DISCHARGE COEFFICIENTS FOR GATES AND VALVES AS DETERMINED BY FIELD AND LABORATORY STUDIES

by

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INTRODUCTION

If ultimate advancement in irrigation and water conservation is to be realized, accurate and reliable measurement of water is essential. Quantity determinations must be made in the streams for development of design data. Adequate control of water cannot be effected without adequate measurement. This is true whether the water is passing through complicated developments in river valleys or being routed to irrigated lands. In the latter case, efficient operation cannot be sustained without proper measurement at many points in the system. An equitable distribution of the water to the land areas served is dependent upon quantity measurements.

To accomplish these measurements, numerous procedures and devices have been developed and standardized. Today we may have a choice of more than one dependable method that will meet the conditions existing at a particular site in the field. In other instances it may be difficult to find a satisfactory method to satisfy all conditions.

Although extensive use is made of the primary devices and methods for water measurement, many times it may be economical or convenient to utilize control devices and structures as indications of the quantity of water flowing. Such structures are for the most part designed without thought of their use for this purpose. The difficulties of so adapting them may be many, but the information resulting from calibration may be adequate for operational purposes and, in some instances, may be of a high order of accuracy. The primary problem is to determine just how well a control device will serve in the capacity of a measuring device and the expected accuracy of the results.

To obtain a calibration of a control device, it is possible to apply data derived from similar structures and develop calibration curves that permit flow measurement with a fair degree of accuracy. If the flow phenomena are well understood or if the similarity is quite complete, more dependable results can be obtained. However, one properly authenticated gaging of the stream by another well-established method will considerably heighten the value of the structure as a measuring device, particularly in the eyes of the operating personnel.

Measurements conducted under field conditions are relatively expensive and many times require considerable equipment. If large amounts of water are involved or if velocities are high, the forces encountered are great, and special equipment and techniques may be necessary. Probably the primary difficulty in obtaining complete calibrations on a prototype structure within a reasonable time is the fact that the flow cannot be varied at will and flow quantities desired are not available.

The use of hydraulic scale models has come into quite general use as a means of obtaining calibrations of prototype control devices and structures that might otherwise prove costly and difficult. The design, construction, and testing of hydraulic models and interpretation of data obtained is a science in itself which must be thoroughly understood if dependable results are to be realized. If the structure possesses such characteristics that the similitude relationships are not well defined, the quantitative values may depend upon the opportunities to be found for full-scale comparisons. In any event, because of the facilities they provide for interpolation, completely conducted small-scale studies will reduce the number of full-scale observations that are necessary.

Regardless of the method used to obtain a calibration of a device primarily intended for control of flow, the accuracy of the calibration can be no better than the accuracy of the primary device used to effect the calibration. This applies equally to studies made in the field or by means of models.

A review of all of the control devices that may be calibrated and used for the purpose of measuring flow is beyond the scope of this paper. The discussion will be limited to calibration of gates and valves for use as measuring devices, and will be primarily concerned with these types of controls installed in conduits. However, some data are included on gates operating between free water surfaces.

It is not intended that information contained herein is adequate to solve all of the questions regarding model-prototype conformance. Representative examples of available information are given, together with some comments on what may appear to be nonconformance.

Mention is made of some precautions to be taken to avoid errors.

Adequate data may eventually be available to generalize results, provide explanations of what appear now to be discrepancies, and result in highly accurate calibration curves for prototype control devices from the study of models. If it can be satisfactorily demonstrated to users and operators that such calibrations can be developed and that they can be used without reservation, much time and money can be saved that is now spent on field observations.

CALIBRATION BY MEANS OF MODELS

Construction of hydraulic models may be necessary to aid in the design of control devices. In the course of these design studies, at least a partial calibration may be effected to determine the adequacy of design. If the model is large enough and has been constructed carefully to duplicate field conditions, complete calibration curves can be established for application to the prototype.

In recent years, a number of hydraulic model studies have been made of completed structures containing gates for the primary purpose of establishing calibration curves. In these instances it was not practical or economical to effect field calibrations.

It appears unnecessary to repeat here the history of the use of scale models to establish calibration of prototype structures. The flexibility regarding changes in flow conditions and modifications in the structure and the availability of high-precision measuring equipment make this type of study quite desirable.

The limitations of the model must be thoroughly understood. For instance, with very low heads and very small discharges, the effects of gravity, viscosity, and surface tension may all be evident and a single model will not accurately demonstrate the behavior of its prototype. When it is anticipated that calibrations will be made on a model, the size of the model and testing technique must be considered in order to minimize scale effects. However, there may be occasions when a small model is calibrated. When transferring results from such a model, the scale effects may not be negligible and the background must be known in order to evaluate the results and apply them to the prototype.

Unstable flow conditions existing in the prototype may not be demonstrated in the model. An example of this is cited in the report of the studies of the sluiceways at Assuan Dam on the Nile River in Egypt,1/ where the top of the prototype sluice was shaped in such a manner that the jet from the control gate alternately filled the tube and then broke free. This condition could not be duplicated in the model although careful studies were made.

CALIBRATIONS BY PROTOTYPE MEASUREMENTS

It has been previously stated that prototype measurements may prove costly and difficult. The probability of errors may also be greater than in model studies. Measurements conducted under field

1/ Minutes of Proceedings, Inst. C. E., Vol. 212, Part II, 1920-21, p. 228; also Vol. 218, Part II, 1923-24, pp. 72 and 113.

conditions are relatively expensive and time-consuming. Many times, considerable equipment is required. Unless experienced personnel supervise the tests, errors may be evident in the results. Hydraulic laboratory practice and equipment must be extended to the field insofar as is possible.

In addition to the methods and equipment used, the accuracy of the final results is dependent upon the care and precision exercised in the procedure, the training of the personnel, the analysis of the data, and the stability of flow through the structure, as well as the stability of the structure itself.

Experience has shown that there are four principal sources of error in prototype measurements made to calibrate control structures for use as measuring devices: (1) the means utilized and the procedure followed in making measurements of discharge; (2) the determination of head at the control device; (3) the actual opening of the gate or valve; and (4) the physical dimensions of the control.

There are a number of primary devices and methods that may be used to measure the discharge through the structure being studied. Probably the most common is the gaging station utilizing current meters. There may be permanently installed measuring flumes or weirs that can be used. At some sites, temporary installations can be conveniently made. The means selected will depend upon the desired accuracy of the results and the cost. Regardless of the methods used, the very best practices should be followed and every precaution taken to avoid errors that will reflect in the final calibration. As has been said, the accuracy of the final results can be no better than the expected accuracy of the primary device or method used to measure the discharge.

In the measurement of discharge, the low flows may normally be measured with greater precision than the high flows. These low flows usually prevail more often than the higher discharges in the field. Hence, there is opportunity for more measurements and the quantity may somewhat correct for the quality. It is often necessary to be content with a minimum of points in the range of the higher discharges.

Only on rare occasions is it possible to utilize a gaging station or other measuring section to determine only the flow from the control being calibrated. Usually the discharge passing a structure is a combination of flows passing through the powerhouse, through outlets and possibly over the spillway. There may be other increments from leakage, surface water, or tributary streams.

Thus it may be seen that exact determination of discharge in the field is not a simple matter.

Observation of the head at the control device does not appear to present great difficulties. In instances where the control is located in a conduit passing through a dam, it is usually necessary to obtain head measurements from the reservoir elevation. Hence the calibration is for the complete assembly and not for the control device alone. The gage selected for use should be of a type that errors are minimized. A great deal of thought should be given to the layout of the test installation, since the major portion of the equipment will be left in place for operational purposes. Permanence, ease of manipulation, and accessibility must be considered.

Instances have occurred where it was definitely determined that the head gage connections were not made at the point indicated in the drawings. In other instances, the permanently installed gages were found to be in error. Hence it is necessary to carefully inspect and check all equipment intended for use in the measurement of head.

Control devices may or may not be equipped with indicators to show the position of the movable parts from the closed position to fully open. If indicators are installed, they are normally intended to provide the operator with approximate information as to the setting. Generally, but not always, it is necessary to provide auxiliary equipment to show the position of the gate or valve with sufficient accuracy for use in calibration tests. If there are permanent position indicators, they must be carefully checked before use in making calibrations to insure their adequacy. There may be slack in the mechanical linkage which will cause differences in readings on the opening and closing cycles. The permanent position indicators on gates, if present, are normally geared to the hoist mechanism. There may be enough deflection in the lifting links or cables to cause errors and the indicators should be checked against actual opening periodically. Probably the major deficiency is that the graduations and pointers permit only coarse adjustment of the gates or valves, and settings of a fine degree of accuracy cannot be repeated consistently. This may possibly be corrected in the field by making new scales or adding a vernier to the existing scale.

The actual dimensions of the water passages should be determined in the field, particularly if the calibrations are being made for comparison to model or analytical data. These openings may not by symmetrical; there may be irregularities, or deviations from the drawings may exist. If measurements are made in the field to ascertain any departure from drawings or expected dimensions, analysis of the data will usually be simplified. At one installation where two Venturi meters of different size were installed, check points of discharge indicated grave errors. Measurements made of the throat diameters revealed that the two meters had been interchanged in position as shown by the drawings and as connected to the recorders.

COMPARISON OF MODEL AND PROTOTYPE CALIBRATIONS

Probably the earliest attempt to correlate model and prototype results of the amount of flow through sluices was made by the Ministry of Public Works of Egypt in their studies of the Assuan Dam on the Nile River in Egypt.1/ The experiments on the Assuan Dam covered a period of 20 years and included studies on the actual sluices and on six models. Approximately 1,500 experiments were made on the models. Many of the discharge measurements in the field were made volumetrically by utilizing a large stilling basin as a tank. The model and prototype results for all experiments, when compared, show that the mean departure from the accepted Froude transfer equation ranged from minus 4.6 percent to plus 4.5 percent.

Since these classic studies were completed, studies by many experimenters have been made on other structures. A survey of results indicates that if proper care is exercised both in the model and prototype studies, and small gate openings are omitted, agreement should be had within ± 5 percent. It is conceivable that a study of the probable errors and appropriate adjustment of data would result in closer agreement.

Without enumerating all the possible discrepancies and the means of correcting at least a part of them, I will touch on only a few points that may be of assistance in the future to draw the data together. It is assumed in the following discussion that the transfer equations generally accepted are thoroughly understood and properly applied.

Models of closed conduit systems including controls may not require strict compliance with Reynolds' law when used for design purposes. However, when model-prototype comparisons of discharge are to be made, it must be established that the model is operated in the range of Reynolds' number, that the inequality of Reynolds' number between model and prototype does not introduce a significant factor.2/ There are other deviations in model studies

2/ Chapter 2, Engineering Hydraulics, edited by Hunter Rouse, John Wiley and Sons, New York, 1950.

that ordinarily exist, but an understanding of their effect on the results, especially when calibration curves are to be developed, will greatly reduce the probability of serious error.

To insure the best possible correlation between model and prototype calibrations, it is necessary that the model be geometrically similar to its prototype. Models of gates and valves can be machined to close tolerances, but this degree of accuracy may not be possible when large castings are being handled. Therefore, all critical dimensions should be measured carefully both on the model and in the field.

Although the model may exactly represent the prototype geometrically, free boundary conditions may not be similar. For instance, the negative pressure existing in a model conduit downstream from a control device may be a very small percentage of the upstream head. In the prototype, this may have an appreciable effect. Since the transference equations are not well defined when negative pressures created by the flow of an air-water mixture are involved, it may be advisable to consider measurement of head downstream from the control both in the model and the prototype. These data may assist in explaining some of the nonconformance found in past comparisons.

The stability of flow through the control is a consideration in making comparisons. Evidence of cavitation erosion on some types of needle valves in the field indicates flow conditions that do not exist in the model. Vibrations in the structure can influence flow to the extent that analogy between model and prototype cannot be obtained.

The fully open Assuan sluice, operating with a reservoir elevation between 6.75 and 10.25 meters above sill level, showed two possible discharges differing by some 7 percent for the same head.3/ The cause of this unstability was not determined exactly, but the average results from the model fell in between the two discharges observed in the prototype.

The value of a model-prototype comparison of discharges will be greatly increased if the methods and procedures used in the tests are similar. It is seldom practical to get close similarity, such as using the same primary discharge measuring device, but the order of magnitude of precision should be as close as is practicable. Personal errors will be decreased if the same supervisor is available for both tests. If this is not possible, it is advisable to utilize laboratory-trained men to at least initiate the prototype tests in order that the field men may be fully cognizant of the order of accuracy expected.

If the prototype calibration is anticipated at the time the control is built, much time can be saved and better accuracy may be obtained by planning the test equipment and installing it during the construction period. Proper prior planning will also assist in reducing the possibility of having model data in one range and prototype data in another, with no possible means of relating one to the other.

3/ Scale Models in Hydraulic Engineering, by J. Allen; publishers, Longmans, Green and Company, London, New York, Toronto, 1947, p. 79.

Normal operation of prototype controls, especially in irrigation systems, does not follow a definite program of releases. This may cause the calibration program to extend over a considerable period of time if unnecessary release and consequent wastage of stored water is to be avoided. Data on releases approaching design, both as regards head and quantity, may not be available for some time after the gate or valve is put in operation. Therefore, some of the following examples show only incomplete prototype data.

