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# HYDRAULIC MODEL STUDY OF TAYLOR DRAW DAM OUTLET WORKS

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16. ABSTRACT

A 1:10 scale physical hydraulic model of the Taylor Draw Dam outlet works stilling basin was tested in Reclamation's hydraulic laboratory to determine the cause of concrete damage and to develop modifications to prevent future damage. Data from the model indicated that the flow exiting the outlet gate lifted off the chute floor and concentrated to one side near the water surface. The concentrated surface flow produced return flow over the downstream basin sill. A vortex generated from an offset bifurcation upstream from the gate caused these flow conditions. The return flow brought rocks as large as 9 inches in diameter into the basin. The churning and tumbling rocks severely abraded the concrete. Rocks up to 4 inches in diameter circulated up, across, and down the parabolic chute face, causing damage up to the toe of the hydraulic jump. The model study indicated the poor flow distribution within the basin that causes the strong return flows near the basin end sill can be corrected by installing two flow deflectors, one over the parabolic chute near the gate and another near the downstream end of the basin. Pressures were measured on the model deflectors to determine the structural loadings. Field tests of the prototype modification were performed to verify the model study.



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by

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Resource Consultants Incorporated provided technical coordination, flow deflector structural designs, and all background data required to conduct the model study. Pete Julius of the Hydraulics Branch and Jeff McLaughlin of the Boise Office completed the model drawings. Brent Mefford supervised the study, performed head loss computations, and analyzed field data. Lee Elgin helped collect the field data. Tracy Vermeyen helped analyze the field data. Mel Sabay obtained most of the early data for this study and wrote the introductory parts of this report. Mike Baker, Grand Junction Projects Office, handled contracting of the study.

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## INTRODUCTION

Taylor Draw Dam and Kenney Reservoir are owned and operated by Water User's Association No.1 in Rio Blanco County, Colorado. The dam is a zoned earthfill structure on the White River located 6 miles northeast of Rangely, Colorado. The dam was completed in October 1984. The reservoir provides recreation and supplies municipal-industrial water. The dam is approximately 74 feet high with a maximum base width of 190 feet, a crest width of 20 feet, and a crest length of 1,150 feet. The crest elevation of the dam is 5,329 feet.

Flow can be conveyed past the dam through an overflow spillway on the left side of the dam and through an outlet works structure. The spillway has a two-stage uncontrolled ogee crest extending 505.13 feet across the dam and a discharge capacity of 69,426 cubic feet per second at water surface elevation 5329 feet. The outlet works consists of separate 24- and 96-inch conduits. The 24-inch conduit is intended for municipal and industrial purposes. The 96-inch conduit bifurcates near the downstream end, forming a 96-inch and a 78-inch conduit. The 96-inch conduit is presently blind-flanged about 100 feet downstream from the bifurcation and will eventually feed a hydroelectric powerplant. The 78-inch conduit serves the outlet works and stilling basin (similar to a Reclamation Type III basin). A 6.5- by 6.5-foot slide gate controls flow through the 78-inch branch, which discharges into a parabolic chute and stilling basin. After passing through the stilling basin, the water flows over a riprapped transition up to the original river channel elevation.

During the relatively short operating history of Taylor Draw Dam, the concrete walls and floor of the outlet works chute and the stilling basin have experienced significant damage. In 1987, after an inspection of the basin, the damage was attributed to the abrasive action of rocks churning in the flow. The basin was dewatered, the concrete was repaired with silica fume concrete, and a cover was installed to prevent rocks from falling or being thrown into the stilling basin. Subsequent inspection by divers in September 1989 revealed significant new damage to the concrete surface.

Following the discovery of the new basin damage, engineers from the Colorado River Water Conservation District contacted Reclamation to determine if similar damage has occurred on Reclamation structures. Discussions centered on two possible causes of the basin concrete damage:

- abrasion caused by rock, gravel, and sand brought into the basin by back flow over the stilling basin end sill; the turbulent flow erodes concrete surfaces by continually moving material about the surfaces; this process is commonly referred to as ball milling

- erosion caused by cavitation formed along the walls and floor

Abrasion damage was again considered to be the most probable cause. As investigated by Zeigler, return flows moving upstream along the basin apron and floor can transport rock and debris upstream and into the basin under certain operating conditions [1][1]. Flow cavitation did not appear to cause the damage because large areas of the chute and basin walls and floor experienced erosion. The erosion damage pattern did not appear dependent upon boundary geometry. A physical model study was deemed necessary to determine damage causes and preventive measures.

## CONCLUSIONS

Model tests of the as-built outlet works geometry show that the jet leaving the control gate becomes highly concentrated within the basin chute for flows up to about 50-percent gate opening. The flow is concentrated to the left side of the chute and lifts off the chute floor. Downstream from the hydraulic jump the flow remains concentrated along the upper left side of the basin. This concentration creates a strong reverse flow into the basin along the floor; highest velocities exist on the left side. The jet concentration can be attributed to the following:

- the close proximity of the outlet works wye branch to the control gate
- the offset centerline of the branch
- the open wall slots remaining after construction from the gate frame blockout

For gate openings of approximately 15 to 40 percent, upstream flow velocities on the basin end sill can move material from the riprap apron over the end sill and into the basin. Gate openings from about 17 to 25 percent create upstream velocities sufficient to move material as large as 9-inch-diameter rock into the basin. Once captured, this material moves about on the basin floor.

Backflow caused by the concentrated jet can move smaller material (rocks up to about 4-inch diameter) up and down the chute. The churning action moves material up the left side of the chute floor and down the right side. This action causes abrasion on the chute starting about 30 feet downstream from the point of curvature and extending to the basin floor.

The riprap just downstream from the basin should be replaced with clean-graded rock material sloped no steeper than 5 horizontal to 1 vertical up to the river channel as shown in figure 1. The 5:1 sloped material should extend laterally to the base of the buttress walls. The riprap outside the basin walls and back to the buttress should be placed horizontally as shown in section A-A, figure 1. Divers should inspect the basin periodically to check for and remove boulders. Rather than using coffer dams to dewater the basin for maintenance, a stoplog structure should be installed in the return channel to the river.

[1] Numbers in brackets refer to references at the end of the report.

The poor flow distribution within the basin that causes the strong return flows near the basin end sill can be corrected by implementing the following recommendations:

- filling the open slots on each wall upstream of the gate frame; these slots promote vortice formation immediately upstream from the control gate, thus increasing jet concentration

- installing two flow deflectors, a curved one in the chute and a straight sloping one in the basin as shown in figure 2; deflectors can greatly improve the flow distribution without wye branch or basin geometry modifications

The curved chute deflector should be supported from above if necessary so as not to interfere with the lateral flow distribution. Model pressure data indicated an average maximum structural unit load of 1,630 pounds per square foot for the chute deflector in the direction of flow.

A design unit load of 421 pounds per square foot for the basin deflector was measured in the direction of flow.

A safety factor of at least two is commonly used in the structural design because the pressures measured reflect average hydraulic forces rather than structural response.

Pressure measurements on the chute and basin floor do not indicate significant potential for cavitation damage. The only potential for cavitation noted in the model occurred along the wye branch crotch at gate openings above 92 percent (reservoir elevation 5317.5 feet). Although cavitation damage has not occurred in the prototype outlet pipe under normal operating conditions, the outlet pipes downstream from the wye branch should be inspected for damage after running above 70-percent gate openings for extended periods.

## DESCRIPTION OF THE PHYSICAL MODEL

To study the problem, a 1:10 Froude scale hydraulic model of the outlet works structure was constructed as shown in figure 3. The model represented about 100 feet of the approaching 96-inch pipe, wye branch, outlet pipe, control gate, chute, basin, and downstream topography. The 96- by 78-inch pipe wye branch, the 6.5- by 6.5-foot outlet control gate, and the stilling basin were modeled as shown in figure 4 using clear acrylic plastic to allow flow observation. The transition from the pipe to square gate approach and the gate leaf were constructed of metal. The riprap protection and topography of the downstream outlet channel were contoured to station 6+51 using 7.5- to 15-inch scaled rock as shown in figure 5. Instead of modeling the complete outlet works system, discharge from the laboratory pumping system was passed directly into a pressure tank. Baffles within the tank dampened large-scale flow turbulence before the discharge entered the 9.6-inch (model) outlet pipe. A piezometer ring installed on the model outlet conduit (sta. 3+69.5) measured piezometric head to set the model reservoir elevation. Energy losses upstream from the piezometer tap were calculated for a range of discharges based on the prototype geometry. True reservoir elevation was then calculated by adding the upstream losses to the measured energy head at station 3+69.5.

The tailwater elevation downstream from the basin was determined for the model using the stage-discharge curve given in figure 6. Resource Consultants Incorporated (RCI), an engineering consulting firm located in Fort Collins, Colorado, developed the relationship for the water district. The low tailwater curve (flow only through the outlet works) indicated by the squares was used predominantly throughout the model studies. The model was tested at tailwater elevations above these levels as needed to determine the sensitivity of the flow to tailwater elevation. Table 1 lists normal test conditions for each gate opening.

Table 1. – Normal test conditions.

| Gate opening % | Energy head Station 3+69.5 (Res. el. = 5317.5) | Tailwater (ft) | Discharge ($ft^3/s$) |
|---|---|---|---|
| 16.68 | 5317.5 | 5267.8 | 321 |
| 25.01 | 5317.4 | 5268.2 | 427 |
| 33.34 | 5317.0 | 5268.5 | 533 |
| 50.03 | 5315.2 | 5269.2 | 771 |
| 66.67 | 5313.2 | 5269.8 | 997 |
| 91.72 | 5310.6 | 5270.5 | 1353 |

## Proposed Scope of Study

The possible contribution of cavitation to the stilling basin damage would be investigated by measuring and evaluating model pressures. Static pressures would be measured at 10-percent increments of discharge.

Stilling basin damage resulting from abrasion would be studied in the model by determining if and under what operating conditions material is drawn into the basin from downstream. Material would then be placed in the basin to determine movement and retention as a function of operating conditions.

The apparent non-uniformity of the flow entering the basin would be investigated by measuring invert pressures, water velocity, and water surface profiles within the chute for 25-percent increments of discharge. An evaluation of the flow characteristics attributable to the pipe junction or control gate would be made.

## Measurements and Observations

Permanently installed venturi meters are used in Reclamation's hydraulic laboratory to measure discharge. Mercury manometers indicate the differential pressure across the venturi meters. The measured flow rates have a traceable accuracy of ±1.0 percent based on volumetric tank calibrations.

