St. Anthony Falls Hydraulic Laboratory
Mississippi River at Third Avenue S.E.
Minneapolis, Minnesota 55414

Project Report No. 257

# POWERHOUSE APPROACH FLOW STUDY FOR MISSISSIPPI RIVER LOCK AND DAM NO. 2 HYDROPOWER PROJECT

by

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and

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Prepared for

City of Hastings

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# I. INTRODUCTION

A 5 MW hydroelectric generating facility is currently under construction on the Mississippi River at Lock and Dam No. 2 near Hastings, Minnesota. As part of its licensing agreement, the City of Hastings was required to have a model study done to ascertain that the impact of the power plant on navigation into and out of the lock and on scour potential of the new facility would be negligable or acceptable. The model study was conducted at the St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, Minnesota. For that study, a 1:72 scale fixed bed model was constructed of a river reach extending 1-1/3 miles upstream and 2/3 mile downstream of the dam. Upon completion of the tests required for the navigation study, it was decided that the model would further be used to study some aspects of the powerhouse approach flow.

## II. OBJECTIVES AND LIMITATIONS OF STUDY

The study of a powerhouse approach and intake flow normally addresses a number of problems common to such a facility. These include vortex formation, non-uniform velocities at the intake, trash accumulation, and intake head losses. Unfortunately, none of these problems can be reliably investigated using a 1:72 scale model due to scale effects. Typically, investigations of this sort employ models larger than one at a 1:72 scale.

Since cost and time considerations prohibited the building of a larger model for the Hastings powerhouse intake, it was decided that the available 1:72 scale model would be used with the objective of studying only flow separation and flow direction in the powerhouse approach. None of the intake problems mentioned above could or would be investigated in this study. It was believed, however, that improvement of the approach flow by minimizing or eliminating flow separation was likely to also improve intake velocity profiles and reduce approach head losses, as well as reduce the tendency for vortex formation. It should be stressed that <u>no conclusions can be drawn from this report regarding the likelihood of vortex formation, intake velocity uniformity, intake head losses, or trash accumulation based on the results of this study.</u>

## III. THE MODEL AND ITS OPERATION

The region of the 1:72 model that concerns the purposes of this study extends from the powerhouse intake upstream approximately 70 ft from the upstream Boule pier face and from the riverward wall of the unused lock to the first tainter gate. In this area, riverbed topography was constructed from drawings provided by the 1985 scour protection plan drafted by the U.S. Army Corps of Engineers, St. Paul District. Lock and dam structures were likewise built to Corps of Engineers specifications, whereas the powerhouse was designed from Mead and Hunt, Inc. drawings. Although simplifications were made in the construction of the lock wall and powerhouse to reduce manufacturing costs, it was decided that flow patterns and, in particular, flow separation in the approach, would be accurately represented as long as one stayed at least 15 ft upstream of the intake.

The model was operated according to Froude similarity. River flows of 5,400 cfs (both turbines operating at capacity, no flow through the dam) and 2,700 cfs (one turbine operating at capacity, no flow through the dam) were modeled. Pool elevation was kept at 687.0 ft (M.S.L., 1912 adj.) for these flows. It was felt that no flow through the dam represented the "worst case" since much of the separation in the approach, particularly that on the riverward side, was due to lateral velocities adjacent to the upstream face of the dam and those would be most pronounced with all tainter gates closed and the powerhouse operating at capacity. A river flow of 38,000 cfs (maximum river discharge before powerhouse shutdown) was run with a number of the potential design modifications in place, as well as for the base (no modification) condition to verify this assumption.

Flow patterns were documented by overhead photography of dye traces for subsurface flow and confetti motion for surface flow. All photographs of confetti were taken with an exposure time of 1/2 second to facilitate comparisons. Additionally, velocity profiles were taken with a Marsh-McBirney Model 523 electromagnetic current meter at 10 positions in the powerhouse approach (Fig. 1). The measuring probe is a sphere 1/2 inch in diameter and reportedly has a spherical measuring volume three times the probe's diameter or 1.5 inches.

## IV. FLOW DOCUMENTATION

### A. Base Conditions

Flow separation in the approach resulting from the original design without modification is documented in Figs. 2 through 4. Significant separation occurs as the flow makes the 90° bend into the approach from both sides. Separation is more pronounced for "two turbine" operation (5,400 cfs) than for the single turbine cases (2,700 cfs). Due to this fact, and for the sake of brevity, only the dye traces for the "two-turbine" case are illustrated here and appear in Figs. 5 and 6. A substantial surface eddy is illustrated in Fig. 7 by floating confetti. Such a surface flow pattern often leads to vortex formation. Additionally, separation occurs on the bed downstream of the scour protection riprap (Fig. 8). It is likely that this flow pattern results in increased turbulence levels, increased approach head loss, and an encouragement of cross stream velocitites in the approach flow contributing to the separation problem. The removal of this obstruction was the basis for the first attempt at approach flow improvement.

### B. Excavation of Scour Protection Riprap

To create a gradually downward sloping bed profile upstream of the powerhouse intake, the Corps of Engineers scour protection plan riprap was removed from the model, as illustrated in Figs. 9 through 11. A transversely more narrow region was tried originally, but proved inferior in its ability to prevent bed flow separation at the outer edges of the powerhouse approach. The resulting approach velocities appear in Figs. 12 through 14. Although substantial improvement is seen in velocity uniformity both in magnitude and direction, significant separation is still in evidence at the walls of the approach, particularly at or near the surface. The dye and confetti patterns verified the presence of separation at the walls and eddying. Again, the single turbine cases proved less severe regarding flow separation than the "two-turbine" flow.

### C. Structural Modifications

After analyzing the effects of upstream excavation on the approach flow, it was decided that excavation alone, although beneficial, would be insufficient to acceptably eliminate separation and eddying in the approach and produce uniform intake velocities, and that further modifications in the form of guide walls and vanes would be needed to attain these goals. After trying many alternatives, four possible modifications proved effective (to varying degrees) in improving the powerhouse approach flow. Four variations of Modification No. 3 and two variations of Modification No. 4 were tested and documented. Flow enhancement may be weighed against construction cost in deciding on a final design. The variations consisted of having parts of the modification submerged 2-1/2 ft below the standard pool elevation versus having them protrude through the water surface. As might be expected, the most effective design modifications proved likely to also be the most expensive.

1. Modification No. 1

Modification No. 1 is illustrated in Fig. 15. It is comprised of a guide wall on the landward side of the approach and a hemicylindrical addition attached to the upstream face of the boule pier. Additionally, the region of the approach adjacent to the landward face of the Boule pier is streamlined by filling in the area indicated. All of these structures extend from the bed through the water surface. The scour protection riprap is excavated as previously outlined.

The influence of this modification is seen in Figs. 16 through 18. The landward guidewall proves quite effective in eliminating separation on that side of the approach where velocities are longitudinal in direction and uniform in magnitude. The riverward modifications are somewhat less successful in preventing separation, although a significant improvement in the flow field results from their implementation. The presence of surface eddies is essentially eliminated with this modification. It should be remembered, however, that scale effects on surface properties and phenomena are severe for a 1:72 model and conclusions should be made accordingly. Specifically, a lack of surface velocities in the model is no guarantee that surface currents (e.g., eddies) will not exist at the site.

2. Modification No. 2

This modification is identical to the previous one except that instead of the hemicylinder, a guide vane is installed near the Boule pier as indicated in Fig. 19. Again, all structural changes extend through the water surface and the upstream riprap is excavated as outlined.

The flow that results from Modification No. 2 is illustrated in Figs. 20 through 25. Flow separation on both sides of the approach is eliminated. Approach velocities are uniform in magnitude and longitudinal in direction. There are no surface eddies in evidence.

This modification is the most effective one found in meeting the design criteria, namely the elimination of flow separation and surface eddies and the achievement of uniform velocities in the powerhouse approach. Aside from economic constraints, this is the design modification of choice.

3. Modification No. 3

In an attempt to find less expensive alternatives to the above modifications while still meeting the design criteria, Modification No. 3 with four variations was developed, tested, and documented. This modification (shown schematically in Fig. 26) consisted of a landward guide wall designed to take advantage of the already existing cofferdam erected for the construction of the powerhouse. Specifically, the landward 35 ft of the cofferdam would be left intact following completion of powerhouse construction. A guide wall configured as a quarter-circle with a 25.5 ft radius would be added to prevent the formation of a separation region downstream from the end of the wall. On the riverward side, the 5 ft wide section of the approach adjacent to the Boule pier would be filled in, as in Modification Nos. 1 and 2. Additionally, a guide vane was designed and implemented. Its downstream edge was located at the upstream limit of the powerhouse approach foundation so that the two structures would be independent of each other. The upstream edge of the guide vane was located so as to not conflict with a proposed log boom that would stretch between the riverward lock wall and the riverward corner of the boule pier. The location of this edge is only a concern for the variation of this modification in which the guide vane protrudes through the water surface. For the variations in which the vane is submerged, the log boom will float above the upper edge of the wall.

The four variations of this modification were all tested with and without riprap excavation and were defined as follows:

Modification 3a - Riverward guide vane and landward guide wall submerged.

Modification 3b - Cofferdam segment of landward guide wall protruding through water surface. The remainder of landward guide wall and riverward guide vane submerged.

Modification 3c - Entire landward guide wall protruding. Riverward guide vane submerged.

Modification 3d - Entire modification protruding through water surface.

All submerged walls had an upper edge elevation of 684.0 ft (M.S.L.) while protruding walls would require an upper elevation of at least 687.2 ft (M.S.L.).

Measured velocities for modification #3 with a river flow of 5,400 cfs (both units operating, no flow through the dam) are shown in Figs. 27 through 34. Velocity measurement and flow pattern documentation were only made for two-turbine operation since single turbine operation had consistently proven to exhibit less severe separation and associated flow problems than flows with both units running for all previous modifications and conditions tested. The documentation thus illustrates "worst case" conditions.

Modification 3a exhibits strong separation on the landward side of the approach both with and without upstream excavation (Fig. 35).

Modification 3b shows significantly less landward separation (Fig. 36) but appreciable riverward separation (Fig. 37) when no excavation is done. With excavation, riverward separation is markedly reduced (Fig. 38) without affecting the landward flow. This variation produces a surface eddy between the cofferdam segment and the remaining portion of the original spillway but no eddying is in evidence further downstream in the approach (Fig. 39).

Modification 3c produces a flow similar to that of 3b in most regards with a small amount of further improvement in separation on the landward side (Fig. 40). As with modification 3b, separation is relatively severe on the riverward side when no excavation is done (Fig. 41) but is virtually non-existent after riprap excavation (Fig. 42).

A surface eddy is present between the cofferdam segment and remaining spillway section but no surface recirculation is in evidence further downstream in the flow (Fig. 43). A significant turbulent wake exists downstream of the submerged guide vane (Modifications 3a,b,c) due to water impacting on the vane from the riverward side and accelerating over and behind the vane (Fig. 44).

Modification 3d exhibits no separation on either side of the approach regardless of whether or not excavation is performed. Somewhat retarded velocities are present in the center of the riverward turbine guide vane. Reduced velocities are also in evidence near the landward wall of the approach. Excavation improves these velocities somewhat and tends to "straighten" flow directions in general. As with Modifications 3b and 3c, an eddy exists on the surface between the cofferdam segment and the remaining spillway section but no surface recirculation is apparent further downstream in the approach.

4. Modification No. 4

The last modification designed and tested is shown schematically in Fig. 45. It is the most economical of all the alternatives developed and consists of a landward wall made from the landward 28.25 ft of the cofferdam protruding through the water surface and a riverward guide vane identical to that of Modification No. 3. As with all modifications, the 5 ft wide area adjacent to the Boule pier is filled in.

Two variations of Modification No. 4 were tested with and without excavation. These were:

Modification 4a - Riverward guide vane submerged 2.5 ft below normal pool, i.e., upper edge at 684.0 ft (M.S.L.)

Modification 4b - Riverward guide vane protruding through water surface.

As noted above, protruding walls require an upper edge elevation of at least 687.2 ft (M.S.L.).

For the same reasons as those given for the testing of Modification No. 3, only a river flow of 5,400 cfs (both units operating, no flow through the dam) was documented for Modification No. 4.

Modification 4a demonstrates a lack of separation in the powerhouse approach (Figs. 46 and 47). Velocities on the landward side are uniform and longitudinally oriented, independent of riprap excavation. Against the riverward wall, velocities are somewhat retarded if the scour protection riprap is not excavated but improve with excavation (Figs. 48 and 49).

Modification 4b likewise results in no separation in the approach flow (Figs. 50 and 51). Landward velocities are nearly identical to those with Modification 4a and again are essentially independent of excavation (Figs. 52 and 53). On the riverward side, velocities are slightly more uniform than those in the case of Modification 4a, both with and without excavation. The differences are marginal, however.

All variations of Modification No. 4 cause an eddy to form between the coffer dam segment and the remaining spillway section (Fig. 54). However, the surface flow downstream from this area shows no tendency towards recirculation.

## D. Performance of Modifications at Higher River Flows

To verify that a river flow of 5,400 cfs represents the "worst case", a flow of 38,000 cfs was established in the model (maximum river flow before powerhouse shutdown) and a number of variations of Modifications 3 and 4 with and without excavation as well as the "base" condition (no modification) were tested. Documentation was limited to photographing dye traces near the walls of the powerhouse approach to visualize separation in those regions and confetti movement to illustrate surface eddies.

As expected, the extent of flow separation was either equal to or reduced from that of the same tests run with a river flow of 5,400 cfs for all variations tested (Figs. 55 through 60). Riverward separation was particularly reduced for the 38,000 cfs flow (Figs. 55 and 58) due to the fact that the flow moves towards that side of the powerhouse approach much more longitudinally when the landward tainter gates are operating than when they are closed. Separation on the landward side may be slightly greater for 38,000 cfs than for 5,400 cfs under base conditions, but for no modification tested did separation appear while testing the 38,000 cfs river flow when there had been none during a 5,400 cfs flow.

## V. DESIGN RECOMMENDATION

To a large degree, the final preferred design modification depends on economic considerations which are outside the scope of this study. However, it is roughly known which possible modifications are relatively more expensive to implement than others. Additionally, since it is not known with certainty that attaining the goals of this study (reduce flow separation, improve velocity uniformity, and eliminate surface eddies in the powerhouse approach) will result in improved turbine efficiency and performance, it would be unwise to choose the design that best satisfies these goals without regard to cost of implementation or to the actual (prototype) effect on turbine operation.

For these reasons, a multiphase implementation is recommended, whereby the impact of a completed phase on powerplant operation is assessed before construction of succeeding phases. In this way, acceptable turbine operation can be achieved with minimum investment.

Although Modification No. 2 achieves the best approach flow, according to the criteria of this study, Modification No. 4 seems to give the best combination of flow improvement and construction economy. The following procedure is recommended for its implementation:

1. The 5 ft wide area adjacent to the Boule pier should be filled in as specified before removal of the cofferdam.

2. The cofferdam segment to remain after the removal of the rest of the cofferdam should be sufficiently supported to withstand the stresses of ice and debris. The coffer dam could then be removed according to Modification No. 4 design.

3. The riverward guidevane should be installed. It should be submerged per Modification 4a specification (i.e., upper edge at Elevation 684.0 ft M.S.L.) and should incorporate devices to facilitate an extension of the upper edge to Elevation 687.2 ft M.S.L. or higher in the style of flashboards, should that be desired at a later time.

4. If the modifications thus far implemented prove insufficient in correcting approach flow conditions, particularly separation and non-uniform velocities on the riverward side, the riverward guide vane should be extended through the water surface to a minimum elevation of 687.2 ft M.S.L. (Modification 4b). This could be done using flashboards which break away under the stresses of flood flows or ice and which are replaced annually if necessary. It should be noted that model results indicate that the addition of flashboards to the guide vane will only marginally improve the

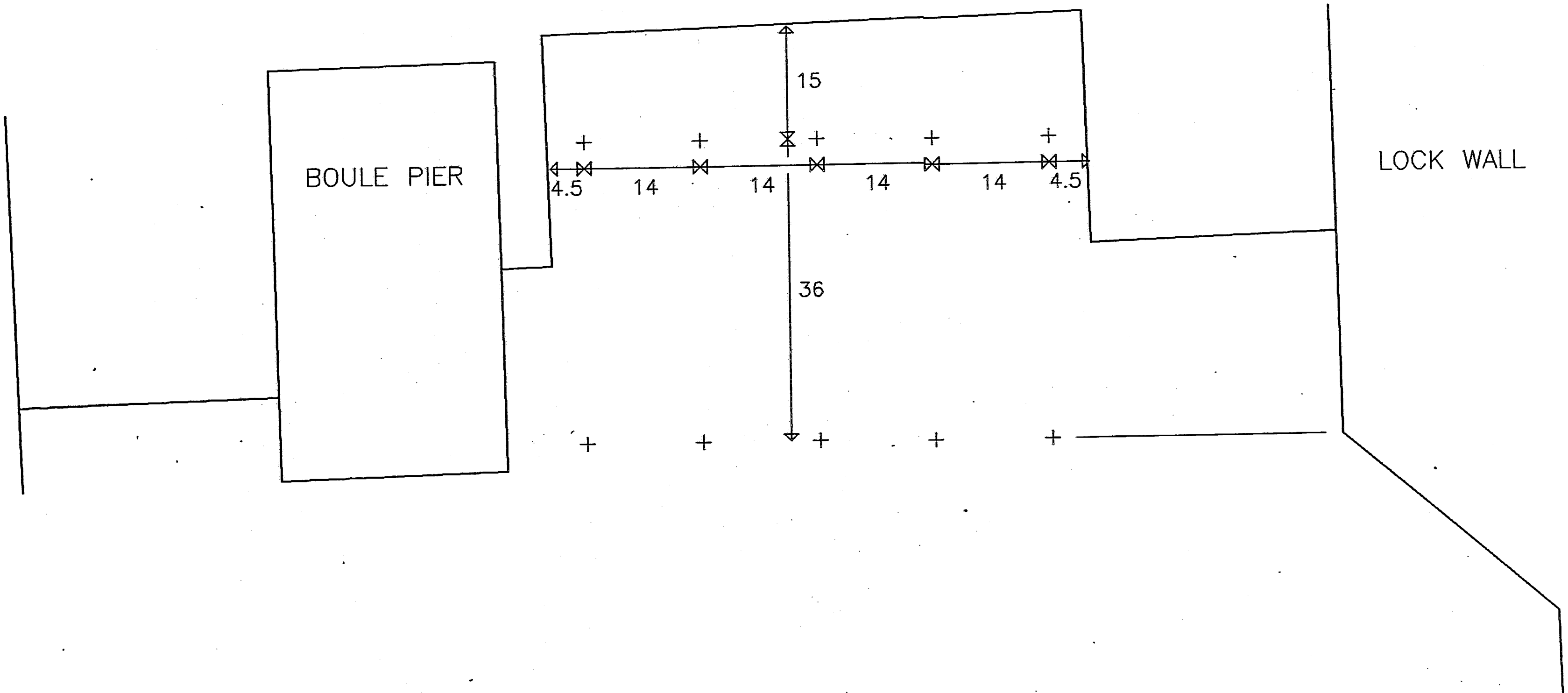
powerhouse approach flow in the absense of upstream excavation (Figs. 48 and 52).

5. Finally, should further flow improvement seem necessary, the Corps of Engineers scour protection riprap should be excavated per Figs. 9 and 10. The Corps will undoubtably have to be consulted regarding this procedure. As can be seen in Figs. 52 and 53, significant enhancement can be expected in the approach flow in regard to velocity uniformity with excavation, particularly in the wake of the guide vane.

## V. CONCLUSIONS

Although the conclusions that can be drawn from flow observations and measurements in the existing 1:72 scale model of Lock and Dam No. 2 regarding powerhouse approach flow are limited, it is clear that intake conditions in the absense of any design modifications will not be ideal. Should no remedial action be taken, it is possible that turbine performance will suffer due to the presence of non-uniform inlet velocities and vorticies. In as much as certain general flow patterns are usually associated with these problems, the correction of the flow patterns should do much to minimize the possibility of deleterious turbine inlet conditions.

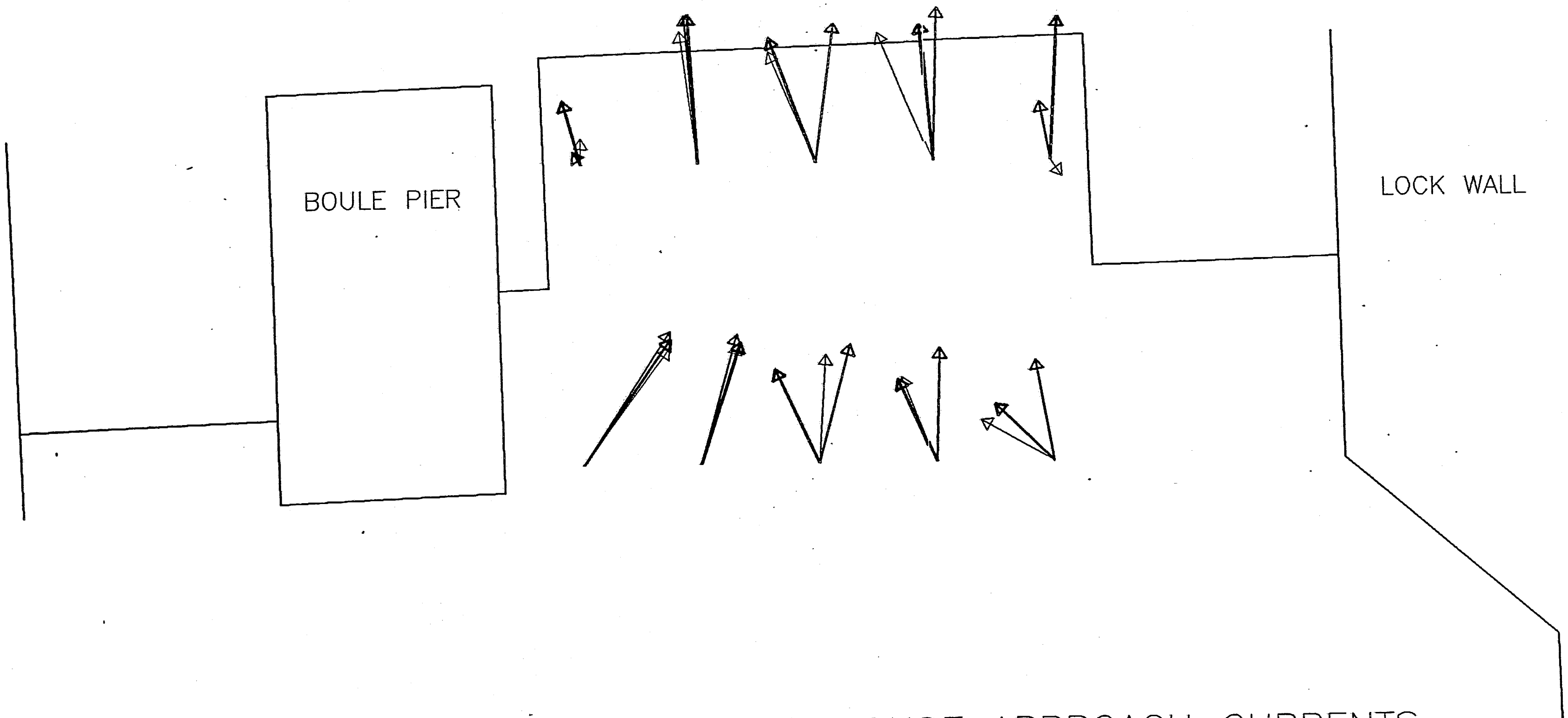
A number of design modification alternatives are contained in this report that make use of the currently existing cofferdam. These can be implemented with good effectiveness with a minimum of construction time and cost. They should be fully considered and decided upon before removal of the cofferdam.