Many of the controls discussed in this paper are located in the Central Valley Project in California. Others are located elsewhere on projects in the western United States.

The water plan for the Central Valley contemplates ultimate beneficial use of all water resources. Since each available increment is budgeted for certain needs, it is necessary to exercise diligent control and measurement throughout the system to insure success of the plan. Numerous standardized measuring devices have been provided and considerable time and effort has been expended to calibrate a number of the gates and valves in the network. Because of the desire to effect the best possible measurements, an opportunity exists to gather considerable data to add to our store of knowledge concerning the calibration of several types of control devices and to make comparisons between model and prototype.

Model studies were made of a number of the controls in the system to provide data for initial operation. After completion of the structures, field data were taken to compare those calibrations, when applied to the prototype, with the results of established field methods used at other points in the system. It is important in the operation of a large network that methods used for checking discharges be standardized insofar as is practicable. Otherwise, what may appear to be discrepancies in summations of flows may actually be a reflection of the variations of results of using a number of different methods of effecting the measurements.

Field measurements are still in progress at most of the gates and valves covered in the following examples, and new points will be added to the curves as operational flow conditions permit.

MODEL-PROTOTYPE COMPARISON OF DISCHARGES FROM THE OUTLET VALVES AT FRIANT DAM

Friant Dam, Figure 1, on the San Joaquin River in the Central Valley of California, creates a reservoir to store water for flood control and irrigation. The stored waters are released into the Friant-Kern Canal, the Madera Canal, or directly into the river. There is no power plant at the dam. Irrigation demands normally deplete the major portion of the storage each year and the reservoir is refilled during periods of high run-off in the winter and spring. Hence, the spillway does not discharge regularly.

Numerous model studies were made to determine the design for the many hydraulic features of the structure. Among these were investigations of the outlet works to include determinations of the discharge of the valves.

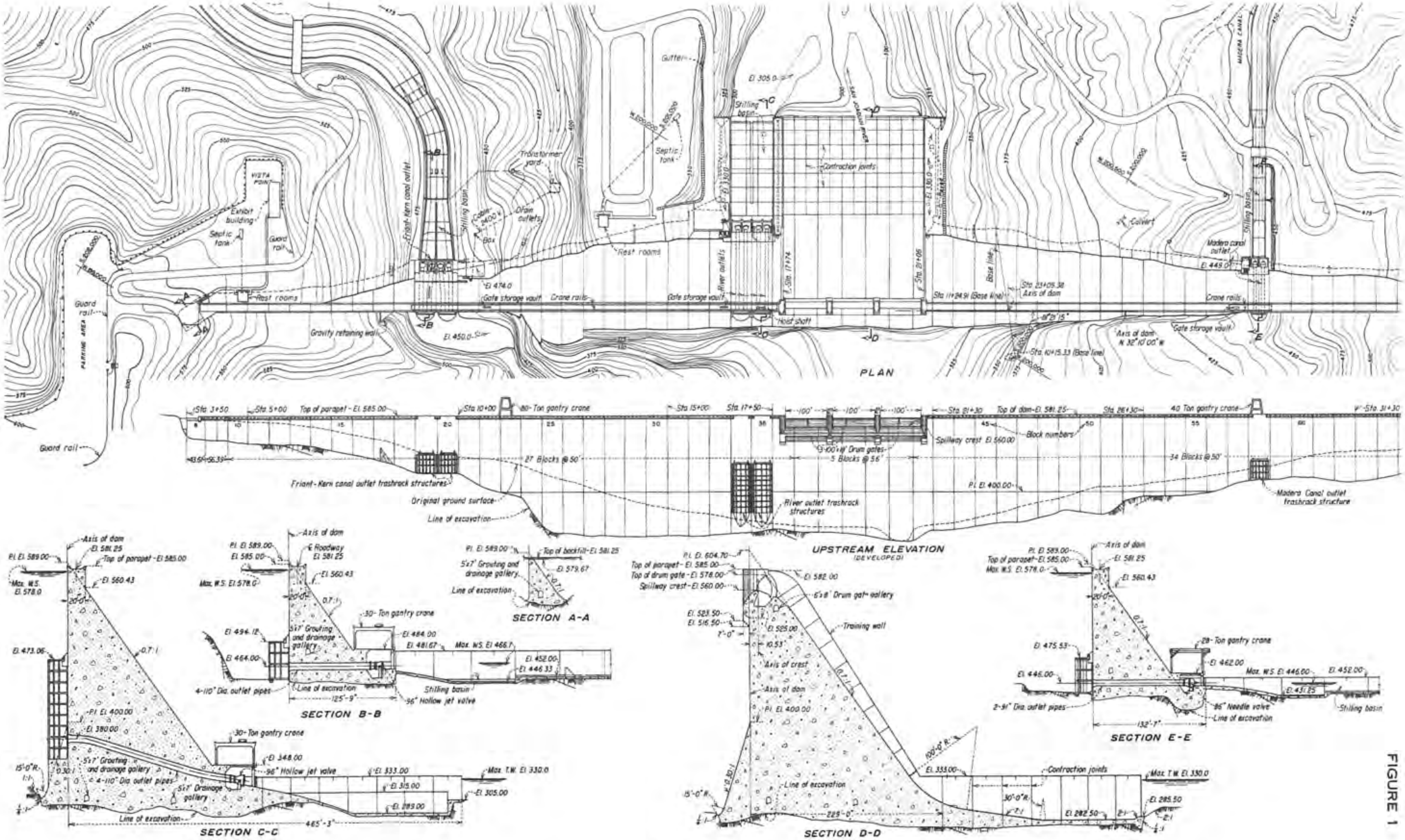

FIGURE 1

FRIANT DAM

CENTRAL VALLEY PROJECT - CALIFORNIA

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All model investigations covered in this paper were conducted in accordance with best current practice. For the sake of brevity, all but essential details concerning their conduct have been omitted.

There are three outlet works through the dam, Figure 1. At each of these outlets there is a single control on each conduit. Coaster gates, operating on the face of the dam, are used for emergency closures and for closure and unwatering to permit necessary maintenance of the valves and tubes.

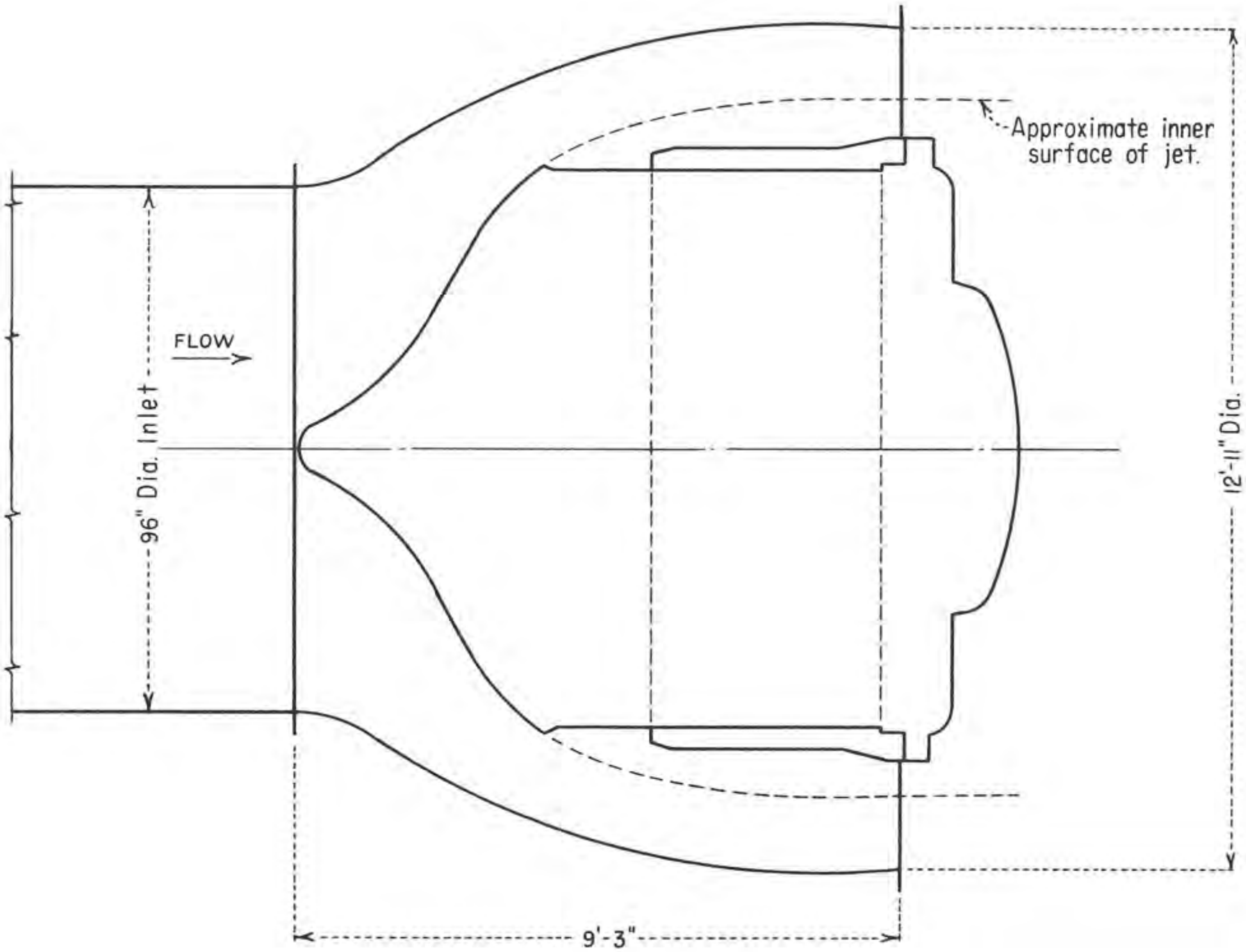
One outlet works, known as the river outlet, occupies a position to the left of the spillway section. Its primary function is to provide regulated release of stored water directly to the river. The works consist of four 110-inch-diameter, steel-lined pressure conduits through the abutment section of the dam. Control is effected by a 96-inch, hollow-jet valve at the downstream end of each conduit. An outline of the hollow-jet valve is shown in Figures 2 and 3. One 18-inch needle valve is also provided for small releases, Figure 3. This valve is installed on the downstream end of a short branch from one of the large conduits.

The center-line elevation of the valves is 247 feet below maximum reservoir. The valves discharge into a stilling pool that connects with the river channel. Each major valve is designed to discharge 4,100 second feet, or a total of 16,400 second feet for the four, under maximum conditions of head and opening.

The flow requirements set up for this outlet to meet the operational demands were as follows: (1) A flow up to 100 second feet to be released at any time with an allowable error of a few second feet; (2) flows of 100 to 4,000 second feet to be released with any stage of the reservoir, with a maximum allowable error of 100 second feet; (3) flood-control release not less than 15,000 second feet with reservoir stages above elevation 545.

A bronze model of one of the hollow-jet valves was built on a scale ratio of one to sixteen. Selection of this scale ratio made the valve 6 inches inside diameter at the upstream flange. A complete calibration of this valve was made in the laboratory. Later a 24-inch bronze valve was tested at Hoover Dam over a complete range of openings. This valve represented a one-to-four scale ratio, and the 6-inch valve could be considered as a one-to-four scale model of the 24-inch valve. The coefficients of discharge determined from the 24-inch valve were in close agreement with those obtained from the 6-inch model. The larger model did give a slightly higher coefficient for valve openings above about 50 percent.