Velocities were measured using an electromagnetic current meter with a 3/4-inch ball-shaped probe (measures average velocity of a 3-ball-diameter area). A water surface probability probe was used to measure water surface profiles on the chute to document jet skewness. On a rough water surface, this instrument determines the percentage of time it is wet versus elevation of the wetness. The elevation at which the instrument is 50 percent wet is used as the water surface elevation. Replacing the design riprap (2 feet) with smaller material (3- to 4-inch prototype or No. 4 sieve size to 3/8-inch model) downstream from the basin end sill as shown in figure 5 accentuated material transport in the basin. The substantially smaller replacement material was representative of most material found in the basin during inspections. Pressure taps were placed on centerline along the curved chute bottom and downstream of chute blocks and floor blocks to determine cavitation potential within the basin.

## MODEL SIMILITUDE

### General

A model must be geometrically, kinematically, and dynamically similar to the prototype to truly represent actual conditions. Geometric similarity exists when the ratios of all homologous dimensions between model and prototype are equal. The geometric scale ratio, or length ratio ($L_r$), equals $L_p/L_m$. The subscripts $p$ and $m$ refer to the prototype and model, respectively. Kinematic similarity, or motion similarity, implies that the ratios of velocities and accelerations between model and prototype are equal. Dynamic similarity requires that the ratios of homologous forces between the model and prototype be equal. Deviation in any one of these three areas of similitude requires careful interpretation of model results. If any one deviation is too large, or too many deviations exist, the model will not represent the prototype and no amount of interpretation will yield the correct results or conclusions.

### Flow Similitude

Similitude analysis and model design are best started by identifying valid homogeneous equations and dimensionless functional relationships that apply to both the model and prototype. The equations and functions selected must be checked for model and prototype application range and limits. Normalizing complete hydrodynamic equations for open channel flow opposed to tractive shear, or friction, and then extracting dimensionless parameters produces a Froude number squared ($F^2$) or ($V^2/R_h g$), and a product of the Darcy-Weisbach friction coefficient ($f$) times Froude number squared as the required parameters for scaling flow. The friction coefficient is a function of relative roughness ($k_s/4R_h$) and Reynolds number ($R_e$) expressed as:

$$f = \phi \; (k_s/4R_h \, , R_e)$$

where:

$R_e$ = $(4R_hV/\upsilon)$
$f$ = Darcy-Weisbach friction factor
$R_h$ = hydraulic radius
$V$ = velocity
$g$ = gravitational constant
$\phi$ = function operator
$k_s$ = rugosity
$\upsilon$ = kinematic viscosity

Based on Froude law alone, and selecting a length ratio $L_r$ of 10:

| | |
|---|---|
| Length ratio | $L_r = 10$ |
| Velocity ratio | $V_r = L_r^{1/2} = 3.16$ |
| Time ratio | $T_r = L_r^{1/2} = 3.16$ |
| Discharge ratio | $Q_r = L_r^{5/2} = 316$ |
| Unit discharge ratio | $q_r = L_r^{3/2} = 31.6$ |
| Tractive shear ratio | $\tau_r = L_r = 10$ |
| Pressure ratio | $P_r = L_r = 10$ |

Selection of the Darcy-Weisbach equation to normalize friction loss in the complete flow equation requires that the ratio of friction factors ($f_r$) in prototype and model must be made equal to 1 to produce similar vertical velocity distributions and secondary flows. The Darcy-Weisbach equation for open channel flow in slope ($S$) form is expressed as:

$$S = f\frac{1}{4R_h}\frac{V^2}{2g} \tag{1}$$

Because the friction factor ($f$) is a function of Reynolds number ($4R_hV/\upsilon$) and relative roughness ($k_s/4R_h$), the modeler must work within Moody-type friction curves. Kamphius found that $k_s$ for river bed material is equivalent to $2D_{90}$ (twice the 90-percent sieve passing size) [2]. At a model scale of 1:10 and a prototype $D_{90}$ size greater than 10 millimeters, sediment can be scaled by the geometric scale for both transport and friction scaling provided the Reynolds number is large enough. Reynolds number and Froude number scaling cannot be attained simultaneously in models. However, if the Reynolds number and relative roughness are large enough, the Darcy-Weisbach friction factor ($f$) can be made the same for both the model and prototype river bed and riprap material. The model must be made to flow at water surface elevations according to a tailwater curve to produce the corresponding velocity. The modeler must check and/or make the model and prototype friction factor ($f$) the same for the discharge range needed. Applying the previous scale relations to the Reynolds number results in a measure of Reynolds number distortion ($R_{dr}$) based on the selected model scale ratio expressed as:

$$R_{dr} = L_r^{3/2} = 31.6$$

Prototype to model friction ratios for the riprap modeled with 3/4- to 1.5-inch gravel varied from 0.97 to 1 for discharges ranging from 250 to 1,400 cubic feet per second. For No. 4 sieve size to 3/8-inch gravel, the friction ratios were 1 over the same discharge range. Thus, the movable bed material scaled in terms of both friction and transport.

## MODEL TESTS

### Tests of As-built Structure

The jet exiting the control gate was visibly skewed across the chute. Several factors cause the horizontal skewness of the jet:

- the close proximity of the outlet works wye branch to the control gate
- the offset centerline of the branch
- the open wall slots remaining after construction from the gate frame blockout

With all the flow passing to the 78-inch branch (only condition presently possible), flow visually separates from the branch crotch and a strong longitudinal eddy is generated along the inside wall of the 78-inch leg. The eddy effects carry to the gate and affect the flow profile of the jet passing under the gate. The offset centerline of the 78-inch leg reduces the branch symmetry and increases eddy strength. The open slots on both ends of the gate cause vertical eddies within the slots, which accentuate flow instability.

The lateral skewness of the jet downstream from the control gate was documented by measuring the water surface elevation across the chute using a water surface probability probe. Profiles were measured at three stations along the chute and for five gate openings from 16.7 to 66.7 percent. Profiles were measured at station 4+43.50, the point of floor curvature, station 4+53.42, and station 4+62.13. Figures 7 through 10 show that flow moving down the chute concentrated to the left side (looking downstream). Figures 11 and 12 show that the unsymmetrical flow across the chute also causes the wave front face to skew from normal.

During these tests, some downstream material moved into the basin. Large material generally moved about the basin floor. Smaller material (roughly 3- to 4-inch) often traveled upstream onto the chute and moved in an oscillatory manner up the right side to nearly the wave front face (fig. 13) and then down the left side.

Static pressures measured along the chute and basin floor were greater than atmospheric at all pressure tap locations and for all discharges. Therefore, cavitation does not contribute significantly to the concrete erosion problem.

Modifying the wye branch or installing vanes within the prototype conduit was considered difficult and less desirable than modifying the chute and basin. The only modification considered upstream from the gate was the grouting of the slots upstream from the gate frame.

### Tests With Slot Blocks

During construction, a blockout wider than the control gate was formed to provide room to install the gate. After gate installation the remaining blockout area was not grouted. Thus, the conduit walls immediately upstream from the gate frame contain large vertical slots (about 1.25 feet wide by 1.0 foot deep). The large slots create vertical eddies suspected of accentuating the skewness of the jet observed downstream from the control gate. The slots in the model were filled with removable blocks to investigate the influence of the slots on the chute flow. Observations and surface profile data were measured again at the previously tested stations and conditions.

Figures 14 through 16 show that although the flow still concentrated toward the left chute wall, the flow profile improved for the 16.7-, 25-, and 33.3-percent gate openings. The flow increase on the right side of the chute reduced the hydraulic jump skewness and the extent of the chute return flow. Some rock material was again drawn onto the stilling basin floor and moved onto the chute. Improvements in the flow skewness produced by filling the slots were less apparent at higher gate openings.

### Tests With Deflectors

A thin, curved flow deflector was placed in the chute and a second thin, flat deflector was placed downstream in the stilling basin as shown in figure 17. The location and angle of these deflectors were varied to determine their potential use for adjusting the flow profile. The chute deflector was designed to force the flow down along the chute floor and reduce the lateral skewness.

The proper location of the chute deflector was found by moving a straight deflector vertically, horizontally, and rotationally, while visually judging the results. The distance the jet traveled along the chute floor, the skewness of the wave front face, and the location and lateral skewness of the bubbly/clear water interface were used as visual indicators of deflector performance. The deflector was positioned to obtain the greatest improvement in flow conditions between 16.7- and 33.3-percent gate openings. After the best position was determined, the deflector was then curved slightly (simple radius with 0.08-foot maximum deflection from the 2.5-foot chord) to reduce flow separation and splashing. Figure 18 shows the chute operating at 25-percent (1.62-feet) gate opening with the curved deflector installed.

The chute deflector was observed with and without blocks in the gate installation slots. Filling the slots noticeably improved the flow action downstream from the deflector. Upon removal of the filler blocks, the bubbly/clear water interface, which provided a clear demarcation between the chute jet and the return flow eddy, moved well upstream (size of the return flow eddy increased) toward the deflector.

The flat basin deflector was intended to force the flow to sweep the end sill and thus maintain a downstream velocity component over the basin end sill and adjacent apron. To find the best position and inclination for the basin deflector, short strings were attached to the downstream edge of the sloped stilling basin end sill to indicate the direction of flow. The deflector was first positioned for flow at 25-percent gate opening. The deflector position was adjusted until all the strings were drawn steadily downstream as parallel as possible to basin walls. The positioning was verified further by observing the action of the strings under flow conditions at all gate openings and over a range of increased tailwater elevations. Figure 17 shows the size and position of the basin deflector. Figure 19 shows the basin deflector tested in the model.

**Effects of Deflectors on Velocity and Sediment Intake Over the Basin End Sill**

An evaluation of the structural modifications was conducted by observing material movement and measuring flow velocities over the basin end sill as modifications were added. The existing basin flow draws the most material into the basin at about 25-percent gate opening. Therefore, a 25-percent gate opening was chosen for velocity measurements, which were taken under the following conditions:

- as-built with slots upstream from gate filled
- filled slots and upstream deflector
- filled slots and both upstream and downstream deflectors

Velocities were measured about 1-foot prototype above the interface between the end sill and the riprap apron. Velocities were measured at three positions across the end sill: near both basin walls and at the center. Figure 20 contains a comparison of the velocity measurements. Resulting velocities for these conditions were as follows:

- With only the slot blocks installed, back flow occurred over the entire sill-riprap interface; velocities ranged from 4.4 feet per second on the left side to 2.1 feet per second on the right side (looking downstream). Both the 3/4- and 3/8-inch (model) riprap material moved into the basin.

- After adding the chute deflector, back flow still occurred over the sill-riprap interface on the left side, looking downstream, and the middle, although the velocity was reduced by 76 percent on the left side and about 67 percent in the middle. On the right side, the flow direction changed to downstream at a velocity of about 2.1 feet per second. Some of the 3/8-inch material moved into the basin.

- With the addition of the basin deflector, all the flow over the sill-riprap interface moved downstream. Velocities ranged from 3.75 to 4.15 feet per second (averaging about 4.0 feet per second). No material was drawn into the basin. After measurements were completed, the deflectors were removed and material again moved quickly into the basin.