LOCK AND DAM NO. 2 — POWERHOUSE APPROACH CURRENTS
MEASUREMENT LOCATIONS -- DISTANCES IN PROTOTYPE FEET

ST. ANTHONY FALLS HYDRAULIC LABORATORY - 1987

**Figure 1**



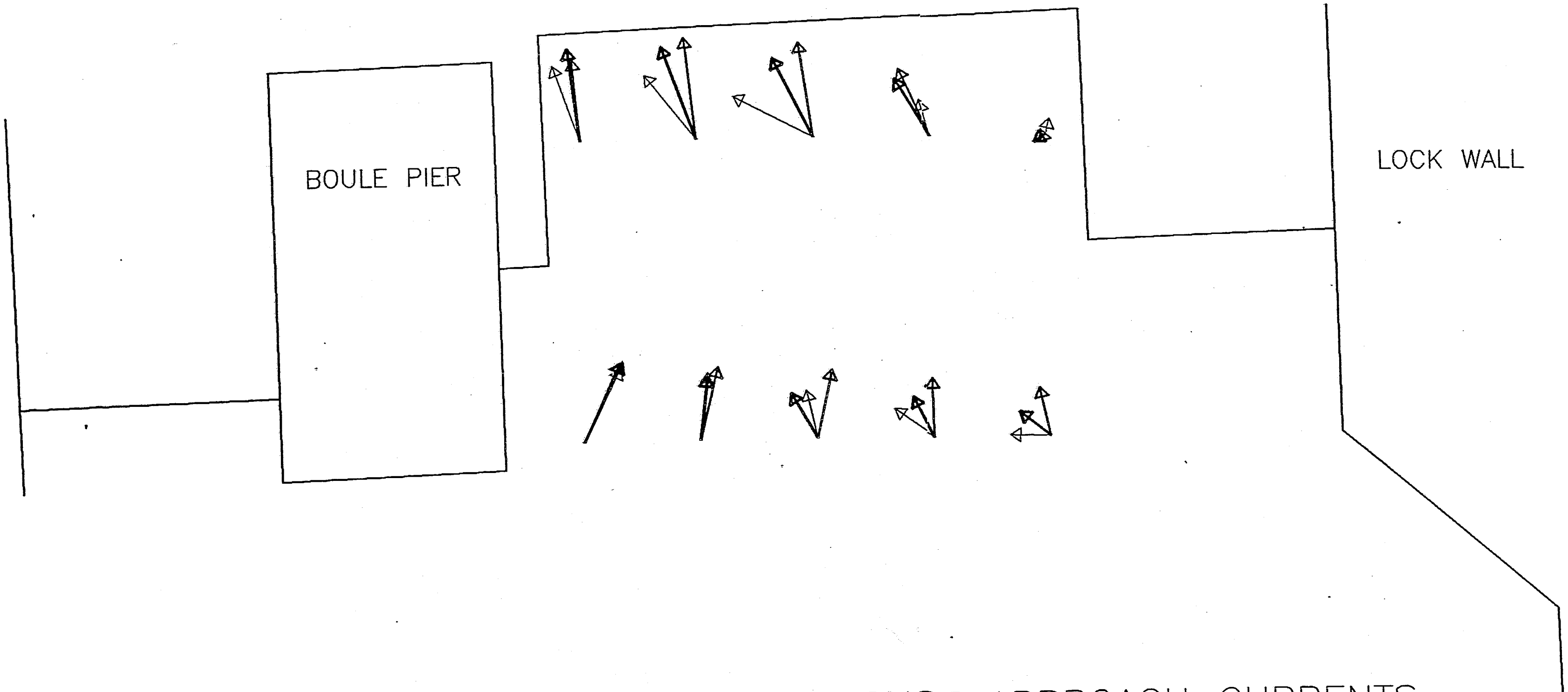

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
BASE TEST, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

→ MEASURED 3 FT. BELOW WATER SURFACE
→ MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
→ MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 2**




LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS

BASE TEST, RIVERWARD UNIT OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

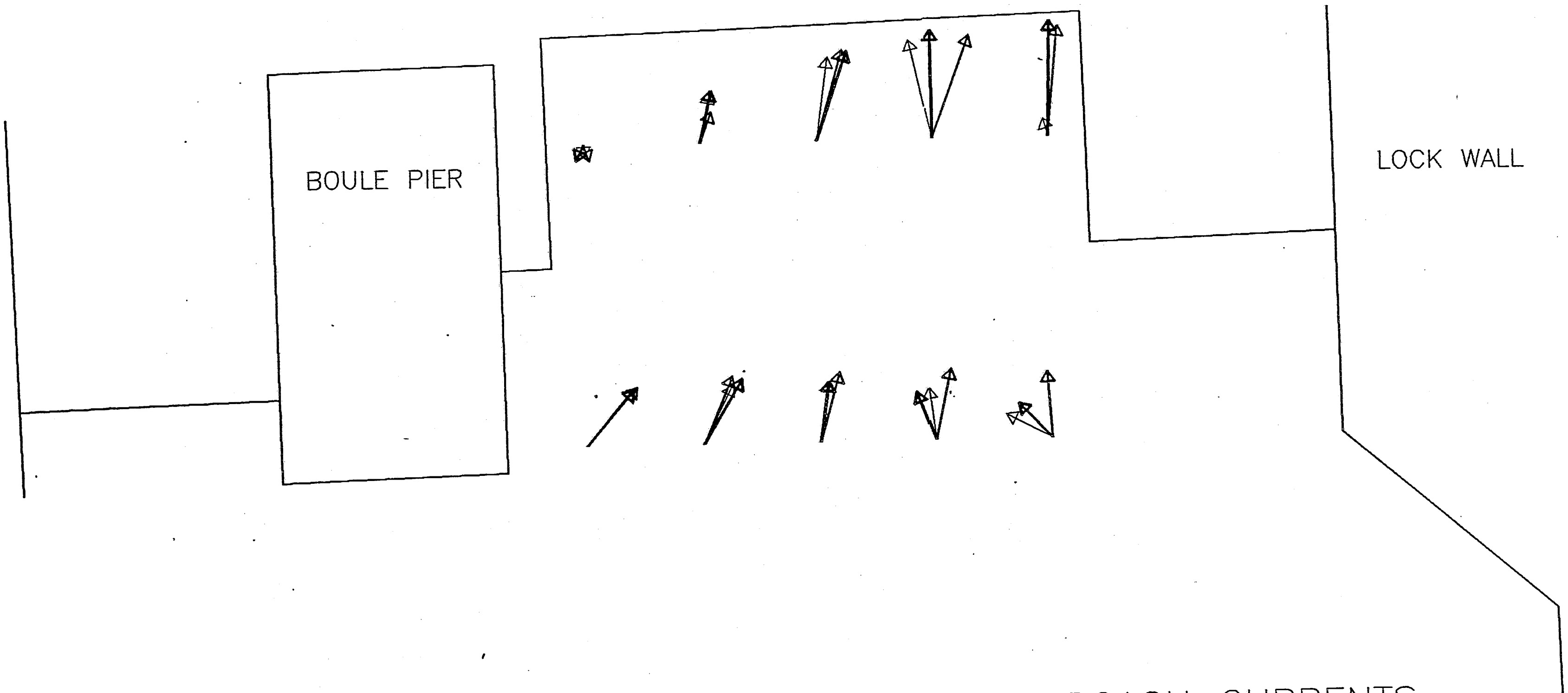
MEASURED 3 FT. BELOW WATER SURFACE

MEASURED MIDWAY BETWEEN WATER SURFACE AND BED

MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 3**




LOCK AND DAM NO. 2 — POWERHOUSE APPROACH CURRENTS
BASE TEST, LANDWARD UNIT OPERATING
NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY — 1987

**Figure 4**

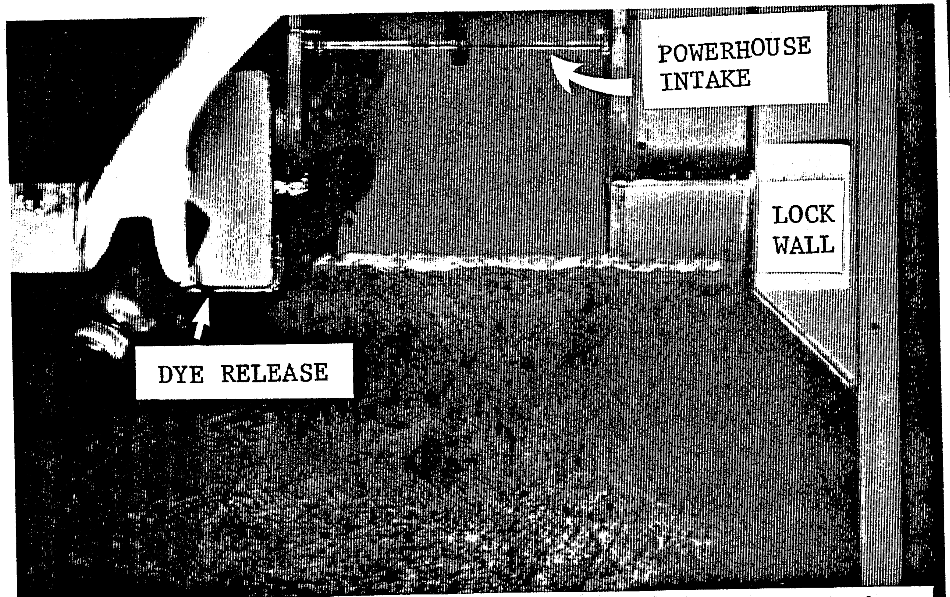



Figure 5. Dye trace, base test, both units operating.

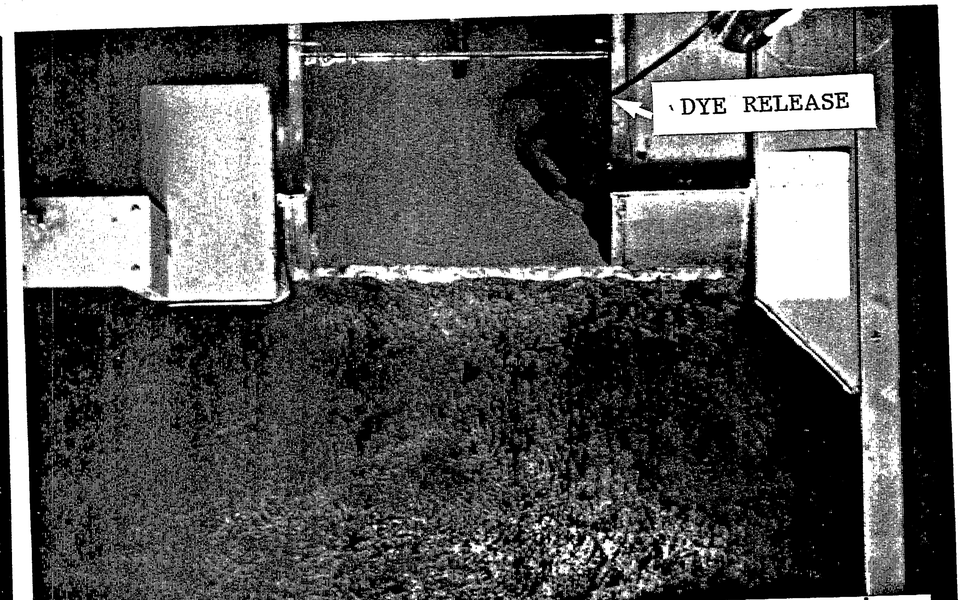



Figure 6. Dye trace, base test, both units operating.

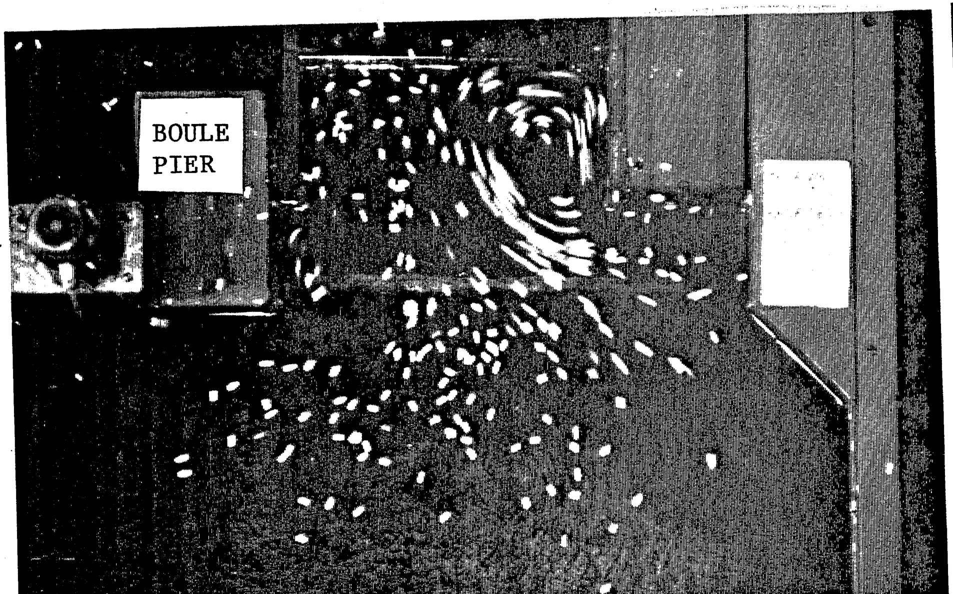
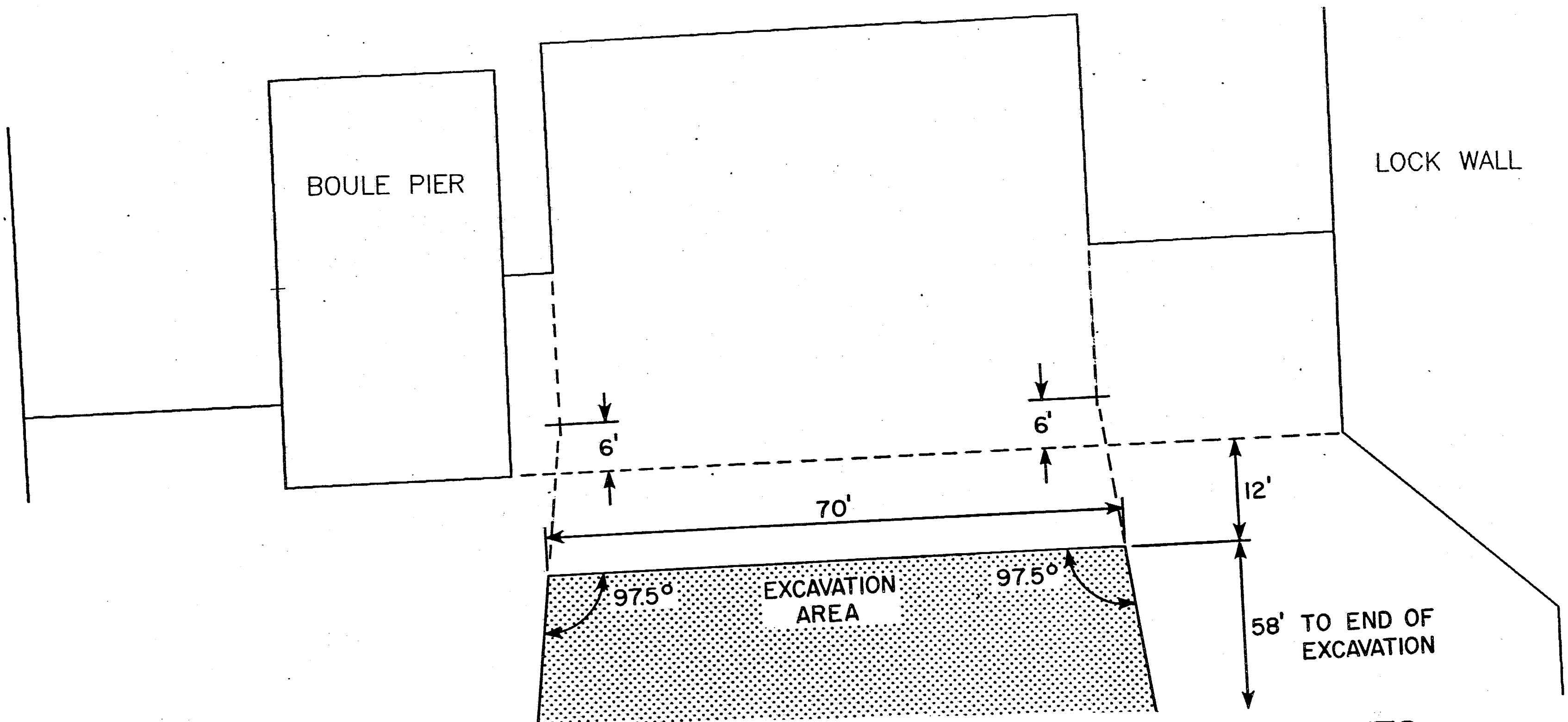



Figure 7. Confetti trace, base test, both units operating.

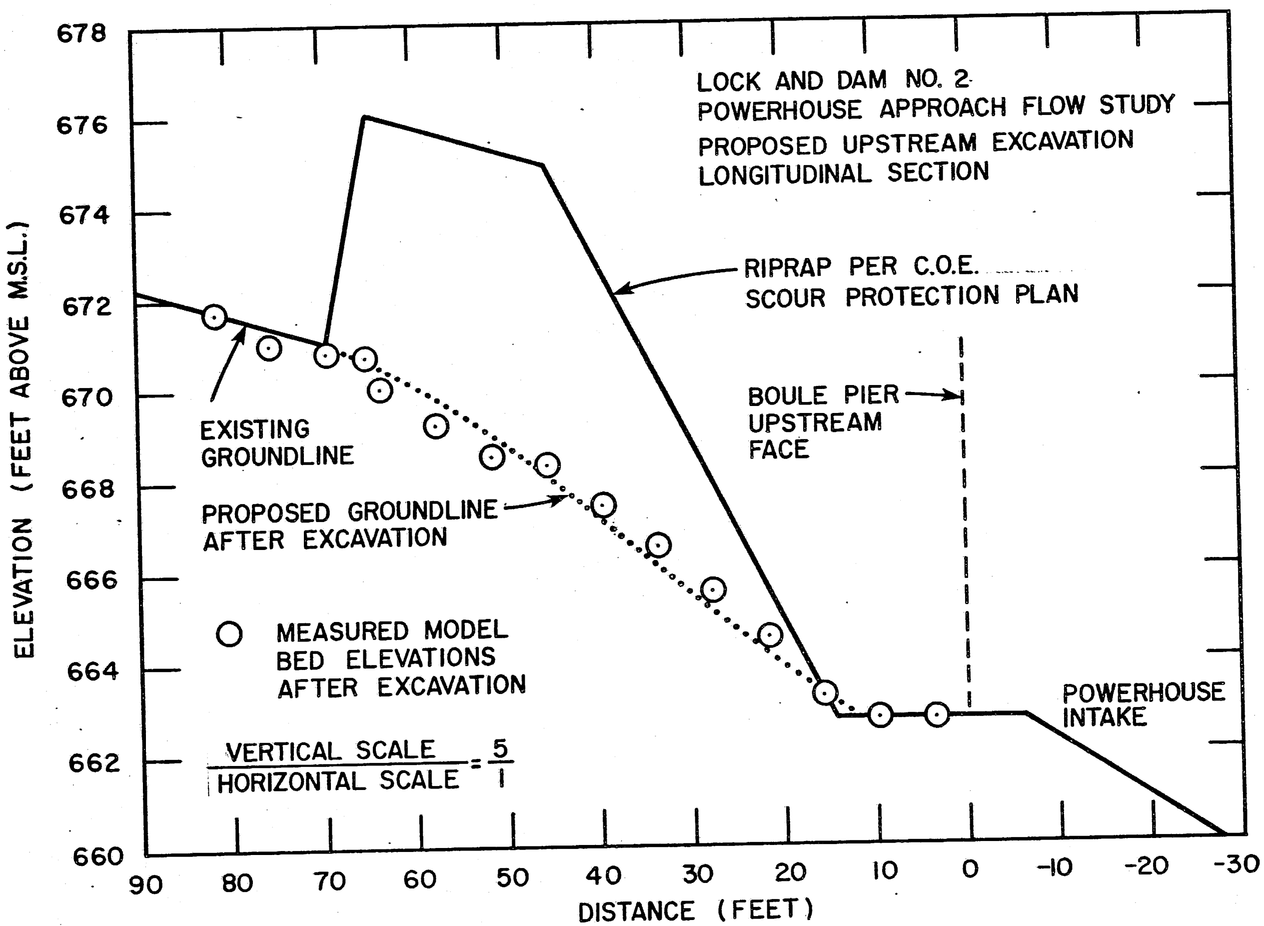

Figure 8. Dye trace, base test, both units operating.




LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
PLAN VIEW OF PROPOSED EXCAVATION

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 9**



LOCK AND DAM NO. 2
POWERHOUSE APPROACH FLOW STUDY
PROPOSED UPSTREAM EXCAVATION
LONGITUDINAL SECTION
RIPRAP PER C.O.E.
SCOUR PROTECTION PLAN
BOULE PIER
UPSTREAM
FACE
EXISTING
GROUNDLINE
PROPOSED GROUNDLINE
AFTER EXCAVATION
MEASURED MODEL
BED ELEVATIONS
AFTER EXCAVATION
VERTICAL SCALE / HORIZONTAL SCALE = 5/1
POWERHOUSE
INTAKE
ELEVATION (FEET ABOVE M.S.L.)
678
676
674
672
670
668
666
664
662
660
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
DISTANCE (FEET)


Figure 10

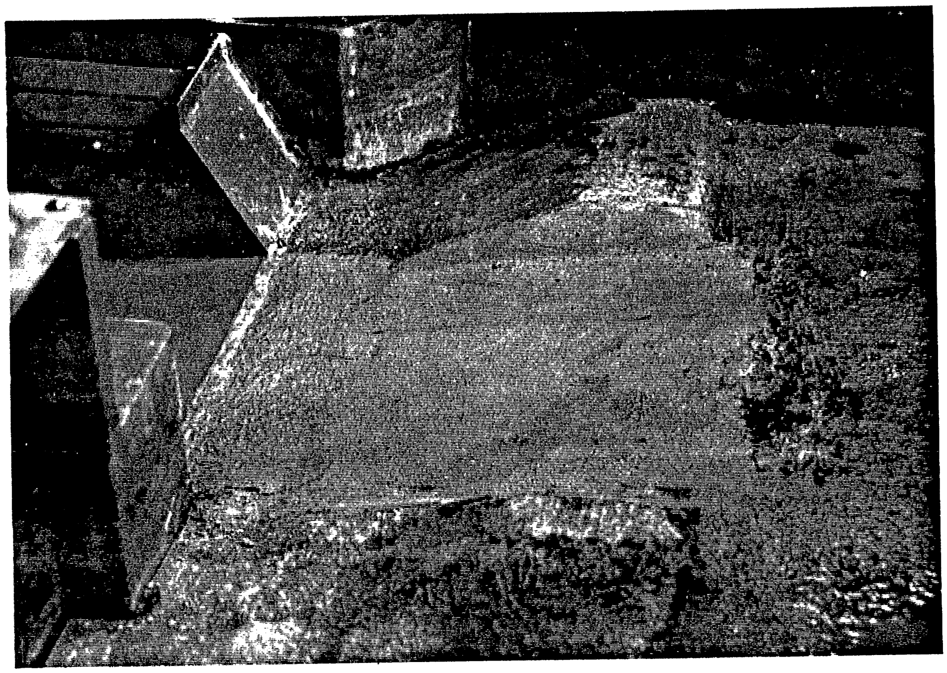
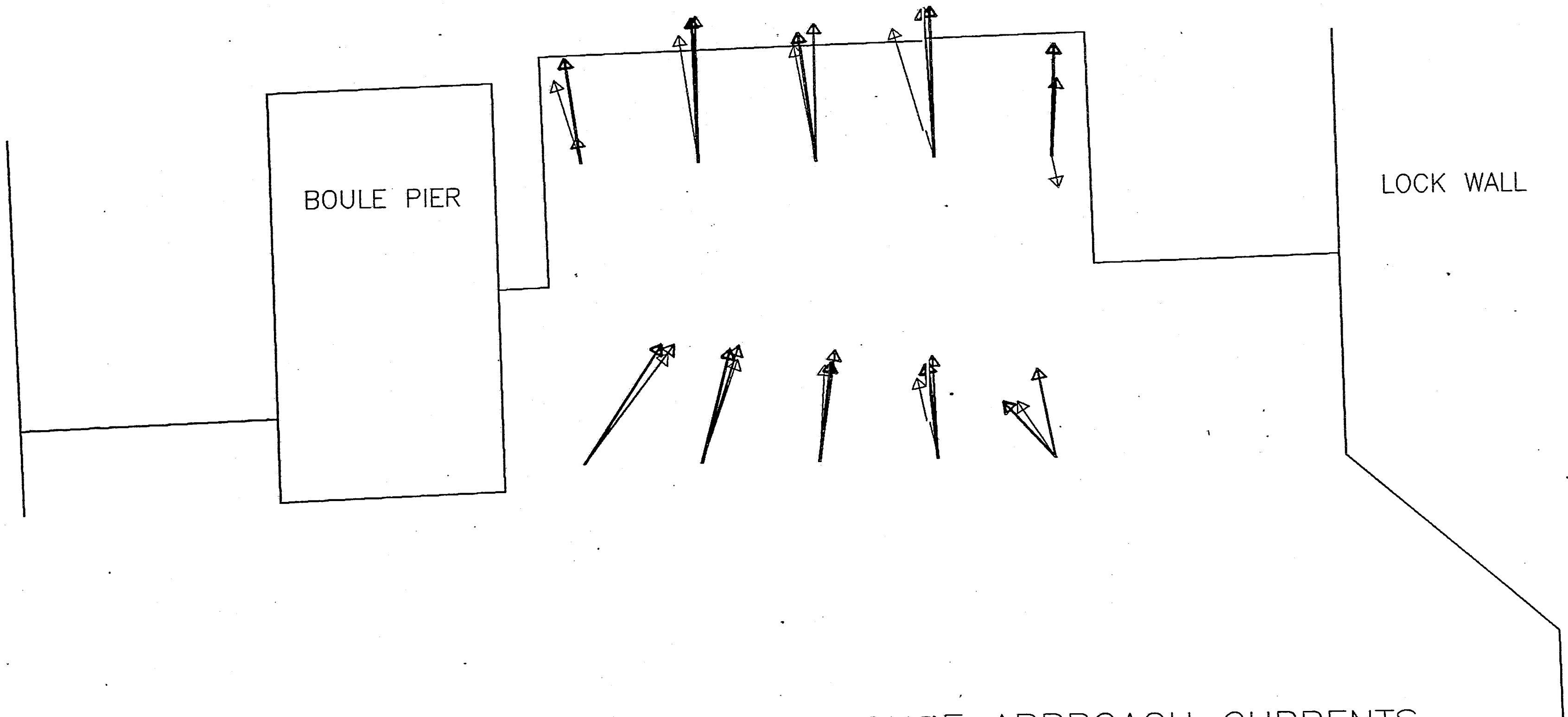


Figure 11. Photograph of model with excavation.



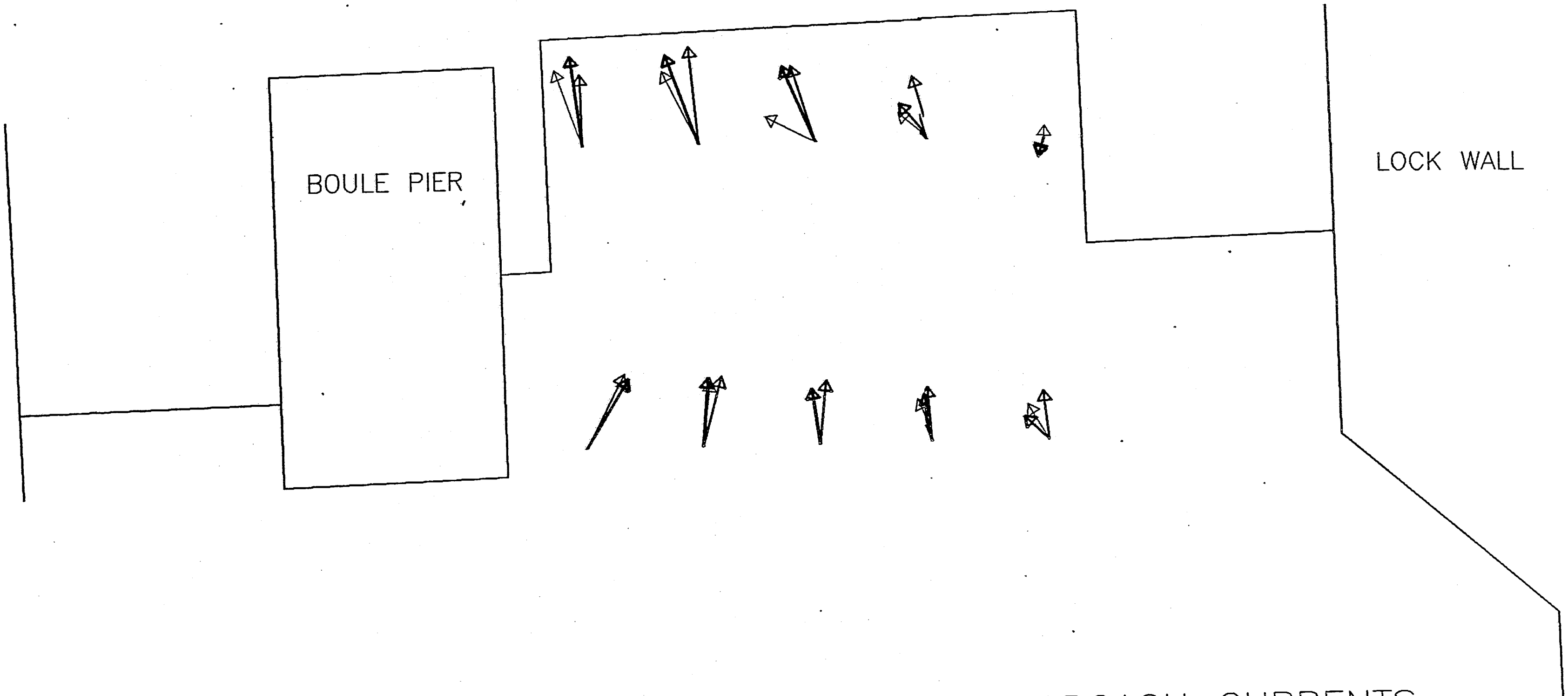

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
EXCAVATION ONLY, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

- MEASURED 3 FT. BELOW WATER SURFACE
- MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
- MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 12**



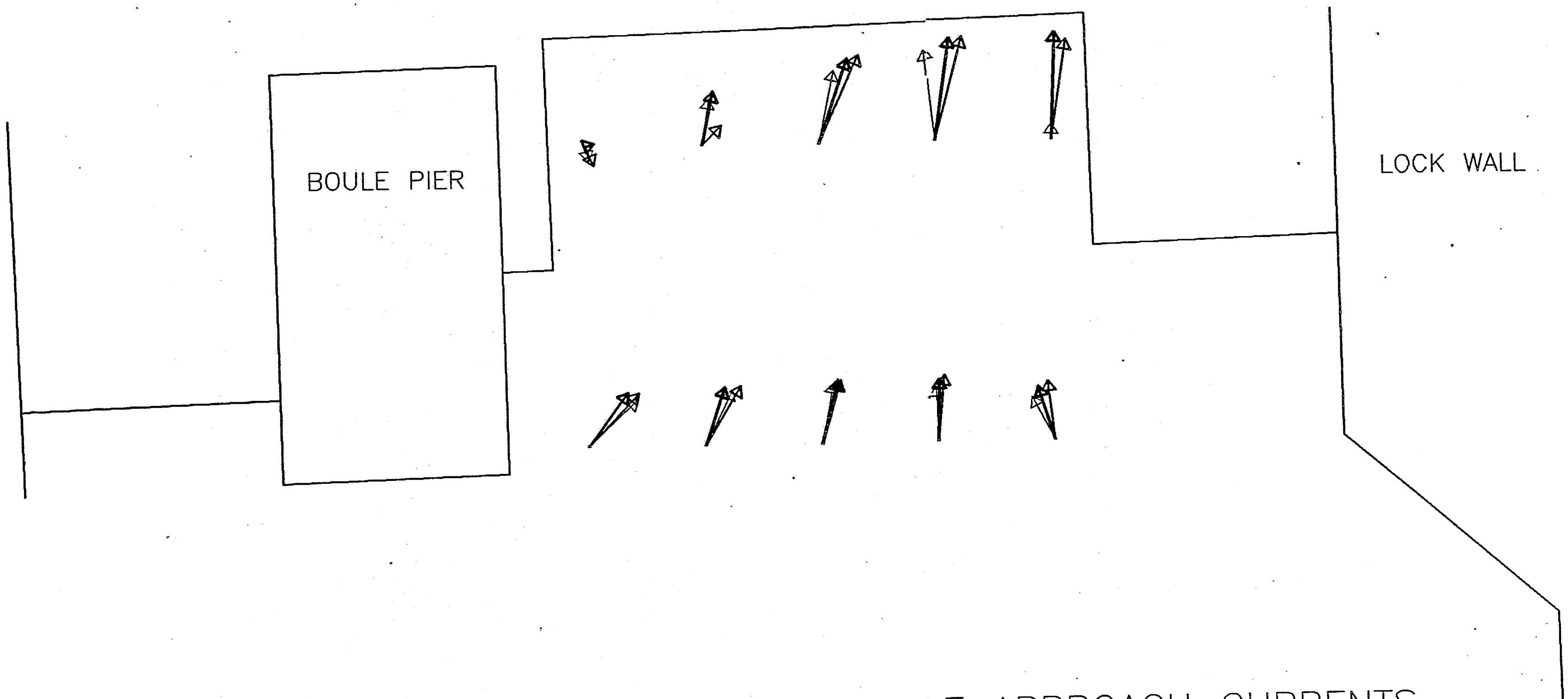

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
EXCAVATION ONLY, RIVERWARD UNIT OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 13**



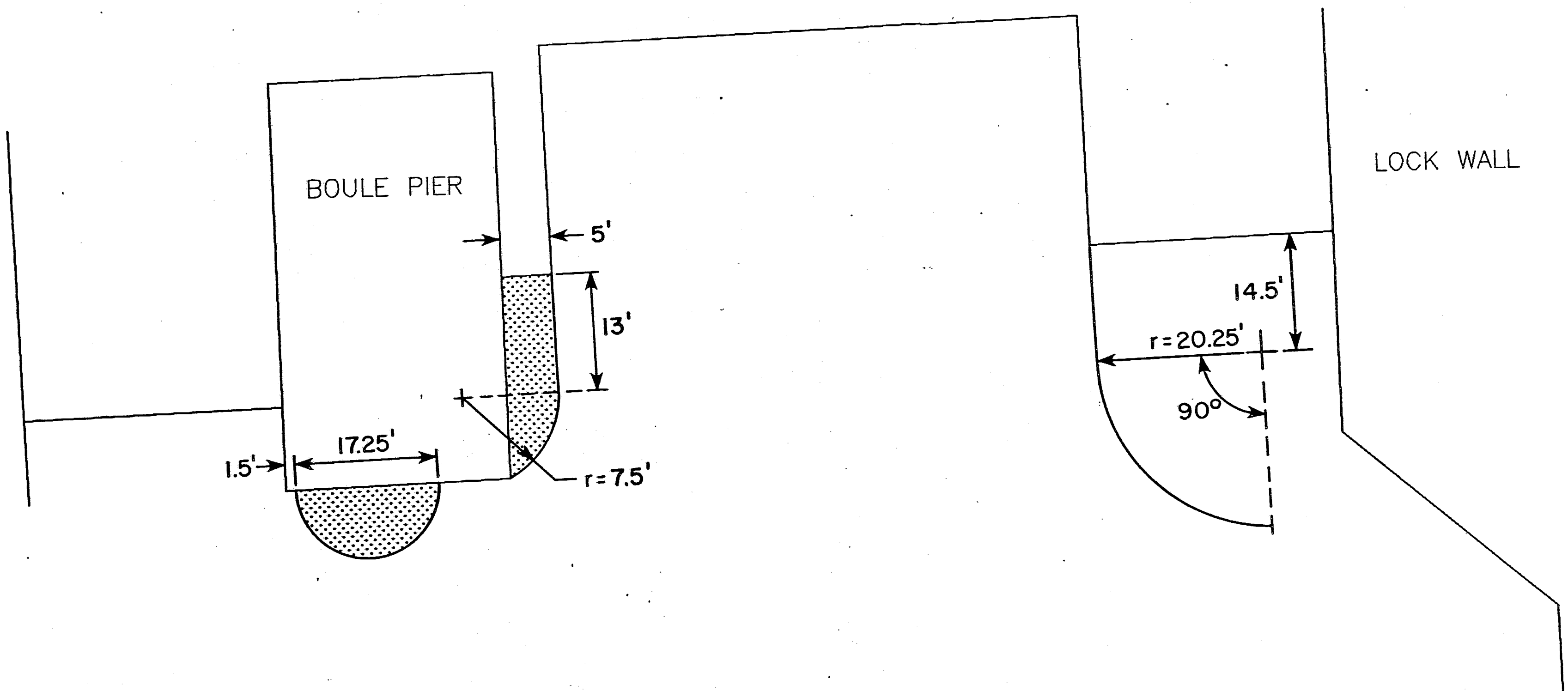

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
EXCAVATION ONLY, LANDWARD UNIT OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

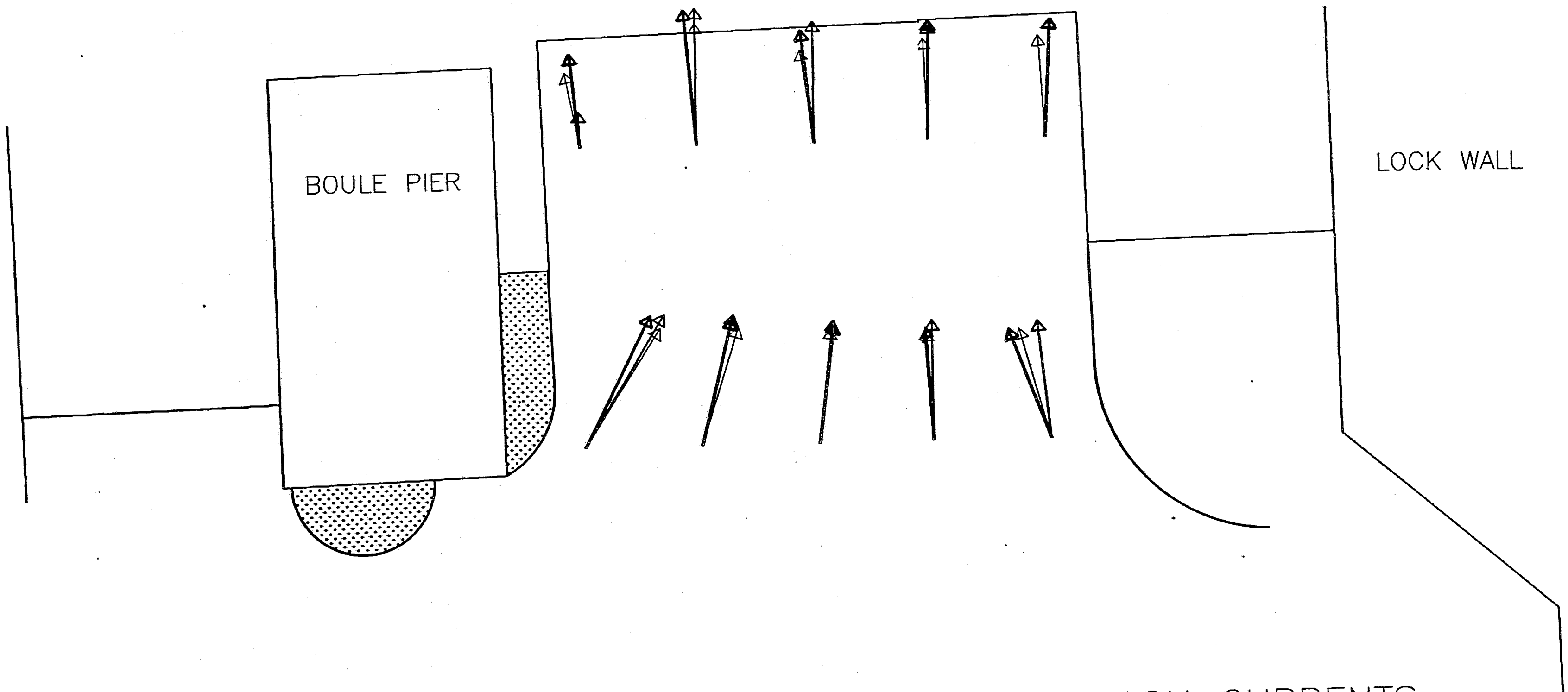
**Figure 14**




LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
SCHEMATIC OF MODIFICATION #1

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 15**



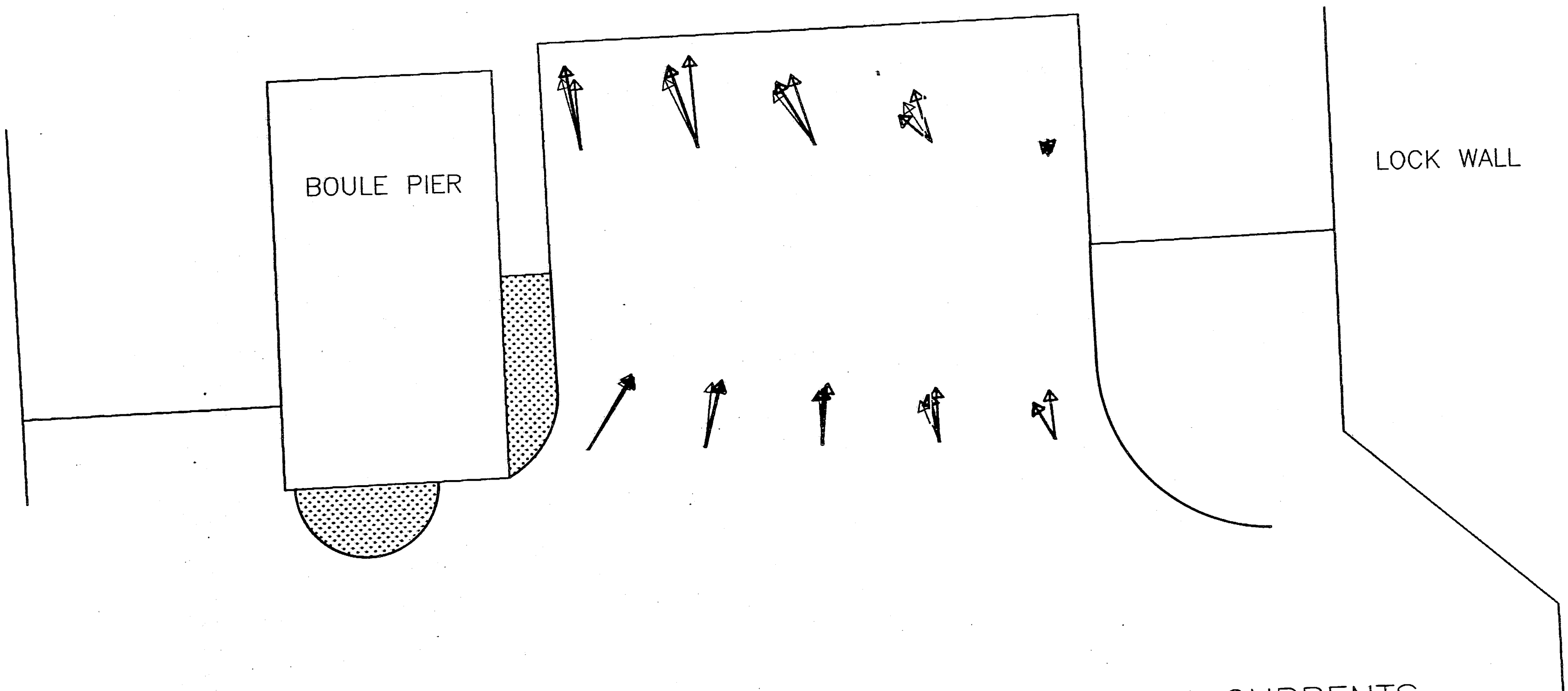

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #1, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 16**



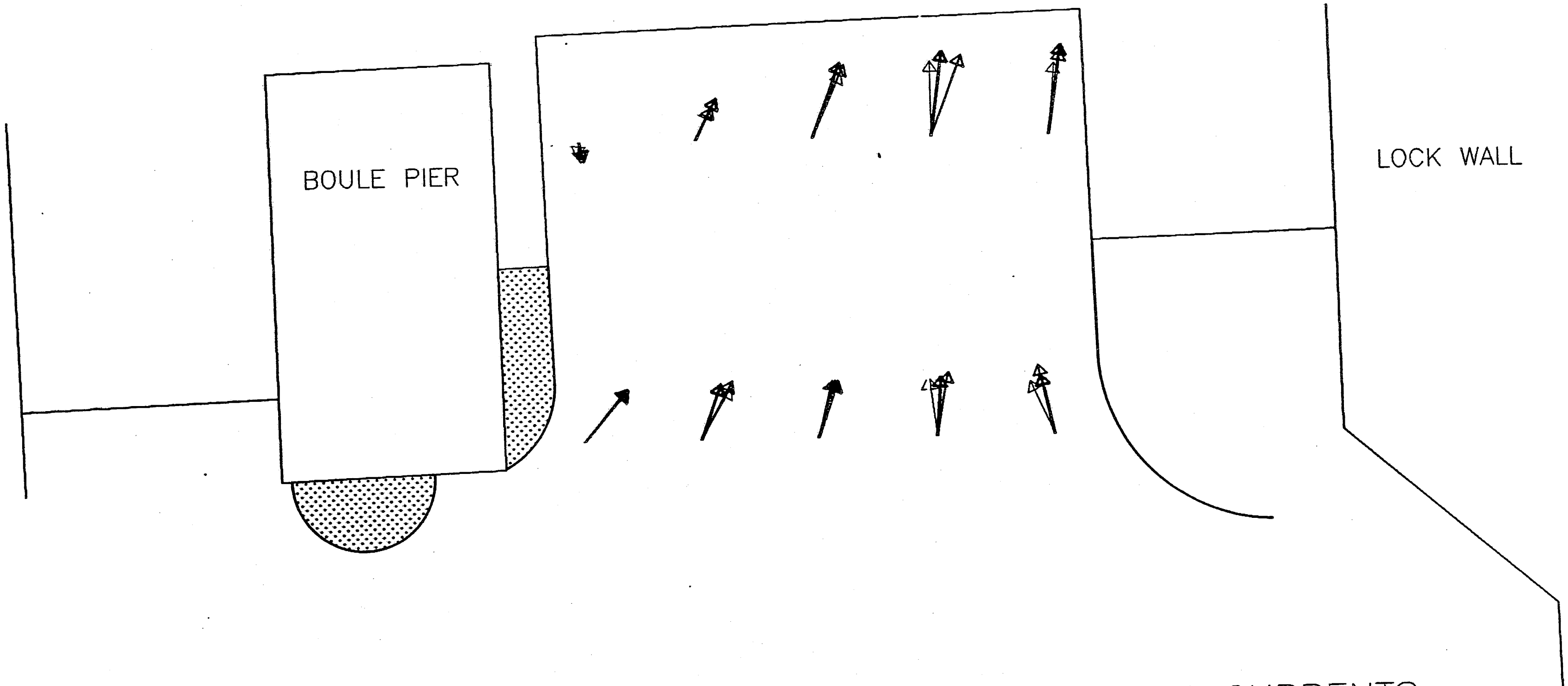

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #1, RIVERWARD UNIT OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED.