A complete outlet was not used in making the calibrations on either of the two models. Therefore, the coefficient of discharge "C" in the equation "$Q = CA\sqrt{2gh}$" as developed from the models is the coefficient of the valve and not the over-all coefficient of the outlet. In the equation, "Q" is the discharge in second feet, "A" is the area of the valve at the upstream flange in square feet, "g" is the acceleration due to gravity, and "h" is



FRIANT DAM

96" HOLLOW JET VALVE
RIVER OUTLETS AND FRIANT-KERN CANAL

CENTRAL VALLEY PROJECT - CALIFORNIA

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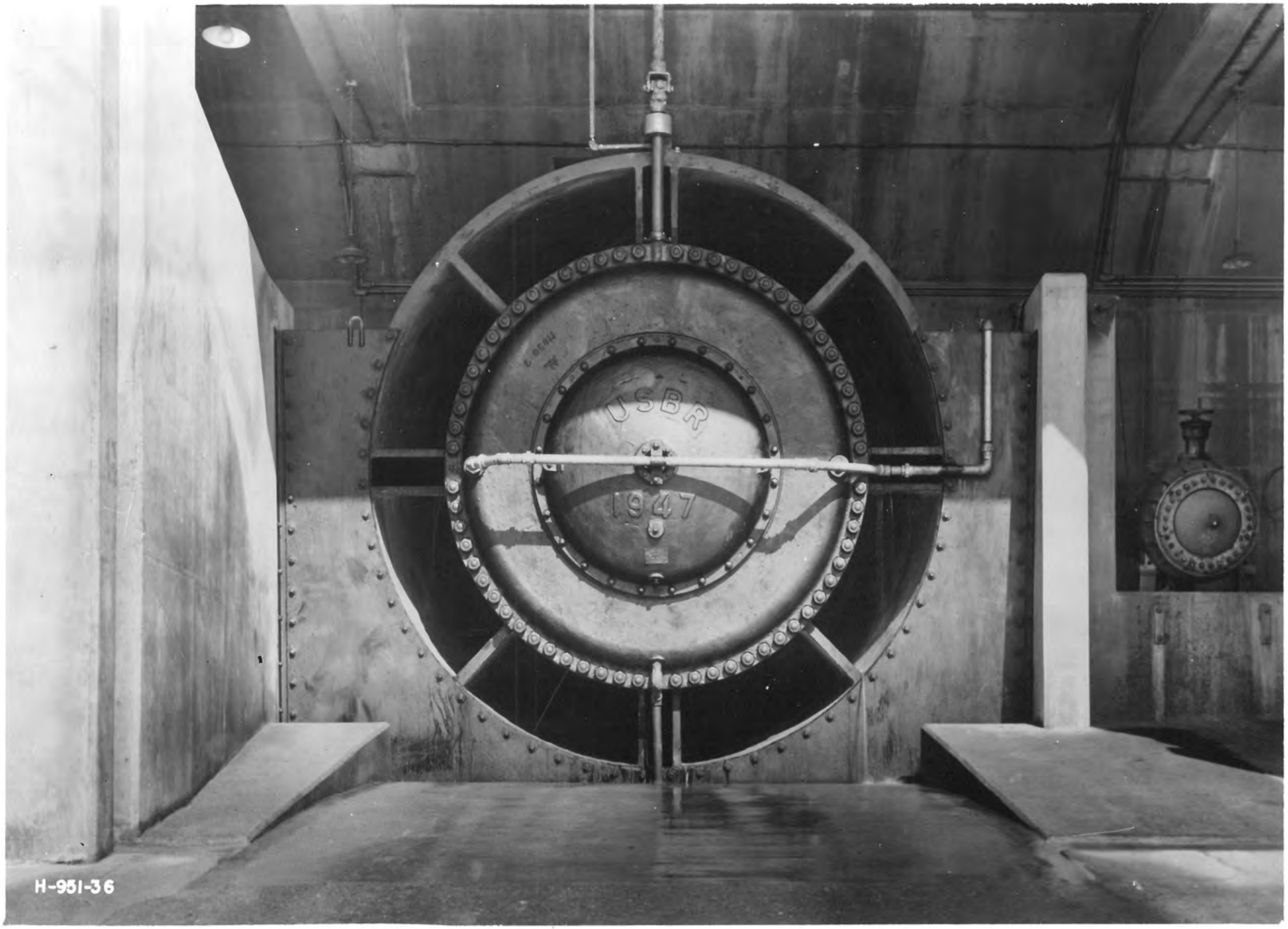
FIGURE 2



Friant Dam River Outlets. Two-rack conduit (horizontal) encasing piezometer leads from valve interior. September 1950.

Figure 3

the total head in feet on the center line of the valve at the valve.

The nomographs developed from the model data for use in the field were corrected for the losses in the outlet from the reservoir to the valve, as calculated from the best information available. This permits use of the reservoir elevation as a measure of head to facilitate setting the desired openings on the prototype valves to obtain predetermined releases.

The coefficients of discharge plotted against percentage of valve opening as determined from the 24-inch model, and corrected for losses in the outlet, are shown on Figure 4. The coefficients of discharge as determined from the available field observations are also shown on this plot.

It should be noted in this figure and the other figures in this paper that this method of handling the data does not reflect any possible change in coefficient that may be caused by change in head. Numerous checks indicate that this is a minor deviation if correct practices have been followed and can be neglected in view of other uncertainties on which the calculations are based.

The prototype observations cover a range of heads from about 100 to 230 feet, and valve openings up to approximately 70 percent of full travel. In this range the average deviation from the model curve is less than 5 percent, including one observation that deviates approximately 25 percent, Figure 4. The prototype measurements show a lesser discharge than that predicted by the models.

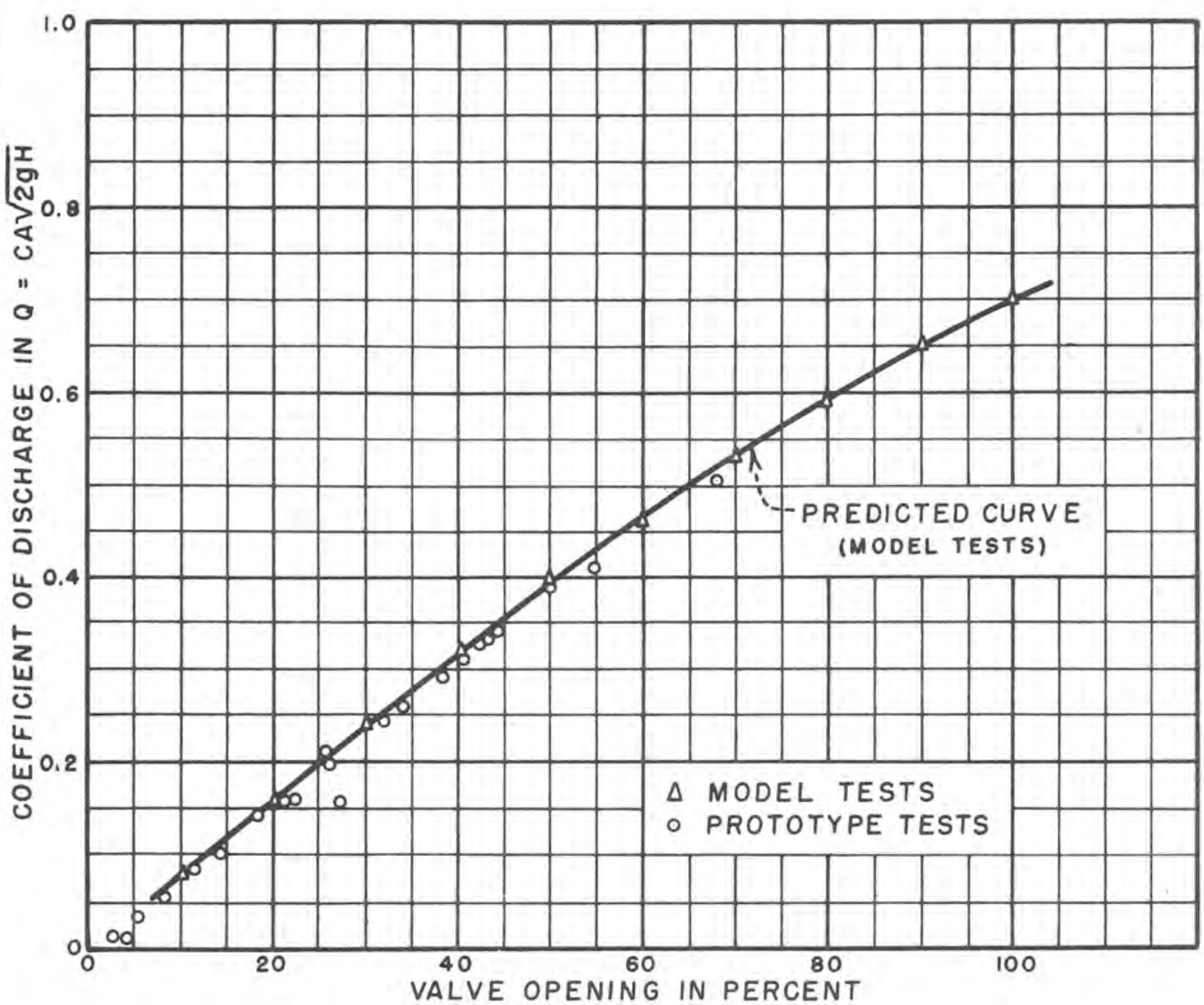
Concerning the field observations, the discharge measurements were obtained from a current meter gaging station in the river a short distance downstream from the dam. There is a very stable section at this station and the gage-height-discharge relationship has been well established by numerous observations. It is believed that the discharge measurements are quite accurate.

At this outlet, as well as other outlets at Friant Dam, verniers of the type shown in Figure 5 have been installed on the position indicators to permit settings of the opening of the valves within close tolerances. The hollow-jet valves are controlled mechanically and can be set very closely to predetermined openings.

The reservoir elevation, used for the determination of head, was measured to the nearest 0.01 foot.

By way of evaluation of the prototype data, it is felt that the accuracy of the measurements is above average. The discharge measurements were not complicated by flows other than those from the outlets and the valves could be set quite closely to the intended opening by means of the verniers on the position indicators.

The outlet valves were not planned for use as accurate measuring devices and no means were provided in the prototype to accurately determine the hydraulic losses in the outlet. If the trashrack, entrance, and conduit losses were known exactly, it is possible that even better agreement between model and prototype results might be had.



DISCHARGE COEFFICIENTS
MODEL AND PROTOTYPE

96" HOLLOW JET VALVES
FRIANT RIVER OUTLETS

FRIANT DAM
CENTRAL VALLEY PROJECT-CALIFORNIA

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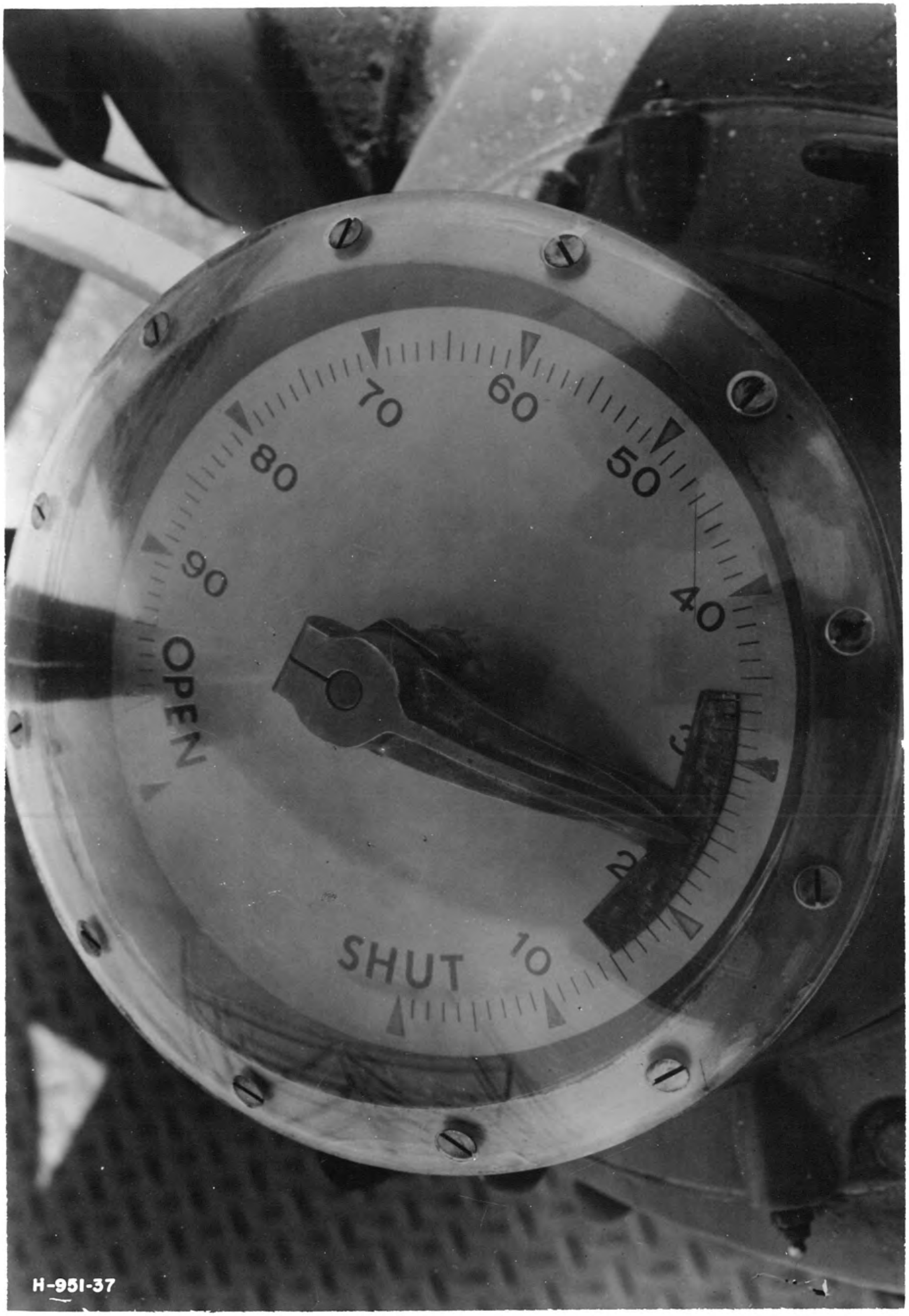


Friant Dam River Outlets. Vernier installed on position indicator area for accurate control of valve opening. September 1950.

The second outlet works is also in the left abutment section of the dam and releases water, through a stilling pool, into the Friant-Kern Canal. This installation consists of four 110-inch-diameter, steel-lined pressure conduits through the dam. Each conduit is controlled at the downstream end by a 96-inch, hollow-jet valve of similar design to those in the river outlet. The center line of the tubes and valves is 114 feet below maximum reservoir. Each valve is designed to discharge a maximum of 2,900 second feet, or a total for the four valves of 11,600 second feet.

