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MODEL STUDIES - FOOTHILL FEEDER PROJECT
METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA
PART I. REGULAR GATE STRUCTURE

by
Alvin G. Anderson,
David J. Anderson
and
Roy M. Kuha

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PREFACE

This report describes a series of model experiments pertaining to the operation of the regular gate structure for the Foothill Feeder of the Metropolitan Water District of Southern California. The regular gate structure is designed to control the flow in the tunnel and provide the head differential that is required in the operation of the system. The tests showed that, in general, the structure operated as designed with smooth quiet flow for normal operating conditions. Information was also provided regarding the head differentials for various discharges. Pressures were measured within the structure and on the piers and floor downstream of the gates to delineate the cavitation potential. Observations were also made to determine the minimum head necessary to prevent sweepout from the gates. In these respects, the design was quite suitable.

The studies also suggested some changes in the vent system and the gate shaft to reduce surges in the event the emergency overflow weir should operate.

Measurement of vibratory pressures on the gates in the model combined with computations of the natural frequency of the prototype gates indicated that special studies of gate vibrations would not be necessary because the natural frequency was appreciably higher than any of the frequencies measured in the model.

The model test described in this report was sponsored by the Harza Engineering Company of Chicago, Illinois which was represented by Dr. David Louie, head of the Hydraulics Section of the Harza Engineering Company. The experiments were performed at the St. Anthony Falls Hydraulic Laboratory under the immediate direction of Alvin G. Anderson. The models were fabricated in the Laboratory shops with much of the research carried on by David J. Anderson and Roy M. Kuha.

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METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA

PART I. REGULAR GATE STRUCTURE

INTRODUCTION

The Foothill Feeder Project of the Metropolitan Water District of Southern California incorporates a long tunnel that will be part of the system which will supply water to a large area in Southern California including metropolitan Los Angeles. In this system head control devices are needed to regulate the discharge through the tunnels and the appurtenant structures and for this purpose gated structures open to the atmosphere were chosen which also provided an access for machinery needed for the tunnel maintenance. The gate structures, circular in plan, with the necessary emergency overflow weirs were made large enough so that the machinery access into the tunnel for maintenance could be incorporated in the structure. The circular plan also provided certain structural advantages. The research described in this report was carried out to study in detail the hydraulic characteristics of these gated structures for a wide variety of possible flow conditions. More specifically, the items of special interest were:

1. Energy losses through the gate and adjacent sections.
2. The possibility of cavitation in or adjacent to the gates during operation with small gate openings.
3. Air entrainment by the flow at the gate structure and subsequent removal of the air in the downstream air collector system.
4. Fluctuating pressures or water hammer resulting from the entrainment and removal of air from the system.

The basic features of the regular gate structure are shown in Charts 1 and 2. It consisted of a gate shaft about a hundred feet high which incorporated in a center dividing wall two side gates each 6 ft 3 in. wide by 18 ft 6 in. high and a center gate 2 ft wide and 18 ft 6 in. high. Overflow weirs, also located in the dividing wall with their crests about 80 ft above the invert, permit emergency flow through the structure when the gates are partially closed. Downstream of the gate structure the crown of the tunnel was raised to provide an enlarged section for the collection and removal of air. Two types of air removal chambers were proposed for study.

Chart 1 shows the design of an air removal chamber with a crown sloping upstream which has been designated as Scheme A, and Chart 2 shows a design in which the crown has been raised uniformly to provide a horizontal collector section with a 3 ft vent at the downstream end for the release of air. This design has been designated as Scheme B. A further modification of the gate shaft involved the provision for access of machinery to the tunnel. In Schemes A-1 and B-1 the machinery access was provided on the downstream side of the gates, and Schemes A-2 and B-2 were developed to provide a machinery access on the upstream side of the gates. The provision for machinery access resulted in a different geometry and different hydraulic conditions for the flow over the weirs.

Preliminary computations of the operating conditions by the Harza Engineering Company indicated that the energy gradeline on the downstream side of the tower would be controlled between 28.25 ft above the invert and 48 ft above the invert for normal operating conditions. It was indicated that the head drop across the gates for normal operating conditions might range from about 27 ft for small gate openings to about 0.3 ft for gates fully open. With emergency flow over the weir the gradeline on the upstream side of the gates could be up to 93 ft above the invert. This would result in a fall into the tunnel proper on the downstream side of the weir of the order of 50 to 60 ft.

A. Description of Model and Appurtenances

The several models used in the study were fabricated of a transparent plastic to a scale of 1:38.3 so that a convenient standard size plastic tube could be used as the tunnel. Photo 1 is an overall view of the model of Scheme B-1 fitted with piezometer taps and pressure transducers ready for testing. The transparency of the plastic permitted observations of the flow patterns within the structure and photographs and movies of the internal hydraulic conditions. Taps were provided at significant pressure points for piezometers, and fittings for transducers to measure fluctuating pressures were installed at various points in the air collector system and gate structure. Banks of piezometer gages and a recorder for the pressure transducers were supplied with the model.

The water supply was pumped from the Mississippi River through the Laboratory supply system. It was controlled by valves in the lines and measured by means of calibrated orifices for both large and small discharges. Before entering the tunnel sections the flow was passed through wire meshes and a honeycomb section in order to remove large fluctuations and provide a reasonably uniform flow into the tunnel system. The model tunnel discharged into the tailwater reservoir, the level of which could be controlled to maintain the downstream tunnel pressure at prescribed values. From the tailwater reservoir the discharge was returned to the river through the Laboratory drainage system.

B. Scale Relationships for Hydraulic Similarity

The gate structure, in which a free water surface exposed to the atmospheric pressure exists, represents a hydraulic system operating under the force of gravity, and the velocities, pressures, and water surface elevations represent gravitational phenomena. For this kind of a system dynamic similarity is obtained when the model-prototype relationships are determined by the Froude law of similarity. The following relationships for velocity, discharge, pressure, etc. in terms of the length scale ratio (L_r = 38.3) are then obtained.

$$\begin{aligned} V_r &= L_r^{1/2} \\ Q_r &= L_r^{5/2} \\ P_r &= L_r \\ T_r &= L_r^{1/2} \end{aligned} \qquad (1)$$

By utilizing the above equations, the model discharge can be determined and pressures and velocities as measured in the model can be readily translated to the prototype values.

Complete similarity for the air entrainment and air removal process cannot in general be obtained because of difficulty in controlling the size of air bubbles in the model. However, the processes involved are qualitatively similar and it is believed that the observations made in the model regarding the air removal pattern are qualitatively correct.

EXPERIMENTAL RESULTS

The results of the studies of the gate structure are described below under several headings describing the particular kind of experiment. They include corresponding measurements for each of the structures in order that the results may be more easily compared. Those experiments dealing with the operation of the gate structures at or near normal operating conditions will be described first. The tests for emergency conditions and non-normal operating patterns, which should be made in order to determine the range of operating characteristics or the safety of the structures in the event that such flow patterns occur, are described in the later portions of the report.

A. Head Differential Through the Structure

For normal operating conditions the gate position for a given headwater and tailwater elevation is predetermined. This normal operating curve shows the head differential at the structure for various discharges in terms of the necessary gate opening. The measurements of the head loss or head differential through the gate structure for various gate openings and discharges are shown in Charts 3 through 6 for structures A-1, A-2, B-1, and B-2. Each plot was established by opening the gates an equal fixed amount and measuring the head differential across the gate for the various discharges within the capacity of the structure. These data are plotted as separate curves for the various gate openings shown on the charts. The normal operating curve has been superimposed upon the measured head loss curve in each case to show the head differential and discharge under normal operating conditions. It will be noted that as the gate opening is increased, the head differential or the head loss at the structure becomes less. When the gates are fully opened the head differential is reduced to approximately 0.5 ft. In order to measure this small difference in the model, special precautions had to be taken in setting the discharge, and the measurement of the small head difference was done by means of a micromanometer. The rating curves for the 2 ft gate and the 6 ft 3 in. gate are shown separately in Chart 6A.

These curves show the gate opening necessary to provide a given head differential at the gate structure for the different discharges. The flow through all of the structures for these conditions is smooth and very quiet. Photo 2 shows the maximum discharge of 2250 cfs through Scheme A-1 with the gates wide open. It is apparent that there is no entrained air at the gates and the surface is undisturbed. Photo 3 shows similar flow conditions through Scheme B-1. In this case the tailwater is maintained at 48 ft above the invert of the tunnels and the photograph shows that the head loss through the structure is extremely small. Again, the flow is smooth without any air entrainment. In Photo 4 the gate opening has been reduced to 30 per cent. The tailwater was maintained at 38 ft above the invert in this test, but the headwater has increased to 61 ft so that for a discharge of 2250 cfs the head drop through the structure has been increased to 23 ft. This is not a normal operating condition, but the flow is still smooth and free of air. Photo 5 is a portion of Photo 4 enlarged in order to show the quiet surface of the upstream and downstream pools and the complete lack of air entrainment for these flow conditions. Further closure of the gates for the same discharge will, of course, increase the head difference so that when the gates are closed sufficiently some of the flow will be forced over the emergency weir whose crest is located 80 ft above the tunnel invert. Such flow patterns will be described in later sections. Photo 6 shows the same discharge of 2250 cfs through the Scheme B-2 structure. Structure B-2 is essentially structure B-1 rotated through a half circle and replaced in the tunnel system. This changes the immediate upstream and downstream flow geometry, since now the machinery access is on the upstream side. The photograph shows that for this condition also, the flow is still very smooth and quiet. Even when the gate opening is reduced to 50 per cent and the head drop has been increased to 5 ft, the flow is still very quiet as is illustrated by Photo 7. These photographs show that smooth operation through the structures will be attained for the normal operating condition and for a considerable range of gate openings on either side of the normal operating line. Throughout the range of head drops and discharges shown in Charts 3 through 6, all of the flow has been through the gate openings and none of the flow has occurred over the emergency weirs. It may be expected, therefore, that for the entire range of discharges and gate openings shown on the charts, the flow would be smooth and undisturbed.

For very small discharges only the 2 ft center gate will be operated with the two side gates closed. For this flow the velocity in the tunnel is very small (for a discharge of 50 cfs the tunnel velocity is less than 0.2 fps). The water surface is quite undisturbed. Special effort was made to photograph this condition and to delineate the flow pattern. Photo 8 is an attempt to show the flow pattern by the injection of a small quantity of dye. Dark streaks against the white background show the streamlines approaching the 1 ft opening of the gate. Photo 9 shows a slug of dye on the floor approaching the gate section.

B. Effectiveness of Air Collectors

The preliminary proposals (Scheme A or Scheme B) were presented to determine the relative effectiveness of the two air collector systems in preventing entrained air from entering the tunnels. The idea in both schemes is that any air entrained by the flow through the gates or over the emergency weirs will rise to the surface and collect near the crown within the air collector systems. From the collectors it will then be released to the atmosphere by flowing back up the sloping crown and up through the shaft for Scheme A and out through the vent pipe in Scheme B. Experiments were made using both schemes with flow over the emergency weirs in order to determine which of the two was more effective and which should be recommended for use as the regular gate structure. It appears from the charts in the previous section that, as far as head loss is concerned, either Scheme A or Scheme B would be equally effective. In this section their relative effectiveness in the release of entrained air is studied.

Photos 10 and 11 show the flow through the Scheme A-2 structure when the discharge is 2250 cfs and the gates are completely open and completely closed respectively. In Photo 10 with the gates fully open as in normal operation the flow is quite smooth and there is no entrained air, while in Photo 11 the gates have been completely closed and the discharge is forced over the emergency weirs. In falling back into the tunnel section, a great deal of air is entrained which begins to rise to the surface in the air collector system. Practically all of the air has been released from the flow to be collected at the top of the collector. Much of the air so collected is being discharged through the gate shaft. Photo 14 is a close-up of the junction of the air collecting segment and the tunnel proper and shows that the volume of collected air at the top of the air collection section is great enough to permit some of the air to enter the main tunnel. The photograph also shows the air bubbles rising to the surface in the air collection chamber.