Mavis' equation and Brooks' gravity slope stability correction equation as given by Vanoni were used to estimate prototype material movement based on the measured velocities with only the slots filled [3]. These algorithms predict material up to 9-inch cobbles could be moved back into the basin, suggesting that flow in the as-built structure could move small or broken riprap material into the basin.

Following the fixed-gate tests, the performance of the three modifications (slots filled and deflectors) was monitored over extended lengths of time for all gate openings. During these tests, no indication of reverse flow or movement of material over the end sill was observed.

The modifications recommended in this study should not be considered 100 percent effective. A single boulder in a stilling basin can damage concrete considerably. Thus, divers should inspect the basin periodically to check for and remove boulders. Rather than using coffer dams to dewater the basin for maintenance, a stoplog structure should be installed in the return channel to the river. Material remaining after coffer dam removal is a probable source of rocks.

## Pressure Forces on Sheet Metal Version of Model Deflectors

Pressure measurements at 100-percent gate opening were obtained on both sides of the deflectors. The curved chute deflector was subjected to positive pressures on the lower side and negative pressures on the top side. The maximum differential pressure measured across the chute deflector was 1,630 pounds per square foot. The pressure on the basin deflector was positive on both sides. The maximum differential pressure measured on the basin deflector was 421 pounds per square foot acting in the downstream direction. These unit loads are based on average pressure values. Instantaneous peak loads may exceed these values. A safety factor of at least 2 is commonly applied in the structural design because of poor peak load definition.

## Final Structural Version of the Upstream Deflector

Following initial structural design, the chute deflector was tested again to study the effects of the thickened deflector section. To structurally withstand hydraulic loading, the chute deflector was designed with a 2.5-inch nose radius, an 18.5-foot bottom radius over a 2.5-foot chord, and a 9.17-foot top radius. Preliminary operation using the round nose in the model caused a violently rising sheet of water. Thus, the round nose was streamlined to a 45-degree nose angle.

Preliminary model observation using the 45-degree nose angle indicated that the top leg of the angle needed to be tilted 4 degrees below horizontal toward the gate to minimize spray. Also, the downstream end of the deflector was raised to relieve the flow convergence caused by the required structural thickness. Best performance was observed with the 2.5-foot bottom chord set at 21 degrees down from horizontal. Figure 2 shows the final deflector arrangement.

## Model Pressure Measurements of the Final Upstream Deflector

After making the physical changes shown in figure 17, pressures were measured for a 6-foot gate opening. Pressures were measured on the deflector top and bottom (along lines in the direction of flow) at locations one-quarter of the width in from each wall. These pressure measurements yielded an average hydraulic loading (integrated over the surface) of 390 pounds per square foot. The maximum differential pressure at two opposing (top/bottom) pressure taps was 475 pounds per square foot. The maximum probable instantaneous pressure differential was 1,425 pounds per square foot (largest mean at a point plus the largest fluctuation on the surface).

Changes in the downstream deflector thickness did not warrant the collection of additional pressure measurements. The previously measured maximum differential pressure of 421 pounds per square foot is representative of the final design.

## Discharge Calibration

A coefficient of discharge curve was determined for the outlet works. Discharge through the outlet works was measured over the full range of gate stroke at reservoir elevation 5317.5 feet. Discharge was measured by the laboratory venturi meters. Figure 21 contains coefficient of discharge values plotted against gate opening. This curve can be used with equation 2 to estimate discharge.

$$Q = C_d A \, (2gH)^{1/2} \tag{2}$$

The total hydraulic head (H) is determined by subtracting gate opening centerline elevation from the reservoir elevation. The area (A) is the full 6.5- by 6.5-foot open area of the gate. Equation (2) can be rewritten as:

$$Q = 339 C_d \, (H)^{1/2} \tag{3}$$

## Wye Branch Cavitation

During the discharge calibration tests, cavitation occurred in the model along the crotch of the 96- to 78-inch wye branch for gate openings greater than 90 percent at reservoir elevation 5317.5 feet. Although the model was not instrumented to predict the occurrence of wye cavitation, cavitation in the model reflects an even greater potential for cavitation in the prototype. The prototype has not operated at large gate openings for extended periods of time because of gate vibration. No visible cavitation damage has been reported on the wye branch during normal operation (gate openings of less than 4.0 feet). Past operating history did not warrant further investigation of wye-branch cavitation in the model. Dam operation criteria should be amended to state that the wye branch can cause cavitation during flow at gate openings above about 4 feet.

## FIELD TESTS OF MODIFIED STILLING BASIN

The prototype stilling basin, as modified according to the recommendations contained in the conclusions of this report, was tested in August 1991. Prior to testing, strain gauges were mounted on the deflectors to monitor stress levels during operation. Four gauges were mounted on the upstream flow deflector and two on the downstream deflector. Also, several rocks ranging in size from about 3/4-inch to 9 inches were painted, numbered, and placed just downstream from the stilling basin end sill. Rock locations were documented before the basin was watered up.

The outlet works was operated for about 8 hours under gate openings of 6 inches to 4.5 feet. During operation, flow deflector stresses (streamwise direction) were measured, observations of flow conditions were made, tailwater elevations were recorded, and an attempt was made to determine flow direction near the basin end sill.

The stress data for each flow and location was reduced to peak stress versus occurrence rate in histogram format. This data verified that the model pressure data was adequate for structural design. The data was sent to RCI and is not reproduced in this report.

Approximate tailwater elevations were determined by reading a measuring tape temporarily mounted on the downstream stoplog basin dewatering structure. These data are plotted as a function of discharge in figure 22. The measured tailwater elevation lies between the high and low computed tailwater curve given in figure 6.

Flow from the outlet at gate openings below about 2 feet produced a noticeably larger rooster tail compared to model results. The higher trajectory in the prototype causes a portion of the jet to pass above the chute deflector. The overshoot portion of the jet impinges in the basin at a shallow angle typical of conditions existing prior to deflector installation. A determination of the percent of flow passing over the deflector and an estimation of any loss in deflector effectiveness was not visually possible. Although model scale effects (Reynolds number distortion) may contribute to the jet differences noted, it is suspected the prototype and model may differ in transition, gate chamber, or alignment geometry. Future inspections of the upstream transition and gate chamber should consider the cause of the large rooster tail.

RCI constructed a flow direction vane indicator to lower into the flow. The indicator consisted of a shaft running through a 20-foot pipe. A flat vane was attached vertically to the shaft end protruding from the pipe bottom, and a direction indicator was mounted on the shaft end protruding from the top of the pipe. Access limitations prevented placement of the flow direction indicator directly over the basin end sill. Therefore, the flow direction indicator was held approximately 6 feet upstream of the end sill crest. At this location, the vane was located 4.3 feet above the basin floor. During most flow tests, the flow direction was largely upstream but tended to oscillate. Similar results were found during subsequent monitoring of the flow direction at the same point in the model. This upstream flow is caused by return flow moving in behind the downstream basin flow deflector. To monitor flow direction on the end sill, an indicator must be mounted not more than 1 foot above the end sill crest.

After the flow tests were completed, the outlet works gate was closed and the basin dewatered. An inspection of the basin revealed no material had been drawn into the basin during the test. The painted rock placed just downstream from the end sill and throughout the riprap apron had not moved upstream. Although no material was drawn into the modified basin during the 8-hour test, annual inspections of the basin should be conducted to verify long-term effectiveness of the basin modifications.

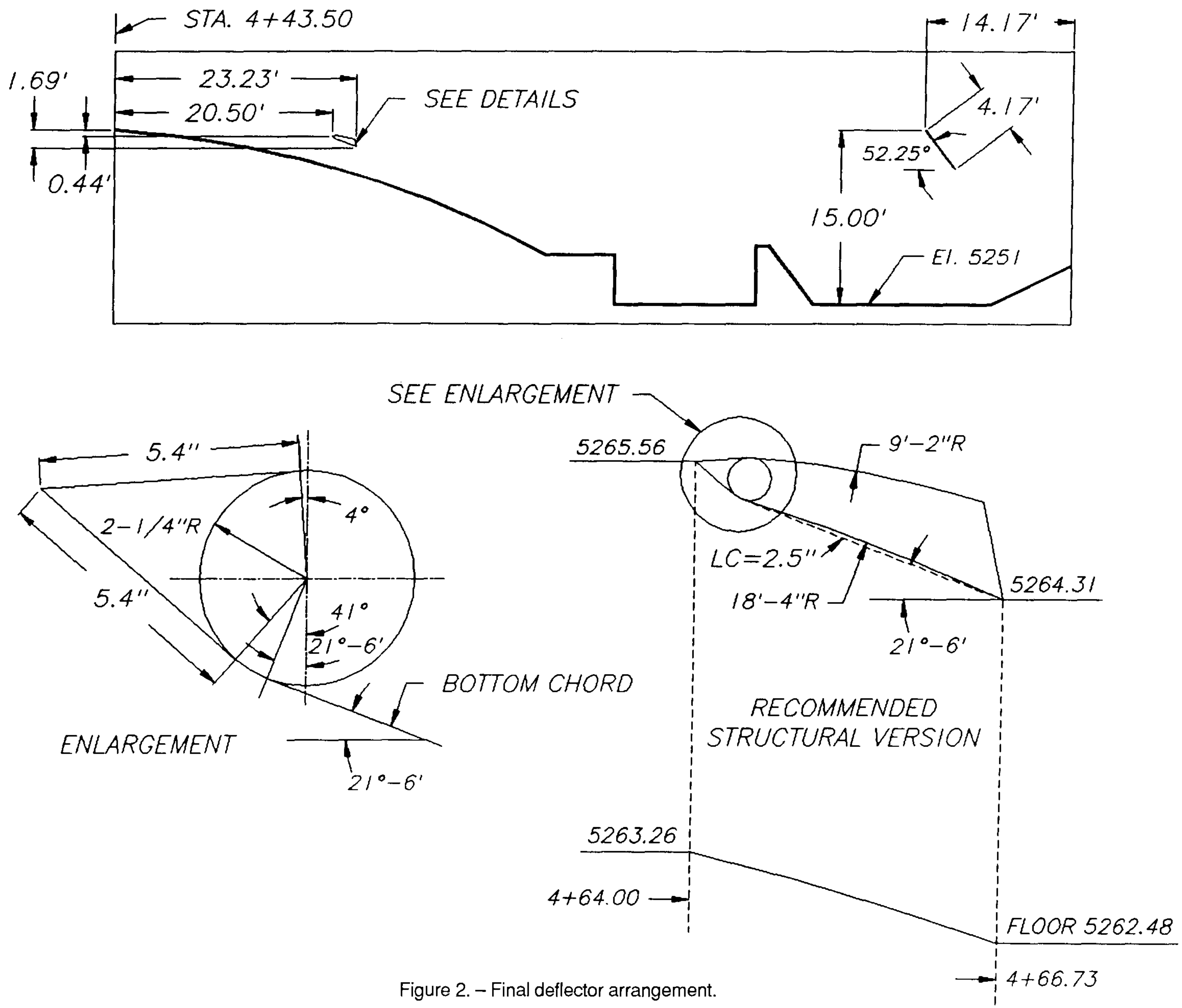


Figure 2. – Final deflector arrangement.

