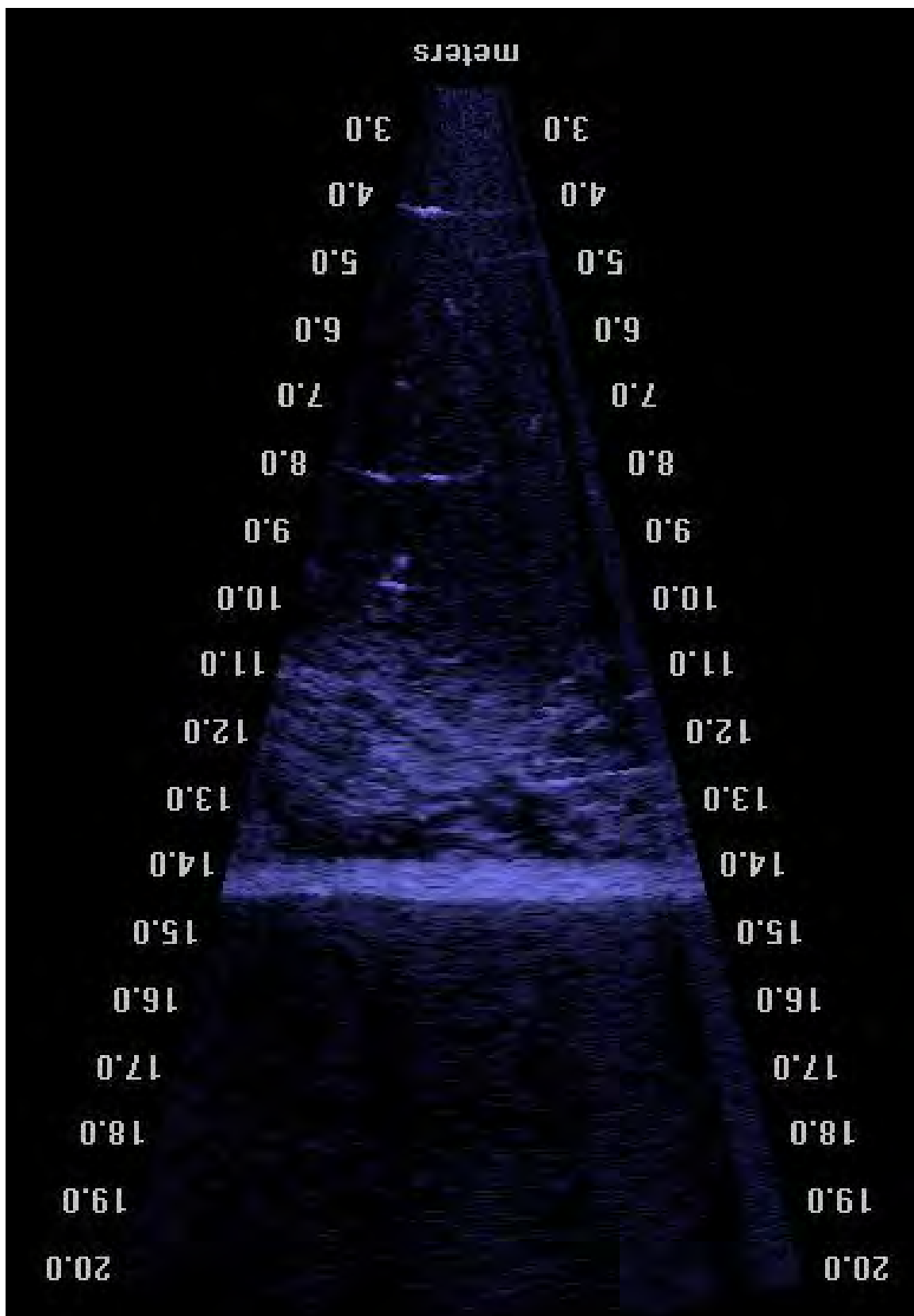Figure 33. Image of bottom 26 ft from dam apron in middle of gate bay 9.