It would appear from Photo 14 and as was observed in the experiments, that more of the air could have flowed upstream along the sloping crown to be discharged through the drop shaft if the slope of the crown had been steeper. This, of course, would have made the tunnel near the gate shaft considerably deeper, and the exit of the air collection chamber would have been further up on the side of the shaft. Conceivably, the downstream portion of the air collection chamber could have been made steeper and the upstream portion might have been flatter and still be effective in removing the entrained air. The extreme case of such an arrangement is Scheme B in which the downstream portion of the air collector has been made vertical while the crown itself remains horizontal. It would appear that the sharp shoulder at the downstream flange in Scheme B would be effective in preventing air from entering the main tunnels if the volume of air in the collector is small and easily released through the vent pipe. This condition is illustrated in Photos 12 and 13, which show a discharge of 2250 cfs through Scheme B with the gates fully opened or completely closed respectively. In Photo 12, in which the gates are wide open, the flow is again very smooth and without entrained air, while in Photo 13 the discharge is over the emergency weir with a consequent high degree of air entrainment. Here again, the entrained air rises to the crown well within the air collector system and is discharged through the vent pipe. The tailwater was maintained at 48 ft for both of these conditions. Photo 13 shows the collected air forming large bubbles at the crown of the collector and moving downstream toward the vent. Photo 15 gives a close-up view of the downstream end of the air collection chamber and junction with the tunnel for the same flow conditions as in Photo 13. The collected air has formed a large bubble which extends to the downstream end and which is discharged through the vent pipe in a rather large gulp so that the water surface strikes the crown of the air collection section with a considerable force. This effect is more noticeable for the high tailwater because of the additional pressure acting on the collected volume of air. Photo 15 shows that some air might be carried into the downstream tunnel because of the disturbance caused by the flow of air up the vent pipe. It was suggested that if the vent pipe were moved upstream, this possibility would be reduced. This question has been studied and will be described in a later section.

In the experiments just described, a maximum discharge of 2250 cfs was passed through the structure in order that the worst conditions might be illustrated. The amount of air entrained by the flow going over the weir, however, is a function of the discharge. As the discharge is decreased, the amount of air entrained is also decreased so that the conditions shown in the photograph represent the worst conditions that might be expected to occur. These experiments have demonstrated that the operation of Scheme B with the abrupt downstream junction combined with a horizontal crown and a vent pipe can be improved and is considerably more effective than Scheme A.

Along with the relative effectiveness of air removal goes the generation of sizable pressure fluctuations caused by the weir flow plunging back into the downstream pool. To investigate this aspect, pressure transducers were installed at several points in the air collector systems of both Schemes A and B. Typical results of these measurements for the maximum discharge are shown in Charts 7, 8, and 9. In Chart 7 are typical transducer tracings recorded when the gates are wide open and when the gates are completely closed and weir flow occurred. When the gates are fully opened, the records of transducers A and B demonstrate a smooth quiet flow for normal operations. The pressure fluctuations are very small so as to be essentially negligible. When the gates are closed, on the other hand, and the flow is over the weir, very large pressure fluctuations up to 25 ft of water are generated by the jets plunging into the pool. Somewhat similar conditions are shown in Chart 8 except that the pressure fluctuations in Scheme A-2 for flow over the weir are appreciably less than those measured for Scheme A-1. This reduction in magnitude is probably due to the fact that the drop shafts on the downstream side of the weir have a reduced cross-section so that they are essentially sealed by the flow coming over the weir, with a consequent reduction in the magnitude of the pressure pulses. Chart 9 shows the results of some pressure fluctuation measurements in the Scheme B-1 structure when the gates are wide open for normal operation and when the gates are completely closed and flow takes place over the weirs. The discharge for this condition is 2250 cfs. When the gates are open the pressure fluctuations are a minimum and the flow is quite smooth. When the gates are closed, however, pressure fluctuations of appreciable magnitude occur at both transducers A and B. The pressure pulses having a period of approximately 6.4 sec are due to the sudden periodic releases of air through the vent pipe. These sudden releases are caused by the water forced into the vent pipe by the high tailwater which is above the crown of the collector. When sufficient air has collected at the crown of the air collection chamber, it tends to rise in the vent pipe and carries some of the water with it. The air is explosively discharged with a momentary reduction to atmospheric pressure in the collection chamber. The high tailwater then causes the water level in the air collection chamber to rise rapidly to impact against the crown of the chamber. Each time this occurs, the pressure pulse so generated is recorded on the pressure transducer. Pressure pulses of the order of 90 ft of water were measured in these experiments.

The experiments described in this section show that as far as air removal is concerned, Scheme B is more effective than Scheme A even though the pressure pulses as measured were appreciably higher. This conclusion is reached because subsequent measurements have indicated that the pressure fluctuations can be greatly reduced and the escape of air into the tunnel eliminated by appropriate arrangements of the vent pipe. For this reason the subsequent experiments to be described are limited to the B-1 and B-2 structures, and Scheme A was dropped from further consideration.

C. Pressures on the Piers and Adjacent Floor Areas

One of the objectives of the overall study was to determine the likelihood of cavitation on the piers and floor downstream of the gates and gate slots. This section describes the results of pressure measurements made in the neighborhood of the gates and the piers for both B-1 and B-2 structures.

The first set of measurements was made in the region downstream of the gate slots on the outside wall of the structure. For this purpose several piezometers were installed just downstream of the gate at an elevation about 0.40 ft above the floor of the structure. This arrangement and the results of pressure measurement at these points are shown in Chart 10. The measurements were made for small gate openings in order to create conditions of maximum velocity. The results show that for given gate openings the pressure decreases with increasing discharge. For these small gate openings, however, as the discharge increases above a certain point, the required upstream head is such that some of the water is forced over the emergency weir and the discharge under the gate remains essentially a constant. It would be expected, therefore, that the minimum pressure on the side walls would remain relatively constant even though the discharge increases. The lowest pressure was about 22.5 ft of water which occurred for a gate opening of 1.0 ft for discharges above 1500 cfs. These pressures are well above the cavitation pressure so that cavitation is not likely to be a problem in the area downstream of the gate slots.

The piezometer taps were installed because the values would represent the pressures essentially at a point. Only average pressures can be measured with a piezometer tap, so in spite of the increase in area over which the pressure would be measured, a pressure transducer was installed downstream of the gate as shown in Chart 11. The pressure fluctuations for several discharges were quite small so that the minimum pressure would not be appreciably lowered by the addition of pressure fluctuations. For this reason subsequent pressures were measured by piezometer.

Because of the high velocity downstream of the gates around the piers when they are partially closed, the local pressure is reduced considerably below the tailwater pressure. If it becomes low enough so as to approach vapor pressure, cavitation may occur. Chart 12 shows the pressures measured on the pier wall downstream and adjacent to the 2 ft center gate. These pressures were measured for various combinations of discharges and gate openings such that the head drop, Δh, would be a maximum, and hence maximum velocities and minimum pressures would occur in the region just downstream of the gate. It was not possible to install a pressure transducer in the confined area in which these pressures were to be measured, so recourse was had to pressure measurements by means of piezometers. The values given on the chart are the minimums of the fluctuations observed on the manometer. The minimum pressure in this area was 1.8 ft of water measured during a flow of 2400 cfs with the 2 ft center gate wide open. Even for these extreme, non-normal conditions of flow, the minimum pressure is well above the vapor pressure for the fluid.

Additional piezometer pressure measurements were made on the pier wall and floor for both the 6 ft 3 in. gate and the 2 ft center gate. These results are shown in Charts 13 through 16 on which the minimum pressure in feet of water in terms of the gate opening in feet for various discharges has been plotted. Superimposed on the chart is the normal operating line, that is, a line to represent the minimum pressure on the piers or the floor when the structure is operating under normal conditions. The charts indicate the pressures that might be expected for non-normal operating conditions and purport to show the minimum pressures for the entire range of operating conditions. The lowest pressures measured on the side of the pier are shown in Chart 13, which indicates that the minimum pressure of 6.8 ft of water occurred when the gate opening was 4 ft for a discharge of 2250 cfs and head drop of 47 ft. Normally, for a discharge of 2250 cfs the gates would be wide open and the pressure on the pier would be much higher. It is interesting to note that in all cases the minimum pressure occurred at tap 7 which is located just downstream of the sharp break at the downstream end of the pier.

The data shown in these charts are average or temporal mean pressures as determined by a manometer. Fluctuations resulting from flow past the gate slots can result in a momentary lower value. As a check on the minimum pressure resulting from these fluctuations, a transducer was installed in the lowest pressure point in the side wall as shown in Chart 11. Due to resonant conditions in the chamber resulting from the high frequency of pressure pulses in this region, it was necessary to switch to a surface mounted gage. The measurements indicate that the fluctuations will be less than ±10 ft of water around the mean piezometer pressure, so that for all normal operating conditions the minimum pressure should be of the order of 12 ft (gage). (See Chart 10.) For the lowest pressure, the momentary minimum might be of the order of zero or slightly below zero but still well above the cavitating pressure. Similar measurements were made in the Scheme B-2 structure. These are shown in Charts 17 through 20. In this case, however, because of the long, relatively streamlined piers, the minimum pressures are in all cases appreciably higher than those measured for the B-1 structure.

These results show that in all cases the pressure on the piers and downstream of the gates will always be appreciably above the cavitation pressure even when highly non-normal operations are carried out.

The lowest pressures on the floor and piers are shown in Charts 13 and 14, and the tap where the minimum pressure occurred is just downstream of the break in the pier wall. This low pressure occurs here primarily because of the separation of the flow at this break, but also because the pier is quite short relative to the gate. It was suggested that, if the piers for the B-1 structure were more streamlined, the minimum pressure would be considerably higher and hence still farther above the cavitation pressure. Experiments were performed with streamlined piers and the results are shown in Charts 21 and 22. As expected, the minimum pier pressures are much higher and approach those for the normal operating line.

The experiments demonstrate the superiority of streamlined piers in pressure and flow quality, but since the pressure pattern for the unstreamlined piers is quite satisfactory the extra cost of streamlined piers is scarcely justified.

D. Minimum Tailwater Elevation to Prevent Hydraulic Jump in the Tunnel

For normal operation of these structures tests show that the tailwater elevation as originally prescribed is sufficiently high to completely submerge the gates and thus prevent entrainment of air and the subsequent introduction of such air into the tunnels. In this section tests are described which were made to determine the minimum tailwater elevation that would be necessary if the tunnels are to remain filled and the gates submerged for different discharges and gate openings. At the same time pressures were measured at various points on the piers and floor downstream of the gates to determine the minimum pressures that might be expected for this condition. In these experiments the tests were carried out by adjusting the gates for a given discharge until the headwater was equal to 80 ft for the normal tailwater elevation. The center gate was closed. The tailwater was then lowered until the flow was on the verge of exposing the gates. When this point was reached, the measurements of elevation and pressure were recorded. If the tailwater was drawn down still further, the hydraulic jump would move downstream until it formed in the tunnel itself (see Photo 16). At this point the air that would be entrained in the hydraulic jump would be liberated in the tunnel to be carried further downstream by the flow. These measurements are shown in Charts 23 through 25. The data in Chart 23 show the minimum tailwater elevation as well as the reduced headwater elevation for structure B-1 after the jump has just moved away from the gate. The chart also shows the minimum average pressure on the pier and on the floor near the pier for this condition. It appears that although the tailwater may be reduced to 20 ft above the invert without entraining any air in the tunnel, the minimum pressure on the piers for structure B-1 continues to decrease until a pressure of -20.5 ft is reached when the discharge is 1750 cfs. For discharges in excess of 1750 cfs the pressure begins to increase due to continuing increase in the size of the jet and therefore decreasing velocity. This suggests that in addition to other effects of hydraulic jump sweepout, the piers and the floor might be subjected to cavitation. These minimum pressure conditions are the consequence of the angular geometry of the downstream piers in the B-1 structure. If the downstream piers had been streamlined, these minimum pressures would be considerably higher (see Chart 25). The data for the measurements of Scheme B-2 are shown in Chart 24 which shows the headwater elevation, the tailwater elevation, and the minimum pressures on the pier wall and the neighboring floor for various discharges. Of particular interest is the magnitude of the pressures along the pier and the neighboring floor for incipient sweepout. Because of the long, well streamlined piers in the direction of flow, these pressures are considerably higher than those encountered under similar conditions in Scheme B-1 in which the flow was essentially in the opposite direction. Even at the point of sweepout the pressures here are well above those which might be conducive to cavitation along the downstream piers. Chart 25 shows that when the short piers of structure B-1 are streamlined the minimum pressure is increased by 17 ft of water to approximately -3.5 ft of water.