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 17**



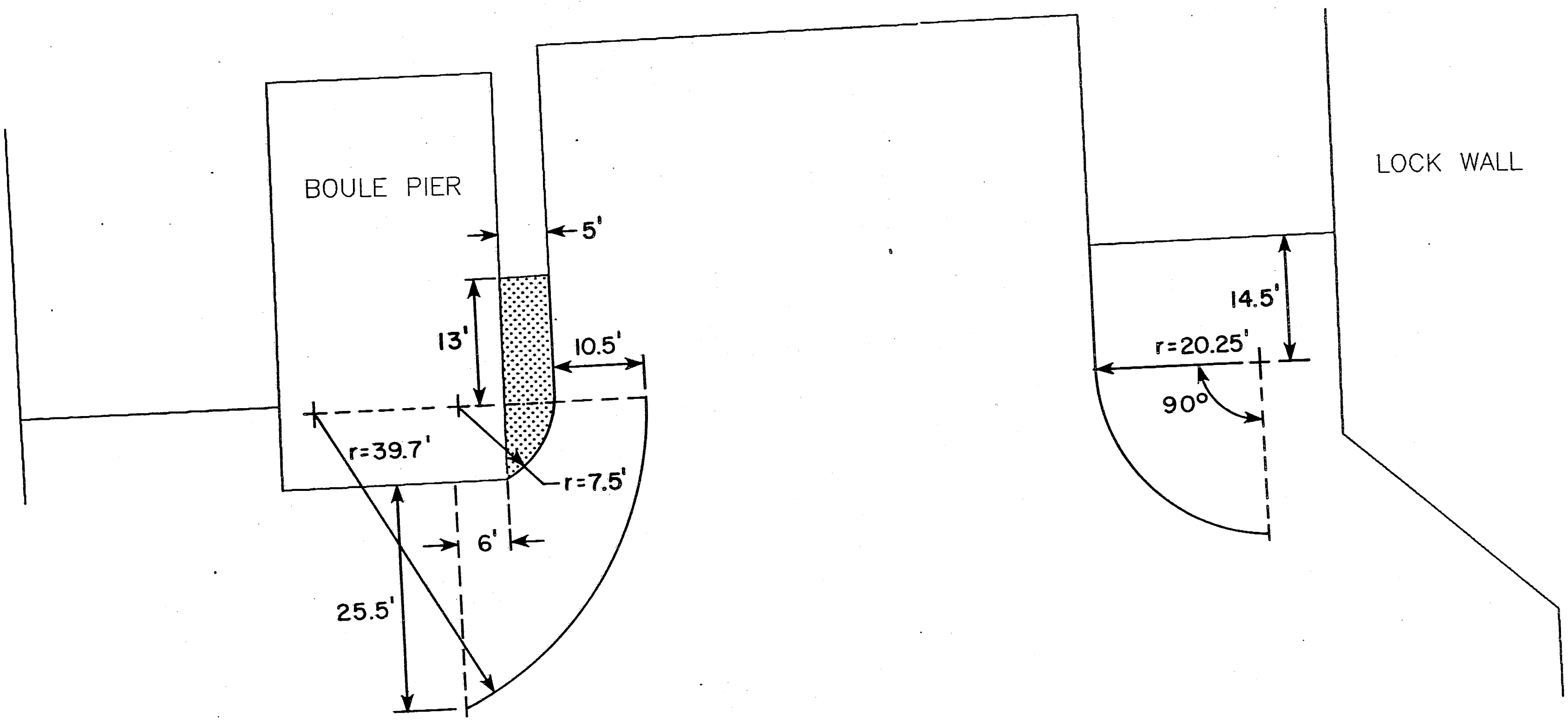

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #1, LANDWARD UNIT OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

- MEASURED 3 FT. BELOW WATER SURFACE.
- MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
- MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 18**

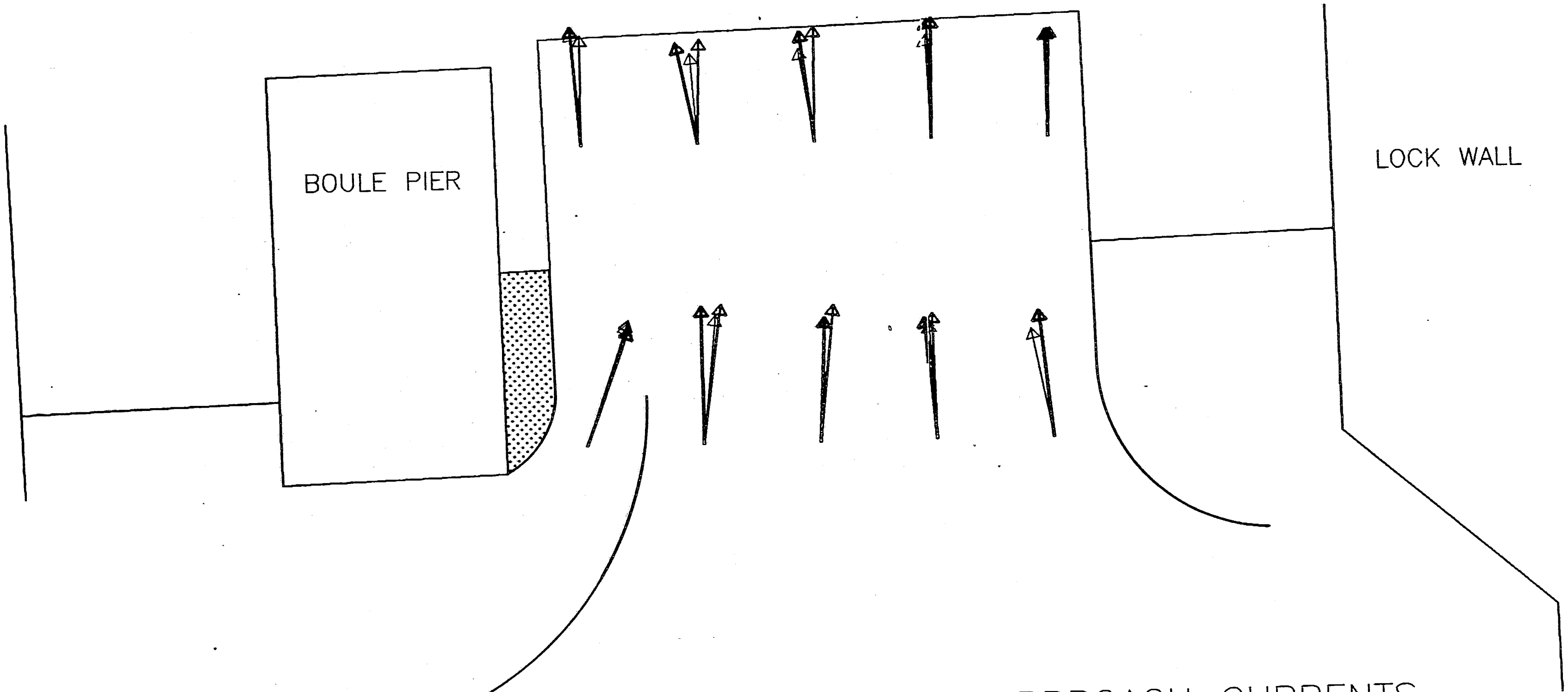



LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS

SCHEMATIC OF MODIFICATION #2

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 19**



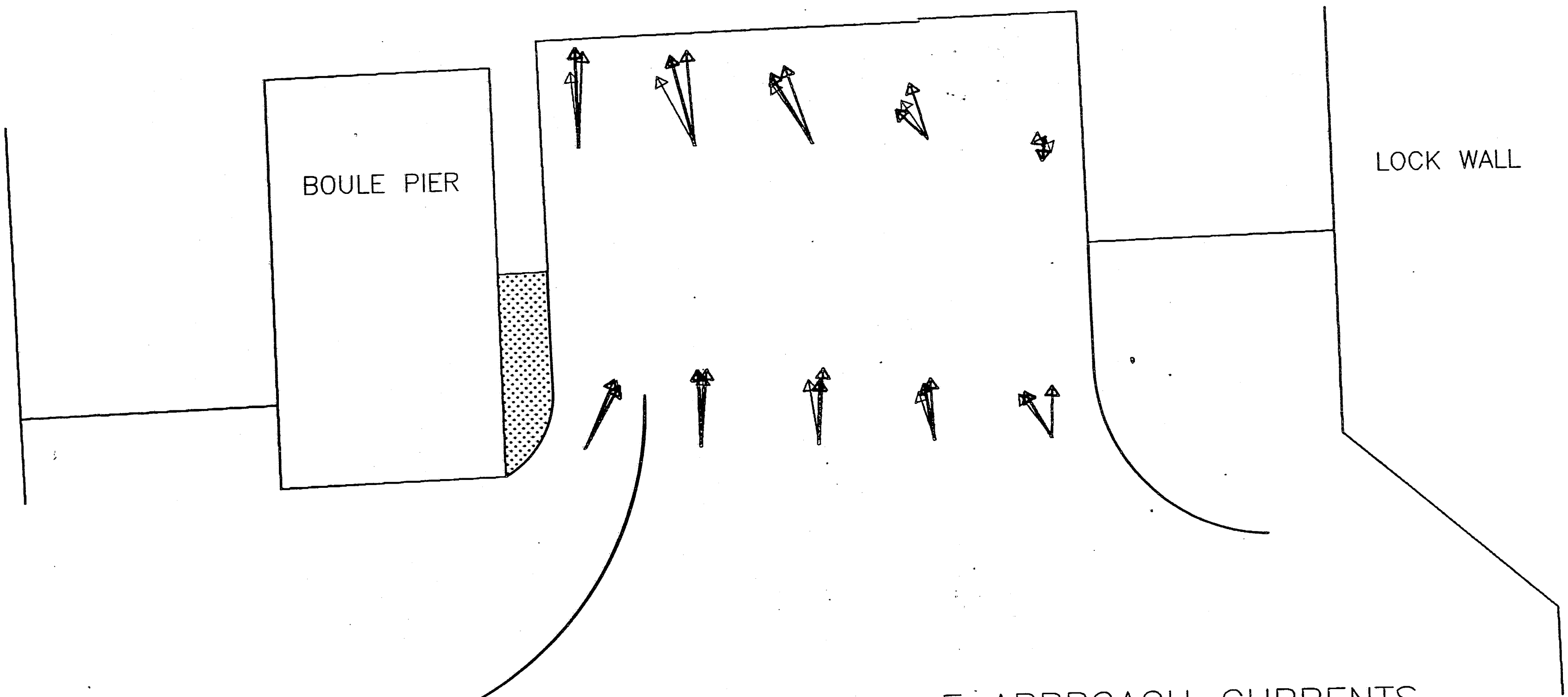

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #2, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABCVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 20**



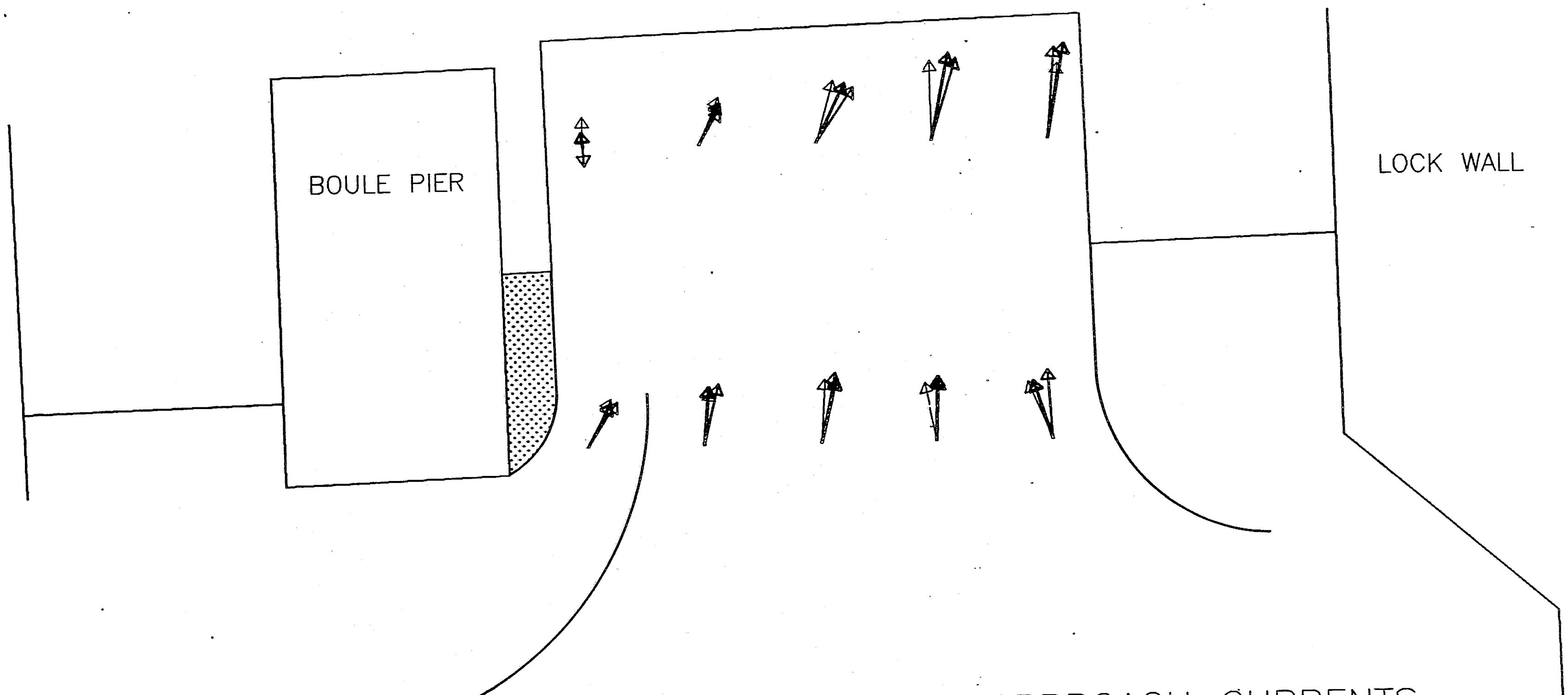

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #2, RIVERWARD UNIT OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 21**




LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #2, LANDWARD UNIT OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 22**

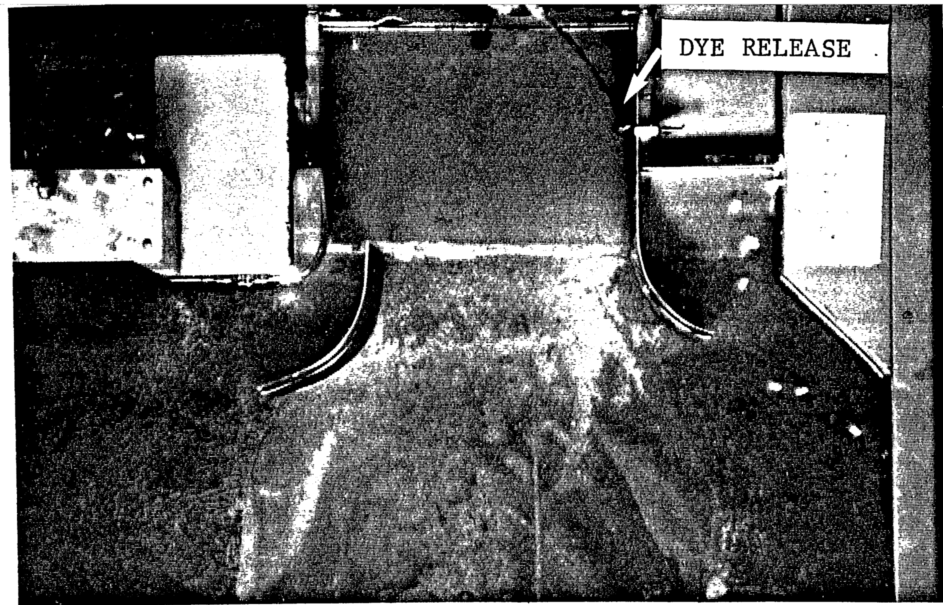



Figure 23. Dye trace, modification #2, both units operating.

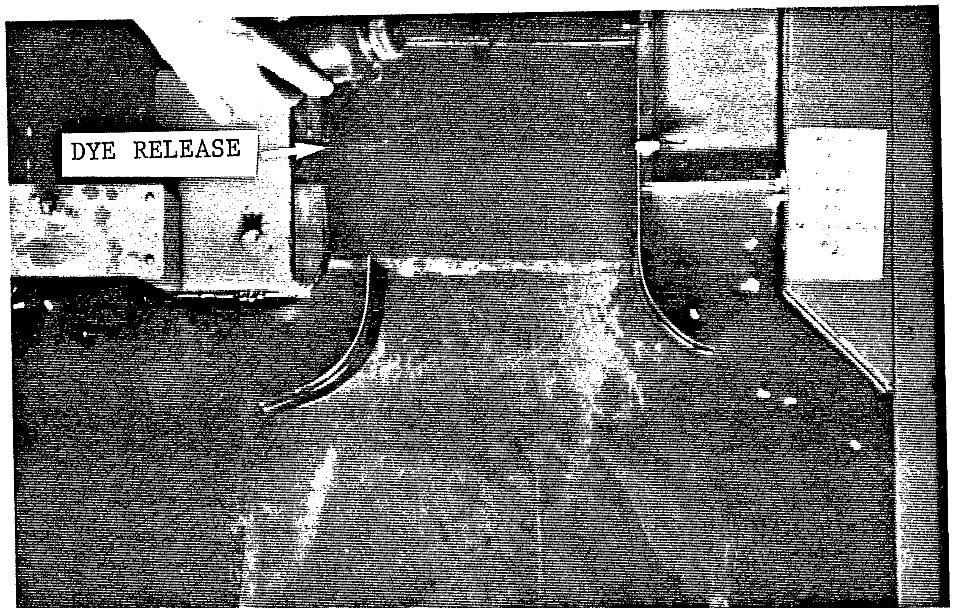



Figure 24. Dye trace, modification #2, both units operating.