The flow requirements set up to meet the operational demands of the system were: (1) A flow of 3,500 second feet to be released from four valves with a reservoir elevation of 480; (2) a flow of 2,000 second feet to be released from four valves with a reservoir elevation of 468; (3) the minimum flow of the canal to be 500 second feet controlled to the nearest 50 second feet.

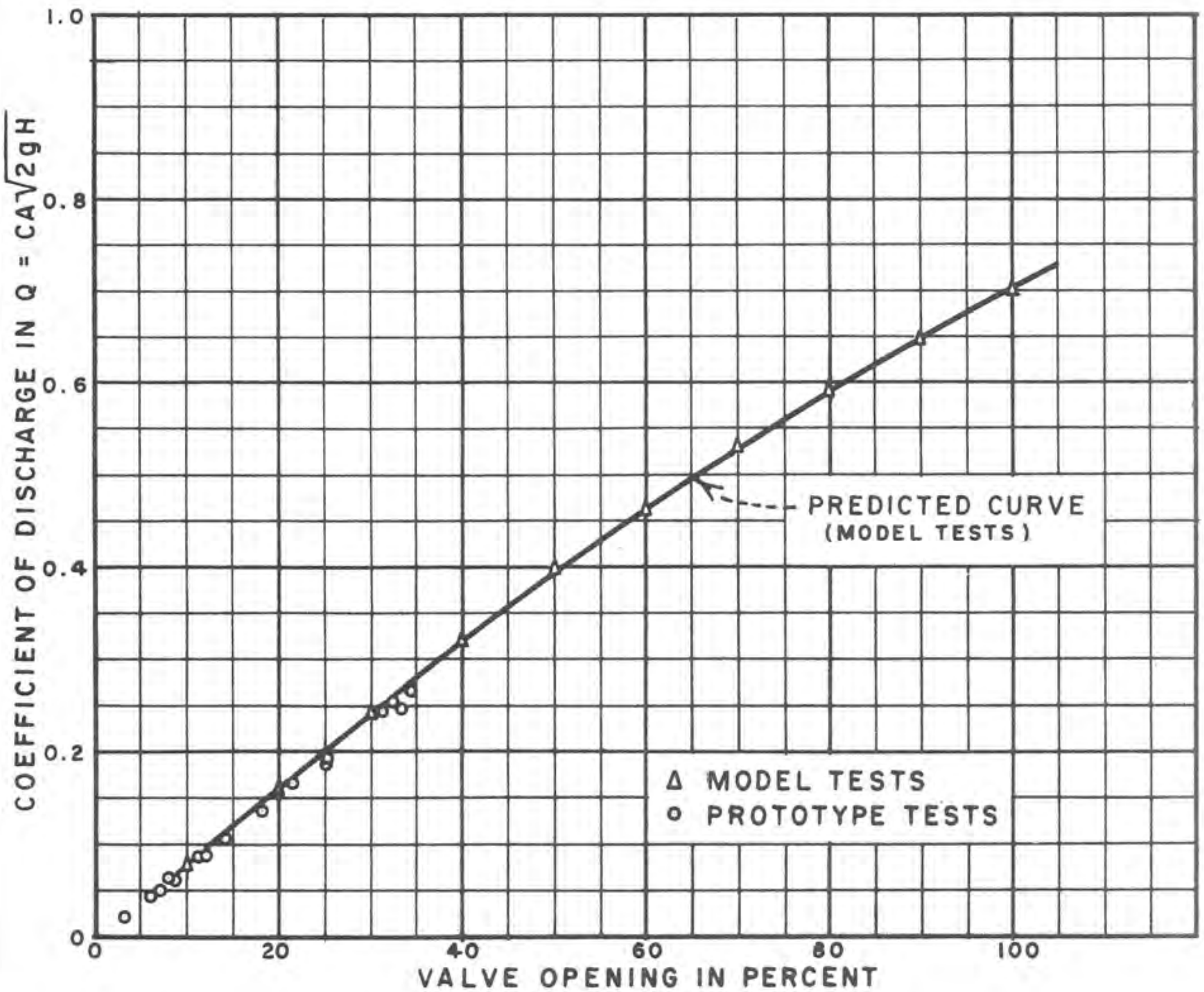
The predicted calibration curves for the valves at this outlet works were obtained from the same models as those for the river outlet. This was possible because the interior water passages of the valves are the same. The hydraulic losses in the conduits are not identical because of the difference of length and configuration, Figure 1. The discharge curves prepared for initial operation of this outlet as developed from the model and corrected for losses are, therefore, not identical with those for the river outlet.

Figure 6 shows a comparison of the corrected discharge coefficients developed from the 24-inch model and those obtained from the 96-inch prototype valves. The prototype points cover a range of heads from approximately 30 to 100 feet. The range of valve openings is less for this outlet than for the river outlet and does not exceed 35 percent of the full valve travel. A complete range of valve openings may not be obtained except for low heads because of the capacity of the canal.

The comments regarding the river outlet are generally applicable to this outlet. The agreement between model and prototype is essentially the same for the limited range of valve openings. The prototype discharge measurements were obtained from a current meter gaging station established in a concrete-lined section of the canal and, for this reason, may be more accurate than those obtained in the river. The relatively short, straight conduit above the valve may give slightly better flow conditions than the curved tube above the valves in the river outlet, and the corrections for losses made in the model data should be more accurate.

The accuracy of prototype measurements is considered to be above average because of the favorable conditions existing.

An interesting incident occurred in the comparison of results from this outlet. The initial field observations were consistently at variance with the nomograph prepared from model results for field operation. A recheck of model data disclosed an error in calculations that might have gone unnoticed had not the field measurements been made.



DISCHARGE COEFFICIENTS
MODEL AND PROTOTYPE

96" HOLLOW JET VALVES
FRIANT KERN CANAL VALVES

FRIANT DAM
CENTRAL VALLEY PROJECT - CALIFORNIA

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The third outlet works is located in the right abutment of the dam and supplies water to Madera Canal. The two 91-inch-diameter, steel-lined pressure conduits through the dam are controlled by 86-inch-diameter needle valves located at the downstream end, Figure 1. The maximum static head on the center line of the valves is 132 feet. Each valve is designed to discharge a maximum of 2,250 second feet, or a total of 4,500 second feet for the two. A cross section of the valve is shown in Figure 7.

The flow requirements for this outlet were established as follows: (1) A flow of 1,500 second feet (ultimate canal capacity) to be released from the two valves with reservoir elevation of 467; (2) a flow of 1,000 second feet (initial canal capacity) to be released from two valves with reservoir elevation of 455; (3) the minimum flow in the canal to be 200 second feet controlled to the nearest 20 second feet.

The two needle valves installed at this outlet are quite different from the hollow-jet valves in the other two outlets, as may be seen from a comparison of Figures 2 and 7. In the needle valve, the control is at the downstream end. Therefore, the coefficient of discharge is based on the area of the nozzle rather than on the area at the upstream flange.

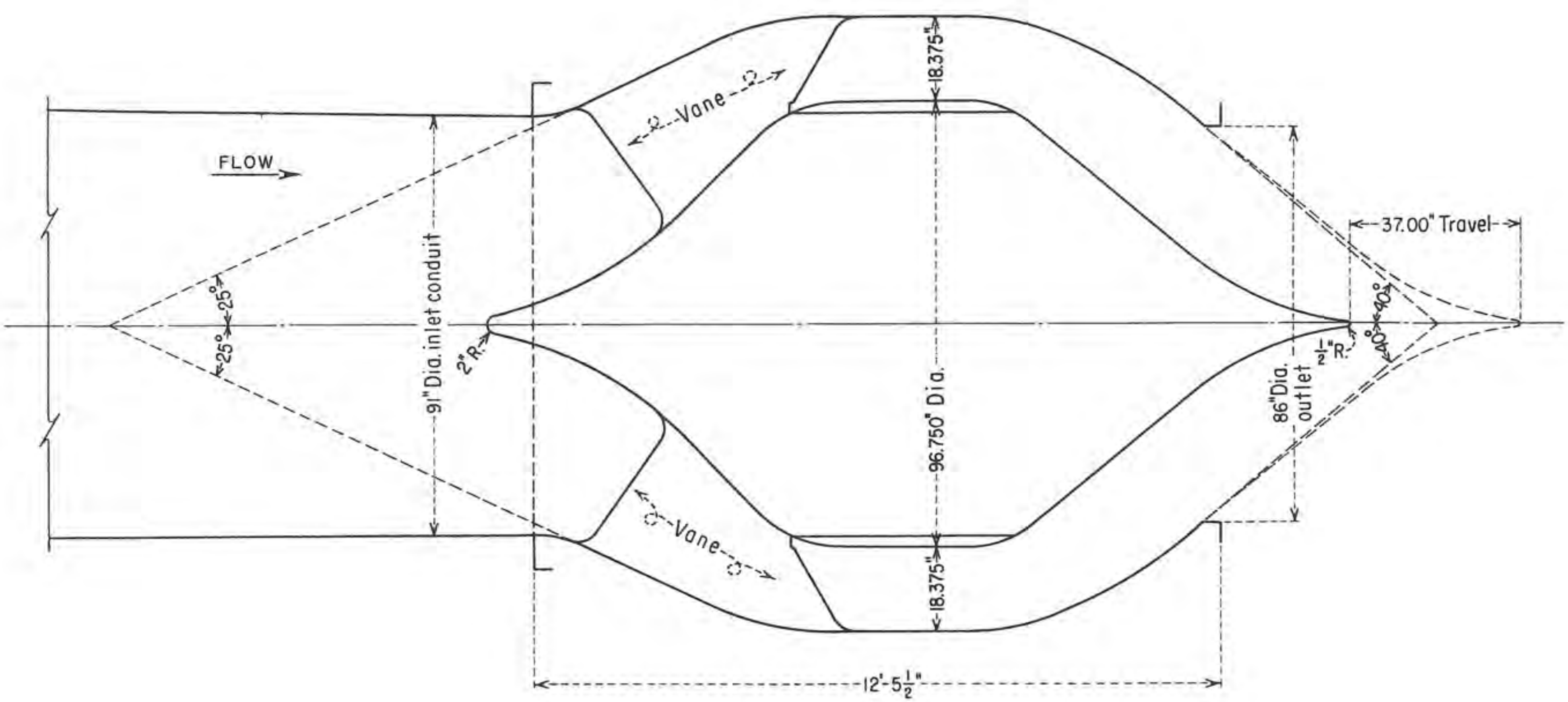
The calibration curves for the 86-inch needle valves were developed primarily from a model valve 9-7/8 inches in diameter at the upstream flange. Some check points were made on a model valve having a 6-inch diameter at the upstream flange. As in the case of the other two outlets for Friant Dam, a complete model of one of the conduits was not built and the predicted coefficients were corrected to reflect the entrance losses and the losses in the conduit to facilitate application to the prototype where reservoir elevation could be readily determined.

These corrected coefficients plotted against percent of valve opening are shown in Figure 8. Prototype coefficients calculated from available field measurements are shown on this same figure. It should be noted that the full range of valve openings is not shown on this plot. Although complete calibrations were made on the model, the prototype data available includes only those valve openings up to slightly over 30 percent, with a range of head from approximately 25 to 115 feet.

Within the range of the prototype tests, the average deviation from the model curve is about 7-1/2 percent if the three points that lie above the model curve are not considered. These points are very probably in error. Such points seem to evidence themselves in experimental work in spite of all precautions.

Additional work is being done to bring the results into closer agreement. The observations taken during the past season were not available for inclusion.