The results shown on these charts indicate that the minimum tailwater for the prevention of the hydraulic jump is approximately 20 ft above the tunnel invert. In order to prevent air entrainment for normal operation, the tailwater should be maintained at considerably higher elevations than this. The experiments also serve to verify the design computations for the downstream tailwater elevation necessary to keep the gates well submerged and prevent air entrainment downstream of the gate and cavitation pressures in the neighborhood of the downstream piers.

E. Gate Vibrations

The gates controlling the flow through the regular gate structure are suspended from the operating platform at the top of the gate shaft by means of semi-rigid gate stems. The gates themselves are fabricated of steel shapes and move up and down on rollers in vertical gate slots. The gate system is a relatively flexible system that could vibrate or undergo an oscillating motion if acted upon by sufficiently large fluctuating forces. Such fluctuating forces are inherent in the flow in the tunnel or can be generated by periodic vortices shed from the gate lip or other irregularities in the geometry.

The gate system itself has a certain natural frequency determined by its mass and rigidity. If the natural frequency is equal to the forcing frequency, resonance will exist and rather large vertical oscillations may occur. The magnitude of the oscillation is governed to a large extent by any damping forces such as gate friction that is inherent in the system and which may be enhanced by the large lateral force due to the head differential across the gate system.

This section deals with the studies undertaken to estimate the natural and forcing frequencies and hence the likelihood that the vertical oscillations of the gates will be deleterious to the system. Since the model gates are not dynamically similar to the prototype gates, direct measurements of the oscillations were not feasible with the present apparatus. The model gates would have to be precisely fabricated so as to be geometrically and dynamically similar and fitted with rollers such that the gate friction will approximate the expected prototype friction reduced to model scale. In order to circumvent this situation, the estimate was based upon a comparison of computed values of the natural frequency and the forcing frequencies measured in the model. In addition, frequency and oscillation data from other model and prototype gates were utilized.

To measure pressure fluctuations on the gates in the model, a pressure transducer was mounted in a chamber in the gate. Small holes tapped into the chamber transmitted the pressure fluctuations to the transducer. The arrangement is shown in Chart 26. The gates were then wedged rigidly in the closed position so that the transducer would measure only the pressures transmitted by the flow. The experiments were made in the B-1 structure in which the vent pipe had been moved to a point adjacent to the gate shaft. Experiments to be described later had indicated that at this position the maximum pressure fluctuations were greatly reduced. Since the gates were closed the flow (Q = 2250 cfs) was directed over the emergency weirs. It was felt that maximum pressure variations would occur for this flow condition.

The nature of the pressure fluctuations and the pressure frequency spectra for pulses on both the downstream and upstream sides of the gates are shown in Charts 26, 27, and 28. Pressure fluctuations on the two outside gates simultaneously recorded are shown in Chart 26. The simultaneous records for the outside gates are essentially identical for both the upstream and downstream sides. This result suggests that for this condition of flow there is no interaction between the gates. It is also to be observed that the fluctuations on the downstream side of the gates are considerably larger than those on the upstream side. The downstream fluctuations are generated by the impingement of the weir flow in the downstream pool, while those on the upstream side are more likely to be caused by the inherent turbulence generated in the laboratory supply system. The frequency spectra of the pressure fluctuations for data similar to that shown in Chart 26 are given in Charts 27 and 28 for the downstream and upstream sides respectively. The plots show the root-mean-square (RMS) of the amplitude of the pressure pulses in terms of the frequency with which they occur. RMS is defined as the square root of the sum of the deviations squared divided by the number of deviations measured. The significant feature of the graph is the frequency with which the various pressure pulses occur. In the case of Chart 27, only a very small portion of the total power occurs at frequencies of 10 cps or more. Although the curve is much more irregular for the upstream face of the gate, Chart 28 also shows a negligible portion of the total power above 10 cps. It is felt that the peaks in the spectrum represent some regular pulse inherent in the flow system rather than a characteristic of the weir flow.

Since the model gates during these tests did not simulate the prototype gates and because the computations were relatively straightforward, the natural frequency based upon the proposed gate design was computed. Since the long gate stem is the most critical portion of the gate system as far as natural frequency is concerned, the computations were carried out for several assumed stem geometries.

The natural frequency is defined by

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M'}} \qquad (2)$$

where f is the natural frequency in cycles per second, K is the combined spring constant, and M' is the effective mass of the system. It is assumed that the gate itself is rigid and acts as a weight at the end of the flexible stem. The gate stem and the hoist screw are flexible but not weightless, so they contribute to the effective mass. The spring constant also incorporates the effect of two flexible members in series as well as the effect of parallel stems for the two outside gates and the single stem for the center gate. The computed spring constants and natural frequencies for several types of gate stems are tabulated in the following table and the range of frequencies determined for all conditions are plotted in Charts 27 and 28.

COMPUTED GATE FREQUENCY

Gate	Gate Stem Extension	Effective Spring Constant K 10^5 lb per inch	Natural Frequency in Air cps
		Gate Open	
6'-3" x 18'-6"	hollow	4.98	20.8
	4" solid	7.4	24.2
	6" solid	16.8	36.0
2"-0" x 18'-6"	hollow	8.76	33.1
	7" solid	11.4	35.3
	9" solid	17.1	38.1
		Gate Closed	
6'-3" x 18'-6"	hollow	4.68	19.8
	4" solid	6.80	22.8
	6" solid	13.6	28.4
2'-0" x 18'-6"	hollow	7.94	30.4
	7" solid	10.0	31.8
	9" solid	15.2	34.0

Since the natural frequency of the various gate combinations falls at values for which the forcing frequency is a small value, the likelihood of resonance is small and any oscillations in the gate will not be magnified.

In addition, the inherent gate friction will further damp any tendency to magnify the oscillations because of resonance.

In order to utilize other experience with gate oscillations both at the model and prototype scale, a figure (page 18) was prepared. These data were obtained from a study of gate vibrations* for a different structure, but the form of the plot should also apply to the present gates. The experiments show that when the gates are as rigidly mounted as those for the regular gate structure, that is, with high values of the spring constant, the motion generated at the gates is quite small and well within tolerable limits. In the figure the gate amplitude has been plotted in terms of the natural frequency of the system. The curve drawn through the data is based primarily on model studies, but prototype measurements of the gates at the Fort Randall Dam have been included. The agreement with the model studies is unexpectedly good. The decrease in vertical oscillation is due primarily to increasing stiffness of the gate components which is exemplified by increasing natural frequency. The natural frequency of the gates proposed for the regular gate structure is also relatively high and falls in the region where the vertical oscillations are quite small. Based upon this analysis and considering the frequencies tabulated in the above table, the oscillations of the gates can be expected to be quite small.

The pressure measurements on the gates given in Chart 26 show that pressure pulses occur simultaneously on both gates, so there is no apparent interaction. These exploratory experiments on pressure pulses and the computations of natural frequency provide sufficient data regarding the stability of the gates to make additional studies on special gate models unnecessary.

F. Effect of Vent Pipe Orifice Size on Pressure Fluctuations

If for any reason the gates are closed and the entire discharge flowing in the tunnel flows over the emergency weir to impinge on the flow downstream of the gates, large quantities of air will be entrained by the falling jet. For this reason a special air collector has

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*Hydraulic Studies of Gates and Gate Slots of Tunnel System for South Saskatchewan River Project, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, February 1962.

been incorporated into the tunnel in this region to trap the air as it is released from the flow and to vent it to the atmosphere through a 3 ft vent pipe at the downstream end of the collector. This entrainment process and the disturbance created by the jet also give rise to large pressure fluctuations which may be transmitted through the tunnel. An attempt has been made to measure these pressure fluctuations and to develop means of eliminating them if they are deleterious to the operation of the system. The high intensity pressure pulses are due to the explosive discharge of air through the water trapped in the vent pipe by the tailwater whose elevation is always above the crown of the collector. As air is released from the flow, it collects along the crown of the air collector. As more air is collected and the pressure increases, it collects in the vent pipe under the water bubble. As it rises up through the vent pipe it is suddenly released through the water to the atmosphere. This sudden release and the momentary reduction of collector pressure to the atmospheric pressure cause the water level in the collector to rise rapidly to the crown resulting in an appreciable impact. This impact may be transmitted down the tunnel.

These pressure pulses can be clearly seen from the recorder traces incorporated in Charts 29 and 30. In Chart 29 the pulses as measured for three discharges at a constant tailwater elevation are shown. For these tests the gates are closed and the entire discharge flows over the emergency weir. As might be expected, if the rate of air entrainment increases with the discharge over the weir, time required to increase the pressure enough to force water out of the vent pipe decreases and the frequency of the pulses as well as their magnitudes increase. This is shown by the recorder trace. As the discharge increased from 500 to 2250 cfs, the maximum pressure pulse increased from 16 ft of water to 90 ft of water. Similar effects are shown in Chart 30 when the discharge is constant at 2250 cfs and the tailwater successively decreased from 48 ft to 33 ft above the tunnel invert. The effect of decreasing the tailwater elevation is to decrease the magnitude of the pressure pulses. This is because the volume of water entrapped in the vent pipe is reduced as the tailwater is lowered so that the air may be released at pressures more nearly equal to the tailwater pressure. Measurements from the recorder traces show that the maximum pressure pulse decreased from 90 ft to 58 ft as the tailwater decreased from 48 ft to 33 ft.

A study of the recorder traces and observations in the model suggested that these pressure pulses would be reduced if the pressure in the vent pipe were held more nearly constant. An orifice at the end of the vent pipe would provide both a more constant pressure in the collector and permit the more uniform release of air as it was collected in the air collector. To investigate this possibility, recordings were made of the pressure pulses when orifices of various diameters were installed at the end of the vent pipe. The data thus obtained are shown in Charts 31, 32, and 33 for the Scheme B-1 structure and in Charts 34, 35, and 36 for the B-2 structure. Chart 31 shows the recorder traces as measured by a pressure transducer at A (the downstream end of the collector) for vent orifice areas of 0 sq ft, 0.5 sq ft, and 9.0 sq ft. The discharge was 2250 cfs and the tailwater was maintained at 33 ft. It appears from the recorder tracings that the pressure fluctuations have been reduced when the vent area was reduced to approximately 0.5 ft. In addition, the periodicity of the pressure fluctuations has been eliminated. The results of additional measurements on B-1 are tabulated in Chart 31 to show the maximum pressure pulse in feet of water in terms of the vent area. Similar results are given in Chart 32 for the same conditions except that the tailwater has been raised to 48 ft above the invert. Here again, the reduction of the pulses and the elimination of periodicity are shown when the vent area is reduced to 0.5 ft. The results shown in Charts 31 and 32 have been plotted in Chart 33 in order to graphically show the effect of vent orifice area on the pressure pulses for both high and low tailwater elevations. It is clear from the chart that the pressure pulses are dramatically reduced if the vent orifice area is in the neighborhood of 0.5 sq ft and that the pulses increase rapidly with increasing vent orifice size.

The results for the B-2 structure are quite similar in character. The geometry of the B-2 structure, however, is such that the drop shafts through which the water falls are appreciably restricted in area so that for the high discharges water does not fall completely free but is influenced by the side walls. This has a tendency to damp out the distinct pressure pulses and reduce their magnitudes. This also gives rise, however, to a secondary effect in the form of a long-period surge superimposed upon the higher frequency pressure fluctuations. A hint of this surge can be seen in the pressure records in Charts 34 and 35. The results of the measurements for the B-2 structure have been collected in Chart 36, which also shows that the minimum pressure fluctuations are recorded when the vent orifice area has been reduced to approximately 0.5 sq ft. The chart also shows the overall reduced magnitude of the pressure pulses for the B-2 structure.

The results of this series of experiments indicate that the operation of the gate structure for emergency flow conditions can be made relatively smooth if the size of the vent is reduced. They further demonstrate that Scheme B can be made effective in removing air from the system under emergency conditions when the overflow weirs are being used. It should be remembered, however, that the entrainment of air does not follow the same laws of similitude as the flow of water over the weirs, so that in this case the results obtained in the model with regard to vent orifice size are not directly transferable to the prototype. This means that the precise determination of the size of the vent must be determined in the prototype and any orifice installed in the prototype should be adjustable to the extent that the correct size can be obtained when the prototype vent is functioning. It would appear also that the 3 ft vent pipe as originally proposed should be retained in combination with an adjustable orifice.