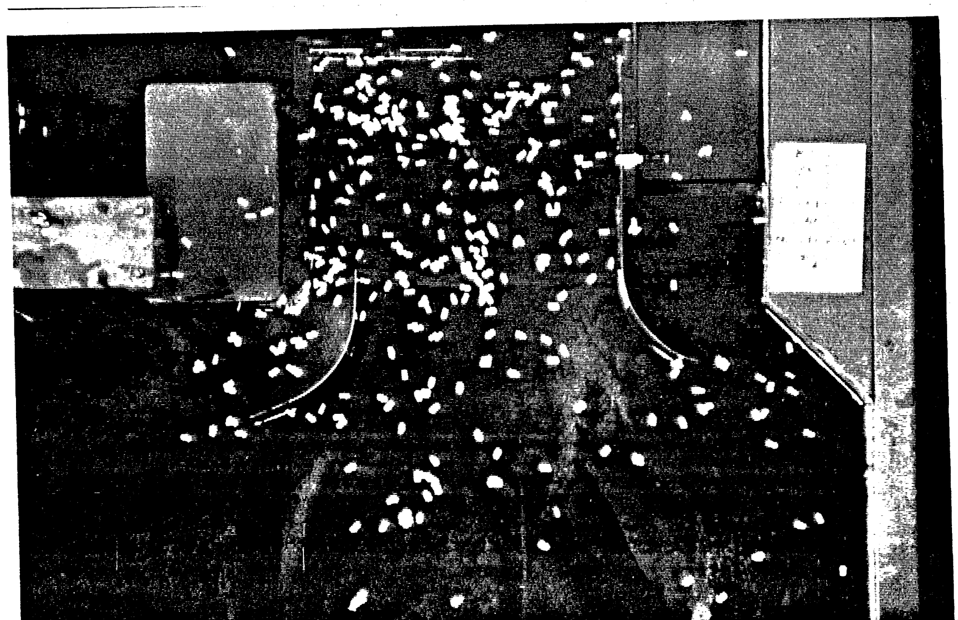
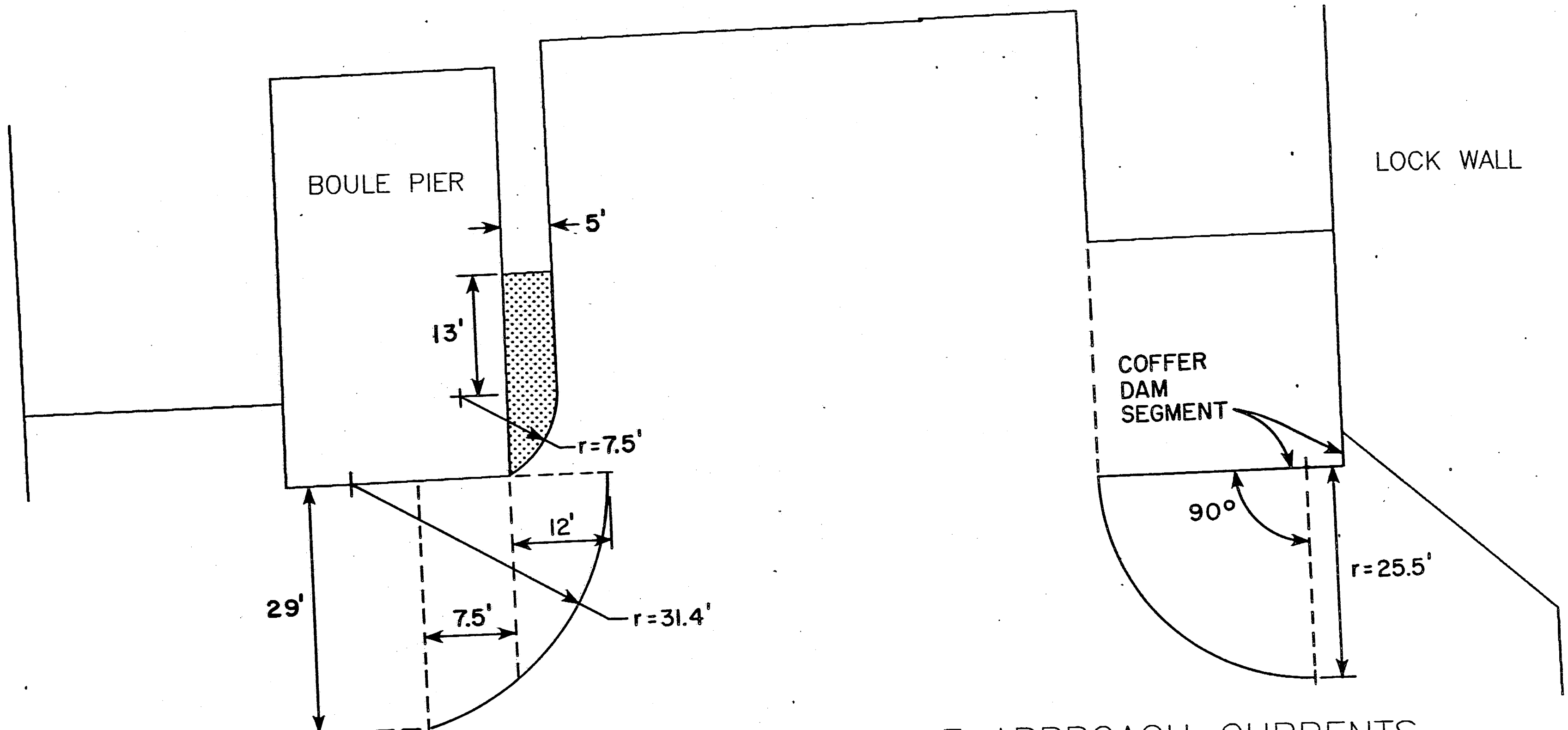


Figure 25. Confetti trace, modification #2, both units operating.

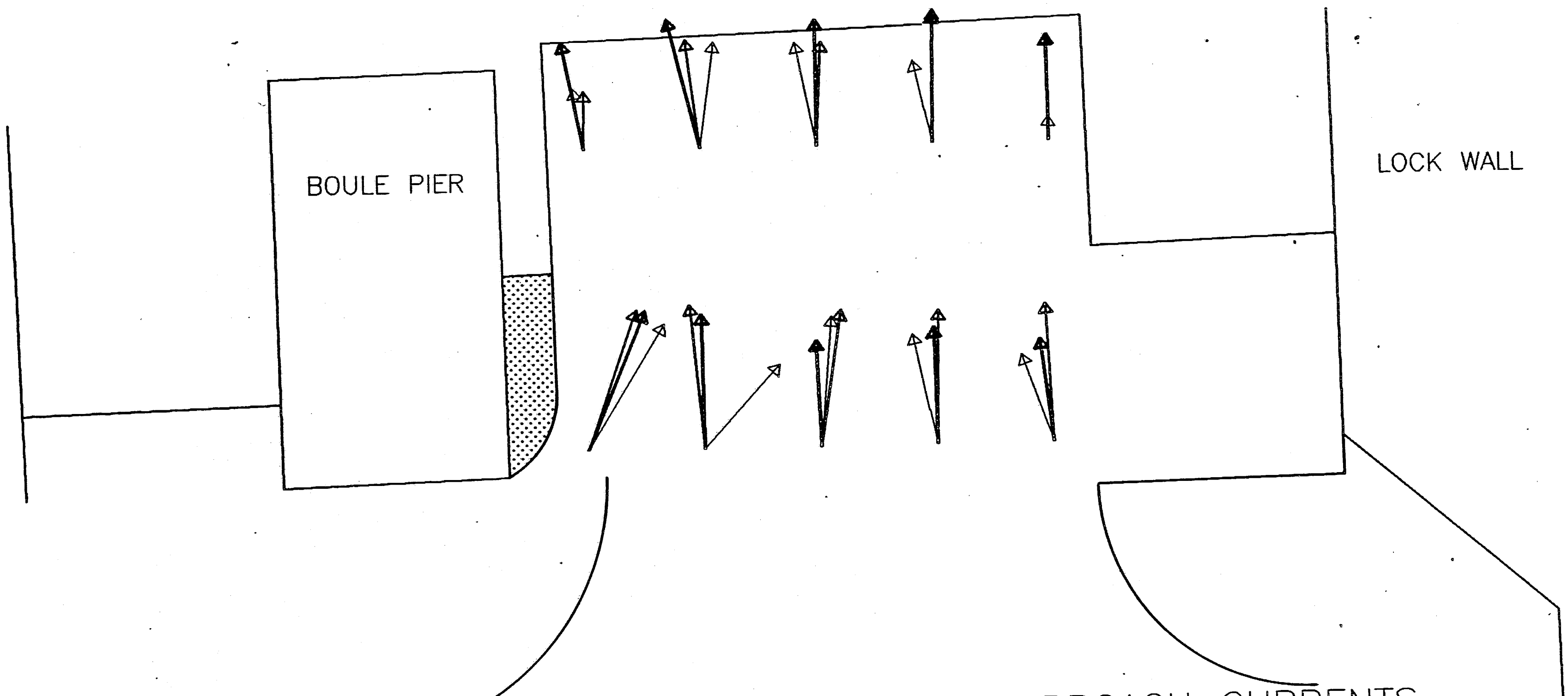



LOCK AND DAM NO. 2 — POWERHOUSE APPROACH CURRENTS

SCHEMATIC OF MODIFICATION #3

ST. ANTHONY FALLS HYDRAULIC LABORATORY — 1987

**Figure 26**



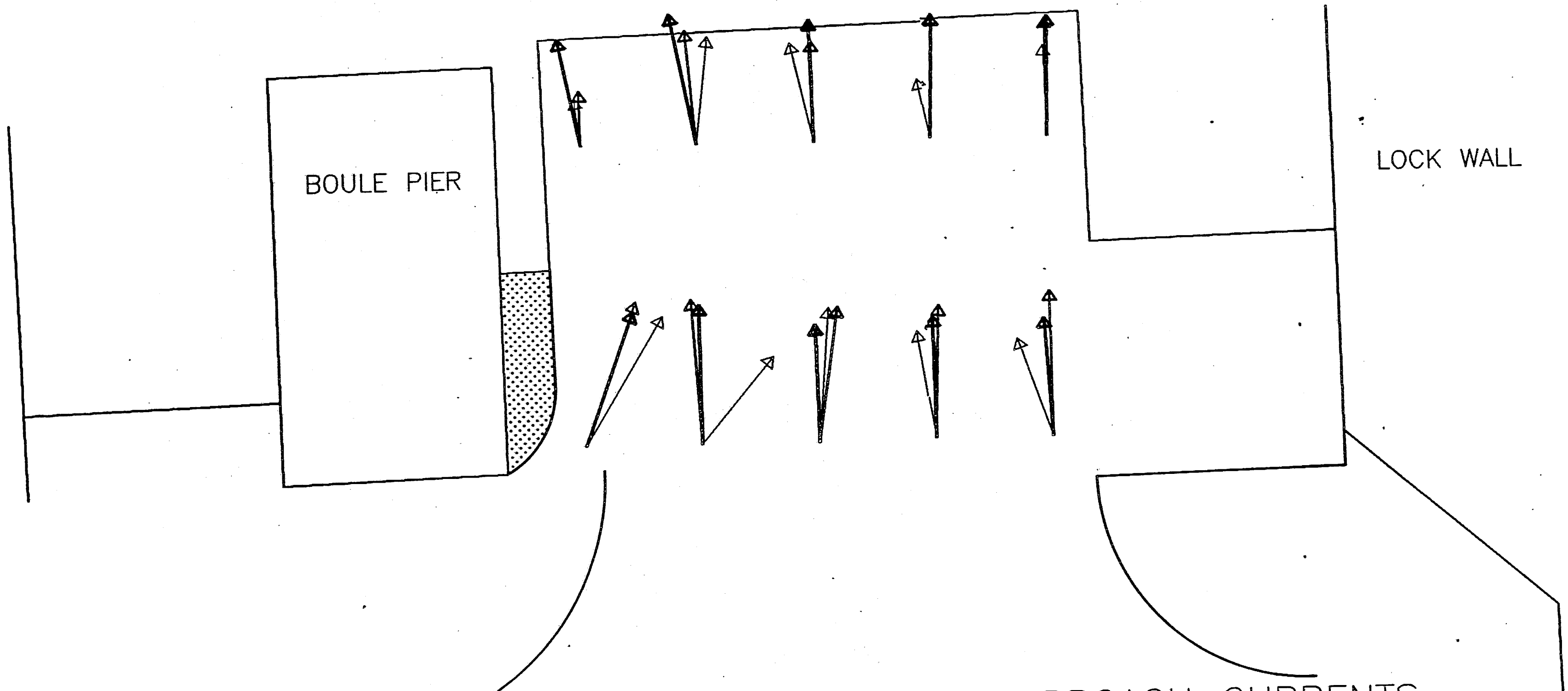

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #3a, NO EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 27**



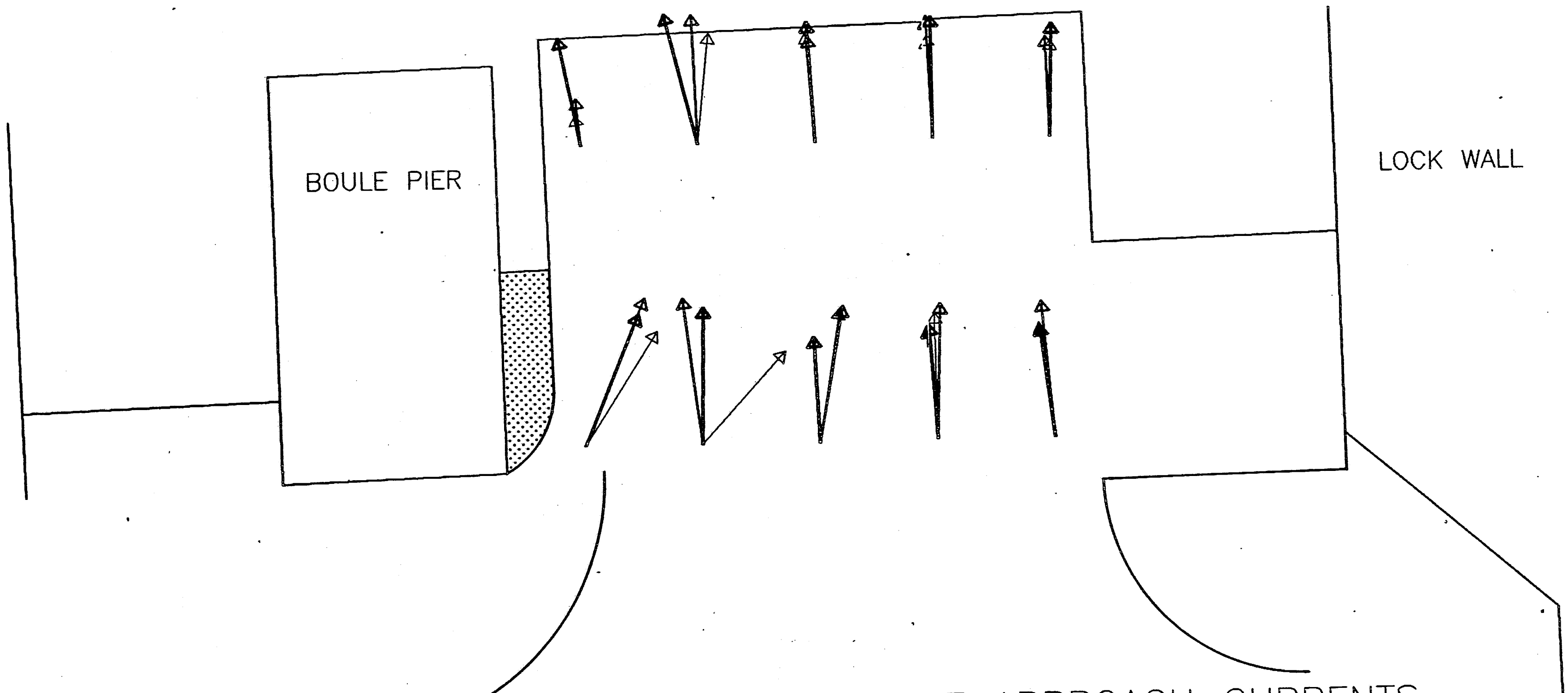

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #3b, NO EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 28**



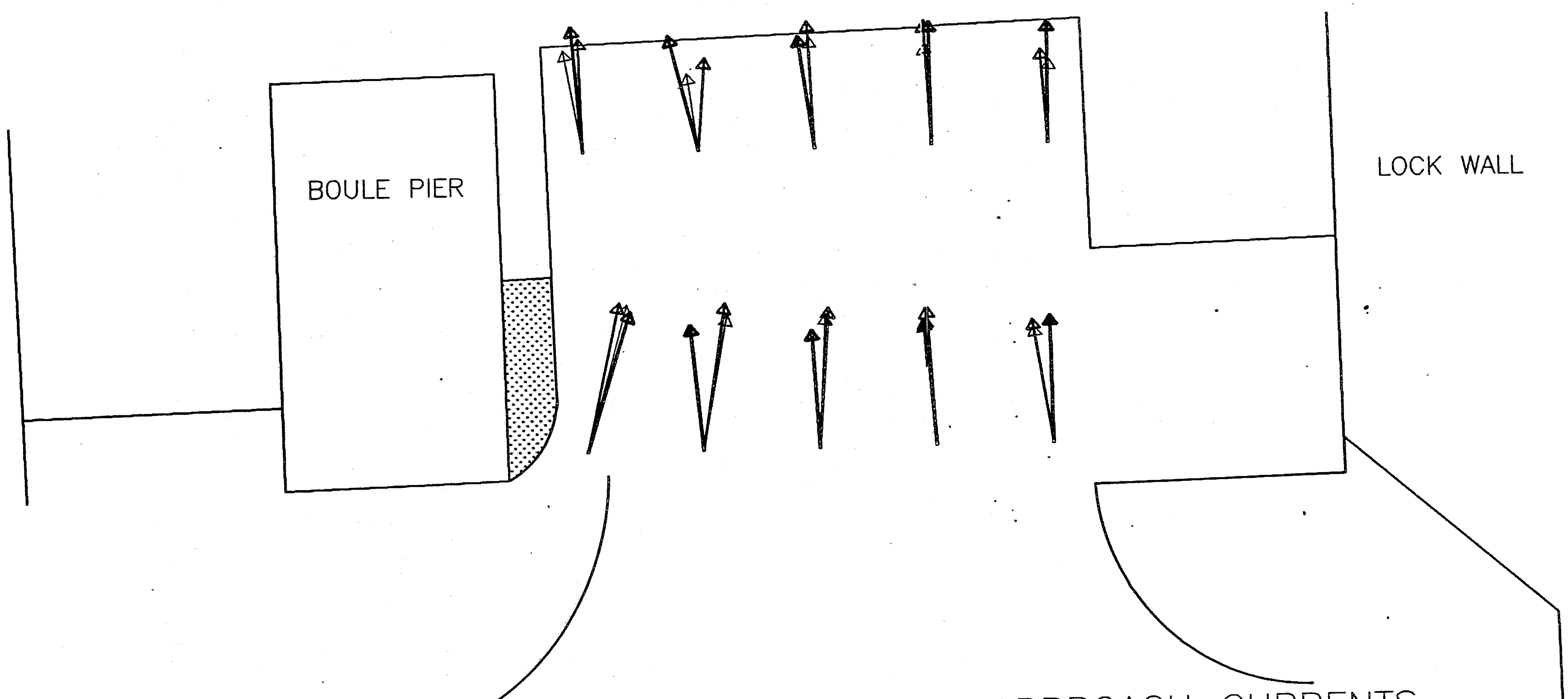

LOCK AND DAM NO. 2 — POWERHOUSE APPROACH CURRENTS
MODIFICATION #3c, NO EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

- MEASURED 3 FT. BELOW WATER SURFACE
- MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
- MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY — 1987

**Figure 29**



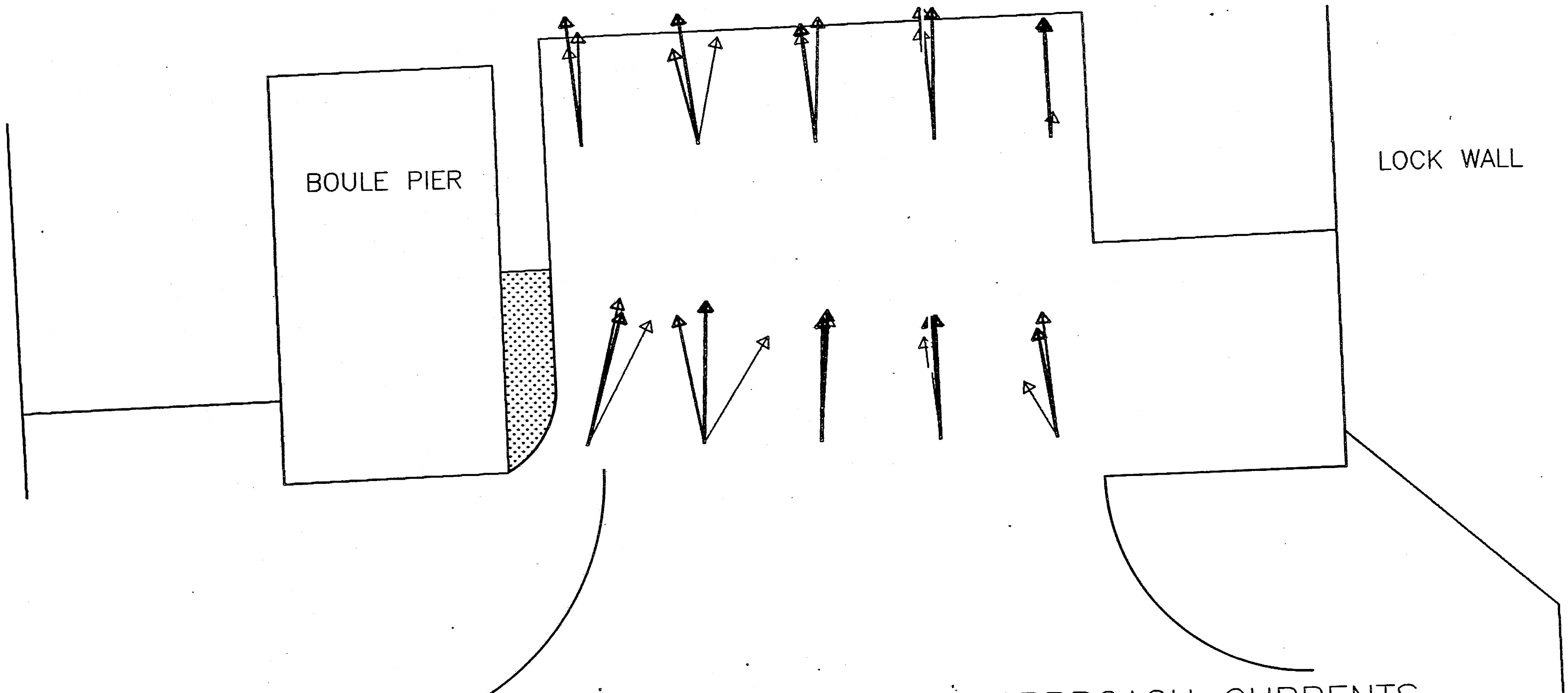

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #3d, NO EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 30**