Figure 34. Area downstream from pier 9-10 towards the dam apron (apron is horizontal feature at bottom).
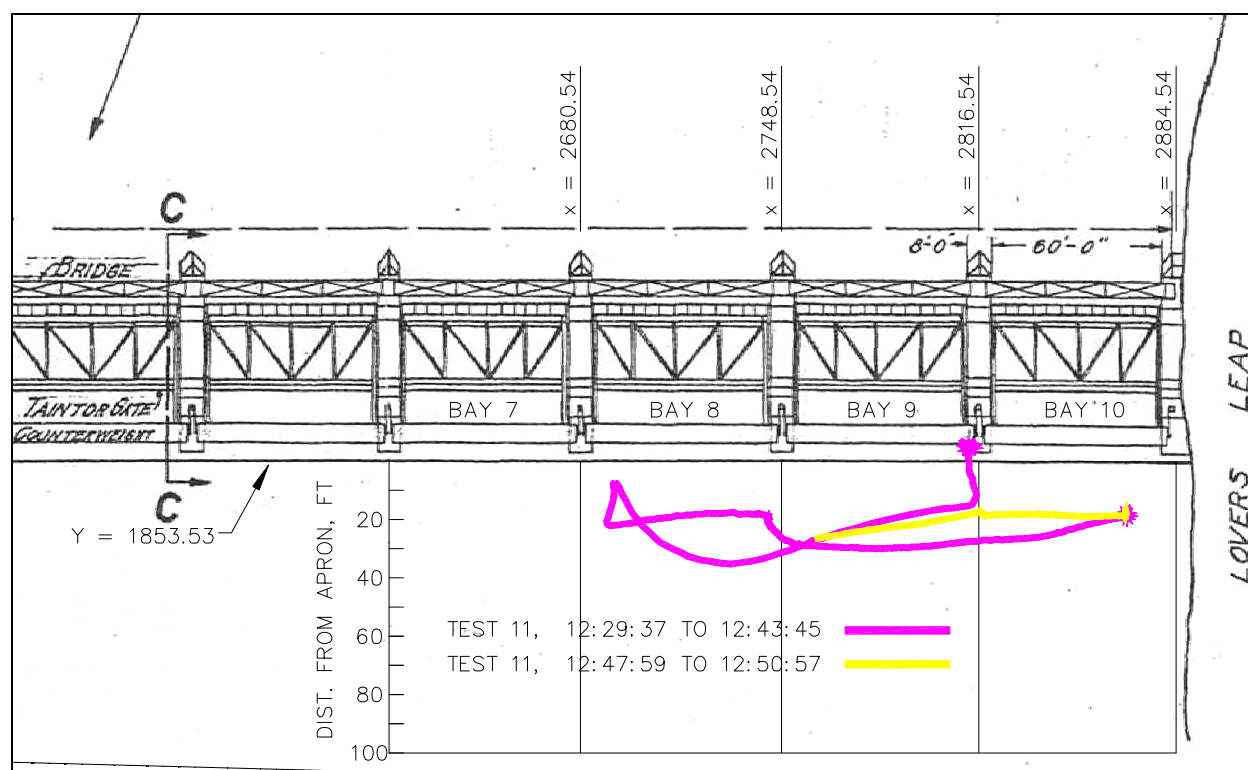
Figure 35. Boat location during Test 11.