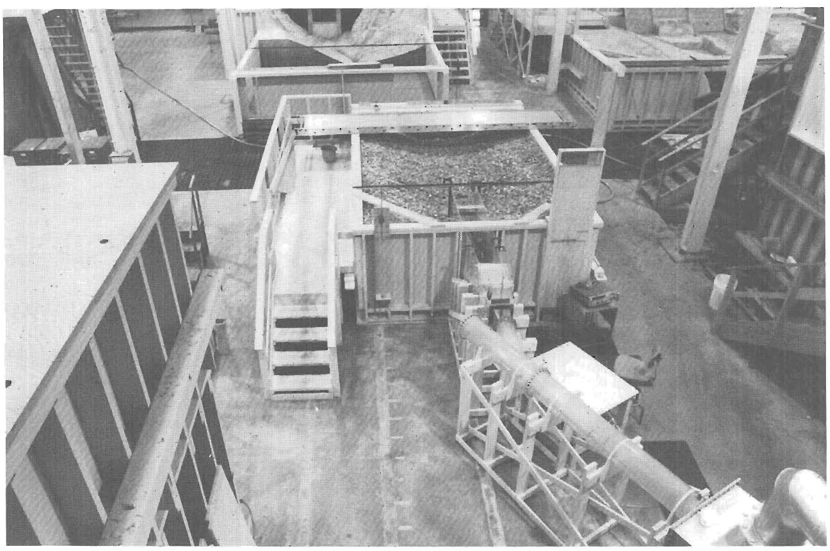

Figure 3. – View of Taylor Draw outlet works model.

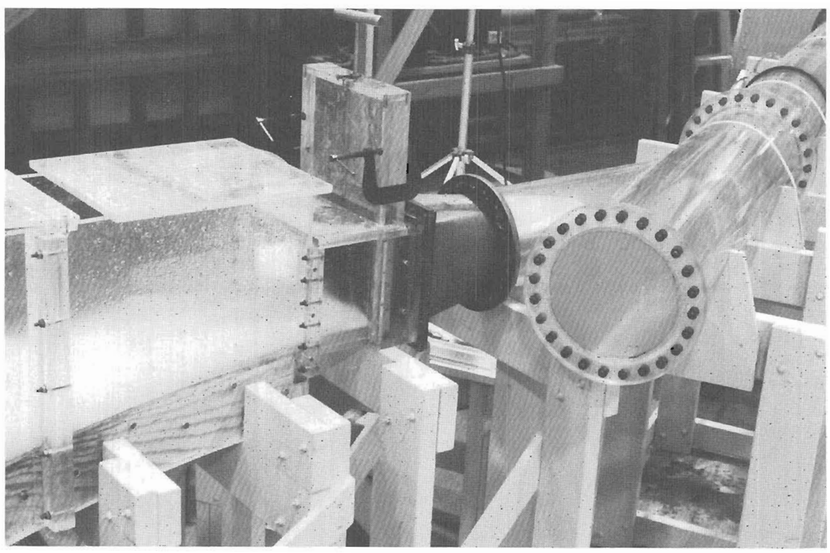

Figure 4. – The 96- by 78-inch wye branch.

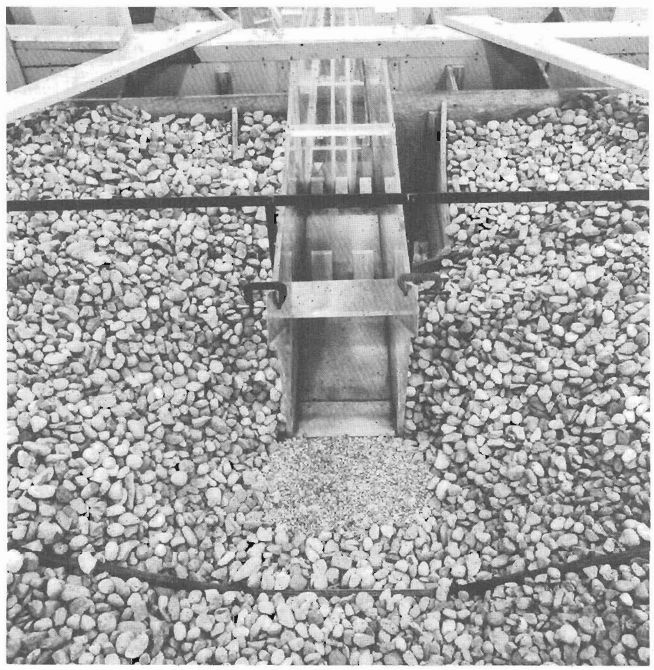

Figure 5. – Downstream model topography.

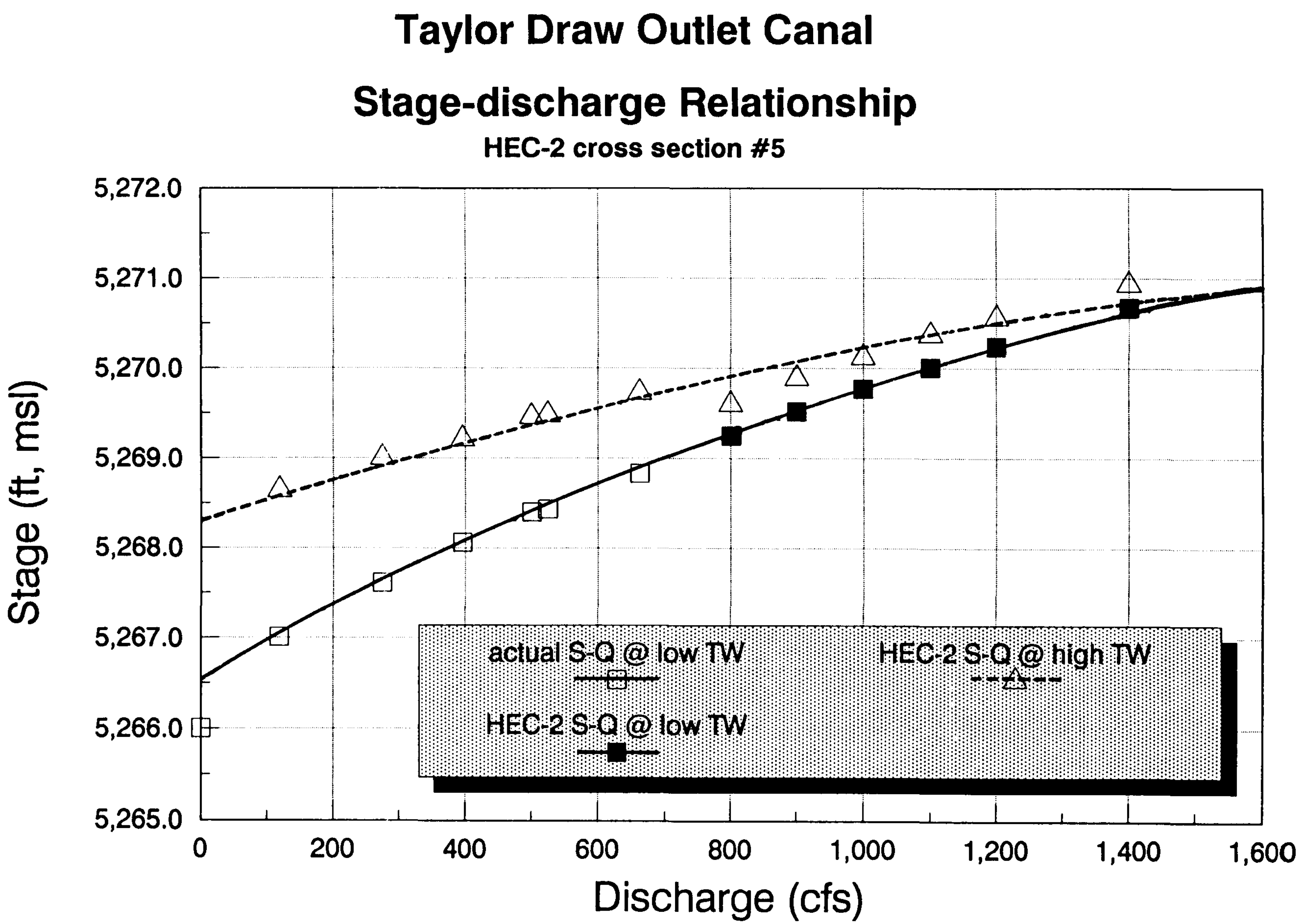


Figure 6. – Outlet works tailwater curve.