The conditions for making the field observations are similar to those at the other two outlets. The current meter gaging station is located in a section of concrete-lined canal; verniers



FRIANT DAM
MADERA CANAL OUTLET
86" NEEDLE VALVE
CENTRAL VALLEY PROJECT - CALIFORNIA

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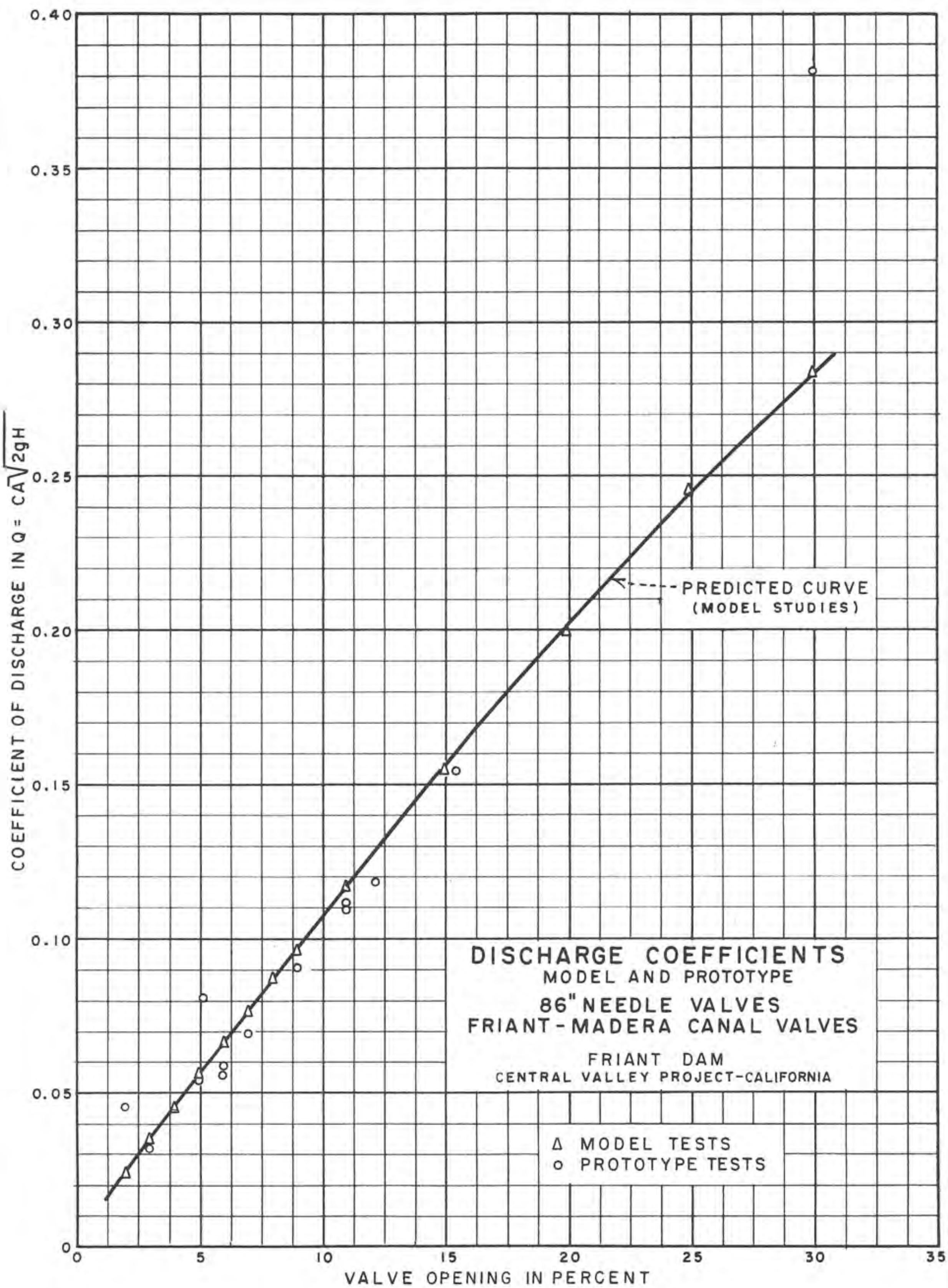
FIGURE 7



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have been placed on the valve position indicators, and reservoir elevation is used for determination of head.

The needle valves are operated with hydraulic controls and during the earlier observations some difficulty was experienced with the needle shifting from the exact setting. This irregularity has been remedied and future results should be more exact.

MODEL-PROTOTYPE COMPARISON OF DISCHARGE FROM THE OUTLET VALVES AT SHASTA DAM

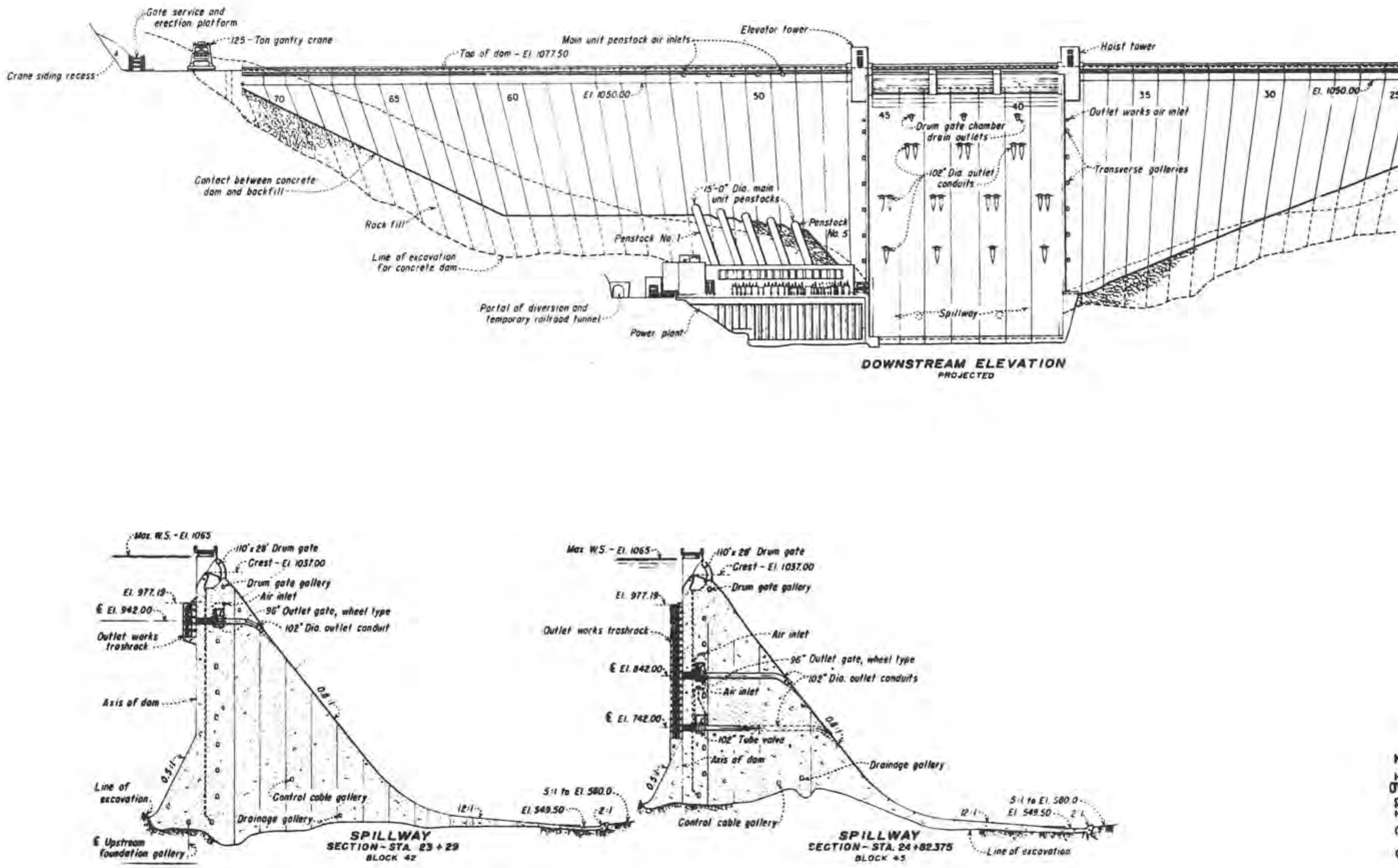
Shasta Dam is a multipurpose structure on the Sacramento River, 9 miles above Redding, California. It is operated to regulate the flow of the river for flood control, irrigation, salinity repulsion, improvement of navigation, industrial use, municipal consumption, and for the generation of electric power. Releases in excess of the capacity of the turbines are made through eighteen 102-inch-diameter outlets in the spillway section of the dam. These outlets are placed at three elevations--four are in the lower tier at elevation 742, eight in the middle tier at elevation 842, and six in the upper tier at elevation 942, as shown in Figures 9 and 10. Thus, the maximum heads on the valves are 323, 223, and 123 feet, respectively, for the lower, middle, and upper tiers.

In each of the 18 outlets it was desirable to use a valve which would operate at any opening in order that close control of the releases could be effected. Since the valves were to be placed in the conduit upstream from the exit, there was danger of cavitation being produced in the valve and in the conduit downstream. A converging cone section was included at the downstream end of the conduit to assist in alleviating this condition.

A type of valve characterized by its long, slim shape and referred to as the "Shasta tube valve" was developed after much study, including numerous hydraulic model tests, Figure 11. This valve, when fully opened, had a discharge coefficient high enough to fill the conduit under pressure. However, despite extensive development of air-relief measures to areas in the valve and downstream from the valve, this control could not be safely operated over the entire range of opening when the maximum head pertained because of existing low pressures. At lesser heads, the inoperative range was greatly reduced.

Four of these valves were built and installed in the lower tier of outlets. The installation proved expensive and a more economical type of control was proposed for the 14 remaining outlets. Again design studies, including hydraulic models, produced a wheel-type gate closing an orifice known as a "jet-flow gate" that will operate satisfactorily in the conduits. The outlets in the middle and upper tiers are fitted with this type of control. It should be noted that each of the 18 outlets has only one control. A coaster gate operating on the face of the dam is used for closure in emergencies and for unwatering the valves for maintenance.

The initial model studies of the tube valve were made on a 1:17 scale model. Thus, a 6-inch pipe represented the 102-inch-



THE 102-INCH OUTLETS IN SHASTA DAM

Figure 9

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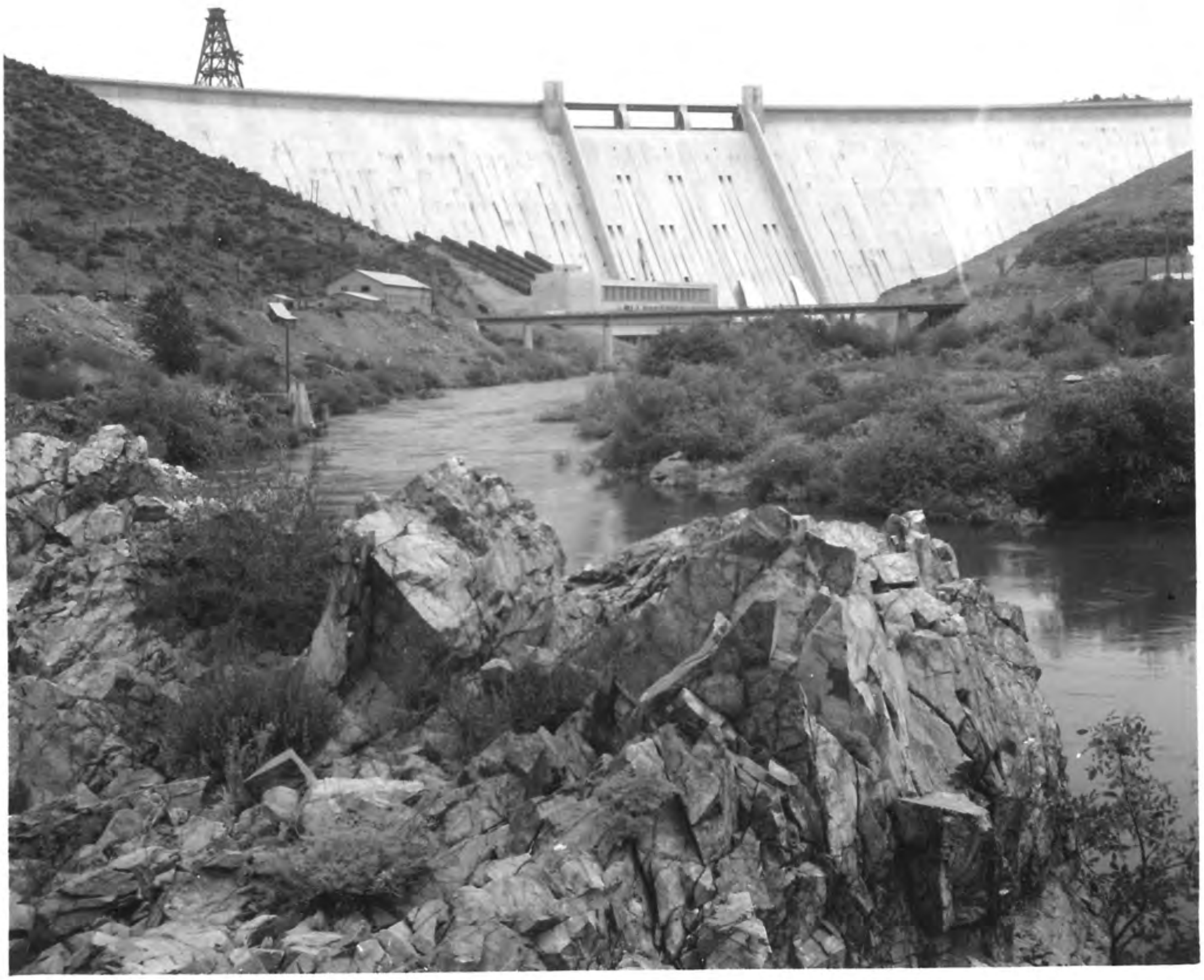
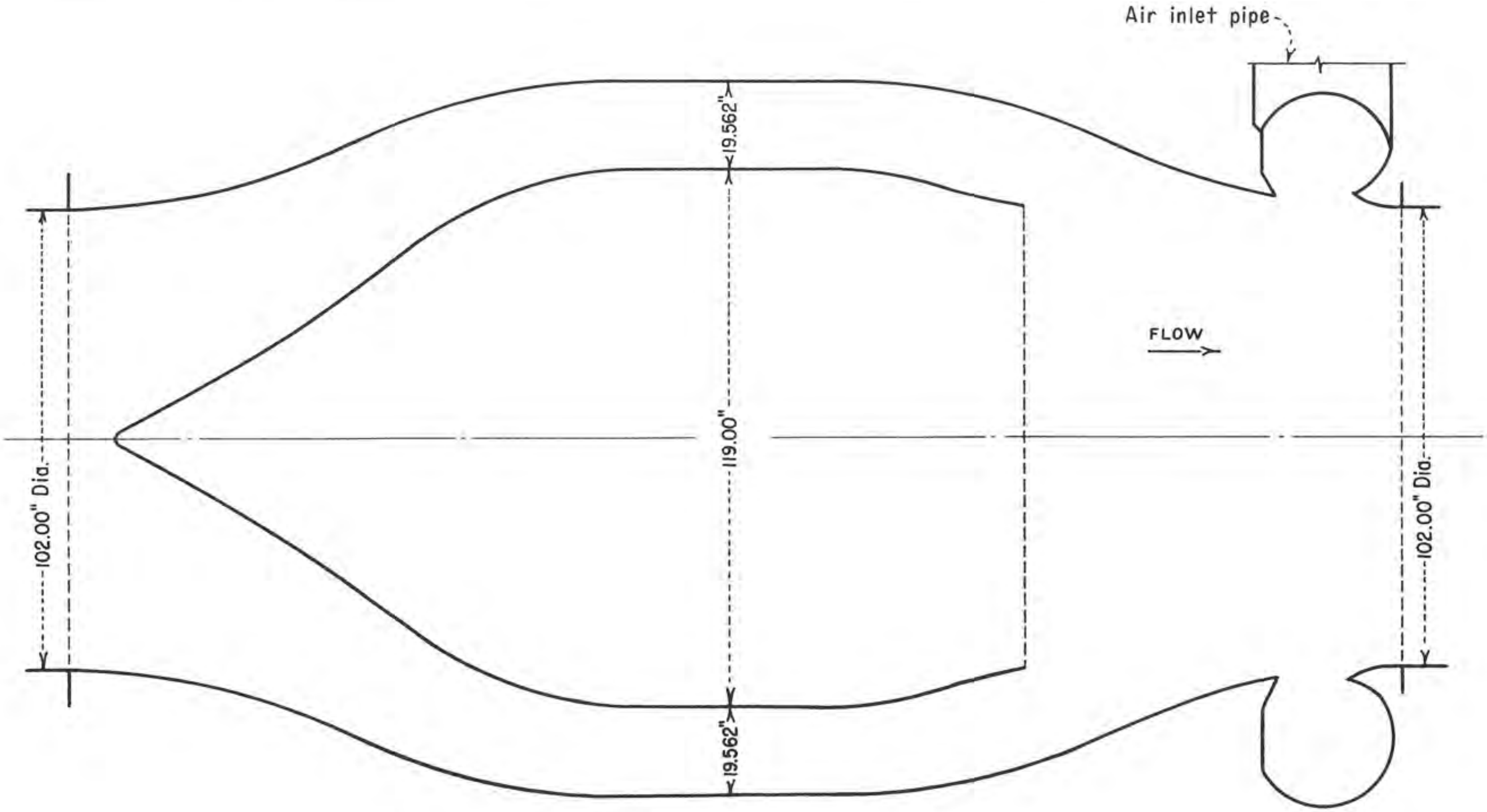
Figure 10