G. Optimum Location of Air Vent Pipe

From earlier experiments it appeared that the release of air through the air vent tended to generate appreciable pressure pulses. It also appeared that these pressure pulses might be transmitted downstream through the tunnel with a consequent adverse effect. In order to explore this condition an additional pressure transducer was located at a point equivalent to 485 ft downstream of the air collector. Simultaneous measurements of pressure fluctuations were made at transducer A and transducer C so that the fluctuations could be compared. These data are shown in Chart 37 for two tailwater elevations, 31 ft and 45 ft above the tunnel invert. The transducer records show that the pulses generated in the air collector are transmitted down the tunnel in a somewhat attenuated state. The pressure pulses are appreciably reduced at point C as compared to those in the air collector, but they are still a sizable fraction of the upstream pulse.

As described in the previous section these pressure pulses could be reduced by installing an orifice at the end of the vent pipe to build up the internal pressure and allow a more uniform release of air. It was also observed that if the vent pipe were moved further upstream the pressure pulses were also reduced. This is brought out in Charts 38 and 39 which show for comparison the transducer traces for three positions of the vent. The pressure pulses are largest when the vent is at the downstream position and a minimum when the vent is at the upstream position. When the tailwater elevation is 48 ft above the invert as in Chart 38, noticeable pulses are observed when the vent is at the midpoint of the collector, but when the tailwater is reduced to 33 ft the pulses, as well as those when the vent is at the upstream position, are eliminated. It appears from these records that additional benefits beyond those obtained by the use of an orifice would be gained by moving the vent pipe upstream.

The flow patterns through the air collector for various positions of the vent pipe are shown in Photos 17 through 20. In Photo 17, when the vent pipe is far downstream from the point where the entrained air is released, the air collects in large bubbles at the top of the collector and is explosively released when the pressure is sufficient to raise the entrapped water. At the upstream end as in Photo 20, the air is more or less continuously released through the spray and turbulence generated by the air rising to the surface.

H. Experiments on Revised Vent System Using Horizontal Plate

In an attempt to reduce the large pressure fluctuations and possibly the surges generated by the jet, it was suggested that the vent system be revised to consist of a horizontal plate mounted across the top of the air collector and extending from the upstream end to a point beyond the region of high turbulence generated by the jet. The air entrapped at the top of the collector was then removed by means of a pipe running up the inside of the tower. In the first design the plate extended 35 ft downstream of the tower and provided a passage 3 ft high at the crown. A transducer mounted at the downstream end of the air collector measured the pressure fluctuations. As in previous tests it was found that the pressure fluctuations were somewhat reduced when the area of the orifice at the end of the vent was reduced. It appeared that for the larger opening the very free movement of masses of water and air in the vent system gave rise to much higher pressure fluctuations. When the vent was partially closed, the pressure in the system was increased, the air discharge was more uniform, and the pressure fluctuations were reduced. Photos 21 and 22 show the action of the air collector when the vent is wide open and the tailwater is the maximum of 48 ft. The two photographs show a wave traveling back and forth in the air collector. This wave gives rise to pressure variations and intermittent releases of air as the wave closes or exposes the downstream end of the air vent. Visual observations of the flow show that the plate was not long enough to prevent the rough surface generated as the air rose to the surface of the air collector from sealing the end of the vent.

After the above test the vent system was further revised by increasing the length of the horizontal plate and extending the plate up the inside of the tower as shown in Chart 40. The chart shows that for downstream tail-water elevation of 33 ft above the invert, the system appears to be relatively stable. Chart 41 shows similar results when the tailwater elevation is raised to 48 ft except that here the maximum pressure pulses have been appreciably increased primarily because a considerable amount of water is trapped in the vertical vent section. As the air is discharged through the vent, the water also moves up and down the vent and causes a very considerable gulping effect as the air breaks through the water barrier. The maximum pressure fluctuations as given in Charts 40 and 41 have been collected together in Chart 42 which shows the maximum pressure fluctuation in terms of the size of the vent for tailwater elevations of both 33 ft and 48 ft. The relationship between orifice size and maximum pressure pulse is well defined and the chart shows that the pressure fluctuations decrease as the size of the orifice decreases.

The flow pattern with the revised vent system and a discharge of 2250 cfs is shown in Photos 23 and 24 in which tailwater elevation is held constant at 33 ft; the vent is fully opened in Photo 23 and fully closed in Photo 24. It will be observed that when the vent is fully opened, the water surface in the air collector appears to be irregular with waves moving up and downstream, while with the vent closed the water surface in the collector is quite smooth, but the volume of entrapped air is much larger since all of the entrapped air must find its way back up the gate structure around the vent.

These experiments show that an additional plate inserted horizontally at the crown of the air collector will serve as a vent. It has a tendency to generate surges as the end of the vent section is exposed or covered by the waves generated in the collector system. These fluctuations are augmented by the release of air past the water trapped in the vent. The results were somewhat better than those obtained with a simple vent pipe at the top of the air collector system, but the additional cost of such a vent system does not appear to be justified on the basis of these experiments.

I. Deflectors in the Gate Structure to Reduce Surging in the Air Collector

In the B-1 structure flow over the weir impinges directly on the downstream wall of the gate shaft and then falls into the downstream pool insufflating a large amount of air. The impact of the jets on the wall of the shaft gives rise to the pressures shown in Chart 43. The chart also shows the distribution of the forces and the area over which they act. In addition, these jets create a relatively long-period surge that is observed in the air collection chamber and which, no doubt, moves down through the tunnel. The character of these surges is clearly shown in Chart 44, which presents a number of typical pressure traces taken at a relatively low speed from a pressure transducer mounted on the side of the air collector. For given gate openings the amplitude of the surges increases with increasing discharge, but the period remains essentially constant. The chart also shows that the surges are appreciably reduced with increasing gate opening, an effect that may be due either to the reduction in discharge over the weir or to the high velocity under the gates that disrupts the surge pattern. The character of the flow with the gates closed is shown in Photos 25 and 26. Photo 25 is a view from overhead that shows the jets spreading out and impinging on the wall from which they fall as a more or less solid curtain (Photo 26) into the downstream pool. The air that is entrained by the jets is distributed through the entire cross-section of the tunnel.

It appeared that the surges were caused by the direct impingement of the flow upon the downstream pool and that the surges would be reduced if the jets were deflected to the side of the gate structure so that they would fall on the concrete shelf before reaching the tunnel flow. To this end several types of deflectors were studied. The most effective deflector was a curved vane attached downstream of the weir which deflected the flow through 90 degrees. The flow pattern and the reduced air entrainment with this deflector are shown in Photos 27 and 28. The effect of this deflection on the surges is shown in Chart 45 which may be compared to Chart 44.

In the B-2 structure in which the machinery access is on the upstream side, the drop shafts from the emergency weirs are very restricted. When the maximum flow occurs over the weirs these drop shafts are sealed by the flow and, because air is pumped from the drop shaft by the entrainment of air released in the air collector, the water surface in the drop shaft undergoes surges of considerable magnitude. The deflectors of the type used in the B-1 structure cannot be used in the B-2 structure because of the shaft restrictions, but other smaller deflectors as shown in Chart 46 and Photos 29 and 30 were used. The jets impinged on the deflectors and a considerable amount of energy was consumed before the water reached the downstream flow. The results of measurements with and without deflectors are shown in Chart 46 for various discharges and tailwater elevations. The use of deflectors resulted in a very large reduction in surge magnitude so that there is practically no fluctuation in the air collector. It is also significant that the entrainment of air has been drastically reduced.

Because of the submergence of the weirs and a certain dissatisfaction with deflectors which intrude on the flow passage, consideration was given to deflectors of the type used in the B-1 structures. It appeared that the drop shaft of the B-2 structure could be appreciably enlarged by the removal of some of the concrete on the outside walls of each shaft so that the drop shaft would conform to the circular section of the shaft. The existence of the enlarged drop shafts for the weir flow was a factor in reducing the surge and eliminating the submergence of the weirs that had occurred with the narrow drop shafts. This effect is shown in Chart 47 and Photos 31 and 32. By this alteration an improvement in the flow conditions was obtained as well as an appreciable saving in concrete volume.

CONCLUSIONS

The experimental study of the Regular Gate Structure was concerned with its operating characteristics for both normal and non-normal conditions. The results of the study led to the following conclusions.

1. For normal operation the flow in all of the structures for all discharges was smooth and relatively undisturbed.
2. The measurement of head differential agreed well with preliminary computations.
3. From the point of view of air collection when emergency overflow weirs are operating, the Scheme B structure was considered to be superior to the Scheme A structure.
4. The pressures on the piers and floor downstream of the gates in the region of high velocity are well above the cavitation pressure for both normal and non-normal operating conditions.
5. The minimum tailwater elevation for which the gates are not exposed and the hydraulic jump is eliminated, is approximately 22 ft. The minimum design tailwater for all discharges is 28.3 ft.
6. The natural frequency of the gates in comparison with the frequencies of the forcing functions are sufficiently large that oscillations of the gates will be at a minimum. These and other experiments indicate that additional experiments on gate vibrations would not be very useful.
7. A vent pipe to release air during emergency operation is necessary. It should be located at the upstream end of the air collector near the gate structure. It should also be fitted with an adjustable orifice so that most efficient operation can be established.
8. A revised vent system consisting of a flat plate located near the crown of the air collector showed some improvement over the simple vent pipe but was felt not justified becuase of added cost.
9. The pressure fluctuations and surges in the air collector and tunnel could be reduced by several types of deflectors in the drop shaft, but inasmuch as emergency flow will occur only rarely the added cost was not deemed warranted.

<u>LIST OF PHOTOS</u>

PHOTO 11 (Serial No. 168-41) In this photograph of a discharge of 2250 cfs in Scheme A-2 the gates are completely closed and the flow is forced over the emergency weirs. Much air is entrained and collected in the air collector to move upstream to the gate shaft.

PHOTO 12 (Serial No. 168-12) View of Scheme B-1 with gates open and flow of 2250 cfs.

PHOTO 13 (Serial No. 168-11) View of Scheme B-1 with gates closed and emergency flow of 2250 cfs over weir. T.W. = 48 ft, H.W. = 93 ft.

PHOTO 14 (Serial No. 168-6) Downstream end of A-1 air removal chamber showing air being carried into tunnel. T.W. = 48 ft.

PHOTO 15 (Serial No. 168-55) View of junction of the air collector with downstream tunnel. Discharge of 2250 cfs over the emergency weir entraining maximum amount of air. The released air is collected at the crown in a large bubble which moves downstream to the air vent. No air enters the downstream tunnel.

PHOTO 16 (Serial No. 168-94) Hydraulic jump will form in the tunnel if the tailwater is reduced below a minimum of about 21 ft. If the jump forms in the tunnel, air will be released to be carried downstream.

PHOTO 17 (Serial No. 168-11) Scheme B-1 with air vent at downstream end of air collector. Maximum pressure pulses were largest with the vent in this position. Photo shows the collector full after release of collected air.

PHOTO 18 (Serial No. 168-10) Scheme B-1 with air vent at one-third point of air collector. Gates were closed and tailwater elevation 48 ft. Pressure pulses were reduced to about two-thirds of values obtained with vent at downstream end of collector.

PHOTO 19 (Serial No. 168-9) Scheme B-1 with air vent at midpoint of air collector. The results were similar to those for one-third point shown in Photo 18.

PHOTO 20 (Serial No. 168-16) Scheme B-1 with air vent near gate shaft. The pressure pulses were a minimum at this point and air was more continuously released as it rose to the surface.

PHOTO 21 (Serial No. 168-29) In this photograph the vent pipe in the gate structure is fully opened to an area 9 sq ft. The relatively free movement of air and water in the vent pipe gives rise to a considerable surging in the air collector downstream of the vent plate. The photograph shows the surging water in the air collector at the moment that the vent area downstream of the plate is completely closed. The tailwater is 48 ft above the invert.

PHOTO 22 (Serial No. 168-30) This photograph is the same as Photo 21 taken at a time that the surge was at the downstream end of the air collector. At this point the vent is almost completely open so that air can escape from the collector. The surging back and forth of the water under these circumstances causes rather large pressure surges in the tunnel proper.