Demonstration discussion

The downstream face of the dam apron is a vertical concrete wall that appears to be about 6 ft thick. The area underneath the apron appears to be rock and also has a vertical face to the intersection with the bottom. On the north side of the pier between gate bays 8 and 9, the apron is about the same elevation as the bottom for a distance of about 15 ft from the pier. In this area, the bottom begins to drop off from the apron elevation around 10 ft downstream from the dam apron. Moving south toward the pier, the vertical distance from the top of the apron to the river bottom appears to be between 11 and 12 ft. This distance increases to over 16 ft on the north side of gate bay 9 and then the distance decreases moving to the south toward gate bay 10. This distance between the top of the apron and the bottom reaches about 6 ft near the middle of gate bay 10.
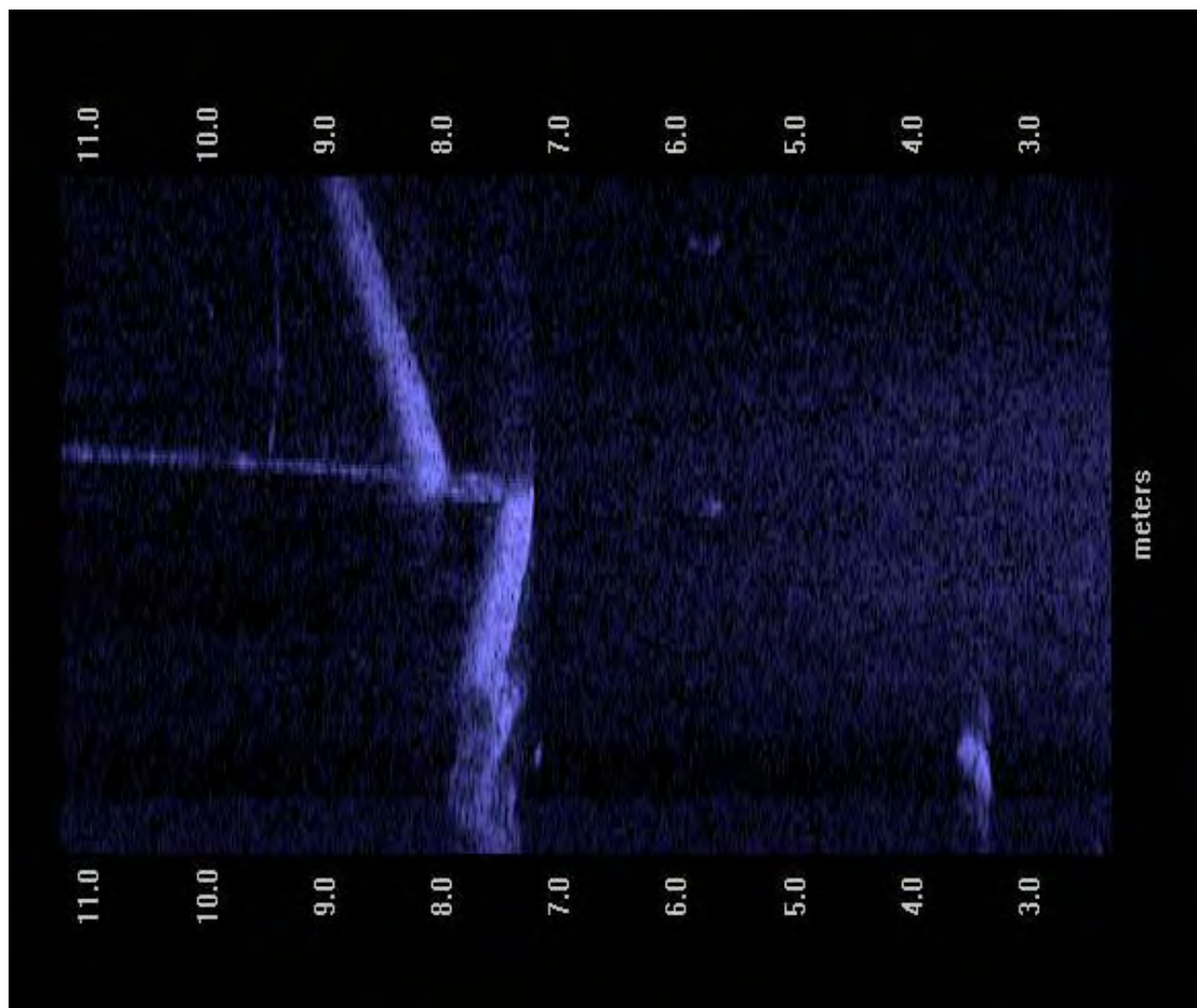
Figure 36. View of pier 8-9 and area below dam apron.