Gaging station in river.

TEST OF LOWER OUTLET - SHASTA DAM - MAY 1947.



SHASTA DAM
RIVER OUTLETS
102" CONDUIT TUBE VALVES
CENTRAL VALLEY PROJECT - CALIFORNIA

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FIGURE 11

diameter outlet through the dam. During the final stages of development, a 20-inch valve was made and tested under high heads at Hoover Dam. The studies on this 1:5.1 scale model were conducted primarily for verification of the results from the 1:17 model regarding the air-relief measures and the quantities of air required to improve the negative pressures created by the valve discharging into the conduit. Very good agreement of results was obtained. Unfortunately, due to shortage of manpower caused by the war, calibration curves were not developed for the final design of the tube valve on the 20-inch model.

The model calibration curves were made on a complete assembly of the outlet constructed to a scale of 1:17. The valve was machined to very close tolerances from brass castings. The results of these calibration studies covering the range of heads and valve openings are shown on Figure 12.

Also shown on this figure are the results of the field calibrations made to date. These observations were made with a head on the outlet of approximately 220 feet and valve openings at 5-percent increments from 5 to 100 percent open. Figure 13 shows the discharge from one of the outlets during the tests.

The discharge was determined from a current meter gaging station located in the river channel downstream from the dam, foreground Figure 10. This is a very stable section, and a gage-height-discharge curve has been established by a large number of current meter observations at this section and at Keswick Dam downstream. Check points on the curve were obtained at the time the Gibson tests were made on the turbines. To obtain the flow from the outlets, it is necessary to deduct the flow through the power plant. This flow is quite well defined.

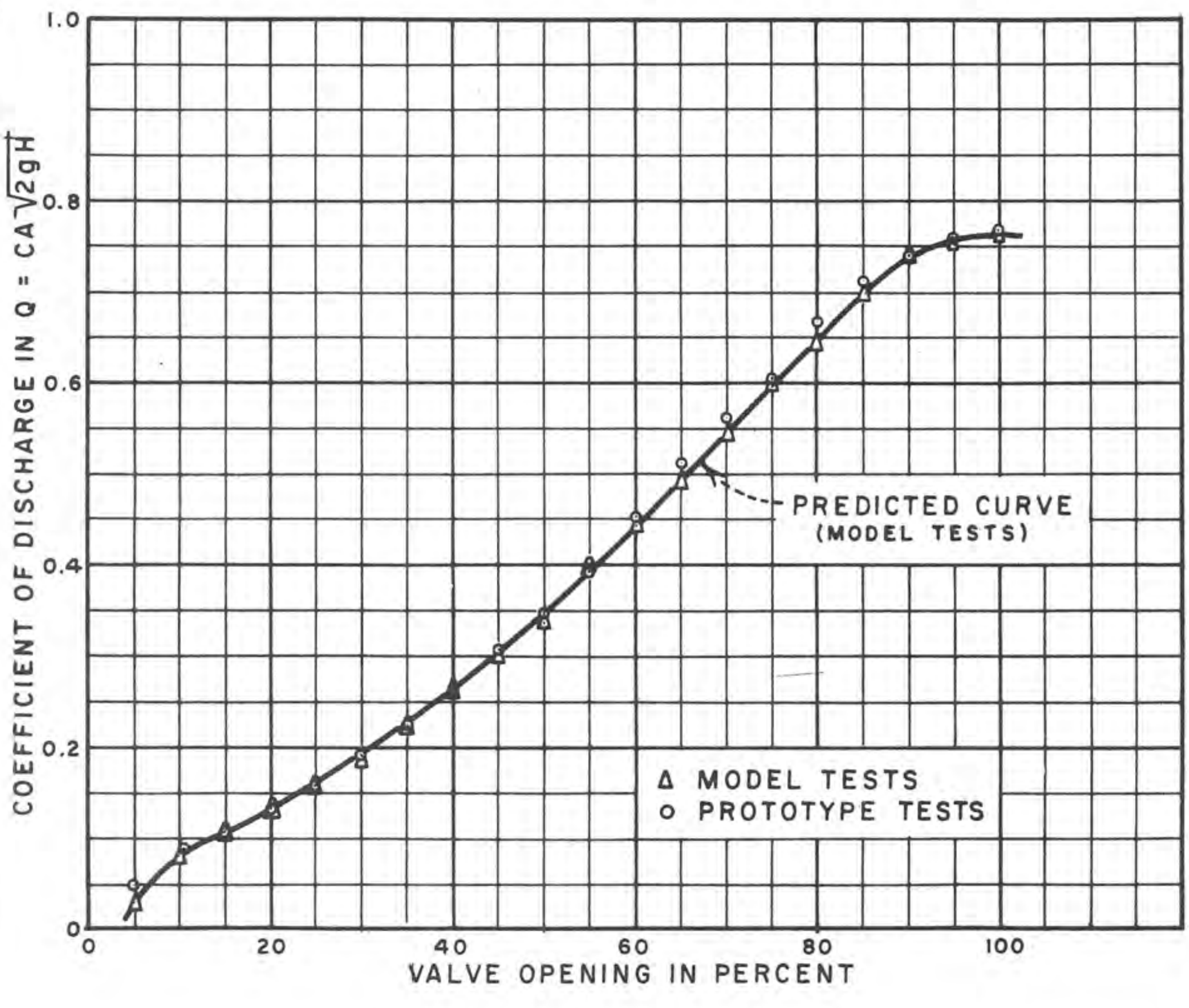
One outlet of the lower tier contains a large number of piezometer openings for determining pressures at various points. By utilizing the drop in pressure through the bell-mouth entrance and applying the coefficient of this entrance as determined from the model studies, a further check on the flow may be obtained. The results of this measurement of flow and those obtained at the gaging station are in very close agreement. Therefore, it is felt that the measurement of flow through the outlets in the field is quite accurate.

The presence of the piezometers mentioned above also permitted a close check on the head measurements.

The travel of the valve was checked on the test valve in the field and the opening could be set within very close tolerances with the mechanical controls provided.

A comparison of the coefficients as determined from the model and the prototype shows an average deviation of slightly over one percent.

The field observations were supervised by laboratory personnel and close control was exercised, because tests to determine air demand and pressures at many points in the outlet and valve were



DISCHARGE COEFFICIENTS
MODEL AND PROTOTYPE
102" TUBE VALVES
SHASTA DAM
CENTRAL VALLEY PROJECT-CALIFORNIA

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A - Outlet 1 discharging at a small opening.

B - Outlet 1 discharging at the wide open position.

TEST OF LOWER OUTLET - SHASTA DAM - MAY 1947.

being made concurrently. This comparison may be used as an example of what can be accomplished in the field when the mechanics of the problem are well understood and experienced personnel supervise the over-all testing program.

Sufficient field data have not yet been collected on the controls placed in the middle and upper tiers of outlets at Shasta Dam to permit making a model-prototype comparison of discharge characteristics. Complete calibration curves were developed from 1:17 scale models of one of the intermediate and one of the upper outlets containing the wheel-type outlet gates known as the "jet-flow gate."

Similar gates were installed in the outlets at Canyon Ferry Dam and some flow data are available.

MODEL-PROTOTYPE COMPARISON OF DISCHARGE FROM THE OUTLETS AT CANYON FERRY DAM

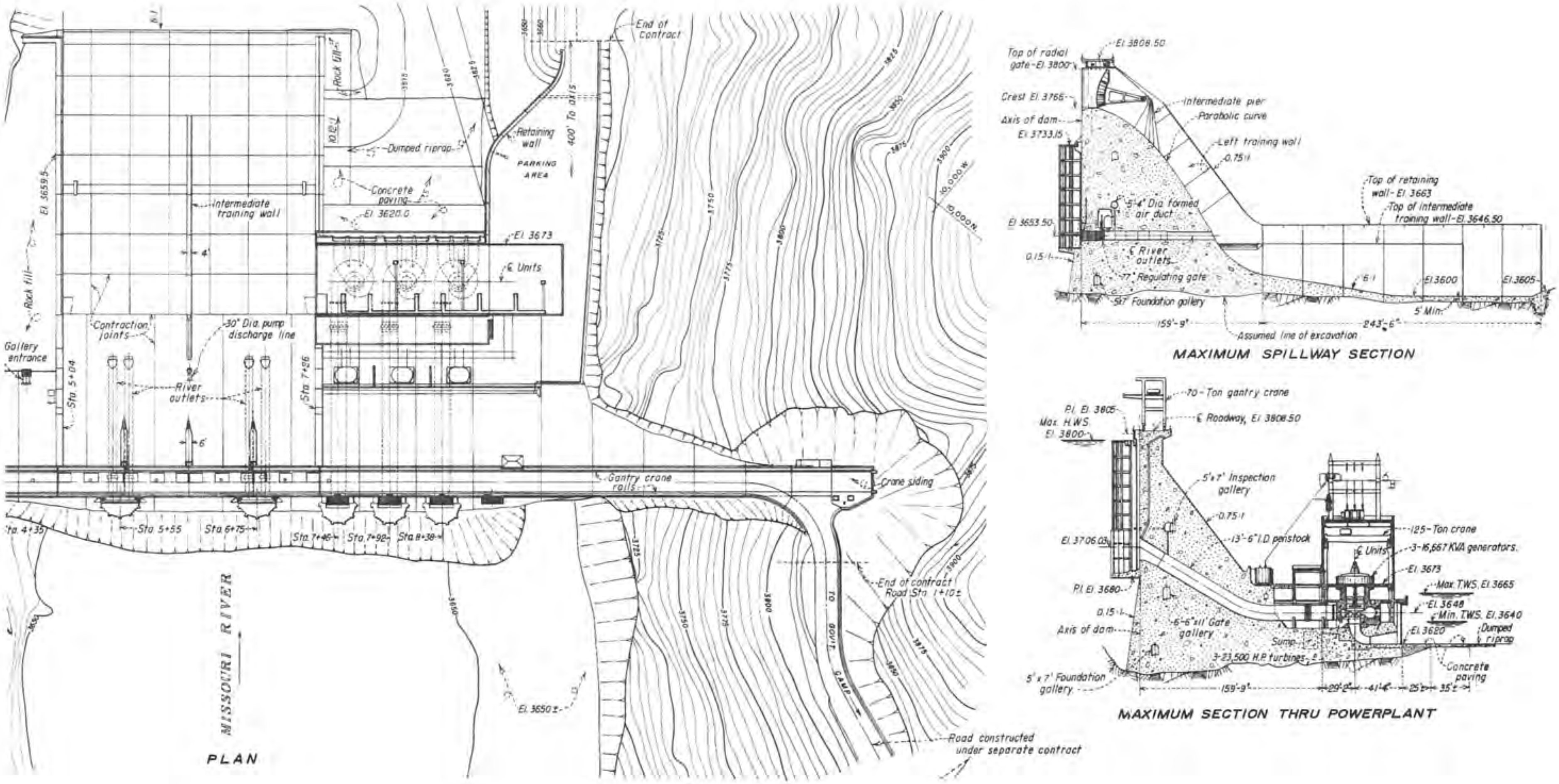
Canyon Ferry Dam, Figure 14, is located on the upper reach of the Missouri River, east of Helena, Montana. The structure is a gravity dam, approximately 175 feet high, with an overfall spillway for release of flood waters. In addition to the spillway, there are four outlets through the spillway section of the dam which are controlled by four jet-flow gates. These outlets discharge into the spillway stilling pool and are used primarily to regulate the river below the dam by controlled releases to supplement the flow passing through the power plant.