PHOTO 23 (Serial No. 168-33) As a result of the previous experiments with the revised vent, the vent plate has been increased to 50 ft downstream of the gate structure and the pipe in the gate structure has been increased in size to 31 sq ft. The photograph shows a discharge of 2250 cfs over the emergency weirs with the tailwater 33 ft above the invert and the vent area completely opened. This method appeared to work well with less turbulence and pressure fluctuations than were observed in the previous photos.

PHOTO 24 (Serial No. 168-36) In this photograph the vent area was completely closed at exit. The increased pressure in the air collector and the increased volume of air collected before it can get back through the gate structure forces the water surface nearly down to the crown of the tunnel proper. In the photograph the air pocket has increased to approximately 7 ft below the crown of the air collector. The increased pressure due to the closed vent has the effect of smoothing out the pressure fluctuations and dampening the surges somewhat. It is apparent that for this arrangement some type of venting system is necessary.

PHOTO 25 (Serial No. 168-65) The jets from the weirs begin to spread out before they impinge on the far side of the drop shaft. The flow then drops straight down into the downstream pool, generating surges of considerable magnitude as well as entraining much air.

PHOTO 26 (Serial No. 168-20) This photograph from the side shows the jets impinging on the side of the drop shaft and plunging into the downstream tunnel. A large amount of air is entrained by the flow. After impinging on the downstream side of the drop shaft, the water falls as a heavy curtain along the wall into the downstream pool. This curtain not only entrains the air but is rather effective in preventing the air in the collecting section from escaping up the shaft.

PHOTO 27 (Serial No. 168-63) As a final effort, curved vanes were installed to deflect the flow 90° from its initial direction. The flow pattern is shown in this photograph.

PHOTO 28 (Serial No. 168-64) The 90° curved deflector is still more effective in reducing the amount of air entrained and in spreading the flow around the entire periphery of the drop structure.

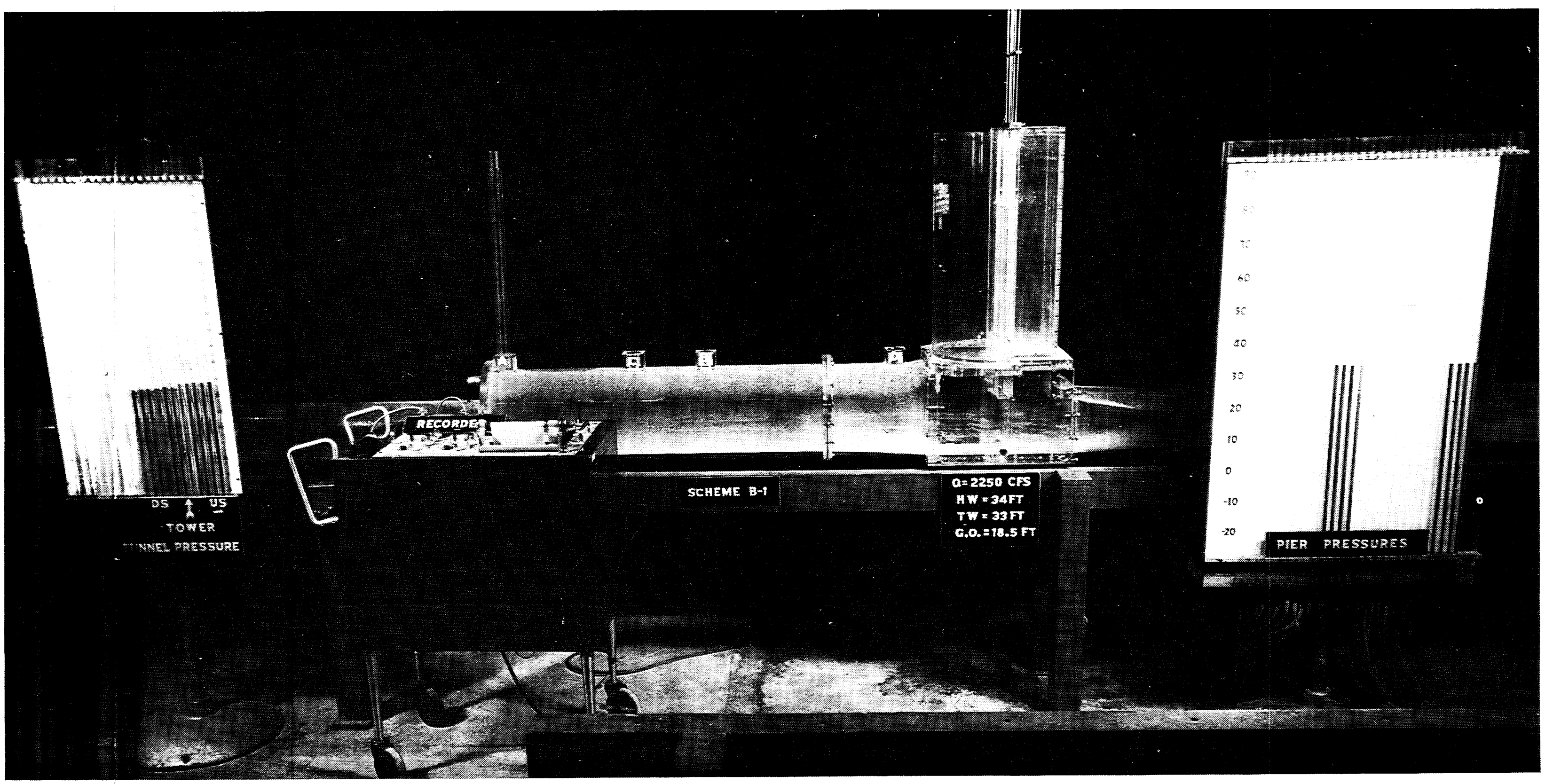
PHOTO 29 (Serial No. 168-73) In order to reduce the surging in the control structure due to flow over the weirs, deflectors were installed in the drop shaft to assist in the dissipation of energy of the jets. These deflectors reduced both the amplitude of the surges and the amount of air entrained.

PHOTO 30 (Serial No. 168-72) For smaller discharges, the degree of submergence of the weir is reduced and the jets striking the deflectors are more clearly defined. In this photograph, the amount of air entrained in the tunnel appears to be more than that entrained for the maximum discharge.

PHOTO 31 (Serial No. 168-79) When the vent area is increased to 9 sq ft, extensive surging exists in the drop structure. This photo shows surging in the drop shaft between the two arrows. This photo was taken when the surge was at the top of its motion. The photograph also shows the surging occurring in the vent pipe at the same time.

PHOTO 32 (Serial No. 168-80) This photograph is similar to Photo 9 except that it was taken at the moment when the surge was at its lowest point in the drop shaft as well as in the vent pipe. The range of surging occurring in this test is shown by the arrows attached to the drop shaft.

PHOTO 1 (Serial No. 168-92) View of model of Foothill Feeder-Tunnel Gate Structure. The model is constructed of plexiglas, to a scale of 38.3 to 1. It simulates a section of tunnel 350 ft long upstream of the gate structure and about 700 ft long downstream of the gate structure. Scheme B-1, with uniform air removal chamber and vent pipe, is shown here.


DS US
TOWER
TUNNEL PRESSURE
RECORDER
SCHEME B-1
Q=2250 CFS
HW=34FT
TW=33FT
G.O.=18.5 FT
PIER PRESSURES
70
60
50
40
30
20
10
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-10
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Photo 1

PHOTO 2 (Serial No. 168-3) View of Scheme A-1 with a flow of 2250 cfs. This photograph shows the absence of entrained air and lack of surface disturbance in the gate chamber with the gates full open.

PHOTO 3 (Serial No. 168-12) View of gate structure, Scheme B-1 with gates full-open and flow of 2250 cfs. The tailwater gradeline was 48 ft above the invert. The pool in the tower was quiet at the surface, even though the maximum discharge was passing through the full-open gates.

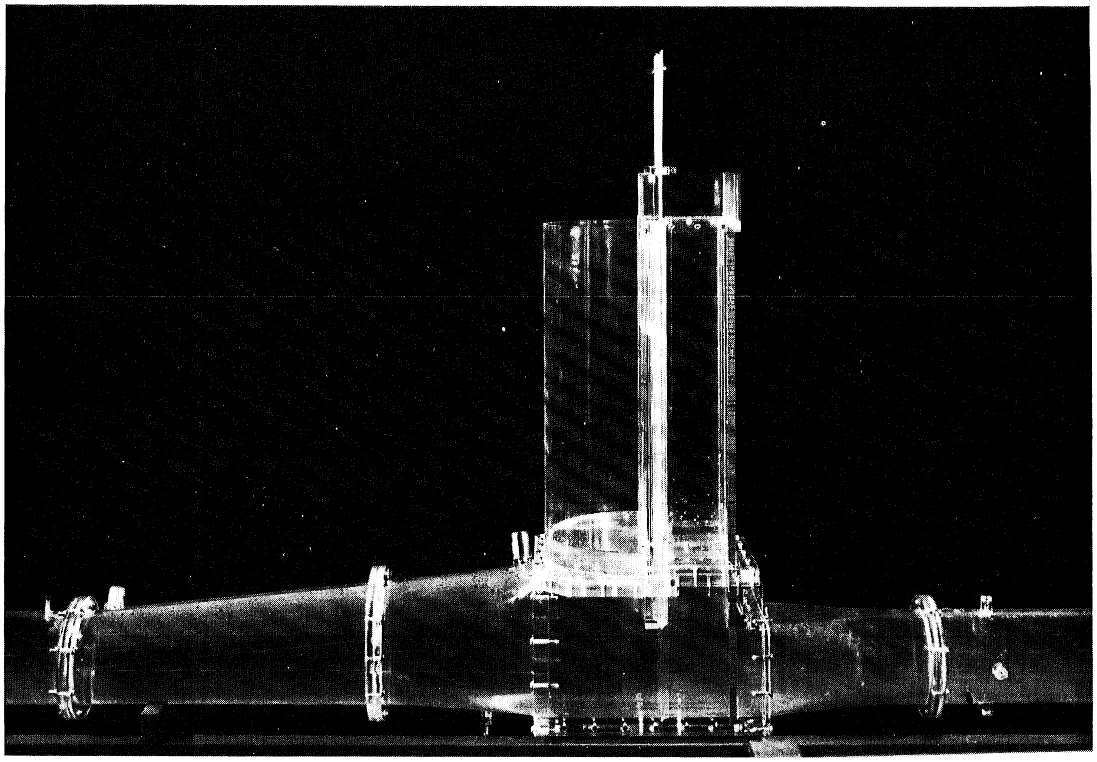


Photo 2

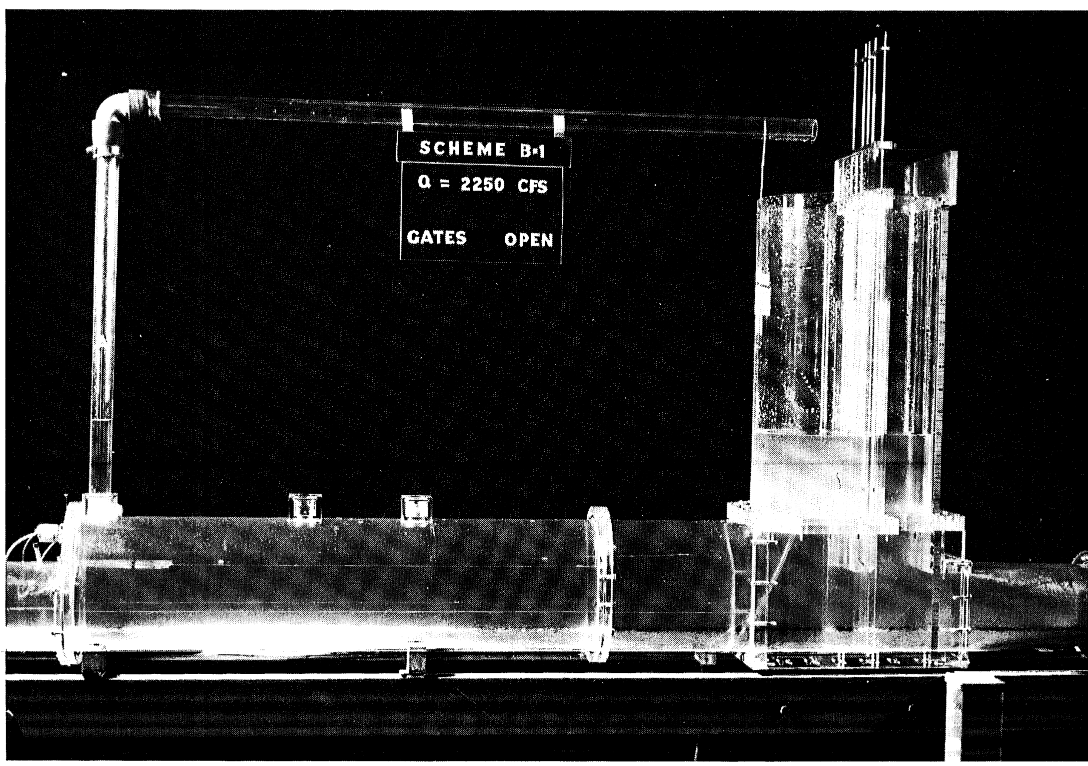


Photo 3

PHOTO 4. (Serial No. 168-19) Scheme B-1 with flow of 2250 cfs and side gates open 30 per cent (T.W. = 38 ft, H.W. = 61 ft).