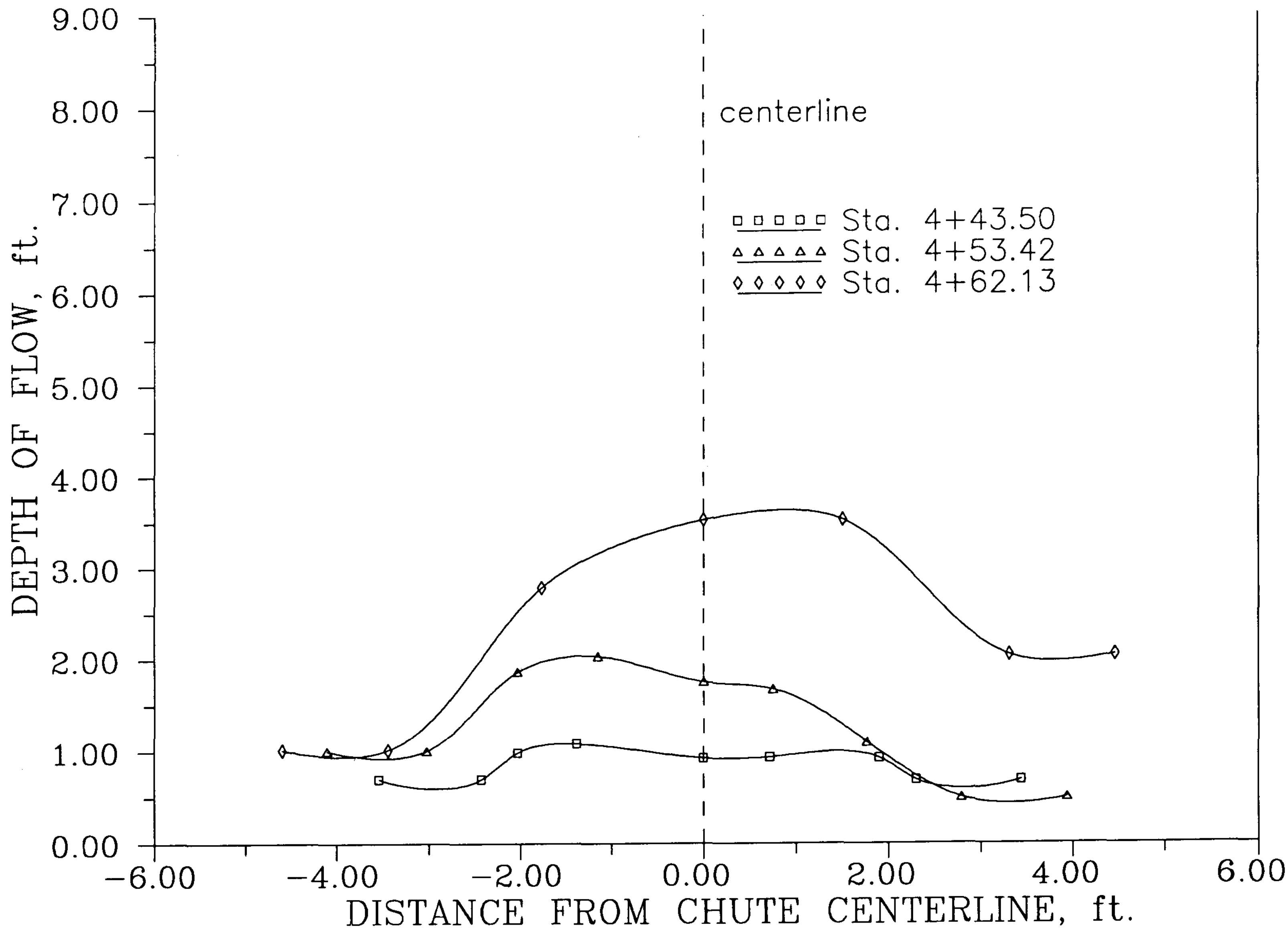


Figure 7. – Outlet works flow profile (looking downstream) for as-built, 16.7-percent gate opening.

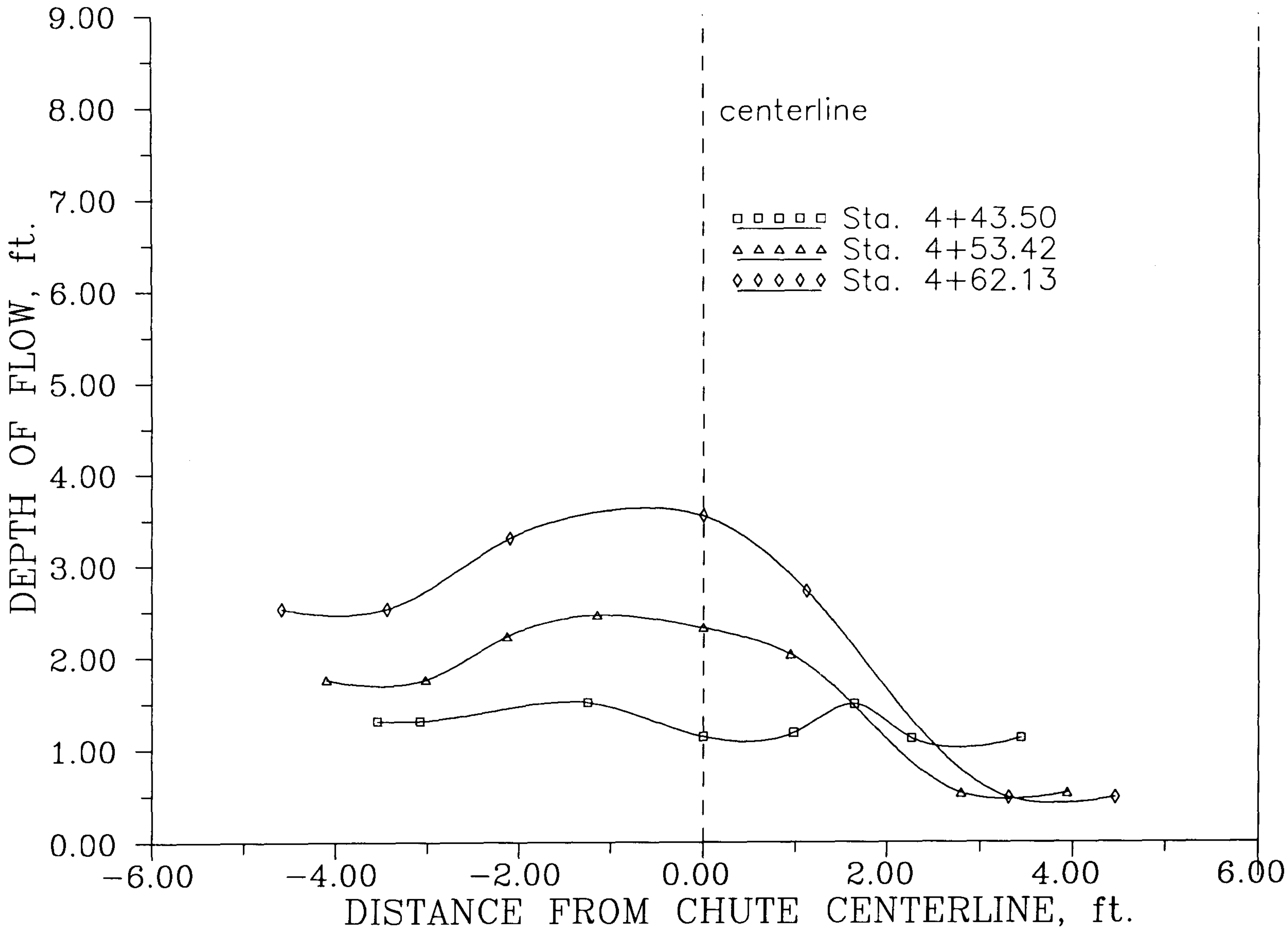


Figure 8. – Outlet works flow profile (looking downstream) for as-built, 25-percent gate opening.

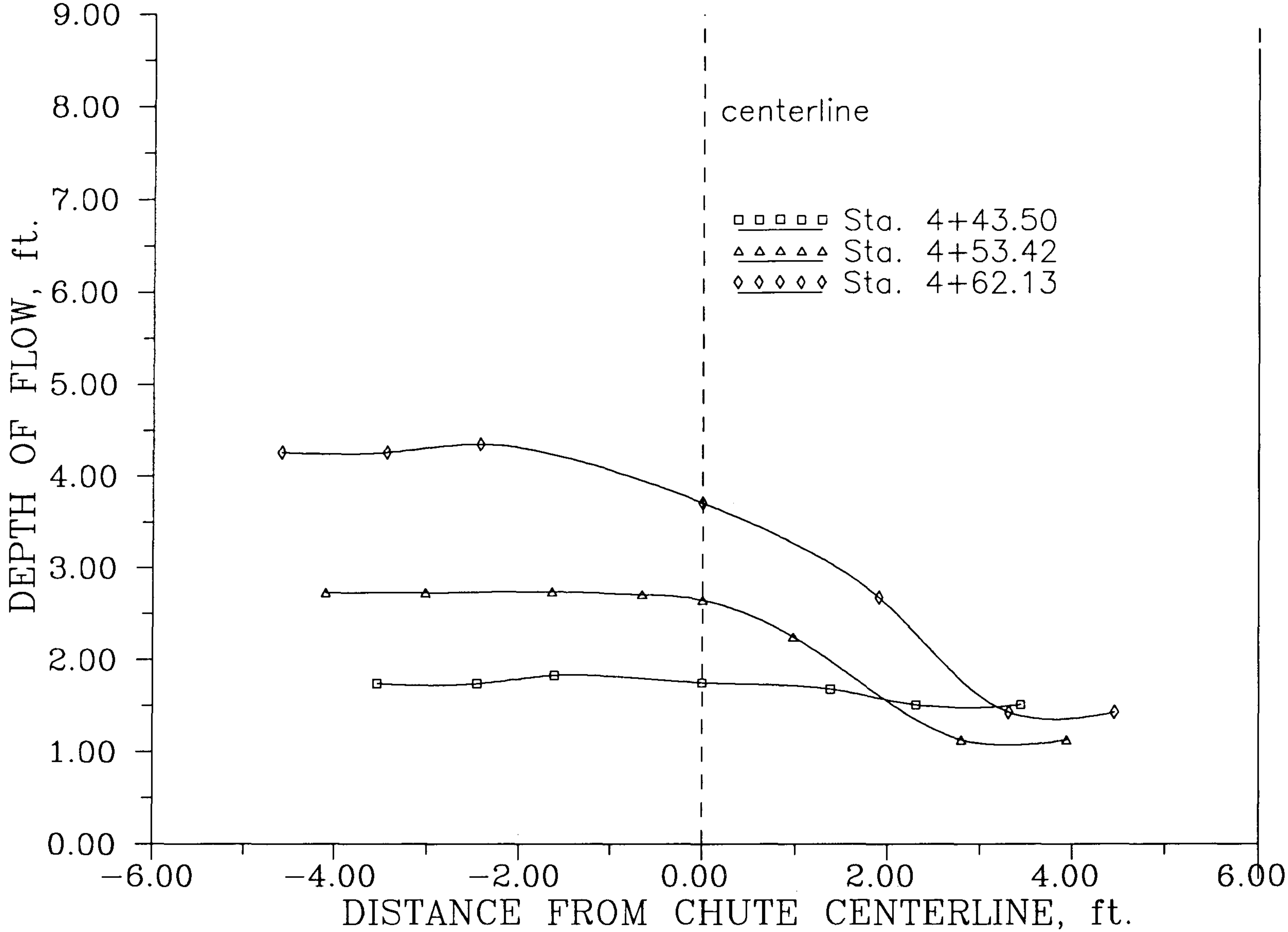


Figure 9. – Outlet works flow profile (looking downstream) for as-built, 33.3-percent gate opening.