The center line of the outlets is approximately 150 feet below maximum reservoir elevation. The four outlets are designed to discharge 9,500 second feet at maximum reservoir elevation. Details of the jet-flow gate used as a control in each of the outlets are shown in Figure 15.

The calibration data derived from the 1:17 model of the jet-flow gates for Shasta Dam were adjusted for application to the Canyon Ferry gates. This was accomplished by considering the 6-inch model as 1:14 scale model of the latter gates. Appropriate corrections were also made for the difference in upstream conduit losses.

The results are plotted in Figure 16 as the relationship between coefficient of discharge and gate opening in percent. The area used in the calculations was that of the fixed orifice in the gate. The prototype diameter of this orifice is 77 inches.

Also shown on this plot are the coefficients of discharge as determined from prototype measurements. Since these gates have only recently been put in operation, available data are quite limited. The points show considerable deviation from the curve as established by the model results. Some of this deviation can be attributed to a geometric dissimilarity between the Shasta model gate and the prototype at Canyon Ferry. It is estimated that this is in the order of 2 percent at 100 percent valve opening. All observations in the field have been made by operating personnel and the data has been analyzed in the Hydraulic Laboratory. How well the field personnel understand the complete mechanics of the problem is not known. Steps have been taken to acquaint them with the problem and point out



CANYON FERRY DAM AND POWERPLANT

FIGURE 14

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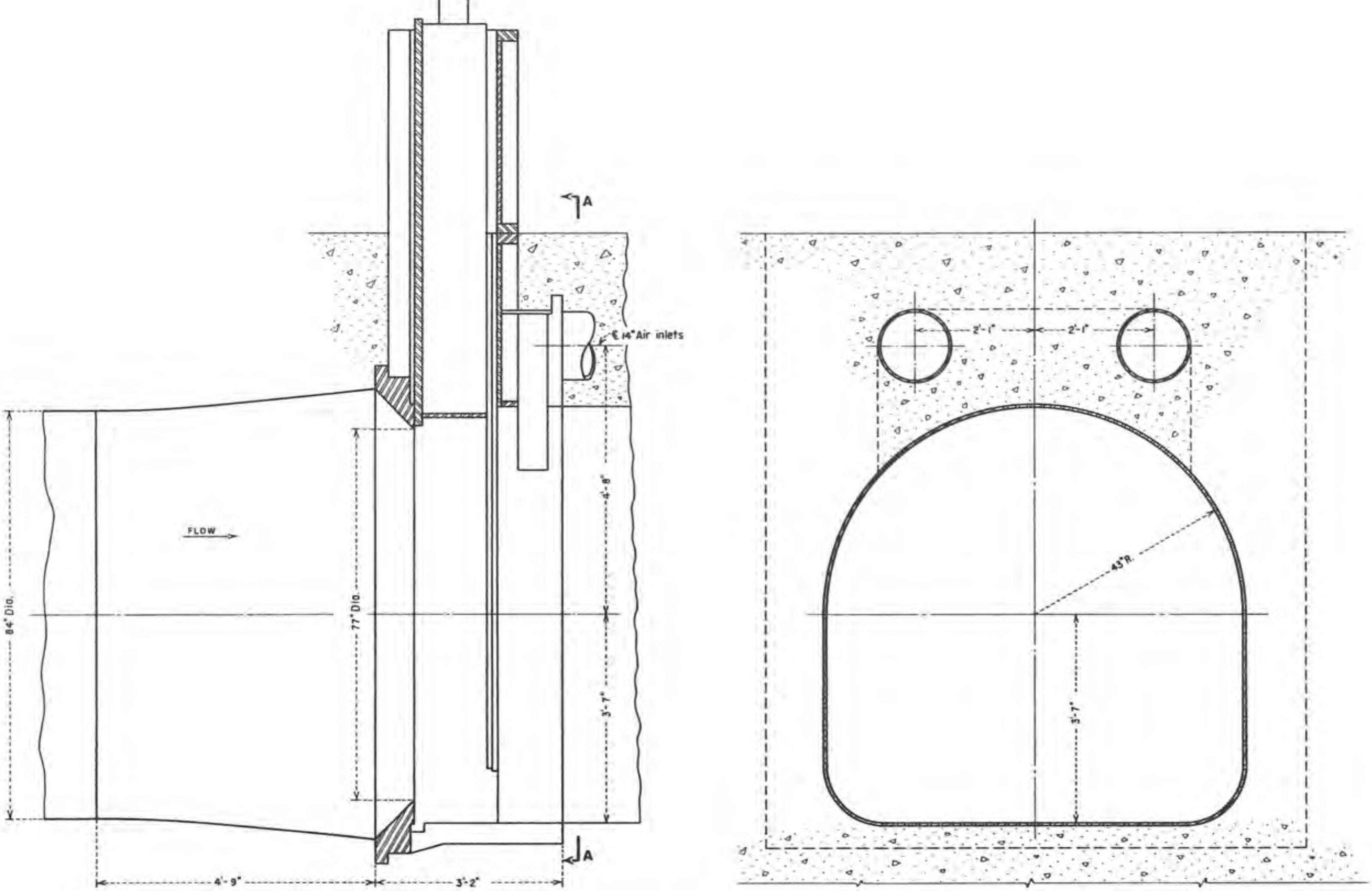

SECTIONAL ELEVATION

SECTION A-A

CANYON FERRY DAM
RIVER OUTLETS
77" REGULATING GATE
MISSOURI RIVER BASIN PROJECT

FIGURE 15

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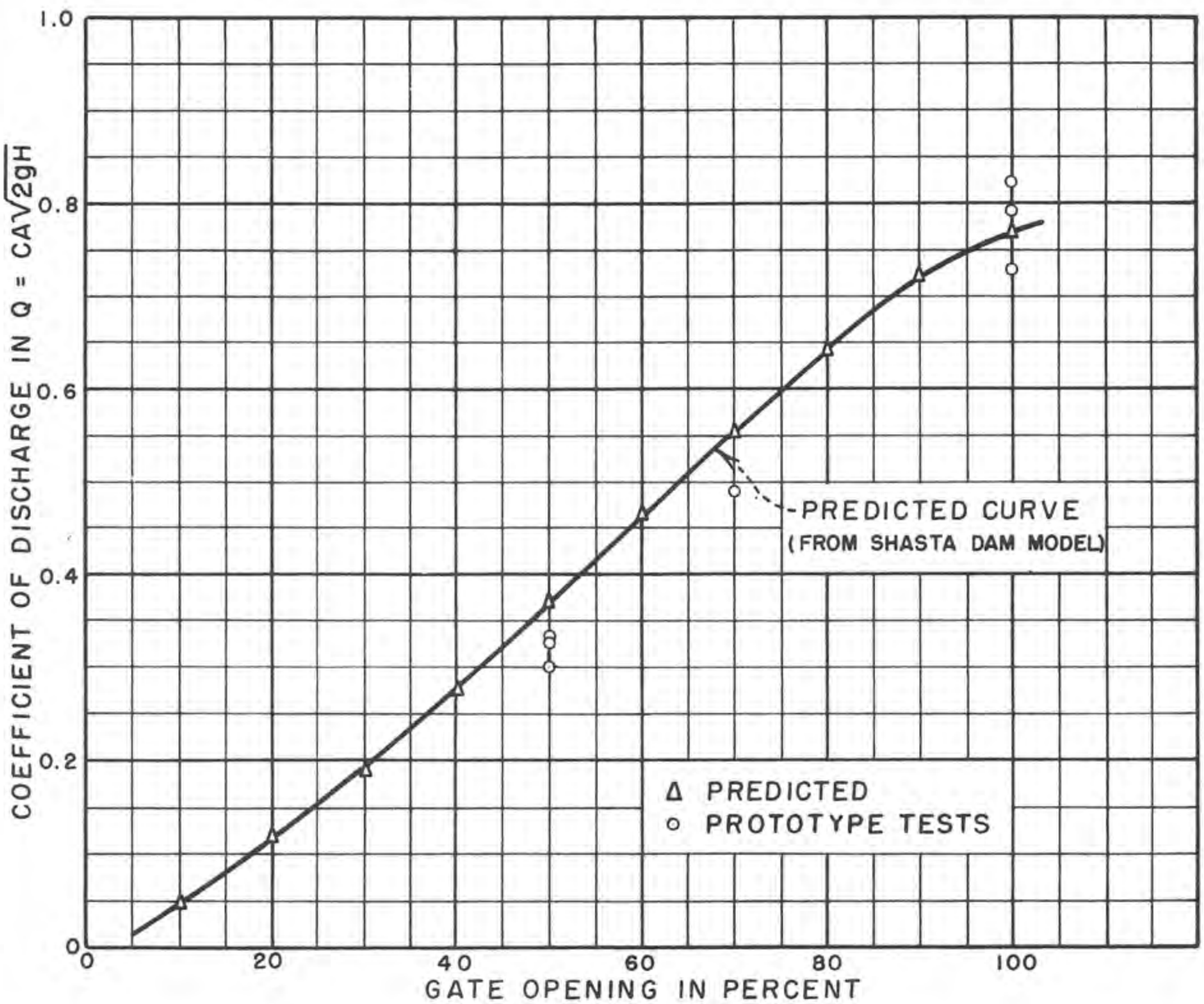

DISCHARGE COEFFICIENTS
PREDICTED AND PROTOTYPE
77" JET FLOW GATE
CANYON FERRY DAM
MISSOURI RIVER BASIN PROJECT

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possible errors in measurements. Data taken subsequent to delivery of these instructions have not been received to date.

The discharge measurements were made at a current meter gaging station in the river downstream from a small power installation. The headwaters of this plant form the tailwater at Canyon Ferry Dam. The river gagings were made by experienced crews. Furthermore, the flows could be checked with a fair degree of accuracy as they pass the small power plant. The Canyon Ferry power plant was not completed and in operation at the time the discharge measurements were made. Hence it is believed that determination of discharge passing through the gates is quite accurate.

The gates were only recently assembled and it is possible that the position of the gate leaf with reference to the orifice is not correctly indicated. The permanent gate-position indicators may need adjustment, and it is possible that some refinements may be advisable.

The degree of accuracy with which the reservoir elevations were determined is not known at present. The heads used in the calculations ranged from approximately 30 to 100 feet.

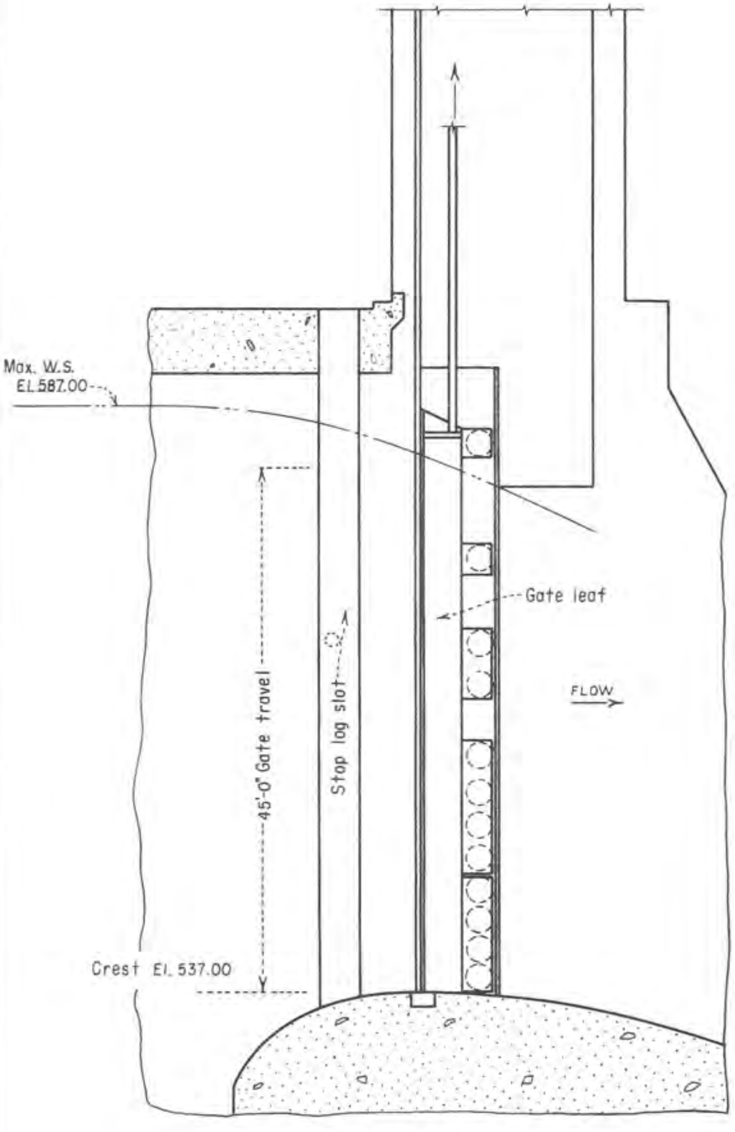
The stability of flow through this type of gate and the absence of aeration difficulties immediately downstream should make possible a very good agreement between model and prototype. It is believed that future data will show better conformance.