PHOTO 5. (Serial No. 168-19 enlarged) View of pools on upstream and downstream sides of gate with head loss of 23 ft (enlarged section of Photo 4). Note the quiet surface of these pools and lack of air entrainment. Tubes from pressure taps can be seen in the background.

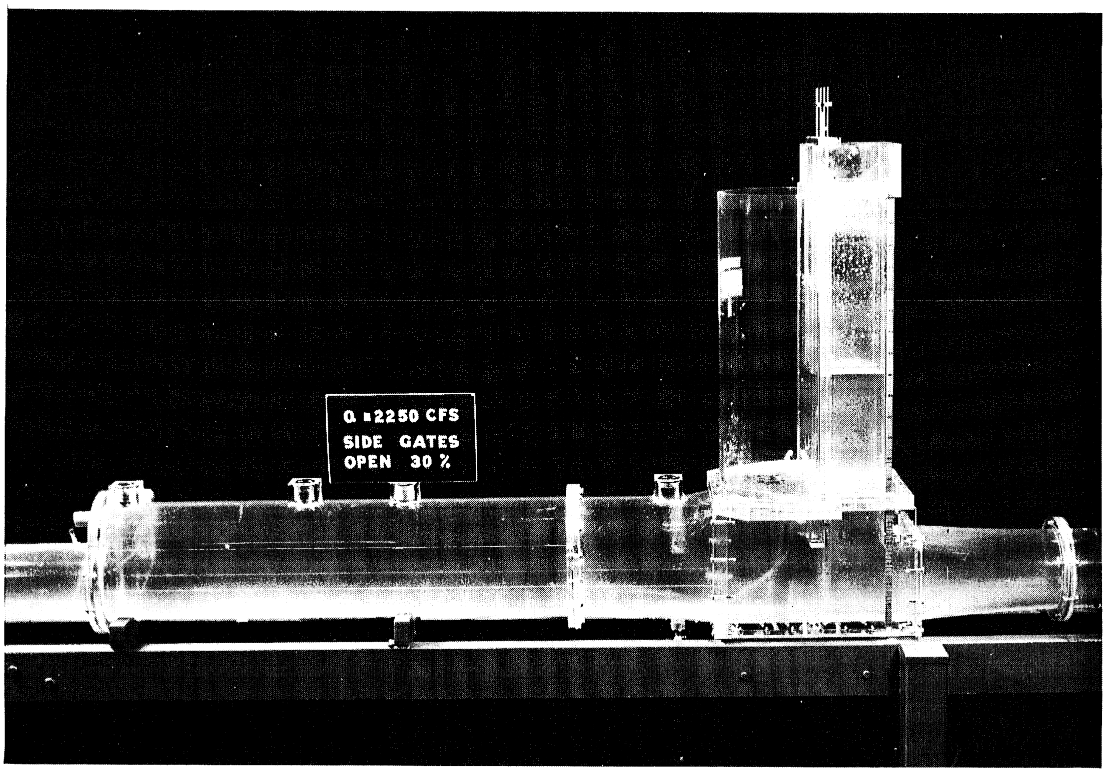


Photo 4

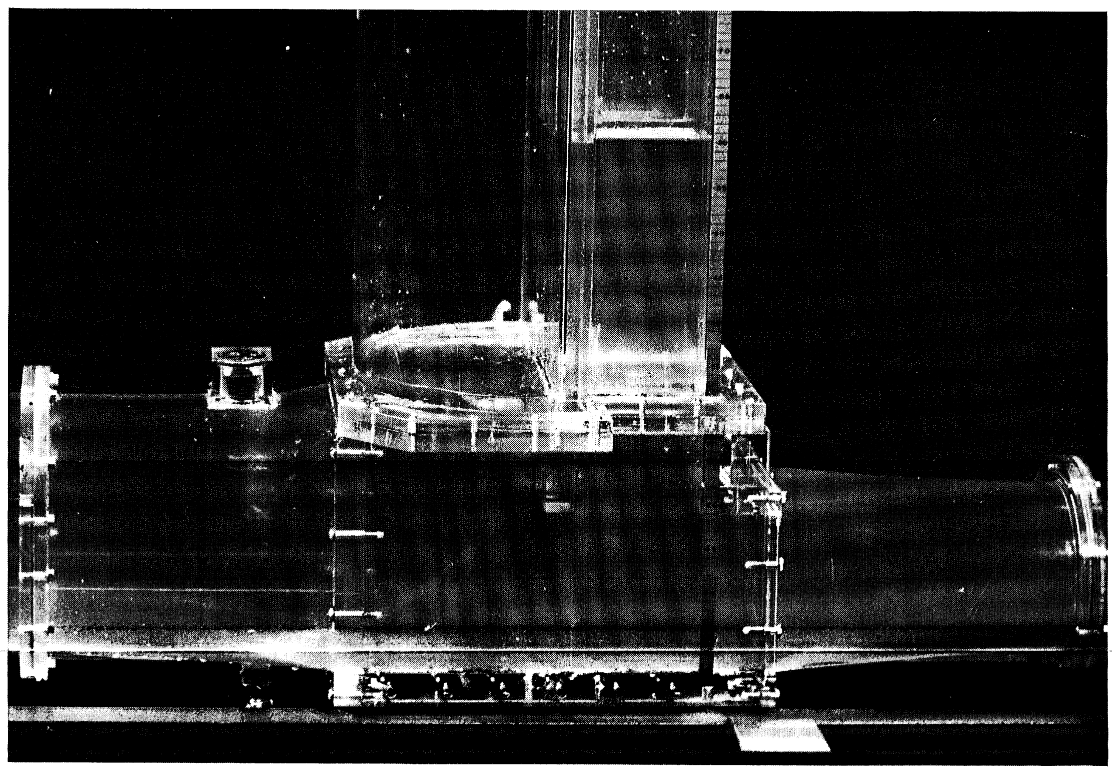


Photo 5

PHOTO 6 (Serial No. 168-47) In this photograph the gate structure is operating in its normal condition. For a discharge of 2250 cfs the gates are wide open as the flow passes smoothly down the tunnel. The water surface in the gate structure is smooth and the water is quiet. The head loss for this operation is approximately 0.5 ft.

PHOTO 7 (Serial No. 168-48) In this photograph the gates have been closed to 50 per cent open. The head loss has been increased to 5 ft, but for a discharge of 2250 cfs the flow is still quite smooth and low in turbulence.

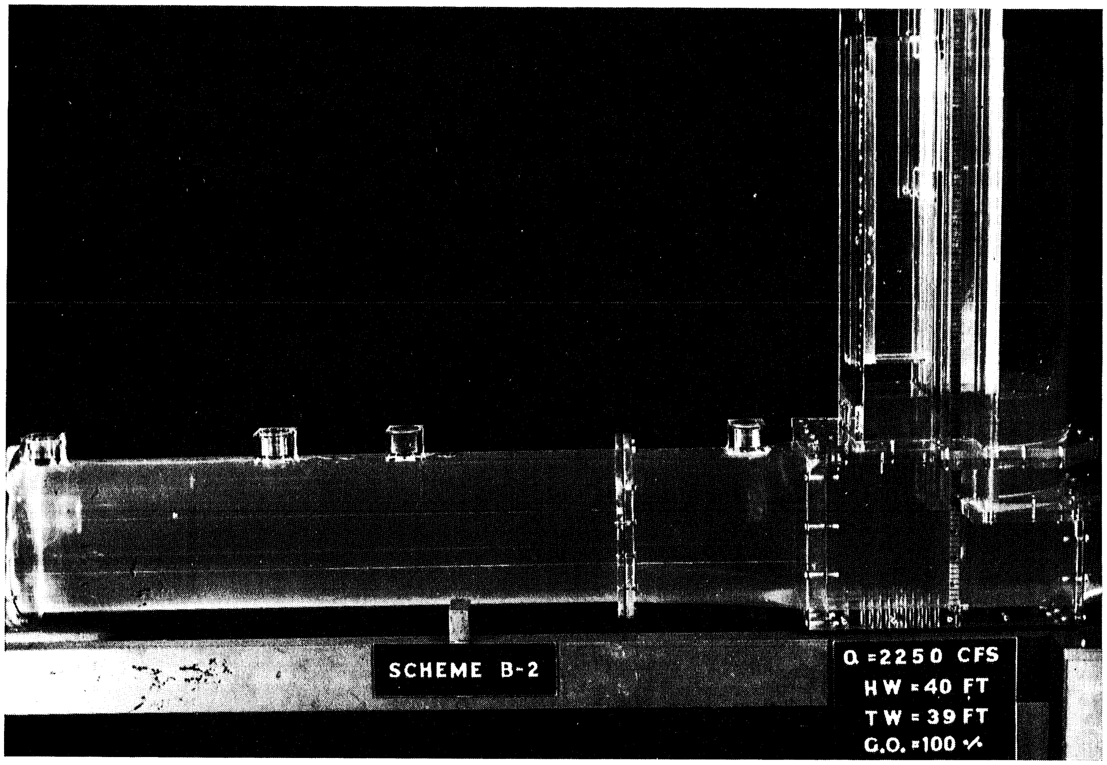


Photo 6

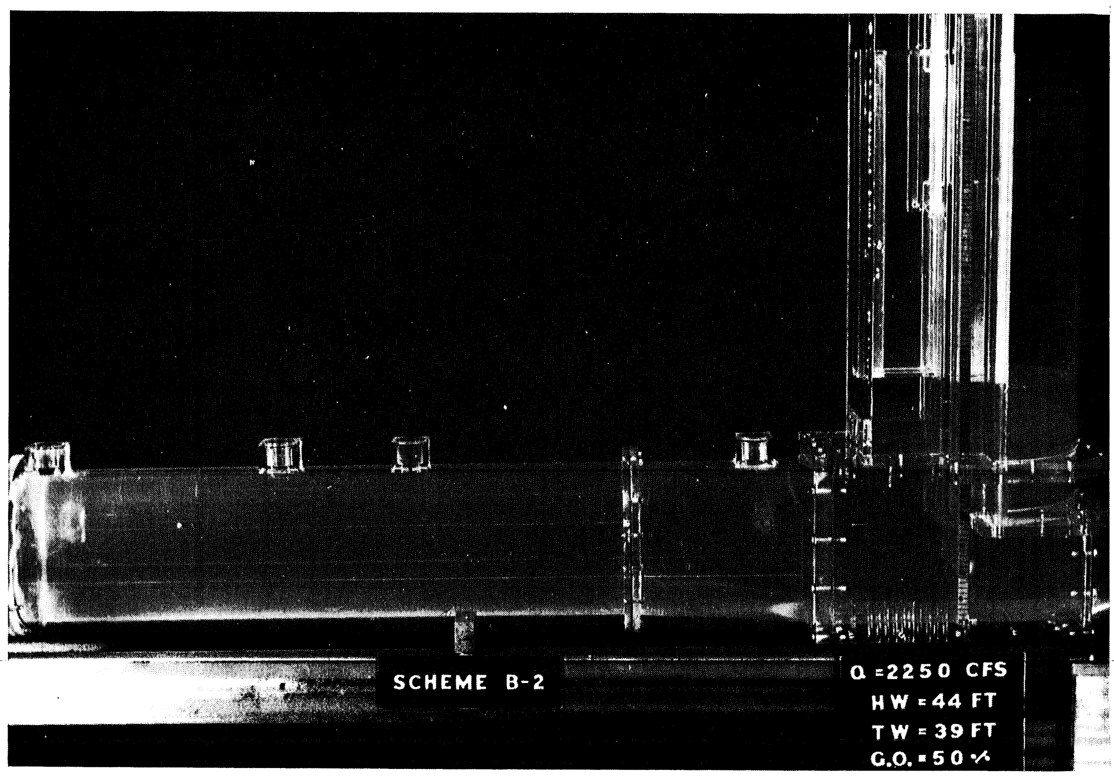


Photo 7

PHOTO 8 (Serial No. 168-97) For a discharge of 50 cfs only the center gate is open. The flow is delineated by dye streaks as it approaches the small gate opening.