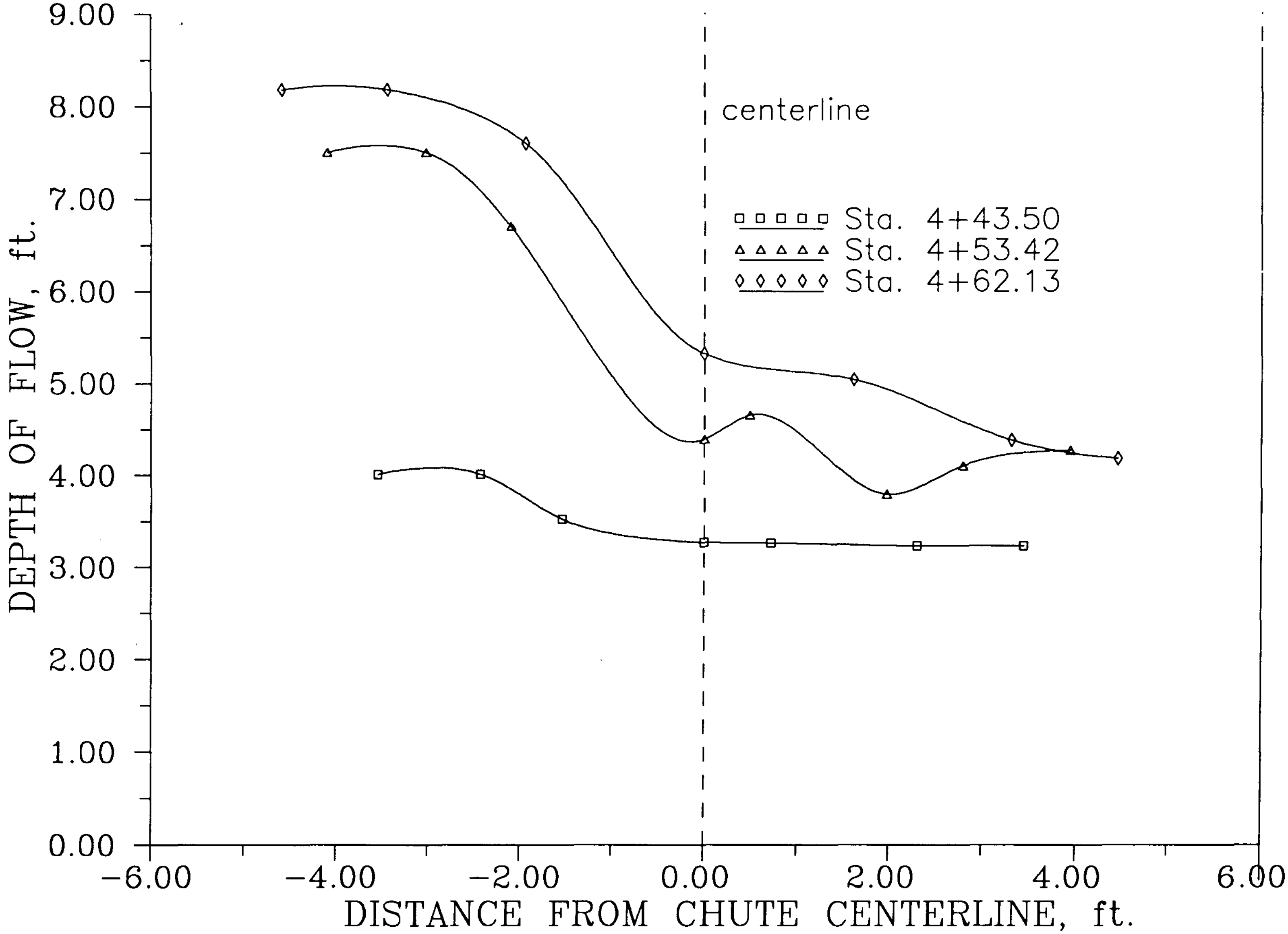


Figure 10. – Outlet works flow profile (looking downstream) for as-built, 66.7-percent gate opening.

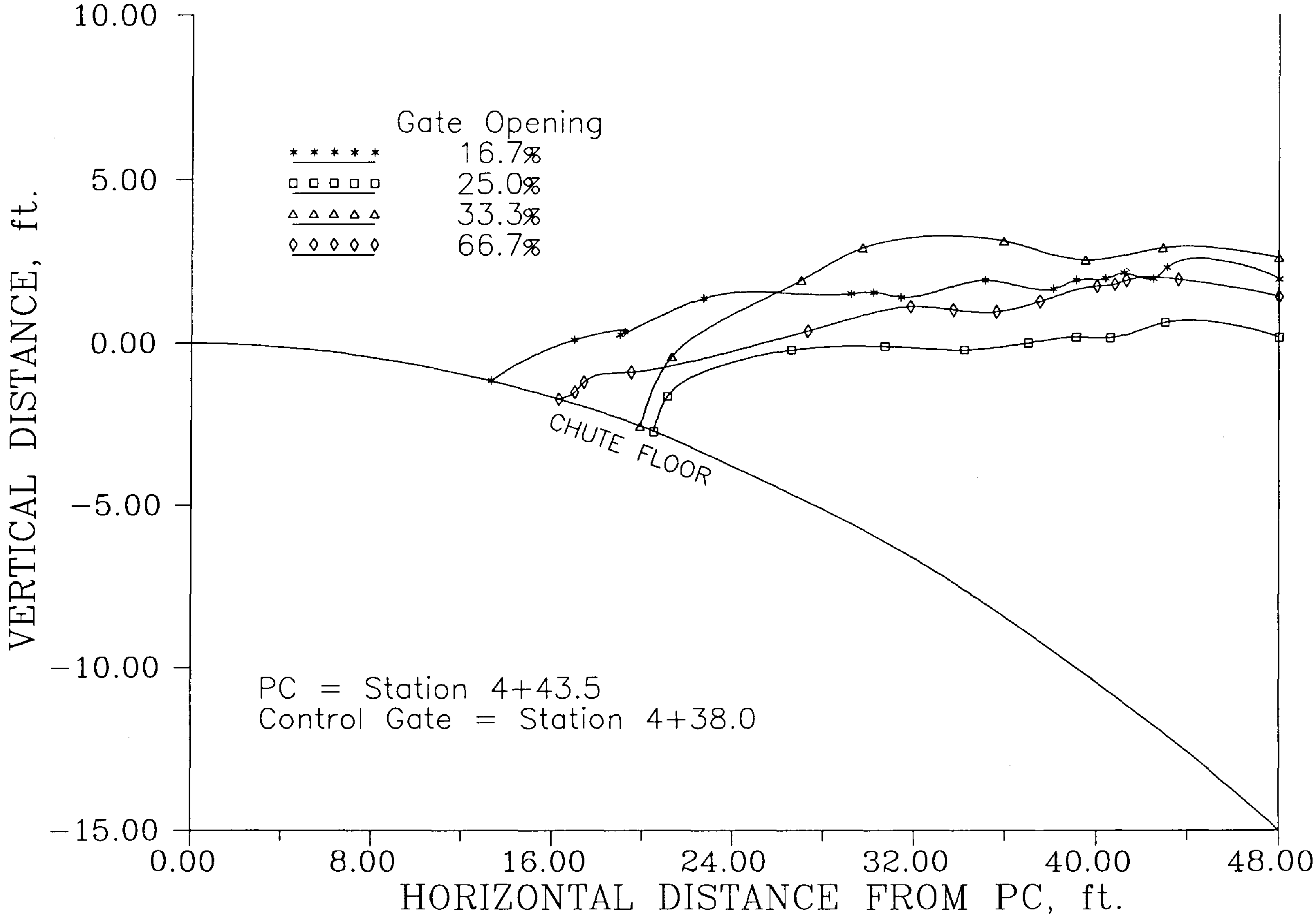


Figure 11. – Average location of back flow wave front at right wall of chute relative to the point of curvature.

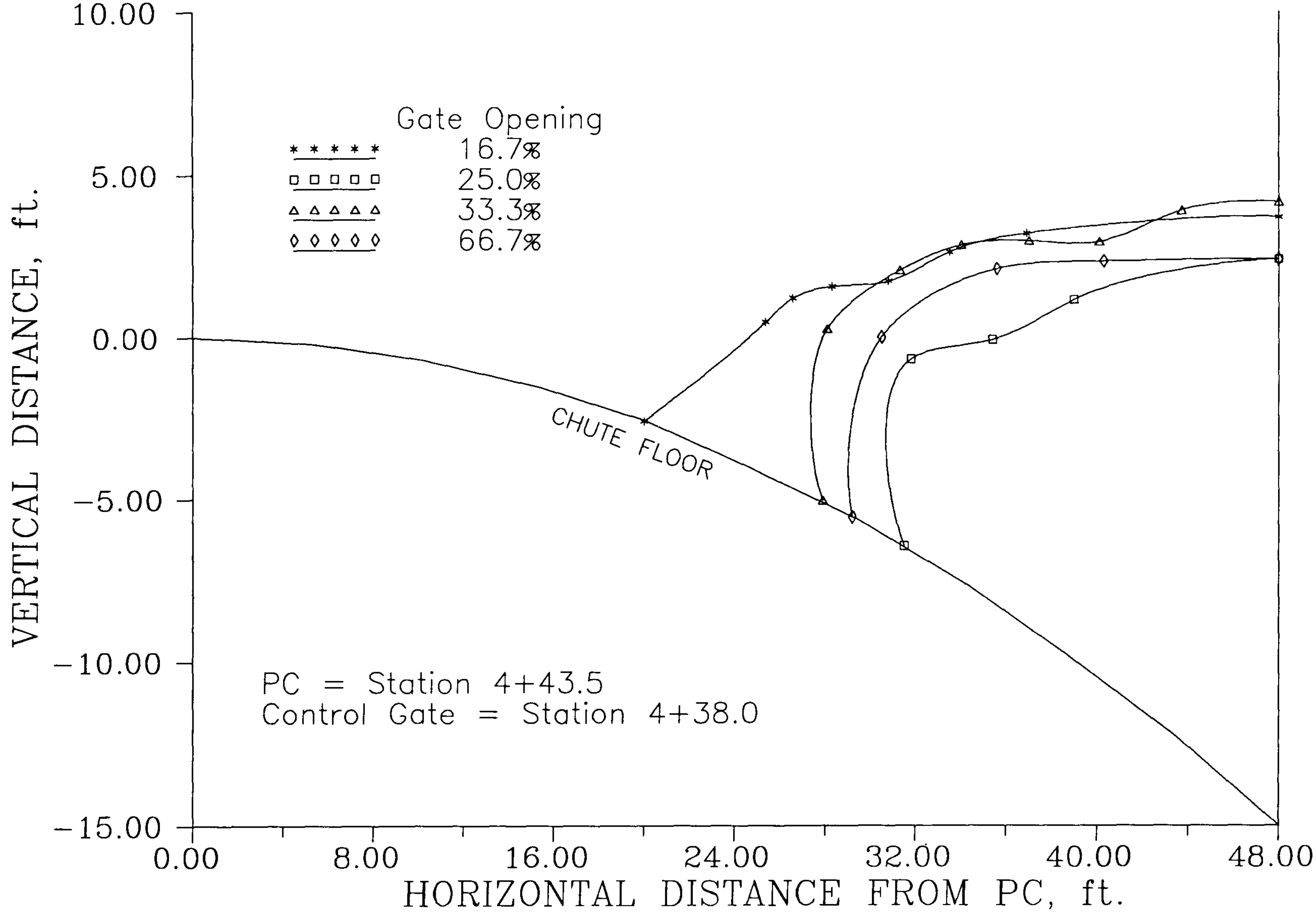


Figure 12. – Average location of back flow wave front at left wall of chute relative to the point of curvature.

Figure 13. – As-built outlet works operating at 16.7-percent gate opening.