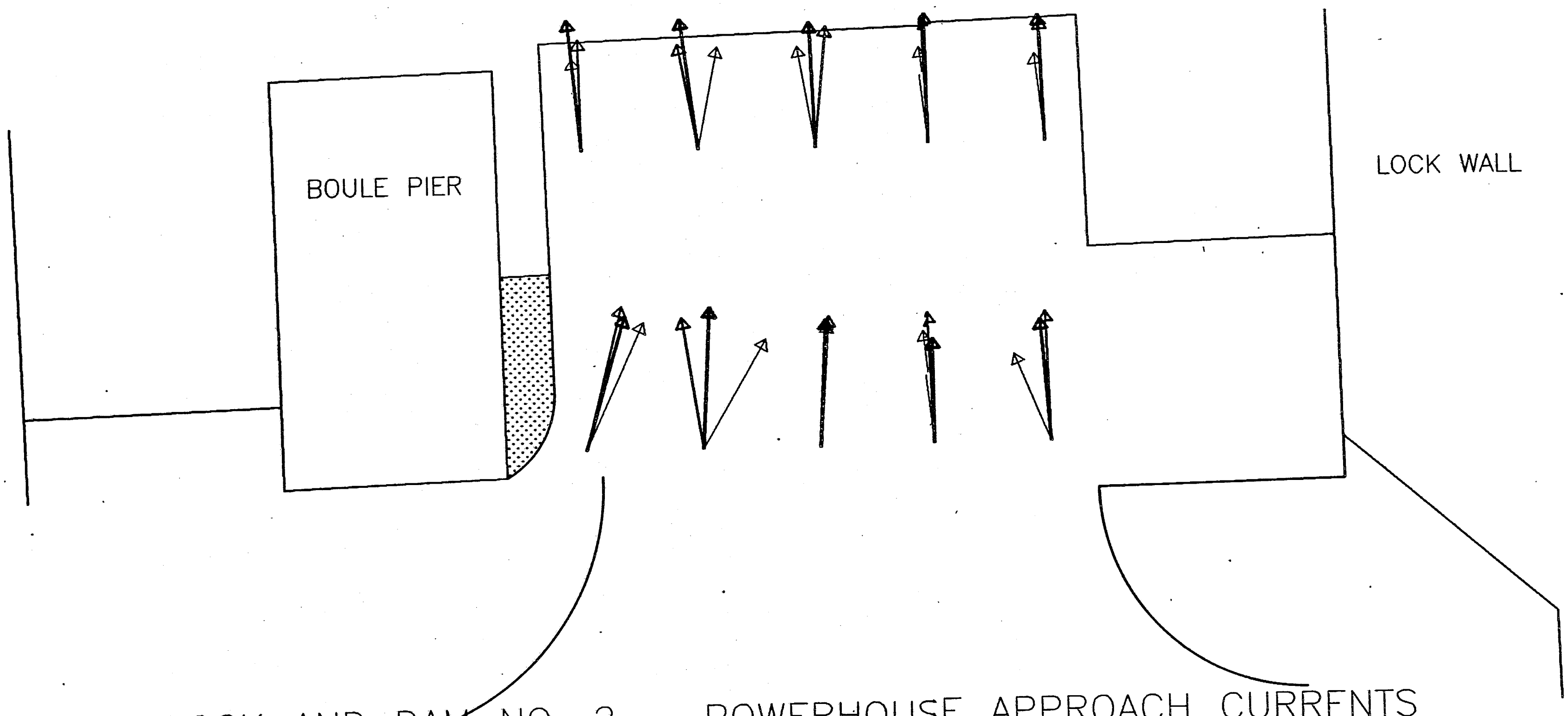

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #3a WITH EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 31**



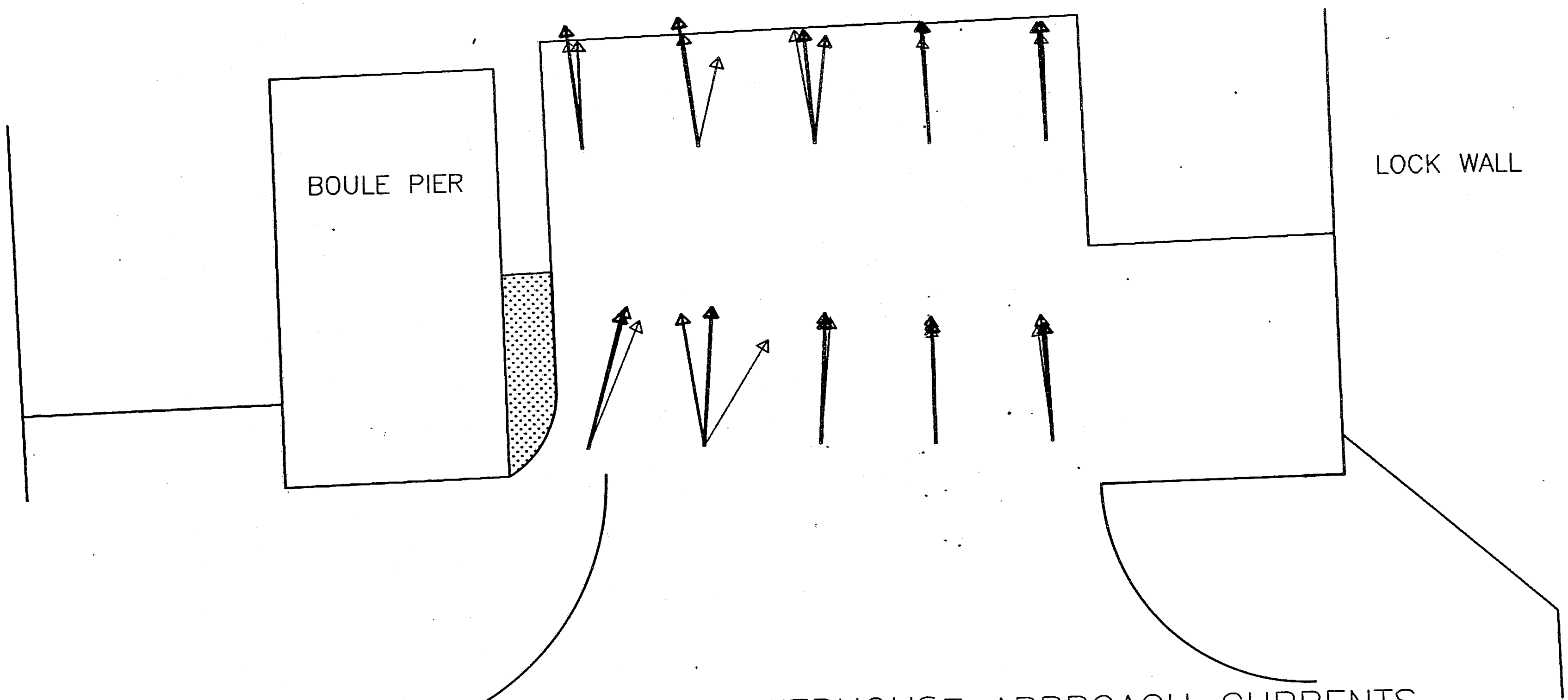

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #3b WITH EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 32**



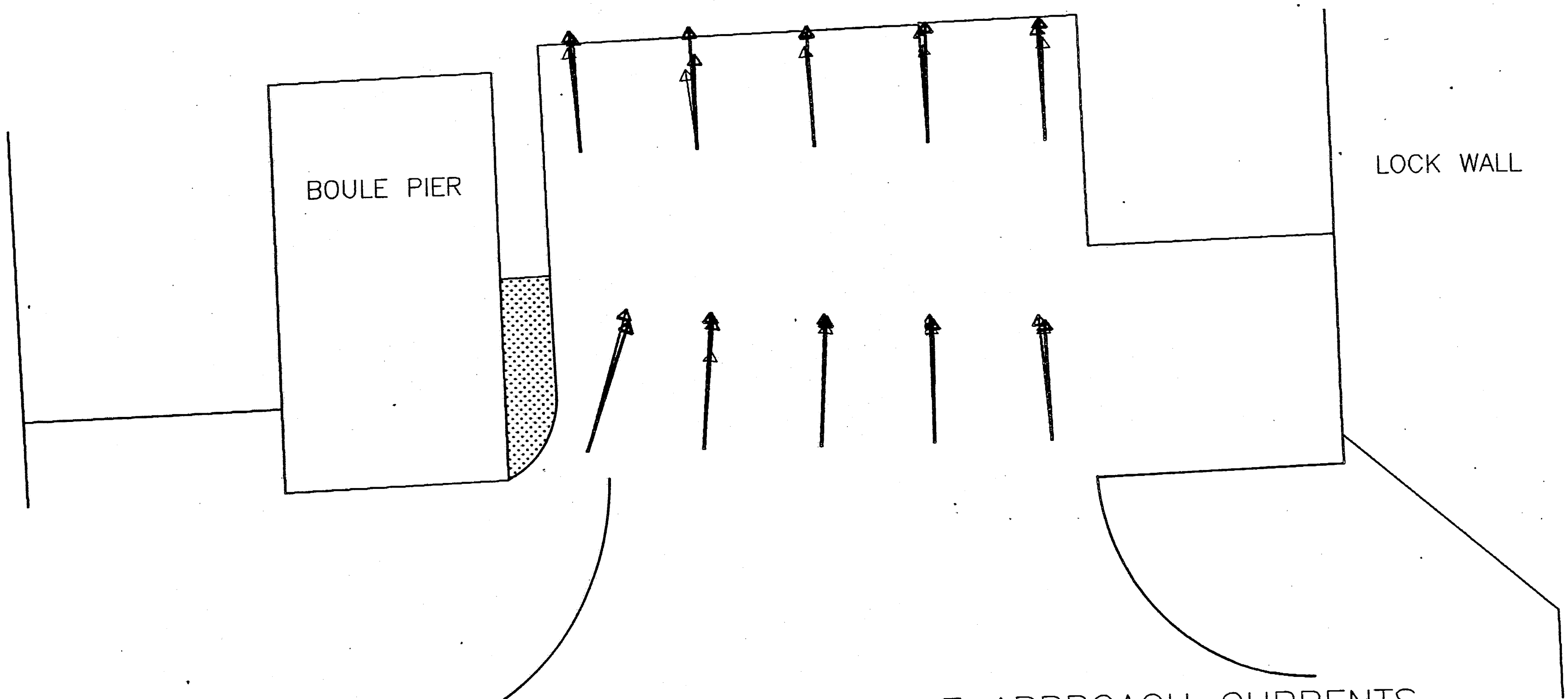

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #3c WITH EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 33**




LOCK AND DAM NO. 2 — POWERHOUSE APPROACH CURRENTS
MODIFICATION #3d WITH EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY — 1987

**Figure 34**

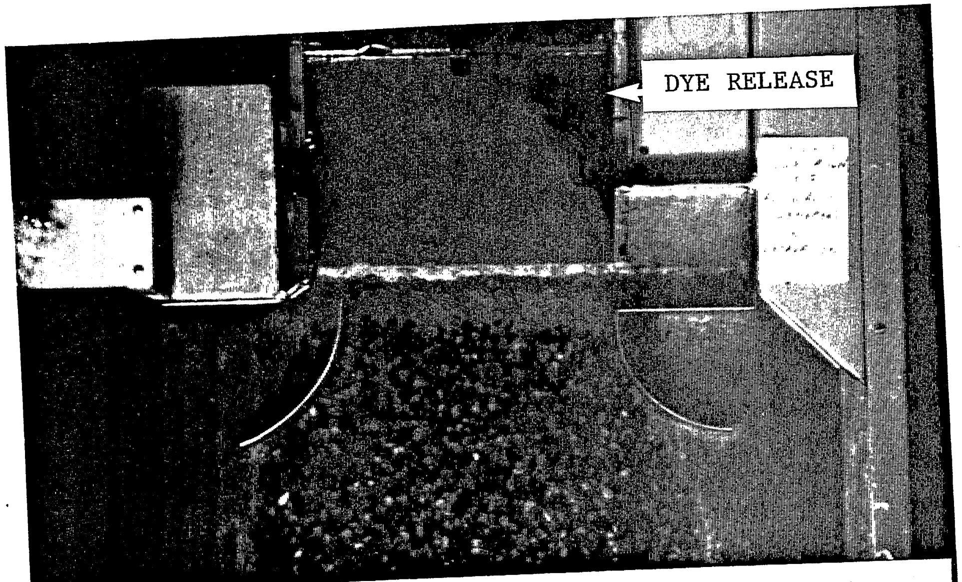



Figure 35. Dye trace, modification #3a, no excavation, both units operating.

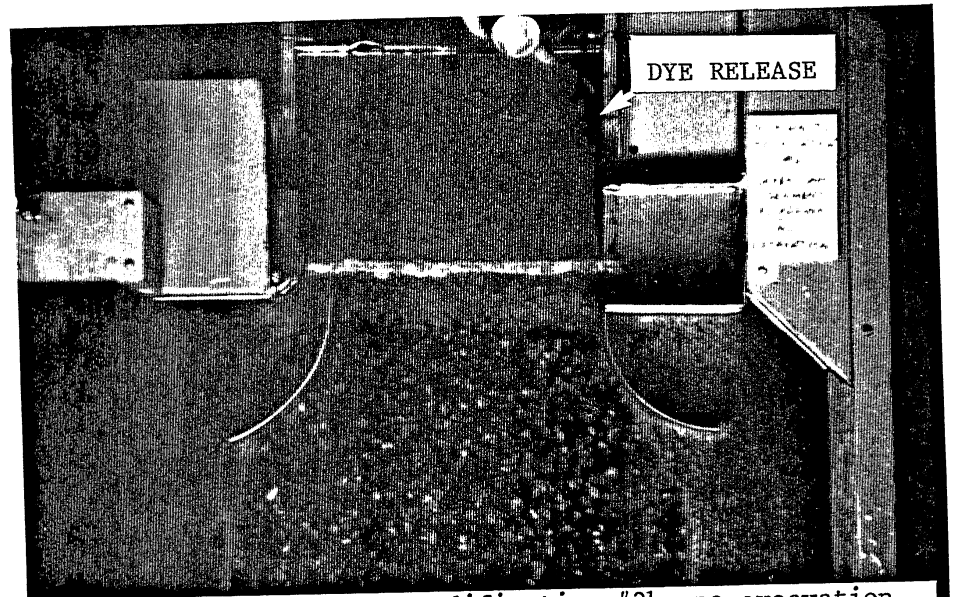



Figure 36. Dye trace, modification #3b, no excavation, both units operating.

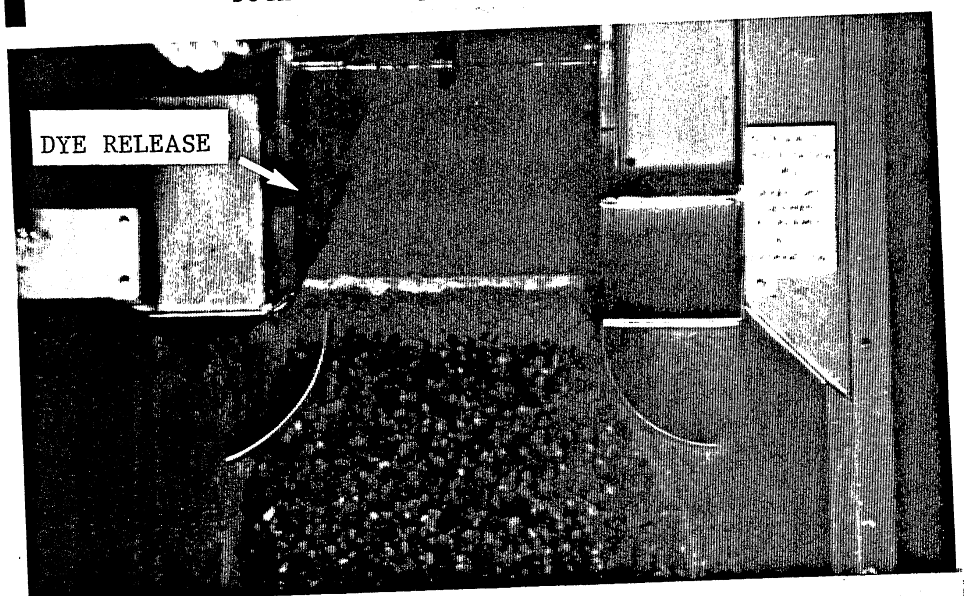



Figure 37. Dye trace, modification #3b, no excavation, both units operating.

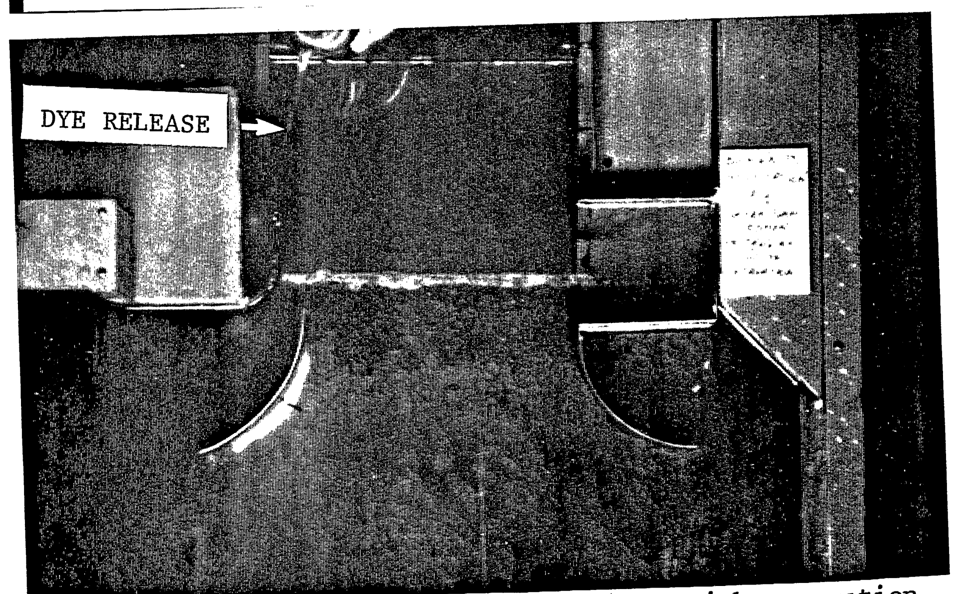



Figure 38. Dye trace, modification #3b, with excavation, both units operating.

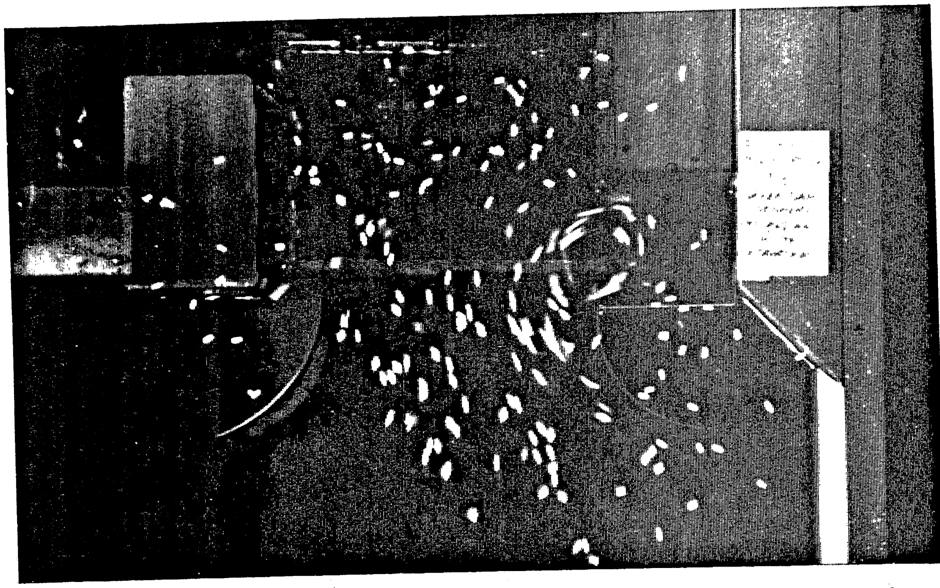


Figure 39. Confetti trace, modification #3b, with excavation, both units operating.

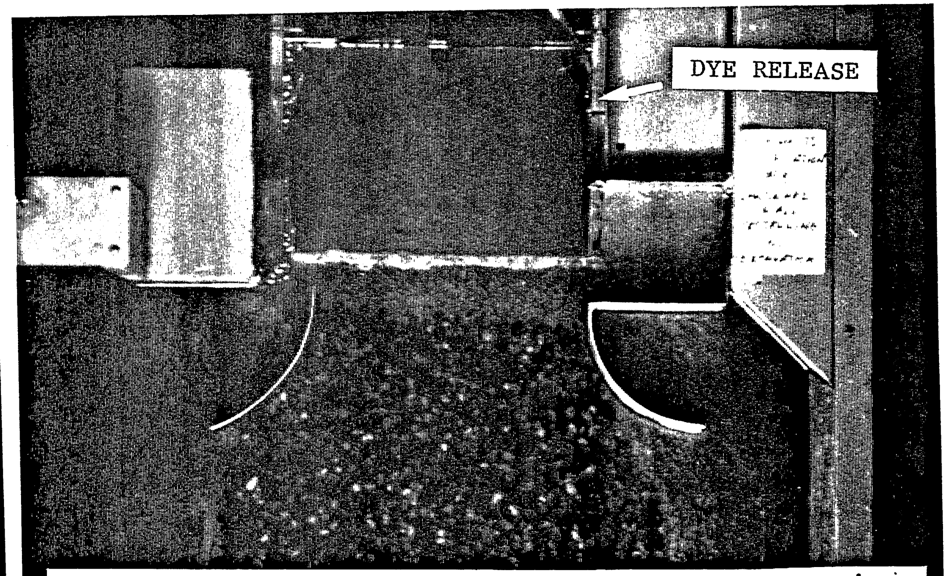



Figure 40. Dye trace, modification #3c, no excavation, both units operating.

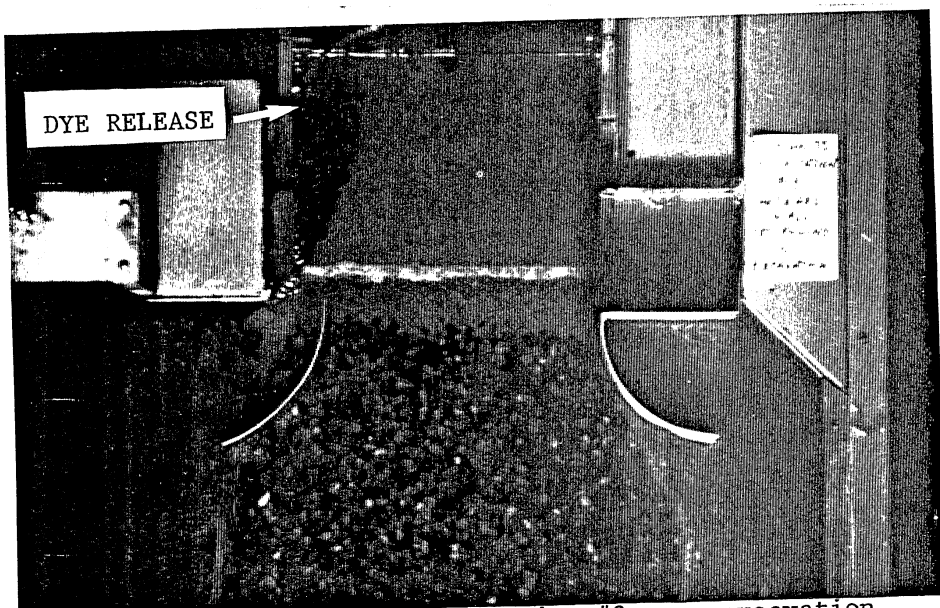



Figure 41. Dye trace, modification #3c, no excavation, both units operating.