COMPARISON OF DISCHARGE COEFFICIENTS FROM THE MODEL AND PROTOTYPE OF THE GATES AT KESWICK DAM

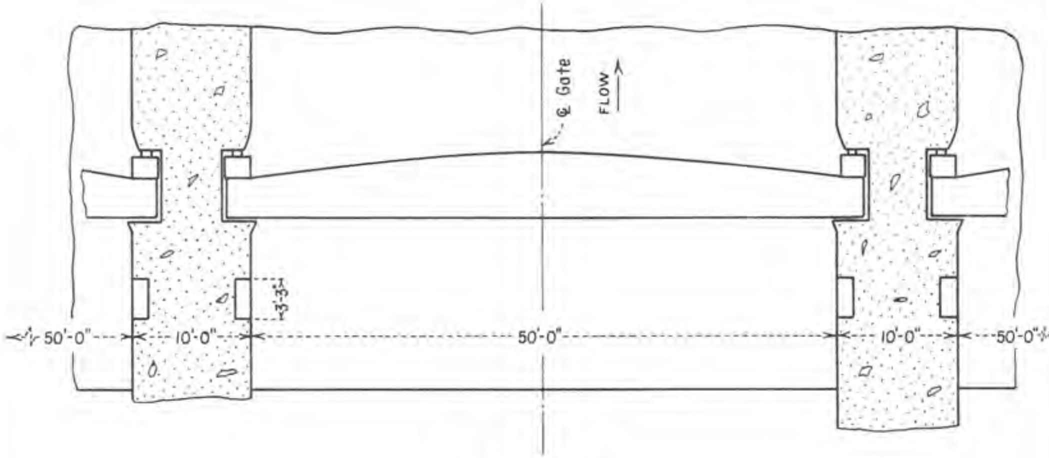
Keswick Dam on the Sacramento River, approximately 4 miles above Redding, California, was built for power-generating purposes, to provide regulation of the river below Shasta Dam, and to serve as a barrier for migratory fish control. It is a part of the Central Valley development. The structure is approximately 60 feet in height above the river bed and consists principally of a powerhouse, a fishway, and a spillway. The spillway section is approximately 250 feet wide and is controlled by five 50- by 50-foot fixed wheel gates separated by 10-foot piers. The spillway is designed to pass flows up to 250,000 second feet, with no flow over the tops of the gates. Details of one of the gates are shown in Figure 17.

Calibration curves for the spillway gates were developed from model studies of the complete spillway. This model was built on a 1:80 scale; thus, the model gates were 7-1/2 inches wide. Limited supplemental data were obtained from a 1:48 scale ratio sectional model. The predicted coefficients of discharge with relation to gate opening are shown in Figure 18 for small gate openings only. The coefficients of discharge shown in this diagram were calculated by using the area of the opening below the gate as "A" and the head on the center line of this opening as "h" in the equation "$Q = CA\sqrt{2gh}$."

A limited amount of operational data from the field is available and has been used to calculate the prototype coefficients



ELEVATION SECTION



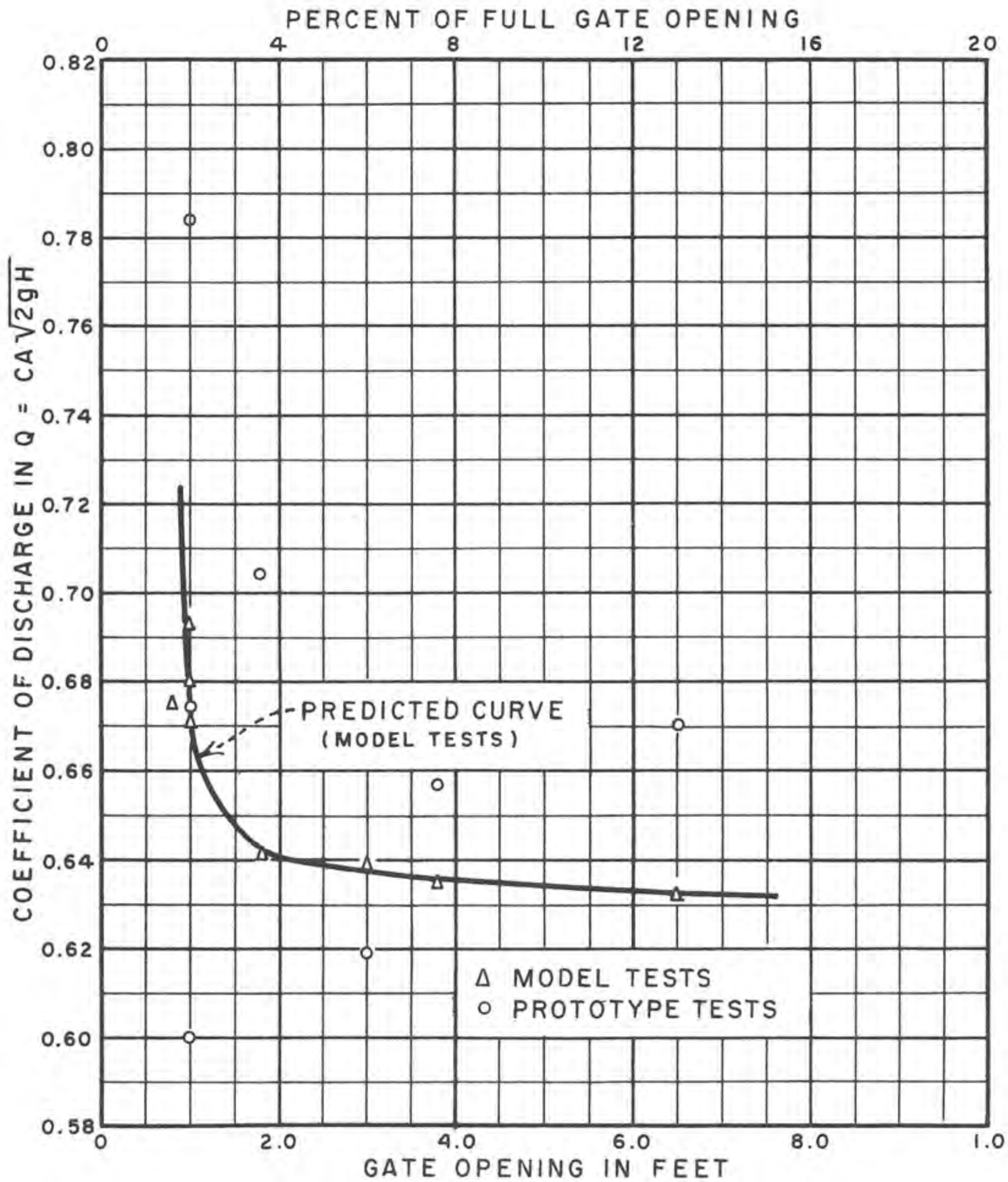
PLAN SECTION

KESWICK DAM SPILLWAY

50'x50' REGULATING GATE LEAF

CENTRAL VALLEY PROJECT - CALIFORNIA

FIGURE 17



DISCHARGE COEFFICIENTS
MODEL AND PROTOTYPE
50'x 50' FIXED WHEEL GATES
KESWICK DAM
CENTRAL VALLEY PROJECT-CALIFORNIA

shown in the same figure. Inspection of the plot shows that these points are quite badly scattered. Since the observations were made at small gate openings, this may be expected.

The notes accompanying the field data indicate that when more than one gate was being used, all gates were open an equal amount. The head ranged from slightly over 40 feet to about 48 feet.

The discharge measurements were determined from a current meter gaging station in the river about 1/2 mile below Keswick Dam. This station is operated by the U. S. Geological Survey. This flow, which is the combined discharge from Keswick spillway and power plant, can be checked by considering the total releases from Shasta Dam and correcting them for any increase or decrease in storage in the reservoir above Keswick. Since the flow through Keswick Power Plant can be determined with reasonable accuracy, it is believed that the measurements of flow are dependable, and the cause of the spread in the plotted points can be attributed to other causes.

The determination of reservoir levels is considered adequate.

For small openings of these large gates, small errors in the settings will cause considerable error in flows. This is especially true if more than one spillway gate is being used. The permanent gate-position indicators on these gates are probably not adequate to set the gates for test purposes. The notes accompanying the data indicated the gates could be set with an accuracy of about 0.1 to 0.2 foot.

Initial operational data from similar gates at Parker Dam on the Colorado River did not permit plotting of smooth discharge curves. A well-supervised program of testing disclosed that the largest error was inconsistent settings of the gates. During the testing program the gates were positioned with a rod and level, and slight changes were made in the flow-measuring techniques previously employed. The resulting observations yielded data that was in very close agreement with the calibration curves predicted from model studies.

An accurate gate-position indicator consisting of a steel tape and an appropriate pointer was temporarily installed on one of the three 50- by 50-foot regulating gates of another spillway to check the permanent indicator geared to the hoisting mechanism. The following tabulation shows the gate openings determined by the permanent indicator and the corresponding true openings:

Opening indicated by permanent indicator in feet	True gate opening in feet	Percent error
1	0.940	6.40
2	1.935	3.36
4	3.900	2.56
6	5.956	0.74
8	7.902	1.24
10	9.890	1.11
14	13.873	0.92
20	19.795	1.48
25	24.700	1.21

If it is assumed that all three gates are discharging and that the same error exists in all three gate-position indicators, the error in discharge will be appreciable for these large gates.

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A test program is being prepared for the Keswick gates. It is hoped that this program, executed under the direction of laboratory personnel, will produce data that will be more consistent.

SUMMARY AND CONCLUSIONS

Accurate control and measurement of flows is essential in the operation of all water developments, both large and small, if the water resources of our country are to be utilized to the maximum. Since control and measurement are very closely associated, it appears logical that, in addition to measuring flows at established measuring points, the control devices should also be used as metering stations if possible. It remains then to determine what types of controls can be readily adapted to this use and the expected accuracy of the results.

An examination of available information reveals that calibrations have been made of numerous types of control devices. However, in many instances the results fail to yield conclusive evidence that accurate measurements of flow have been accomplished.

Hydraulic models provide a very useful means of effecting calibrations of prototype controls. These calibrations will have an order of accuracy of plus or minus 5 percent if the model studies are conducted in accordance with good hydraulic laboratory practice. If the models are large enough, have been constructed carefully to duplicate field conditions, and the flow conditions are well defined and understood, greater accuracy can be expected.

Examples of calibrations of three valves and two gates made both on the model and on the prototype indicate that these controls may be used as dependable measuring devices. Comparisons of the results obtained in the laboratory and in the field show good conformance, generally speaking. Where differences exist, there appear to be logical reasons.

The studies show that the calibrations obtained from the models of these controls are generally within the order of accuracy of the field calibrations. It is possible that similar results can be obtained from other types of controls and that they can be used as measuring devices. If it can be conclusively demonstrated to operating and field personnel that the calibrations of controls derived from models are reliable and that complete confidence can be placed in them, it is very probable that considerable savings can be effected by accomplishing the calibrations in the laboratory rather than in the field.

Furthermore, if it can be shown beyond reasonable doubt that many of the control devices now in use can also be made to serve for accurate measurement of flow, perhaps some of the regularly installed measuring stations can be eliminated. If controls are to be used in this capacity, it would be necessary that the designer recognize that the control will be used as a flow meter and govern his design accordingly. Adequate instruction would also have to be given to construction personnel in order that they might be thoroughly familiar with the associated problems and provide the best possible workmanship to produce structures within the desired tolerances. Operation should also be conducted in such a manner that the dual purpose would be best served.

ACKNOWLEDGMENT

The material presented in this paper is a result of the efforts of many individuals, both in the hydraulic laboratory and in the field. Several offices of the Bureau of Reclamation located in the field cooperated in furnishing the calibration data from the prototype structures. The hydraulic laboratory studies have been made over a period of years by numerous engineers and craftsmen and under the direction of several individuals. Special acknowledgment is due to Mr. W. B. McBirney, who prepared many of the drawings and plots, and to Mr. D. J. Hebert for his interest and advice in the preparation of the paper.

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