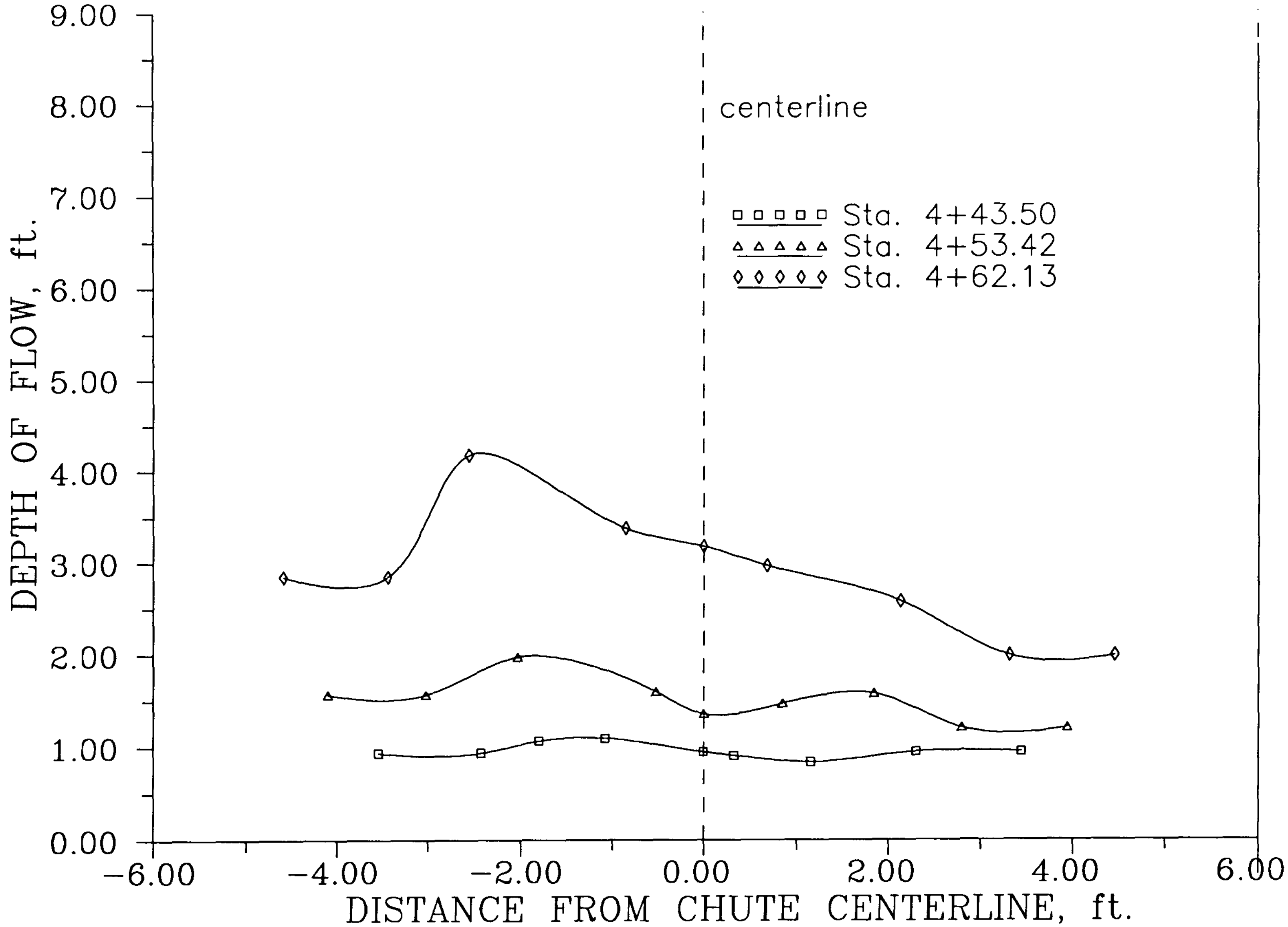


Figure 14. – Outlet works flow profiles (looking downstream) with slots upstream of the control gate filled, 16.7-percent gate opening.

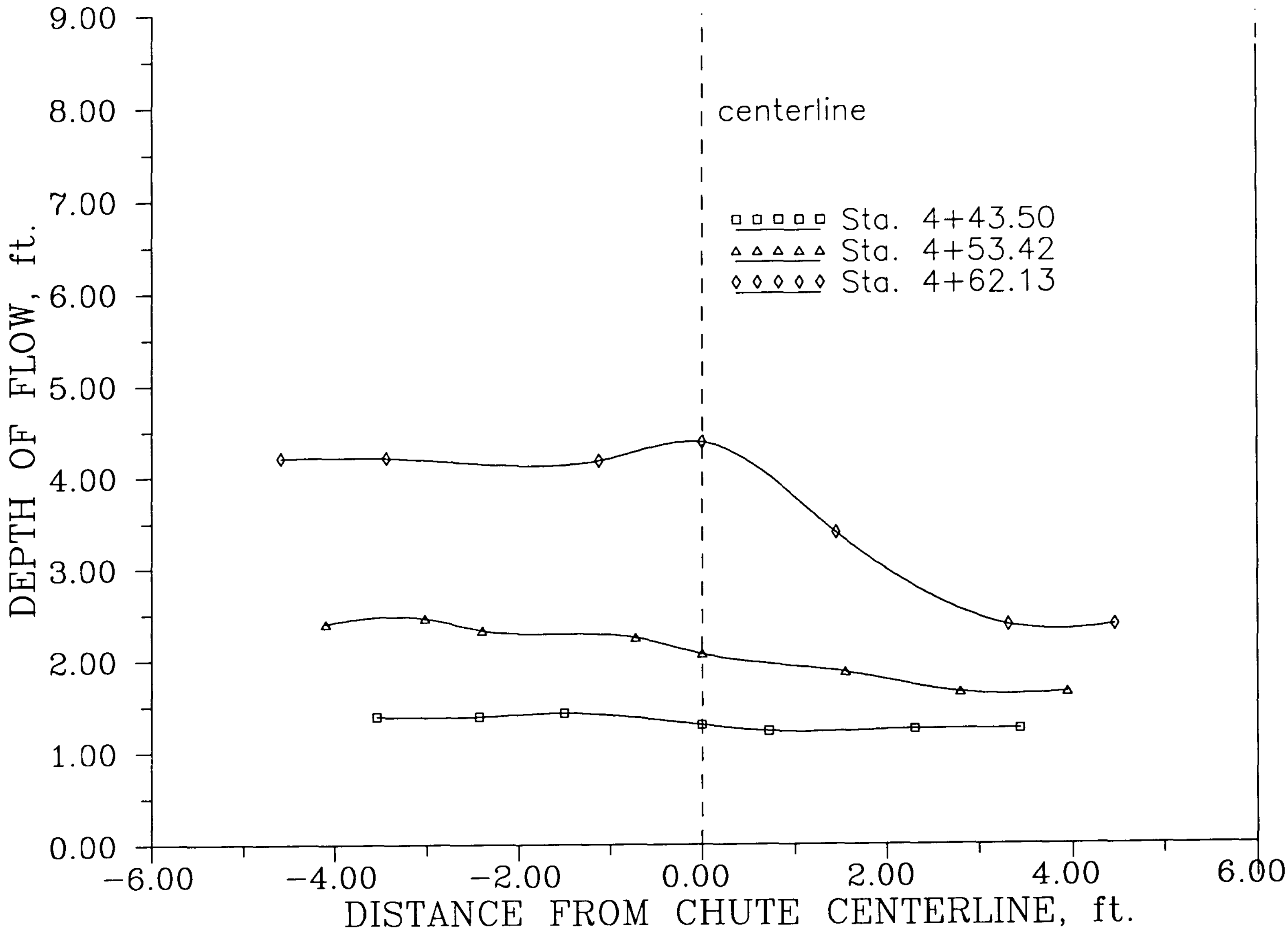


Figure 15. – Outlet works flow profiles (looking downstream) with slots upstream of control gate filled, 25-percent gate opening.

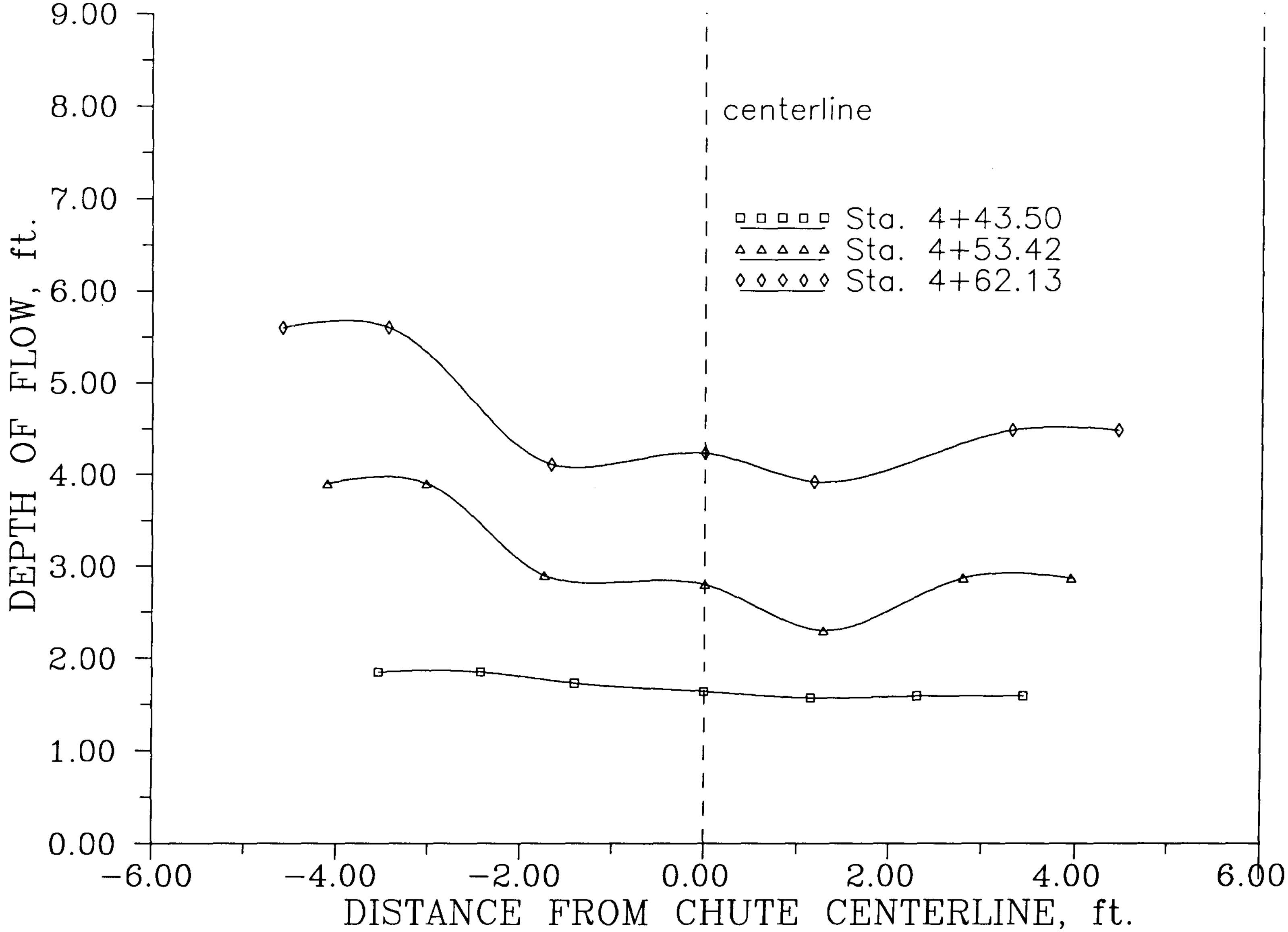


Figure 16. – Outlet works flow profiles (looking downstream) with slots upstream of control gate filled, 33.3-percent gate opening.