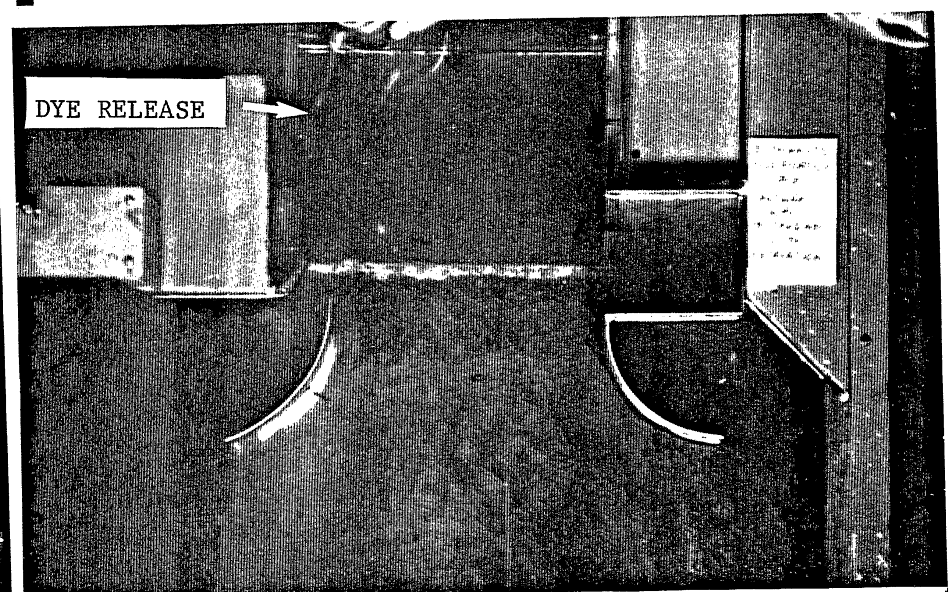



Figure 42. Dye trace, modification #3c, with excavation both units operating.

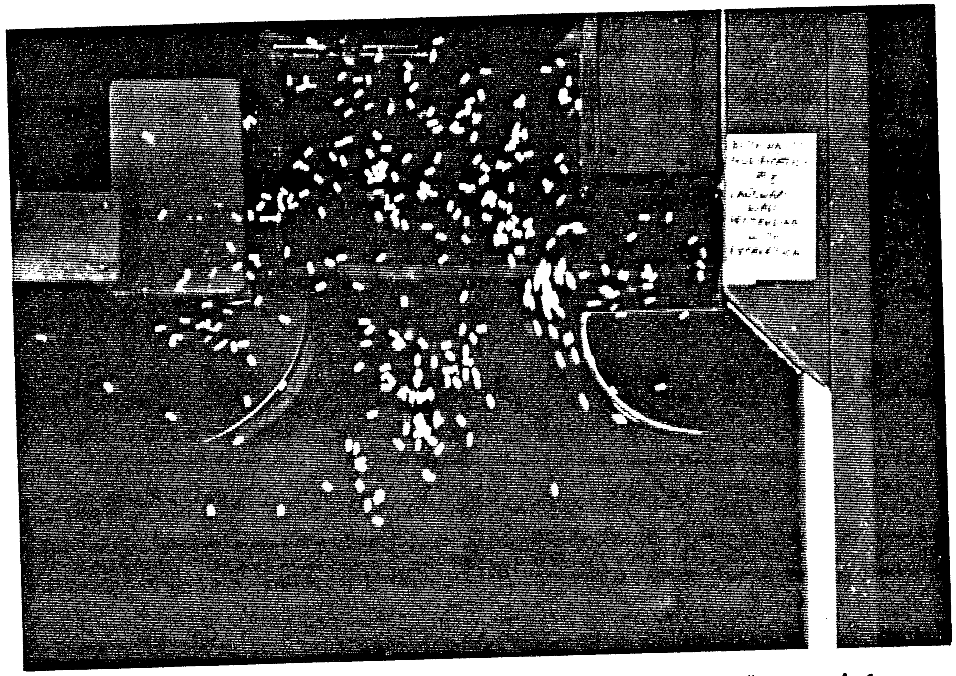


Figure 43. Confetti trace, modification #3c, with excavation, both units operating.

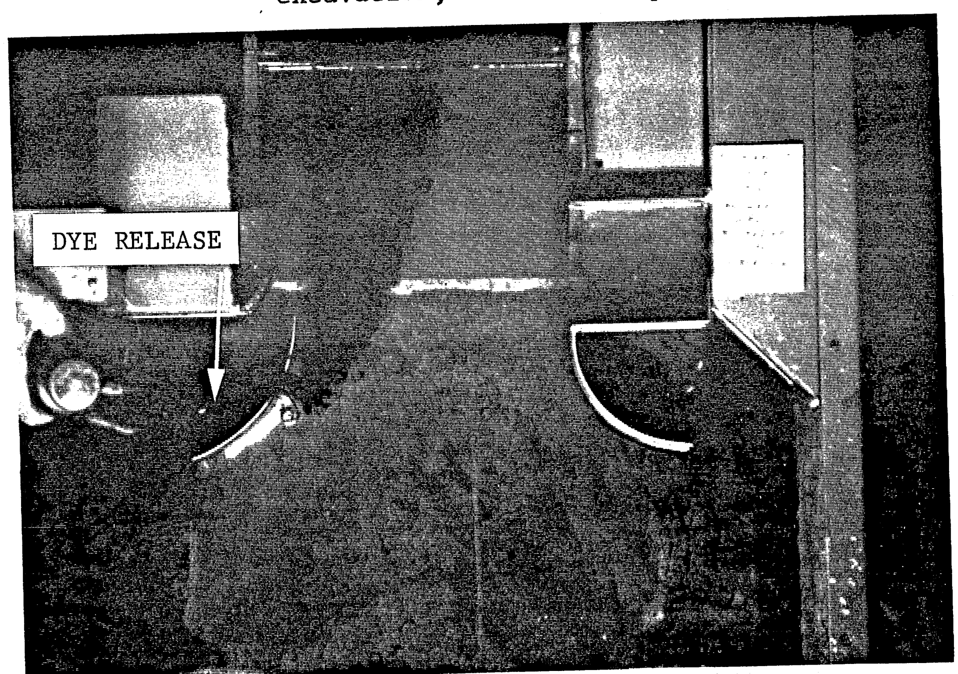
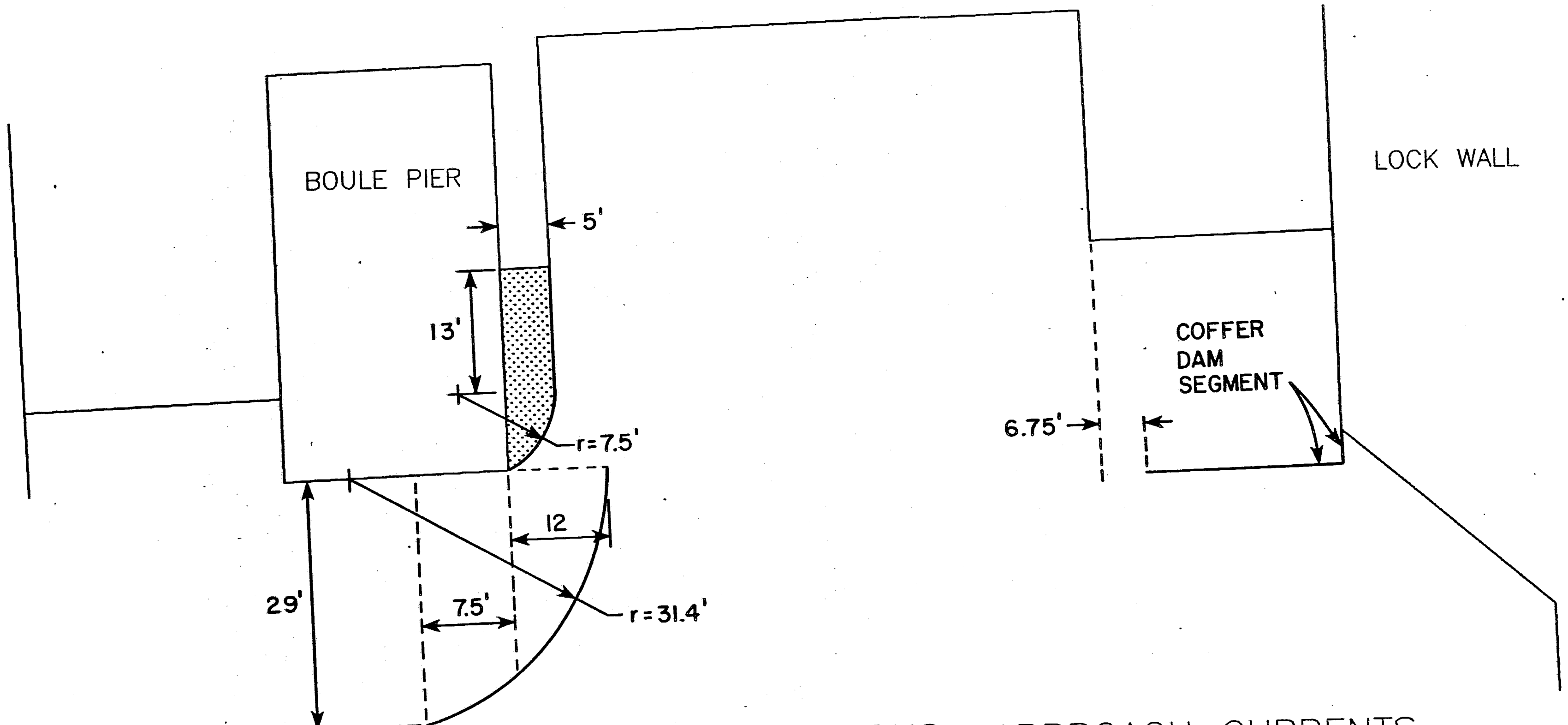



Figure 44. Dye trace, modification #3c, with excavation, both units operating.




LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS

SCHEMATIC OF MODIFICATION #4

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

Figure 45

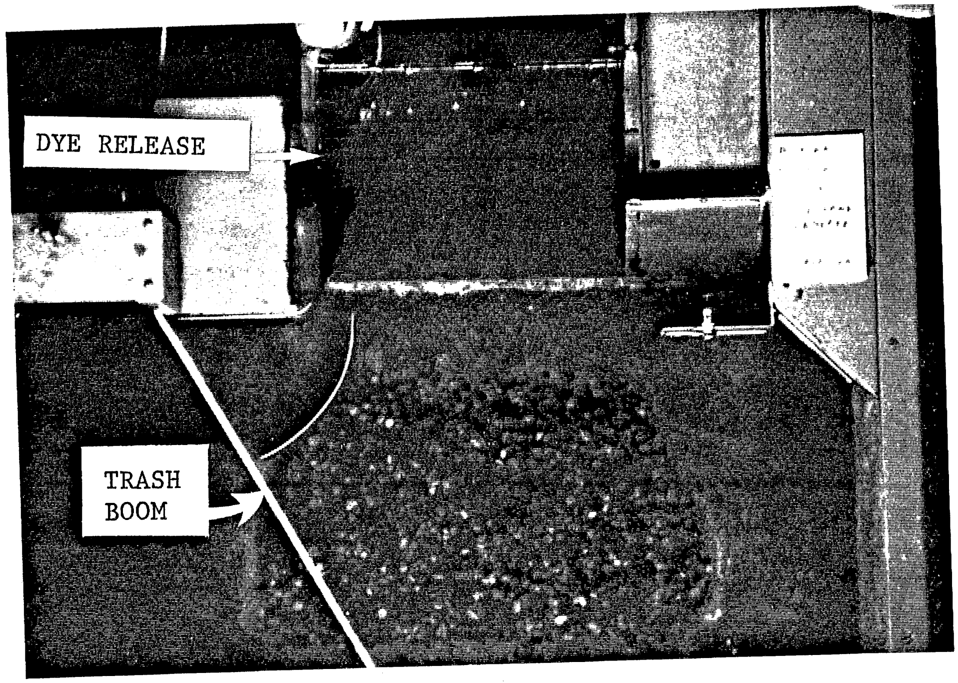



Figure 46. Dye trace, modification #4a, no excavation, both units operating.

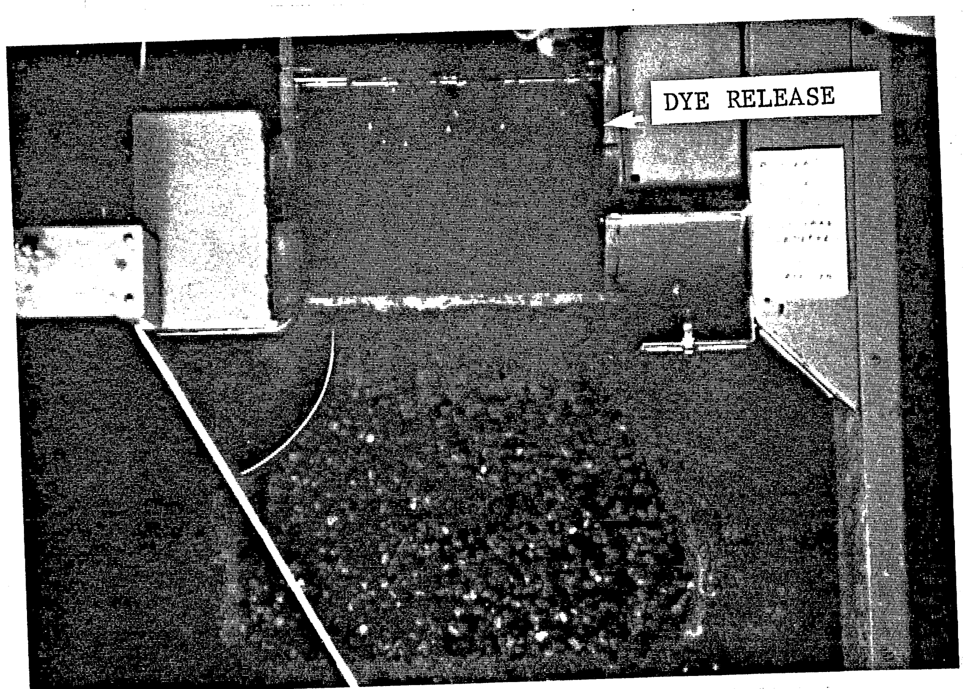
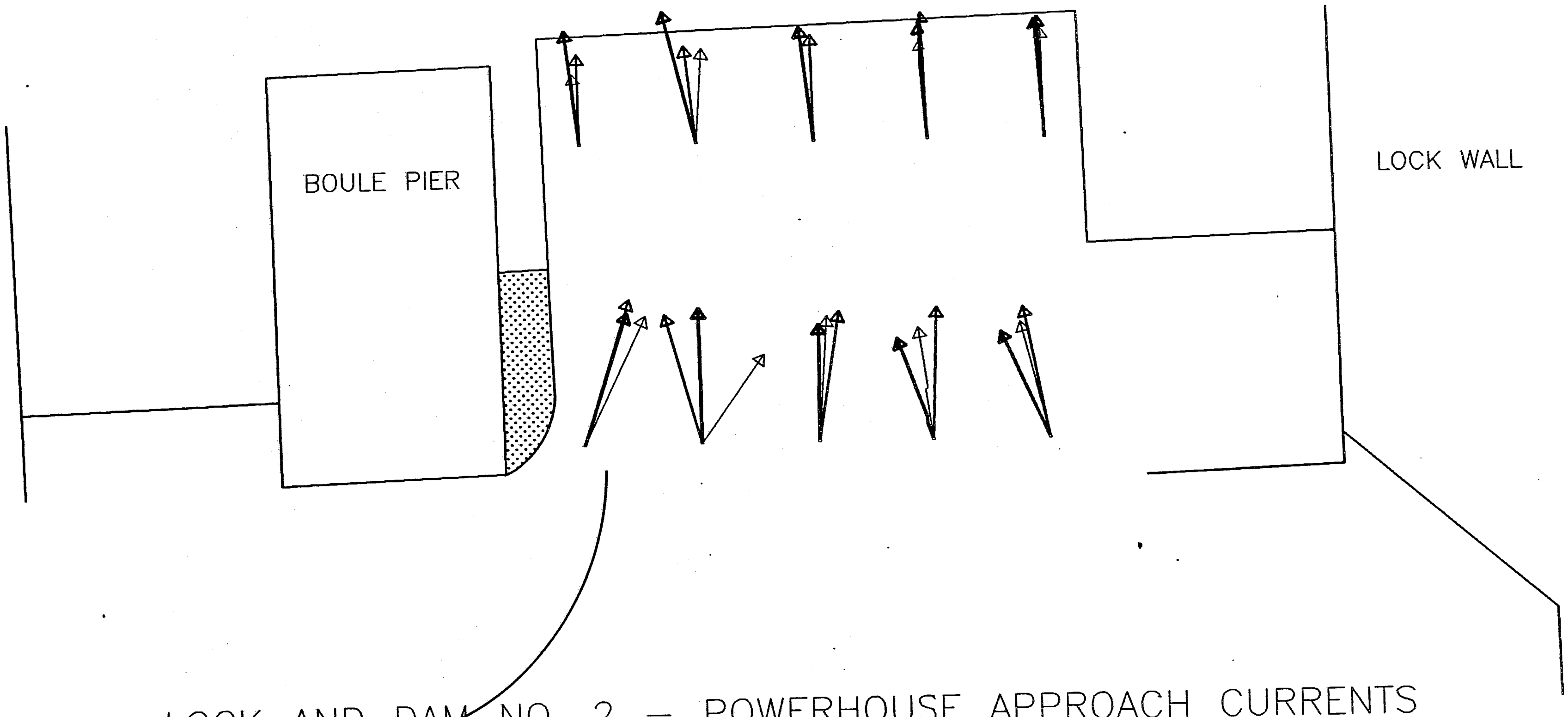



Figure 47. Dye trace, modification #4a, no excavation, both units operating.



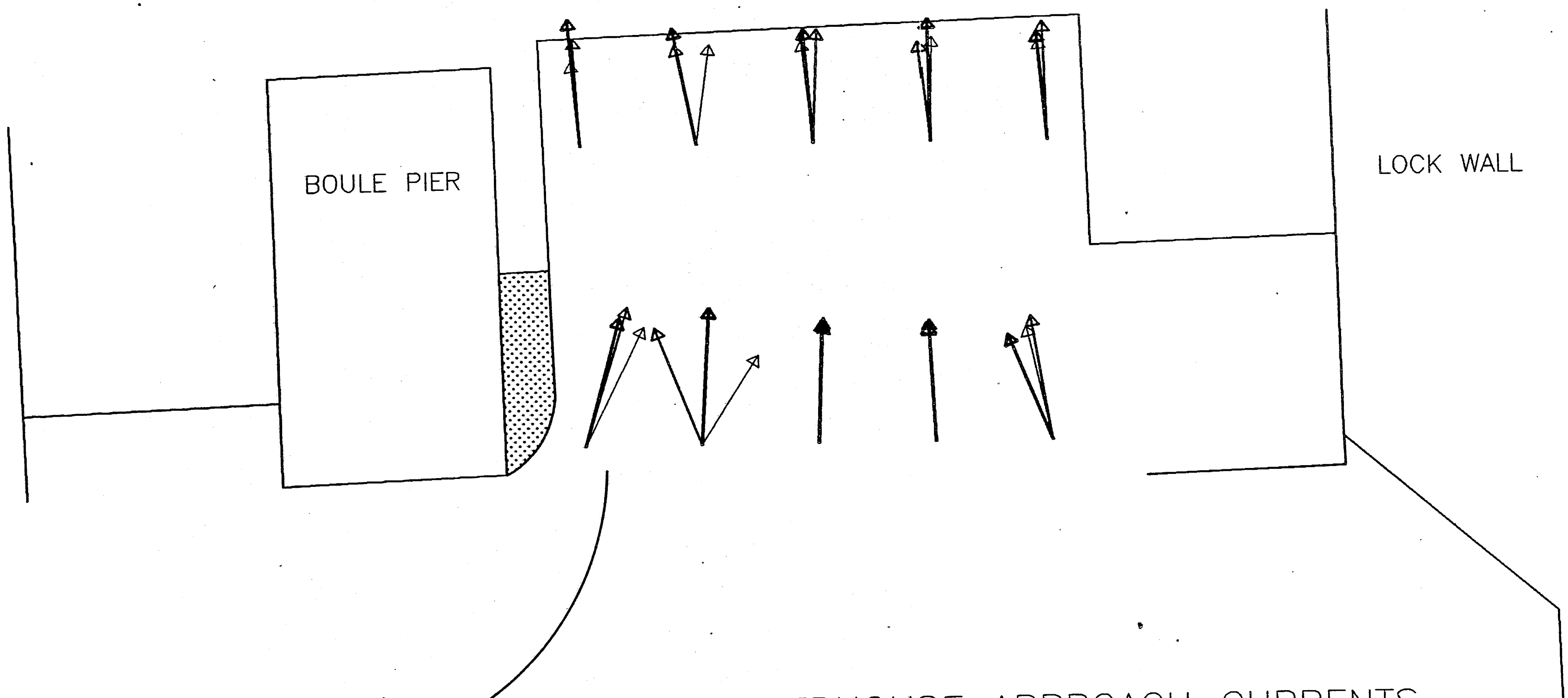

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #4a, NO EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 48**




LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #4a WITH EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 49**

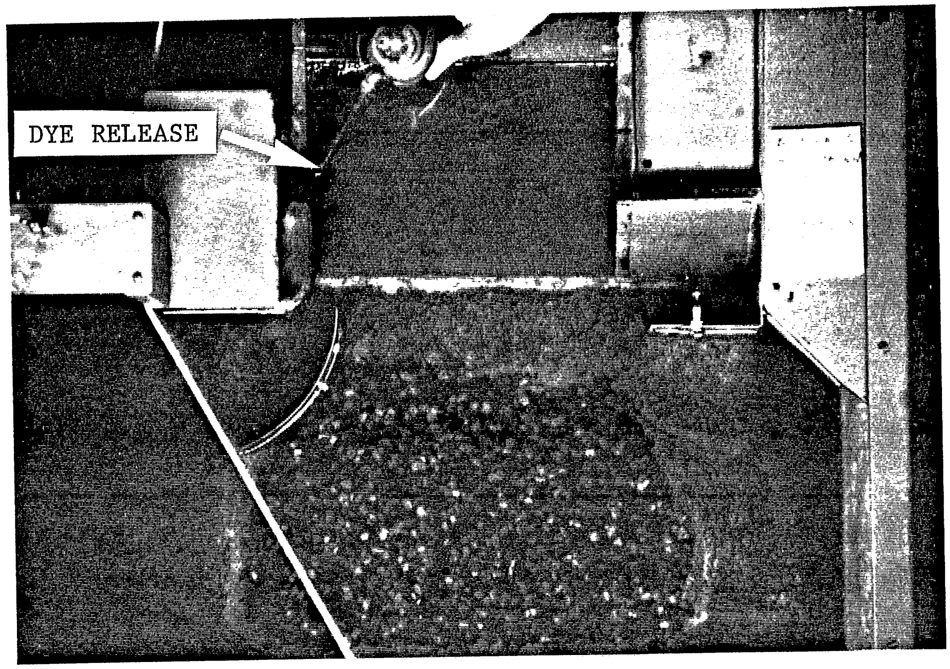



Figure 50. Dye trace, modification #4b, no excavation, both units operating.