Demonstration summary

The images from the DIDSON show that a deeper area is present down-stream from gate bay 9 and about halfway into gate bay 10. No evidence exists of the dam apron being undermined or undergoing any significant cracking of the apron. The demonstration showed that the DIDSON could be used to identify scoured areas suspected underneath a dam apron or stilling basin. Improvements to identify the location of the DIDSON could be made more quickly if additional funding were available. A GPS system could be better utilized to track boat location and a depth sounder may help locate the camera position.
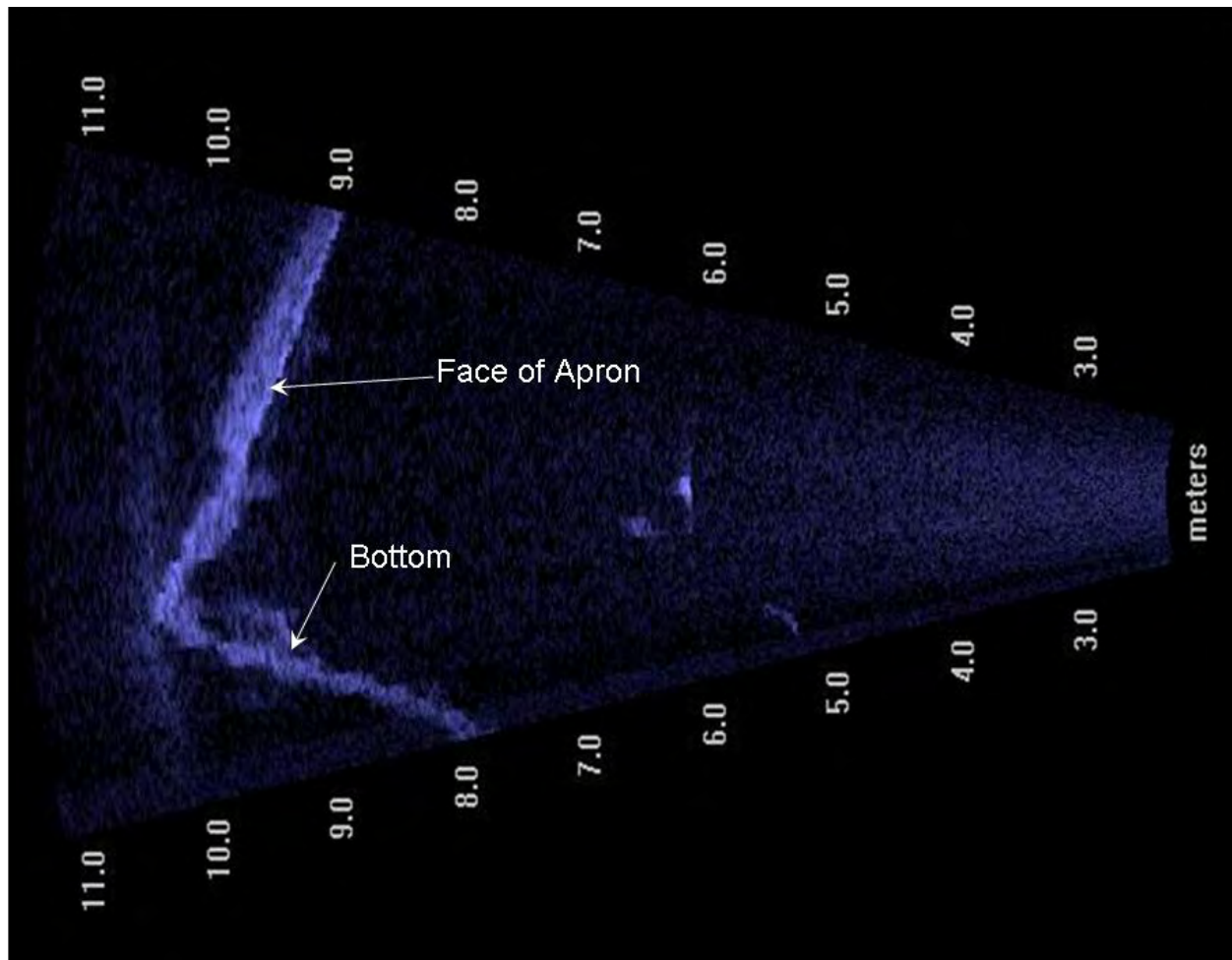
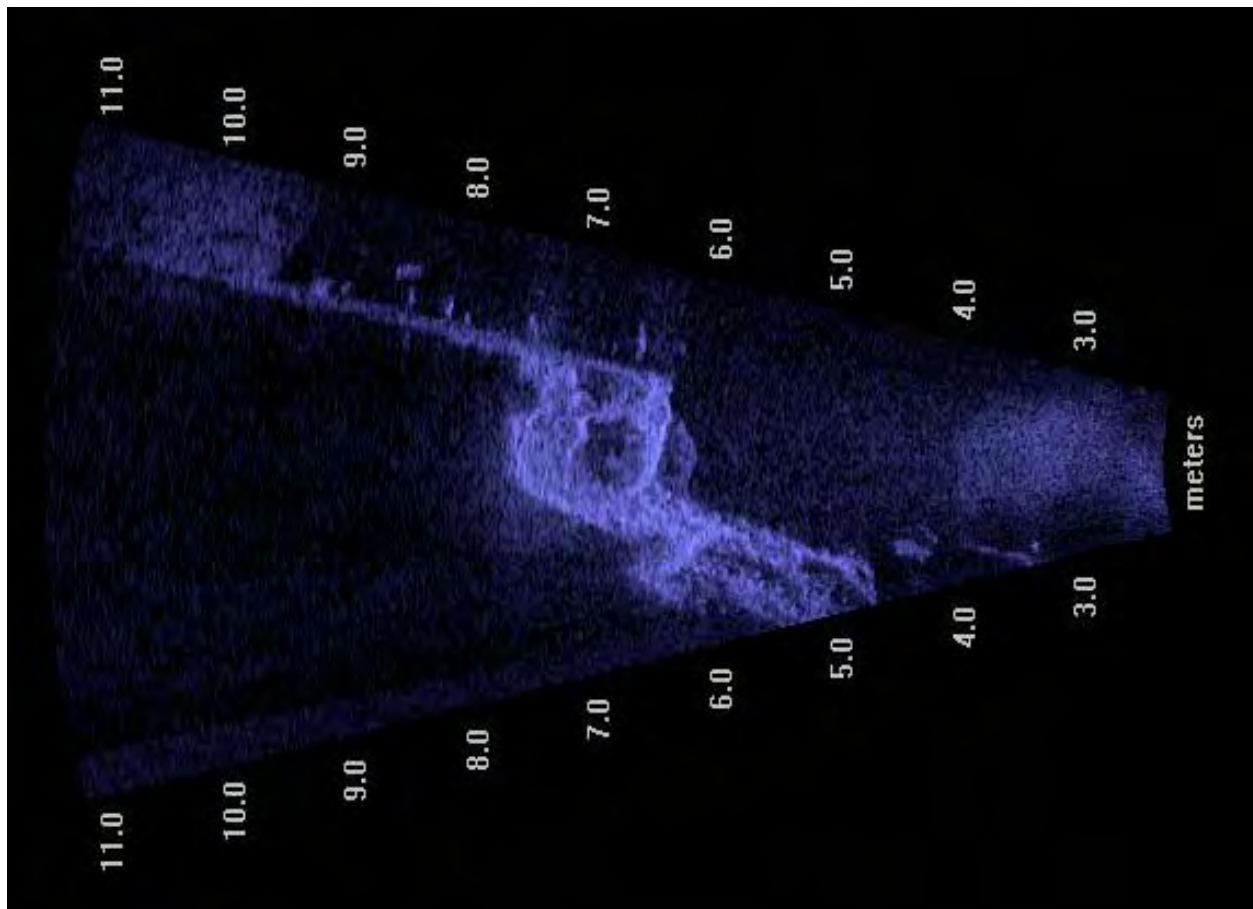Figure 37. Intersection of dam apron and bottom behind pier 8-9.