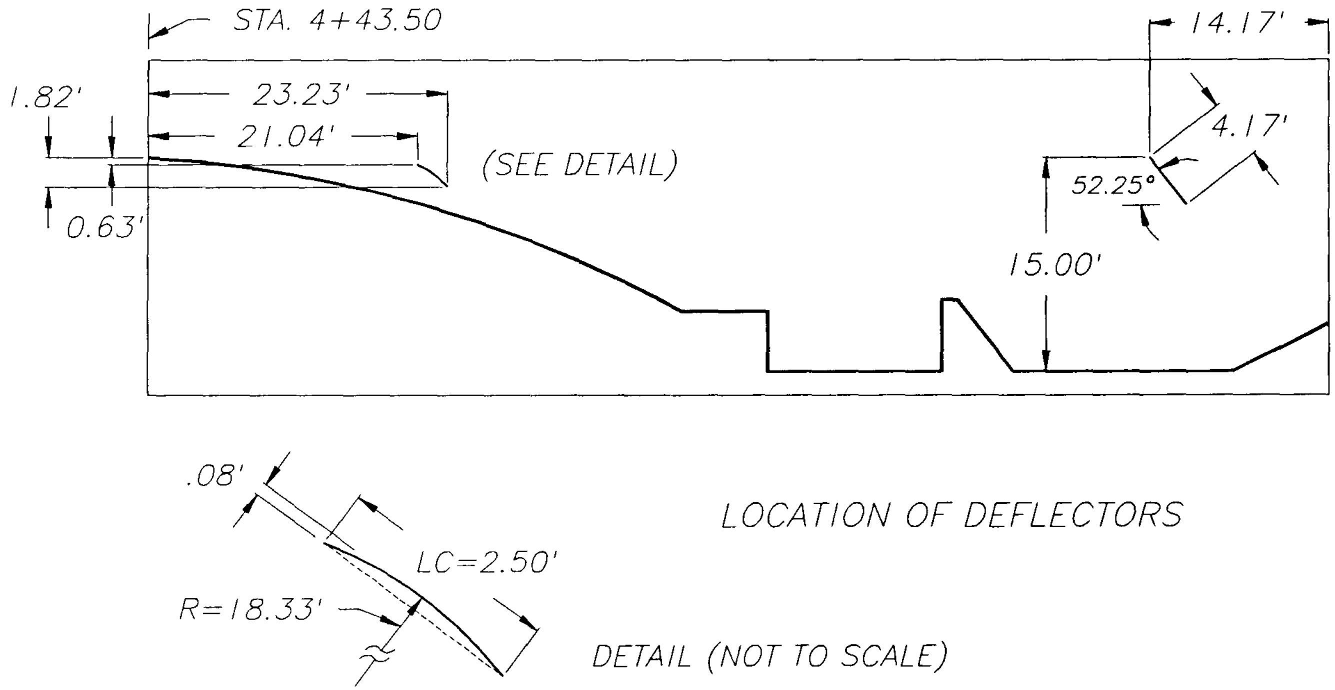


Figure 17. – Position of sheet metal flow deflectors for the chute and stilling basin.

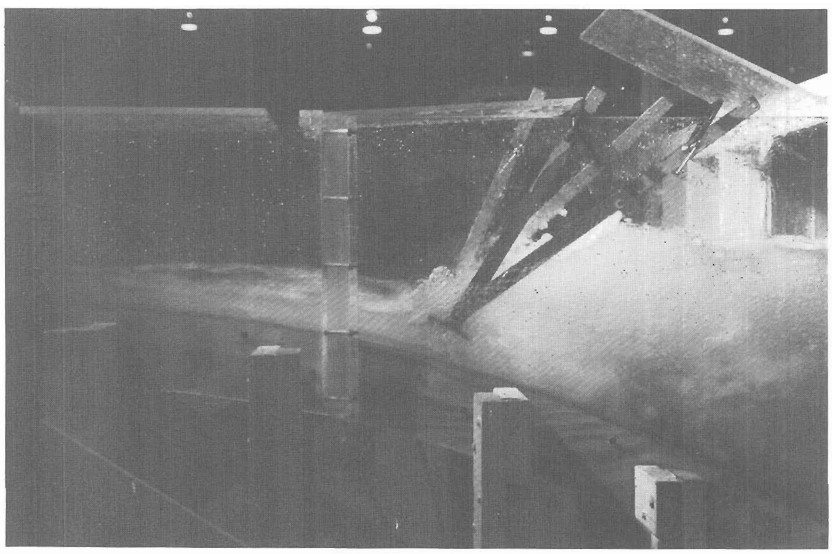

Figure 18. – Chute flow deflector operating at 25-percent gate opening.

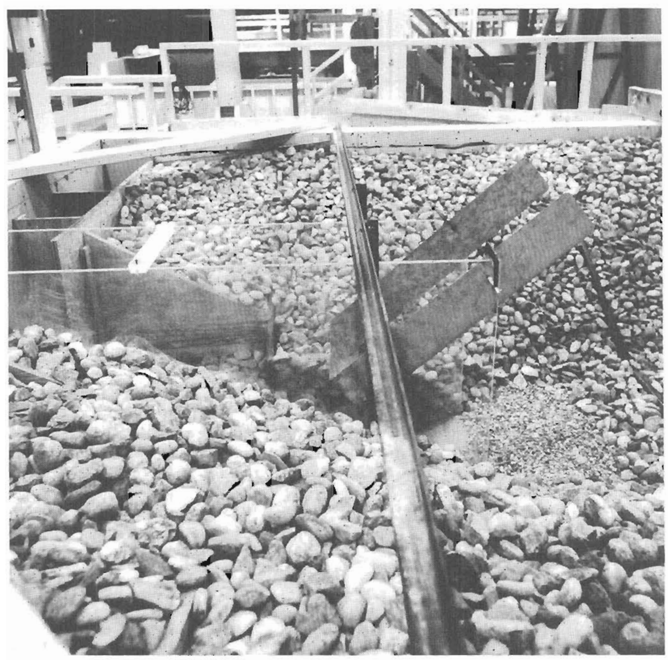

Figure 19. – Basin deflector mounted in the model.

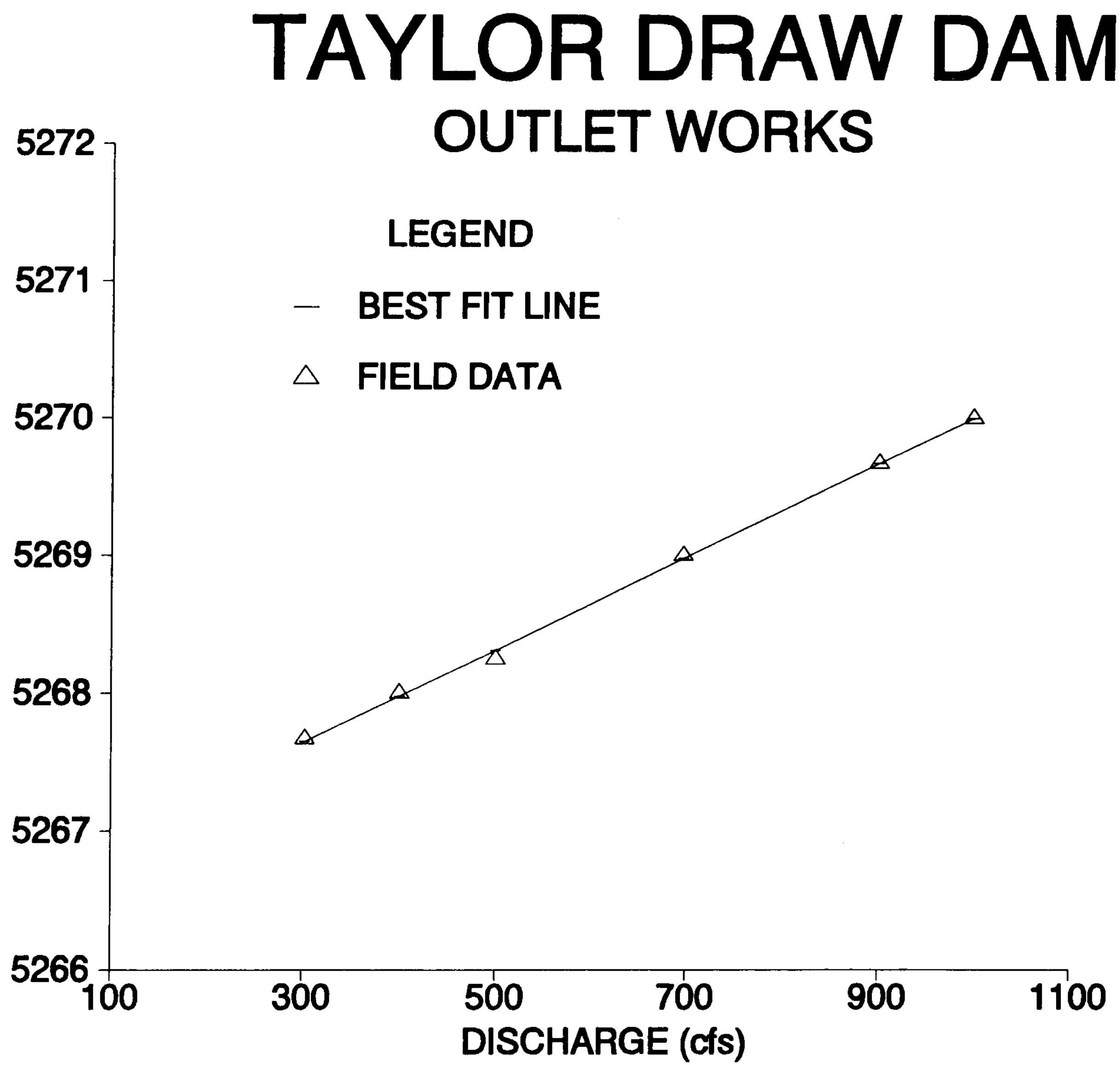


Figure 22. – Tailwater elevations measured during field testing.



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