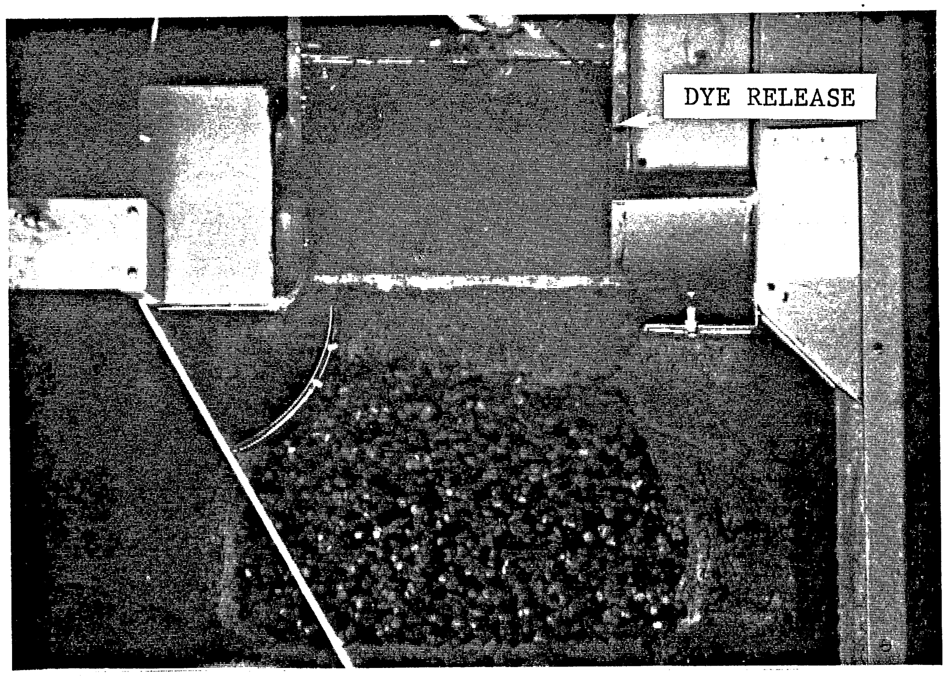
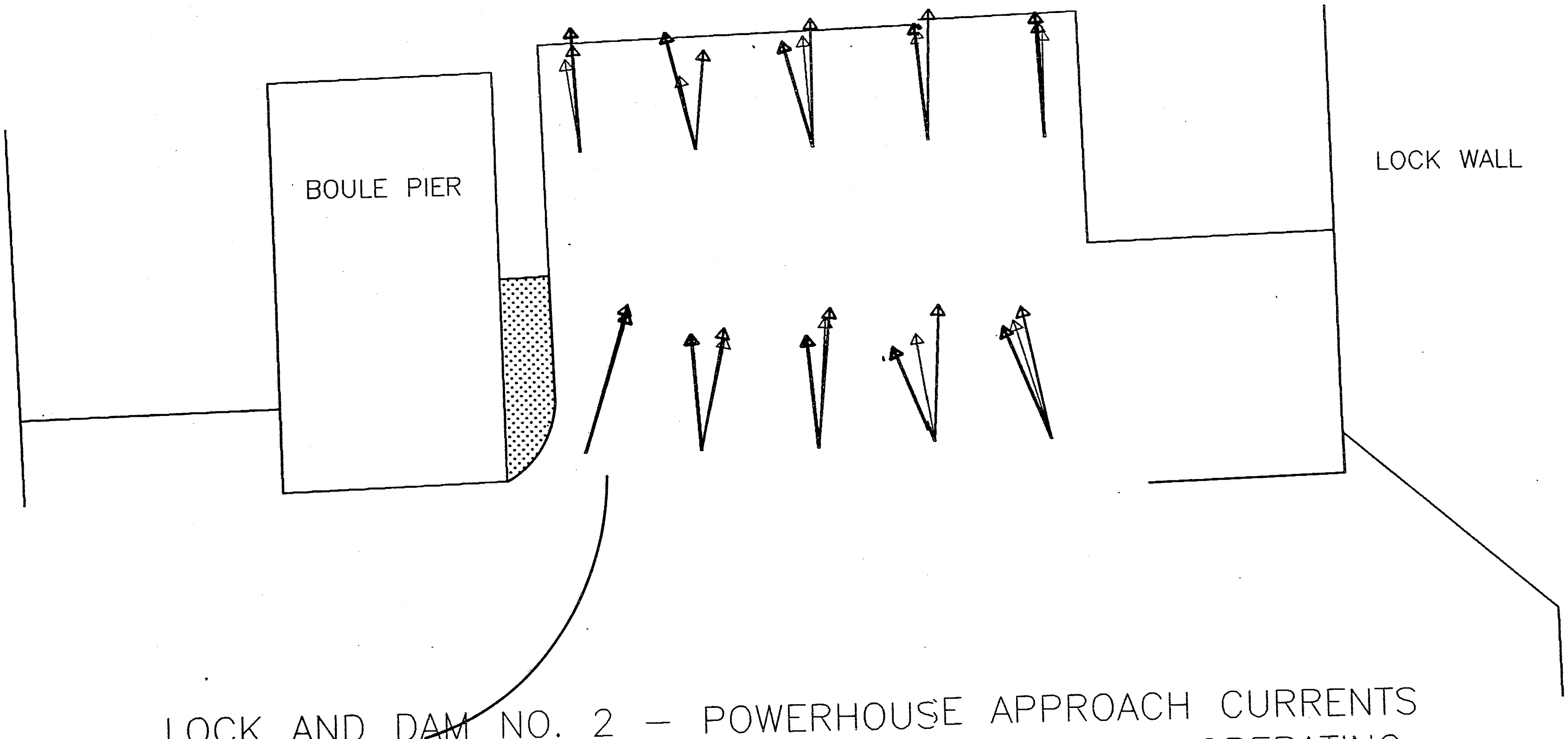



Figure 51. Dye trace, modification #4b, no excavation, both units operating.



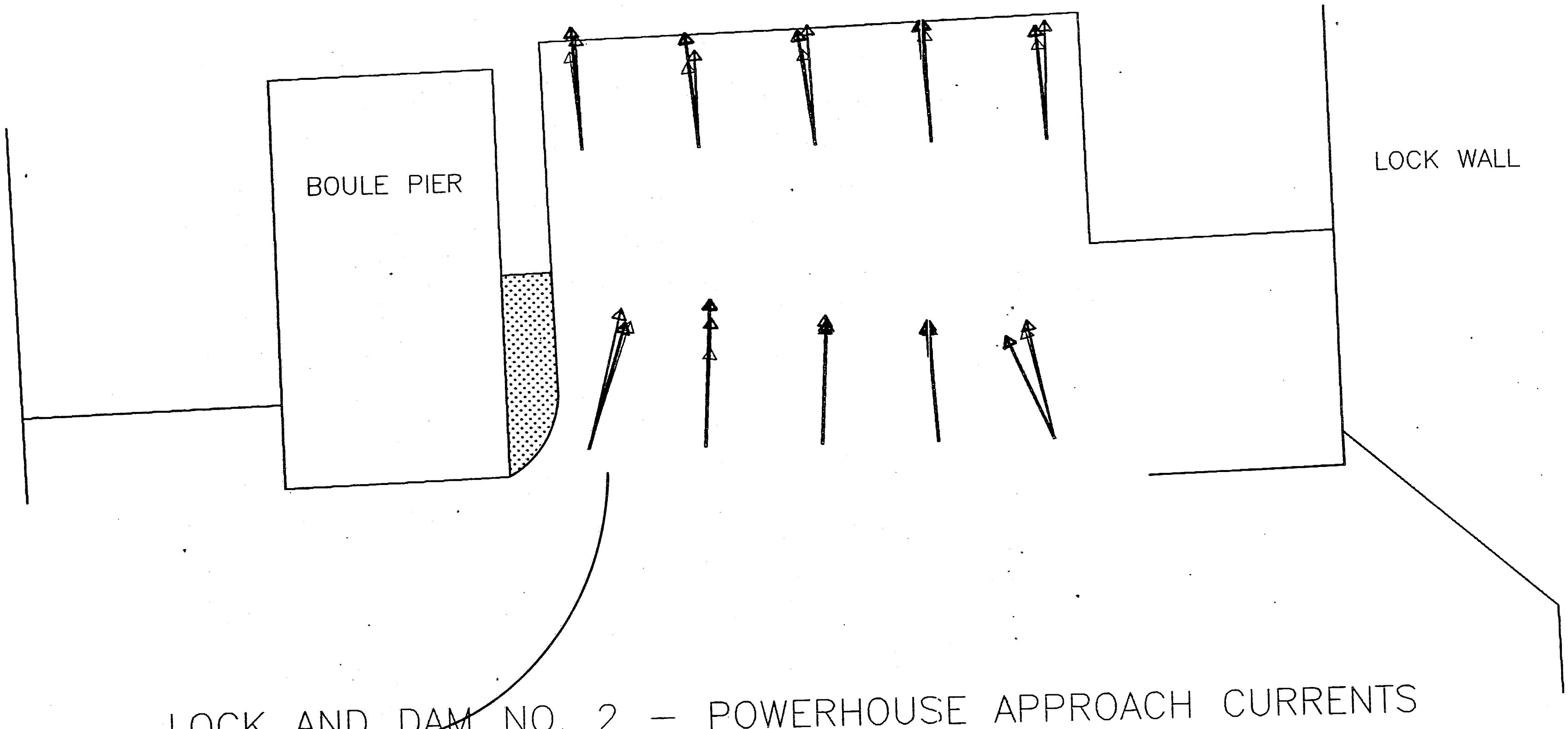

LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #4b, NO EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 52**




LOCK AND DAM NO. 2 – POWERHOUSE APPROACH CURRENTS
MODIFICATION #4b WITH EXCAVATION, BOTH UNITS OPERATING

NOTES ON CURRENT DIRECTIONS AND MAGNITUDES:

MEASURED 3 FT. BELOW WATER SURFACE
MEASURED MIDWAY BETWEEN WATER SURFACE AND BED
MEASURED 3 FT. ABOVE BED

ST. ANTHONY FALLS HYDRAULIC LABORATORY – 1987

**Figure 53**

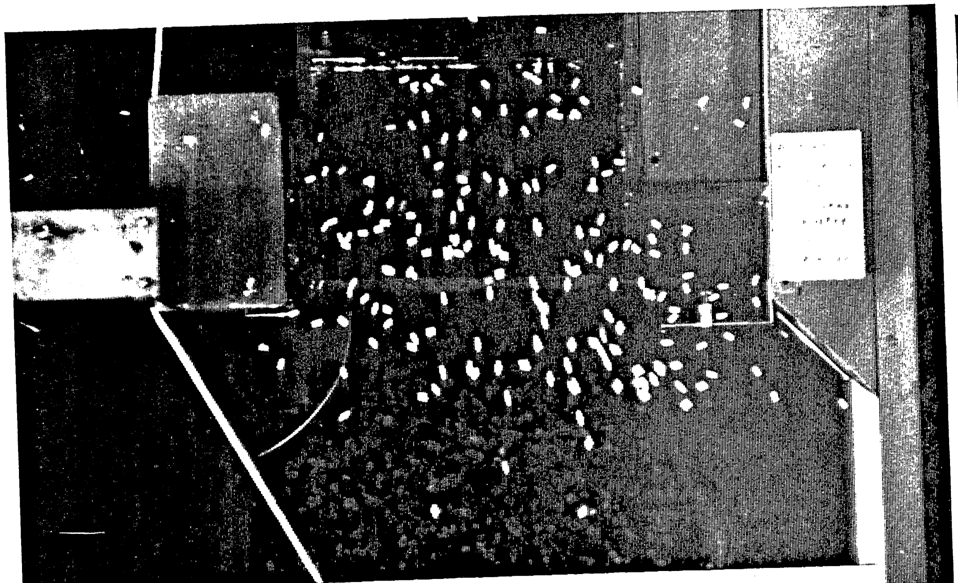


Figure 54. Confetti trace, modification #4a, no excavation, both units operating.

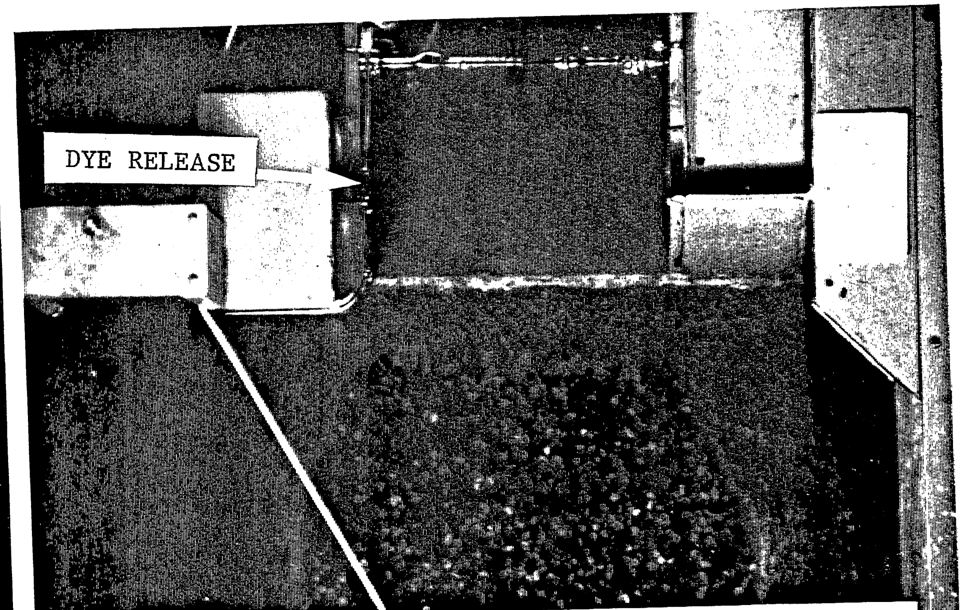



Figure 55. Dye trace, base test, 38,000 cfs.

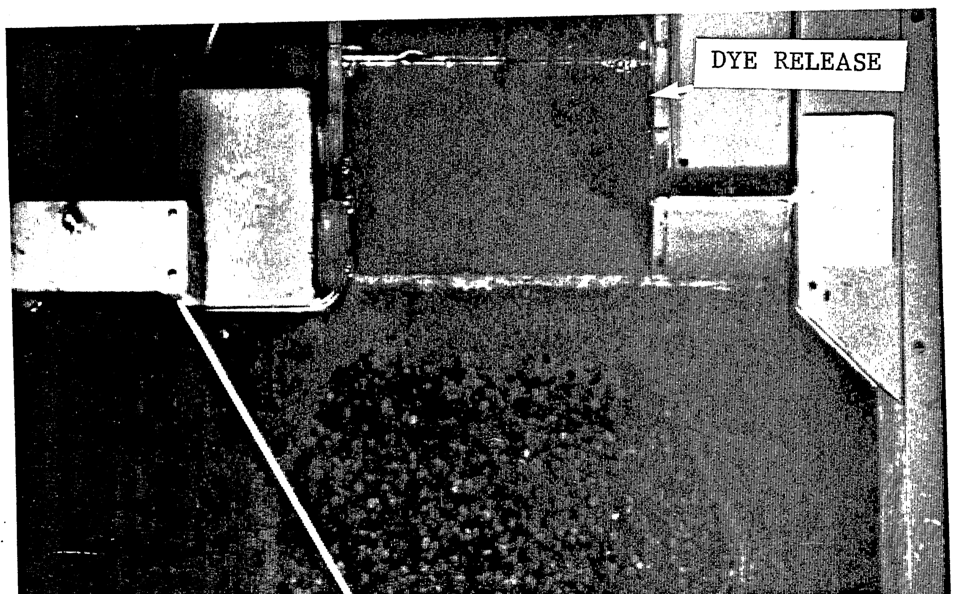



Figure 56. Dye trace, base test, 38,000 cfs.

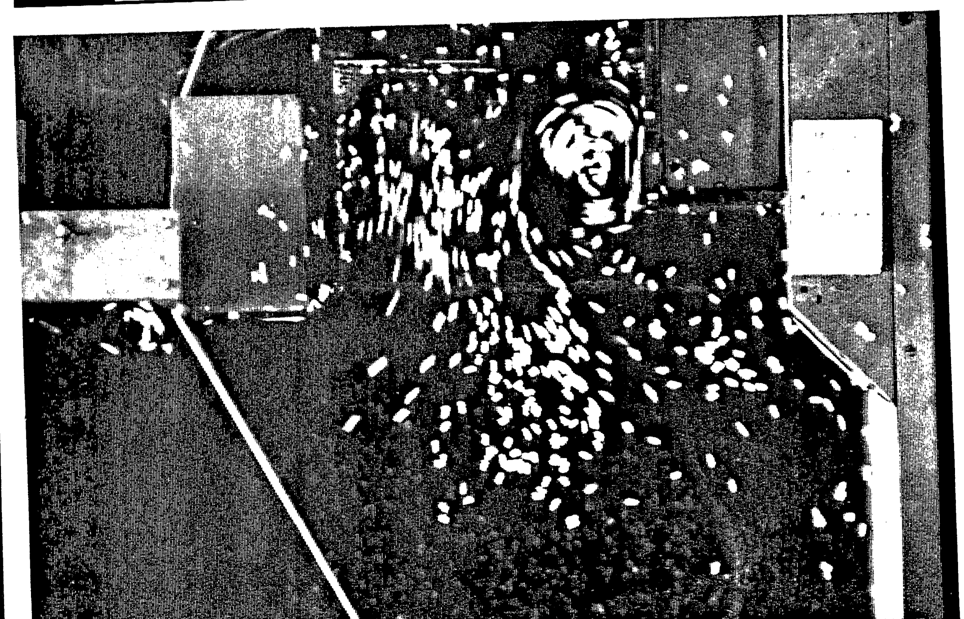


Figure 57. Confetti trace, base test, 38,000 cfs.

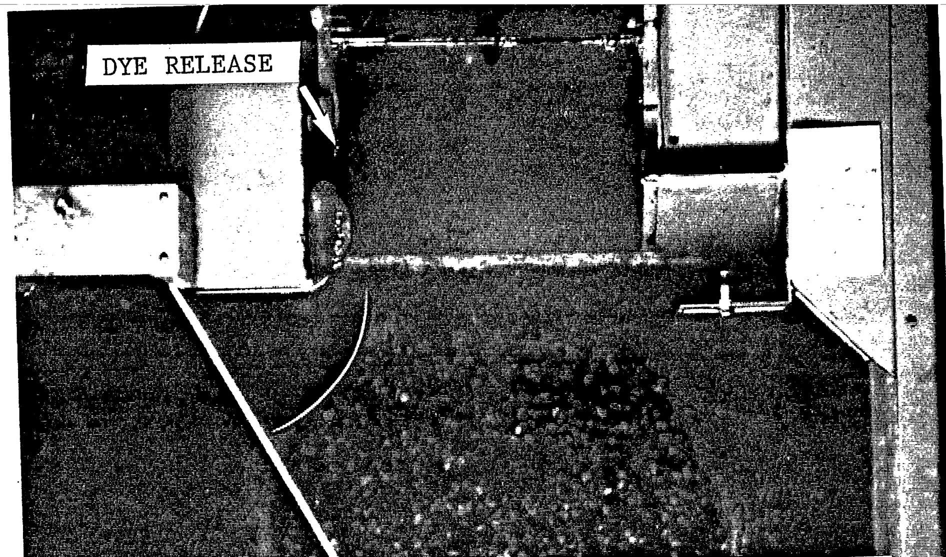



Figure 58. Dye trace, modification #4a, no excavation, 38,000 cfs.

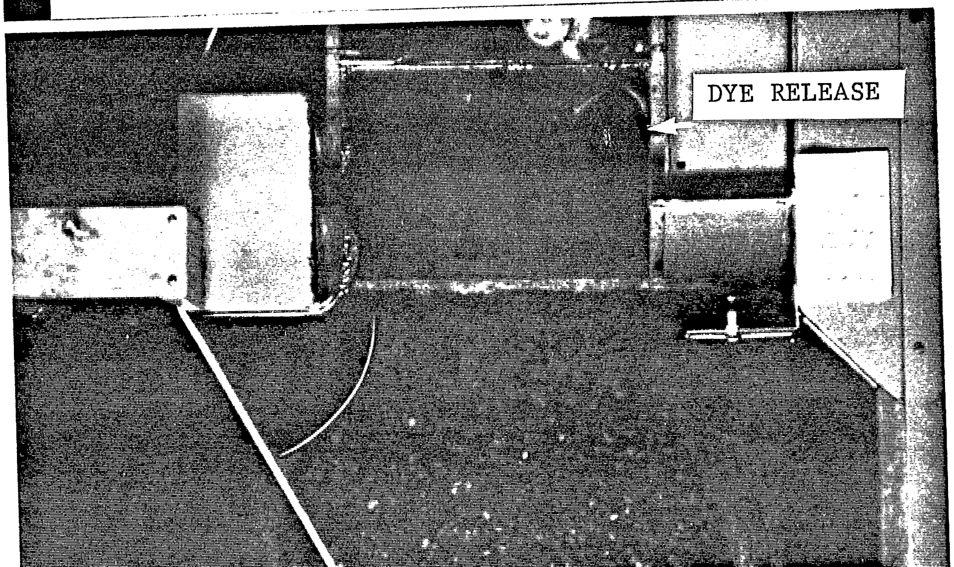



Figure 59. Dye trace, modification #4a, no excavation, 38,000 cfs.

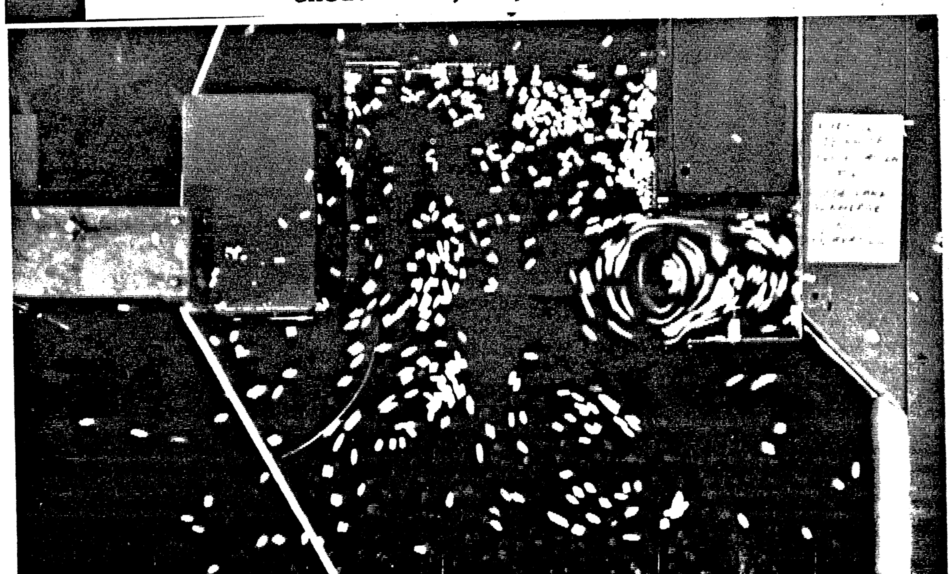


Figure 60. Confetti trace, modification #4a, no excavation, 38,000 cfs.