Figure 38. View of downstream face of apron on south side of gate bay 10 (Test 11).

7   Conclusions and Recommendations

The research performed in this work unit was intended to serve as guidance for detecting and evaluating existing scour protection. Periodic hydrographic surveys are recommended to document the condition of the existing riprap and adjacent bathymetry. Comparing surveys in time should provide the information needed to assess whether scour has or is occurring. The example shown in Chapter 4 is one method to perform an assessment. Hydrographic surveys should also be performed immediately after an extreme flow event, a gate malfunction, or a navigation accident that involves the dam or lock.

If the hydrographic survey indicates significant scour or movement of the original scour protection has occurred since the previous survey, additional steps should be taken to determine the extent of the scour. A map produced by a multi-beam sonar will provide the information necessary to determine the extent of scour repair required. The St. Louis District has used the multi-beam sonar to successfully map scoured areas near some of their navigation projects, and they should be contacted if use of the multi-beam sonar is being considered.

Scour immediately adjacent to the structure should be investigated promptly. The acoustical camera described in Chapter 6 is a good tool for the detection of structure undermining or cracking. ERDC personnel are continuing to conduct research and development on ways to deploy and better utilize the camera. Remote operation techniques are being investigated and better graphics displays are being developed. The field tests performed at Starved Rock Dam and described in Chapter 6 demonstrated that the camera can detect scoured areas in sufficient detail to determine if the structure has been undermined or has cracks.

The procedures described in Chapter 5 are examples of methods to determine the reliability of the existing scour protection. Failure of the scour protection does not imply that structural failure is eminent. The dam, spillway, and stilling basin also have to be evaluated along with the scour protection to determine the project state. The Corps is now using risk and reliability analyses to economically assess project rehabilitation needs. The Planning Center of Expertise for Inland Navigation (USACE Great

Lakes and Ohio River Division) has developed probabilistic simulation models capable of estimating the expected value of future costs given different performance response probabilities and their associated consequences for repair costs and navigation impacts. These models were developed primarily for locks and lock components to maximize benefits and optimize the timing of lock component replacement, but could be modified to include scour protection rehabilitation. Since risk and reliability analyses should be standardized as much as practical, the Planning Center of Expertise for Inland Navigation personnel should be contacted for the latest analysis techniques that could be used for scour protection rehabilitation. Risk and reliability analysis was applied in the Marmet, Greenup/Myers Feasibility and Chickamauga Feasibility Studies, and the London Lock and Dam and Chicago Lock Rehabilitation Reports.

Key scour-related issues identified by Corps Districts were listed in Chapter 1. The first was the uncertainty of horizontal position from hydrographic survey soundings. The need to know horizontal location within a few feet can be important at the downstream end of the dam apron, stilling basin, or adjacent to a structure where the scour protection generally begins. A few feet of discrepancy horizontally can result in a critical discrepancy vertically. The condition of the scour protection immediately adjacent to the structure needs to be known. If soundings indicate an area where substantial scour protection has been displaced, divers, the multibeam sonar, or the acoustical camera should be used to verify this information.

Another issue was the difficulty divers sometimes have when trying to assess the extent of scour especially underneath the structure. The use of video cameras might assist the divers if the water is fairly clear. Since the water is usually not clear, the acoustical camera can be used to help look at the scour protection and underneath the structure. The acoustical camera can be mounted on remotely operated vehicles if divers are not available or if the area is not accessible to divers.