PHOTO 9 (Serial No. 168-96) The flow through the gate is relatively undisturbed as demonstrated by a wedge of dye approaching the opening. Because of the construction of the flow at the gates the velocity will increase and the dye wedge will become thinner and move more rapidly as it approaches the gate. For these relatively small flows only the center gate need be opened.

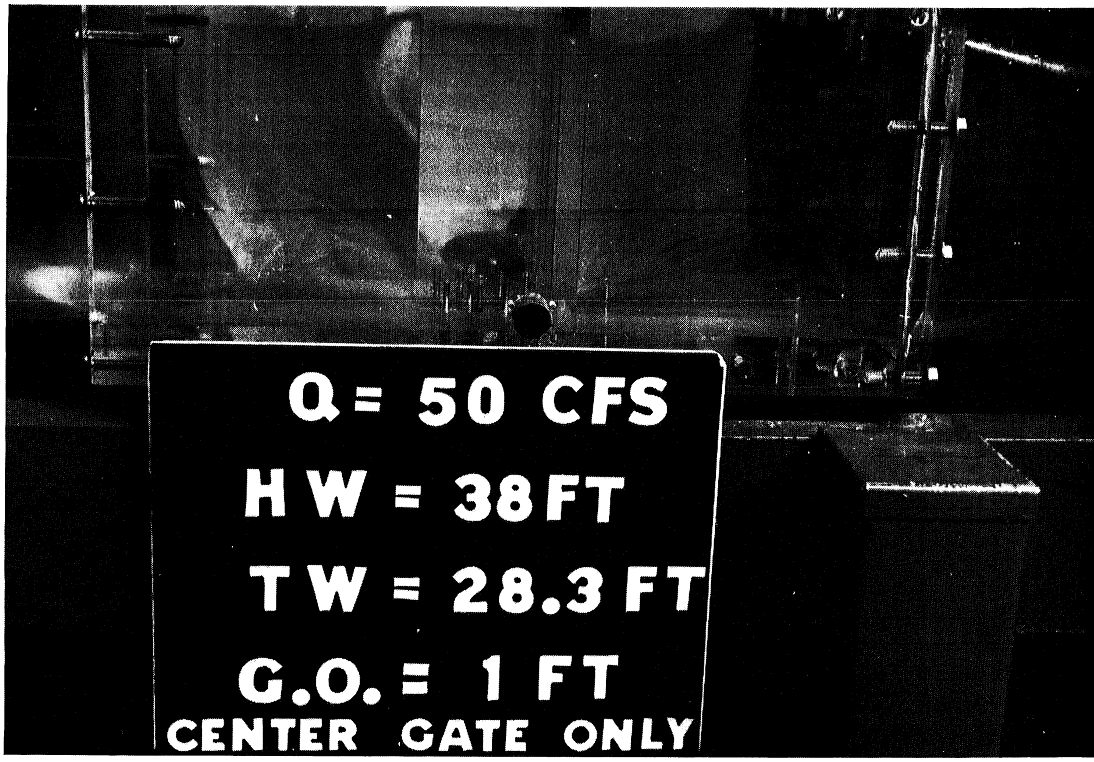


Photo 8

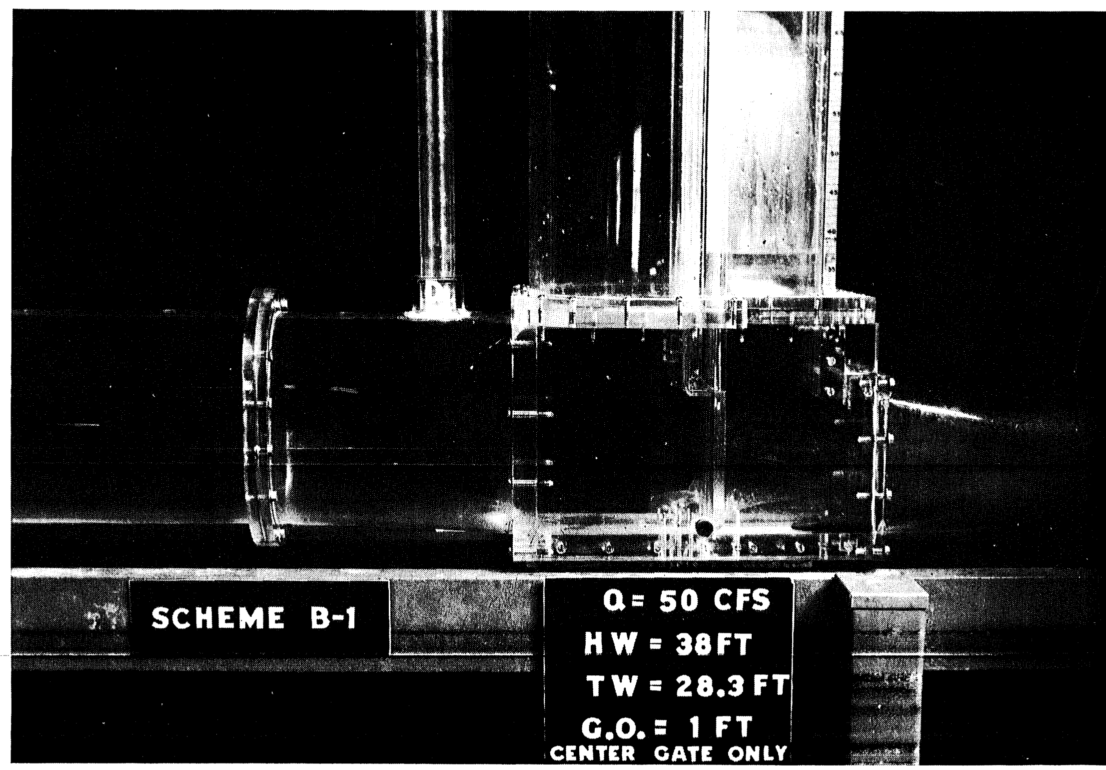


Photo 9

PHOTO 10 (Serial No. 168-46) Flow of 2250 cfs through Scheme A-2 structure when gates are wide open is a normal operating condition for which the flow is undisturbed and the head differential is about 0.5 ft (prototype).

PHOTO 11 (Serial No. 168-41) In this photograph of a discharge of 2250 cfs in Scheme A-2 the gates are completely closed and the flow is forced over the emergency weirs. Much air is entrained and collected in the air collector to move upstream to the gate shaft.

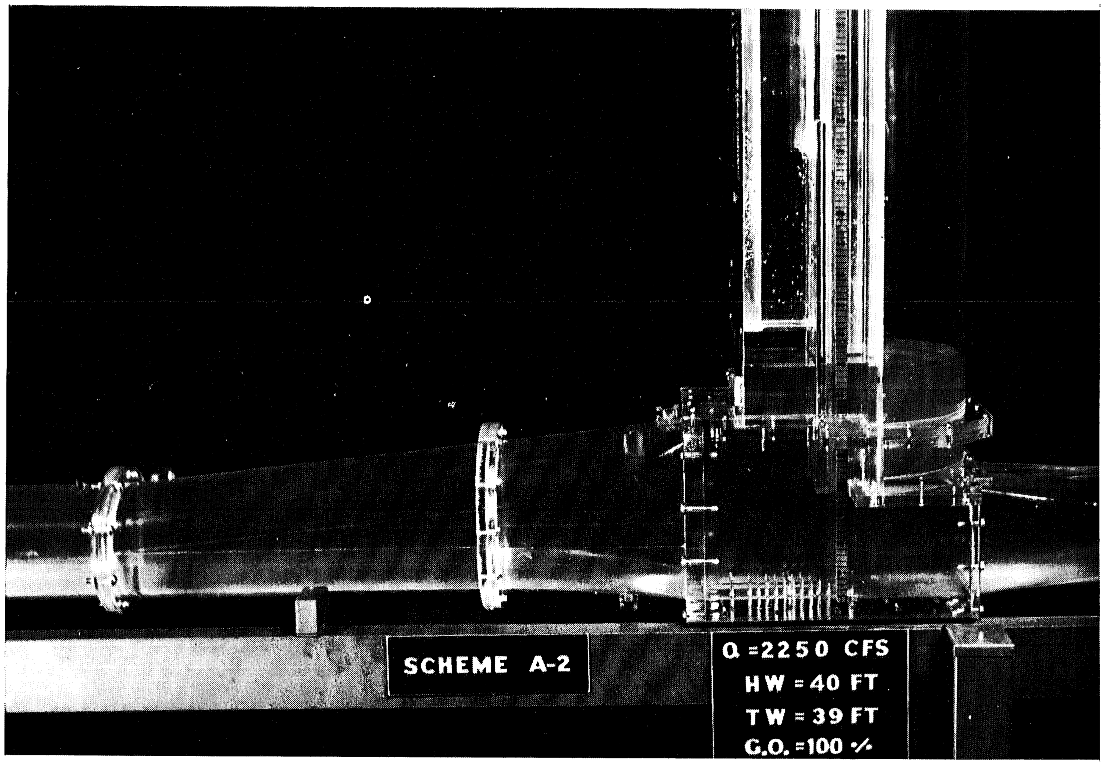


Photo 10

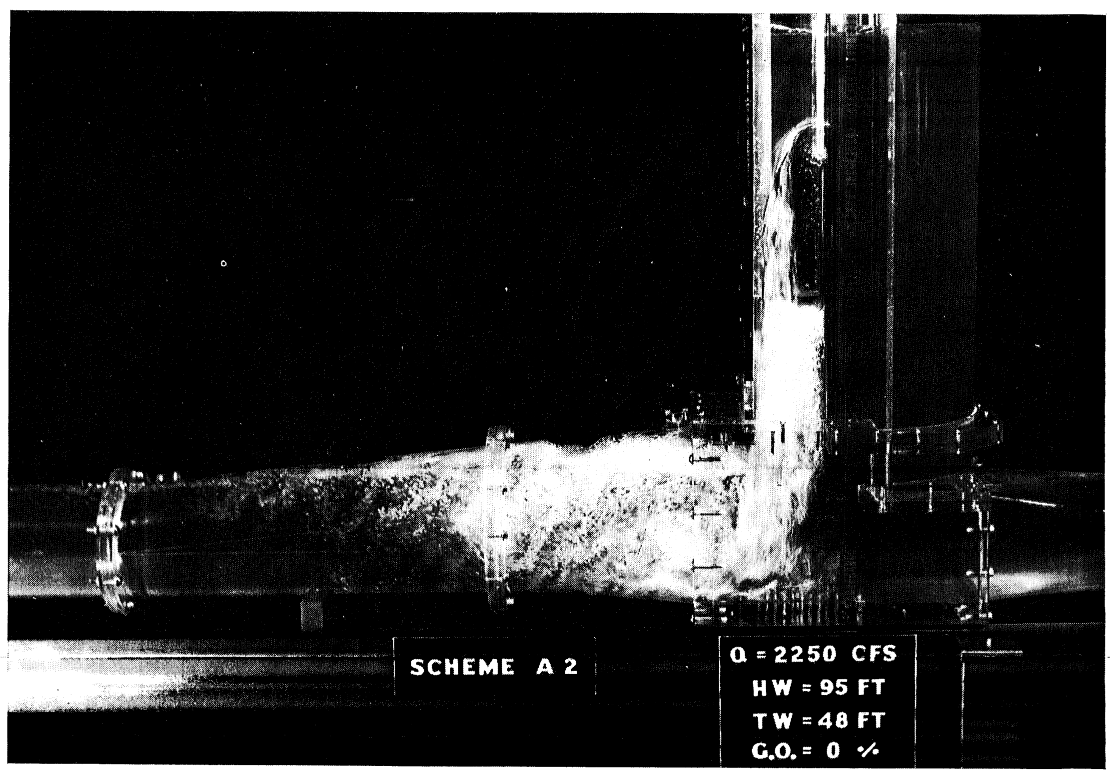


Photo 11

PHOTO 12 (Serial No. 168-12) View of Scheme B-1 with gates open and flow of 2250 cfs.