An important question concerning scour is when the scour starts to threaten the structural integrity of the project. The primary function of the scour protection is to keep the foundation material in place underneath the structure. If loss of foundation material begins to occur, structural failures become very probable. Displacement of significant scour protection adjacent to the structure is an obvious indication that loss of

foundation material may be occurring. The acoustical camera might be used to try and determine if foundation material is in jeopardy. Ground penetrating radar has been used successfully by Xu et al. (2006) to assess the foundation material underneath concrete aprons. This technology may be worth investigating further to determine applicability for assessing condition of foundations. Scour protection can sink due to loss of filter material through piping. The ground-penetrating-radar might also be able to detect sunken stones and/or the total thickness of the stone protection.

Excessive scour can be caused by a single event. A severe gate malfunction or navigation accident can lead to rapid loss of scour protection. Immediately following such an occurrence, hydrographic surveys should be made to assess the damage. If the scour protection immediately adjacent to the structure has been totally displaced, action should be taken immediately to repair the scour protection. If some damage has occurred, but there is still evidence that some scour protection material is in place, the area should be monitored for a period to make sure further displacement is not occurring.

The decision to replace missing rock protection is affected by other factors such as the condition of the dam, the stilling basin, and the accompanying foundations. The Emsworth Locks and Dam Major Rehabilitation Report, completed in 2001, provides guidance on evaluating the dam and stilling basin as well as the scour protection. The Pittsburgh District should be contacted for additional information on the Emsworth Rehabilitation project. If a structure is in immediate danger of failure due to loss of foundation material, the scour protection should be repaired as soon as practical. If some rock is missing and the dam or stilling basin foundation material is intact, the repair could be postponed. If a significant flow event, a gate malfunction, a navigation accident or anything else that might cause additional damage to the scour protection occurs, an inspection of the scour protection should be done as soon as possible. If the foundation material has been exposed, the repair should be done quickly.

References

Harr, M. E. 1987. *Reliability-based design in civil engineering*. New York: McGraw-Hill.

Hite, J. E., Jr. 1988a. *Scour protection downstream from gated low-head navigation dams*. REMR Technical Note HY-N-1.6. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

_____. 1988b. *Scour protection downstream from uncontrolled fixed-crest dams*. REMR Technical Note HY-N-1.5. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Maynord, S. T. 1998. Bottom shear stress from propeller jets. *Proceedings from Ports 98 Conference*, Reston, VA, ASCE, 2:1074–1083.

Melby, J. A., and P. F. Mlakar. 1997. *Reliability assessment of breakwaters*. Technical Report CHL-97-9. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Headquarters, U.S. Army Corps of Engineers (HQUSACE). 1987. *Hydraulic design of navigation dams*. Engineer Manual EM 1110-2-1605. Washington, DC.

_____. 1992. *Engineering and design: Reliability assessment of navigation structures*. Engineer Technical Letter ETL 1110-2-532. Washington, DC.

Xu, X., J. Wu, J. Shen, and X. He. 2006. Case study: Application of GPR to detection of hidden dangers to underwater hydraulic structures, ASCE. *Journal of Hydraulic Engineering* 132(1):1–12.

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14. ABSTRACT

   Scour occurs in the vicinity of essentially every navigation dam constructed. Scour in this report refers to the displacement of natural or engineered materials by flowing water in the vicinity of a navigation project. The severity of the scour depends on many operational and site conditions. To maintain the functional performance of the project, detection and evaluation of the scour and repair or replacement of the scour protection near these locks and dams are necessary. If severe scour exists, rehabilitation of the dam and appurtenant structures may be needed to maintain the structural integrity of the dam. Periodic inspections using hydrographic surveys and divers have typically been used to assess the condition of the need for repair. These methods do not always provide enough information to adequately assess the extent of scour and the repair and/or rehabilitation requirements. This report describes other methods to assess the condition of the existing scour protection and provides examples of reliability analyses that can be used for risk-based decision making.

15. SUBJECT TERMS

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