PHOTO 13 (Serial No. 168-11) View of Scheme B-1 with gates closed and emergency flow of 2250 cfs over weir. T.W. = 48 ft, H.W. = 93 ft.

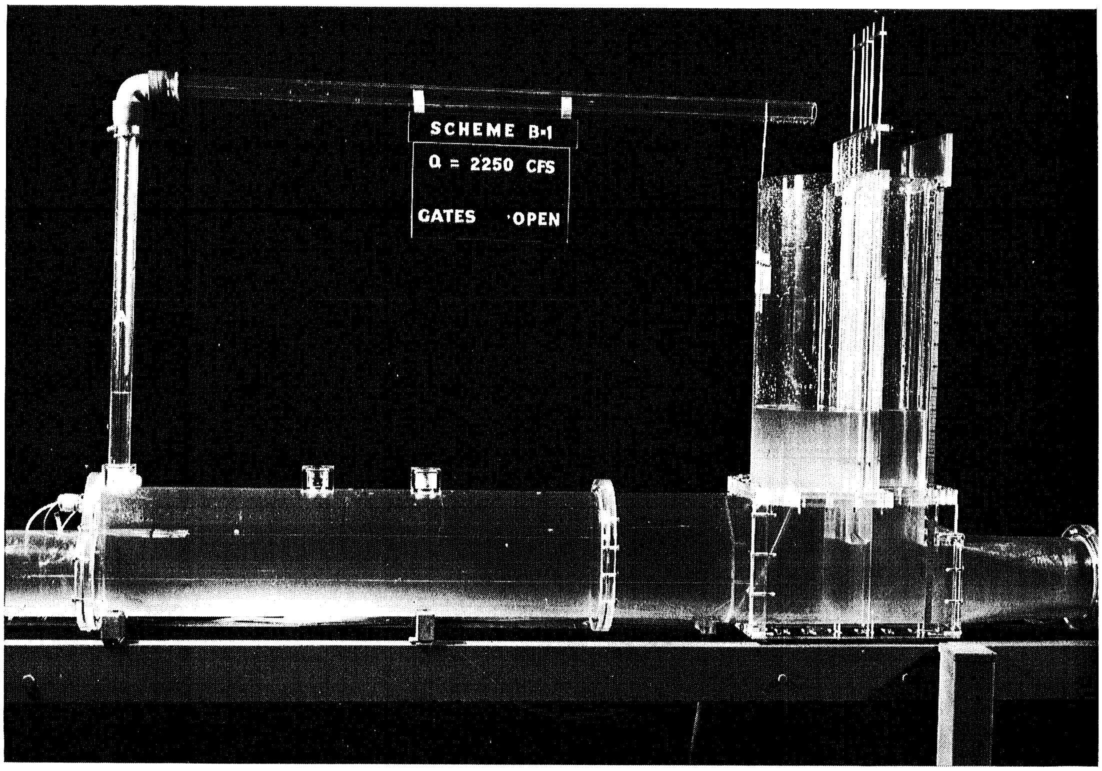


Photo 12

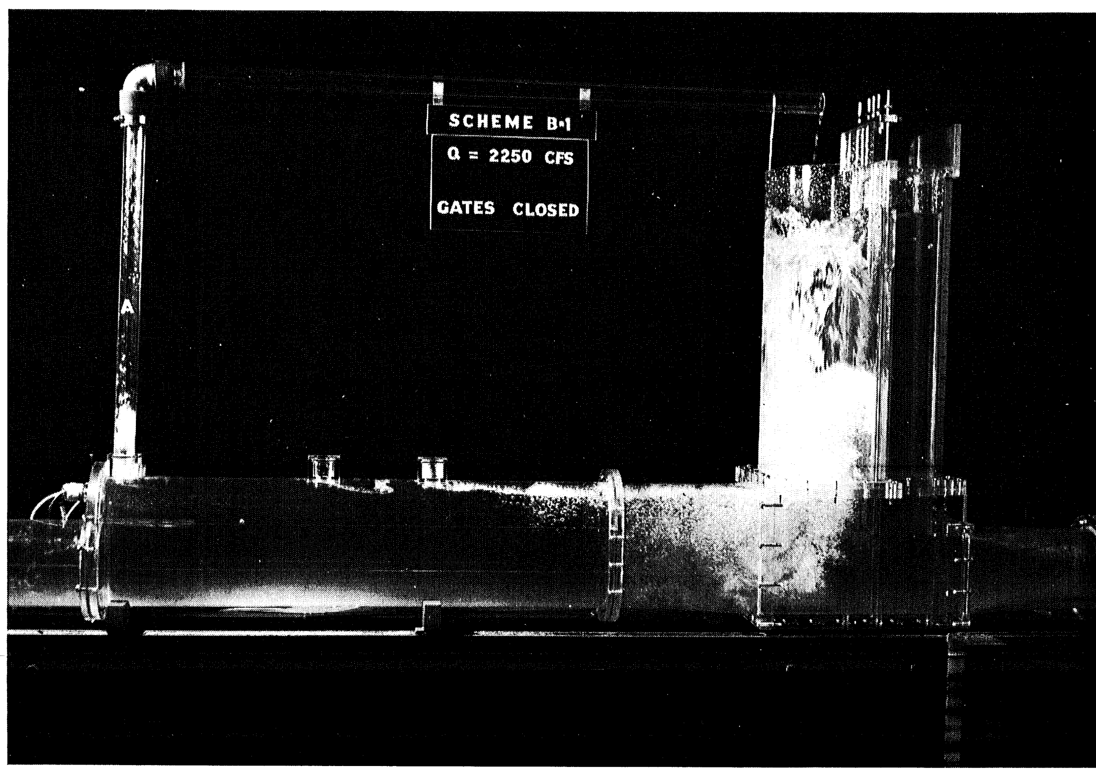


Photo 13

PHOTO 14 (Serial No. 168-6) Downstream end of A-1 air removal chamber showing air being carried into tunnel. T.W. = 48 ft.

PHOTO 15 (Serial No. 168-55) View of junction of the air collector with downstream tunnel. Discharge of 2250 cfs over the emergency weir entraining maximum amount of air. The released air is collected at the crown in a large bubble which moves downstream to the air vent. No air enters the downstream tunnel.

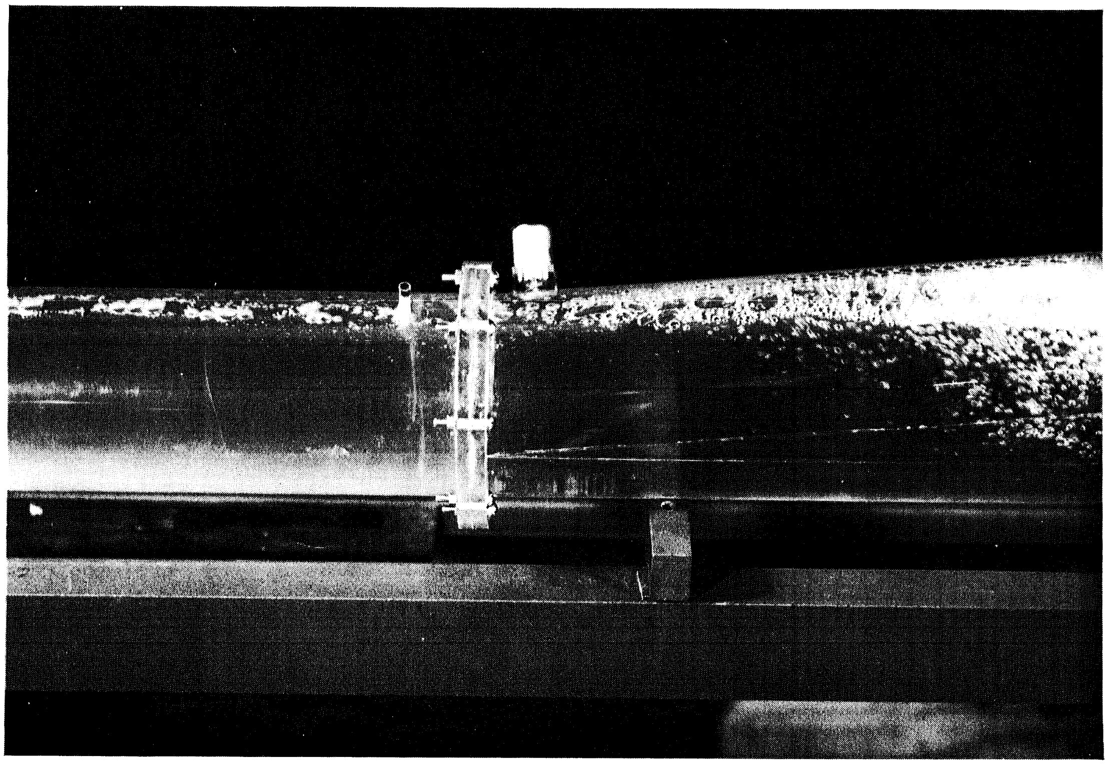


Photo 14

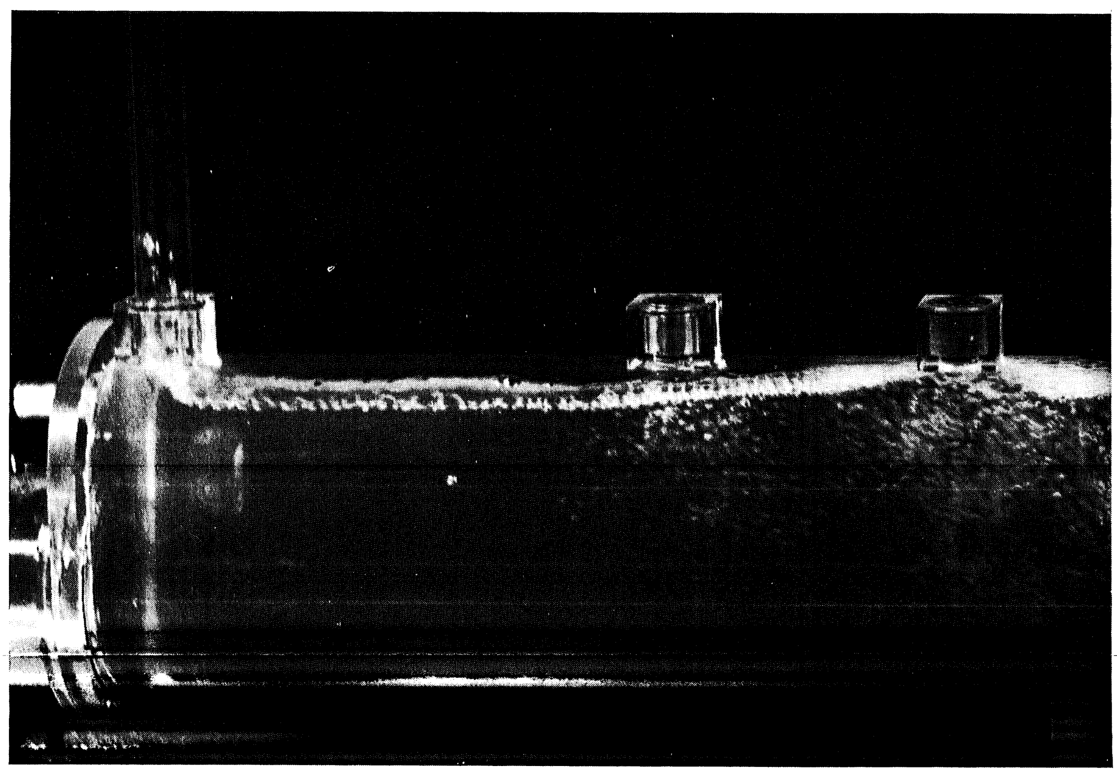


Photo 15

PHOTO 16 (Serial No. 168-94) Hydraulic jump will form in the tunnel if the tailwater is reduced below a minimum of about 21 ft. If the jump forms in the tunnel, air will be released to be carried downstream.

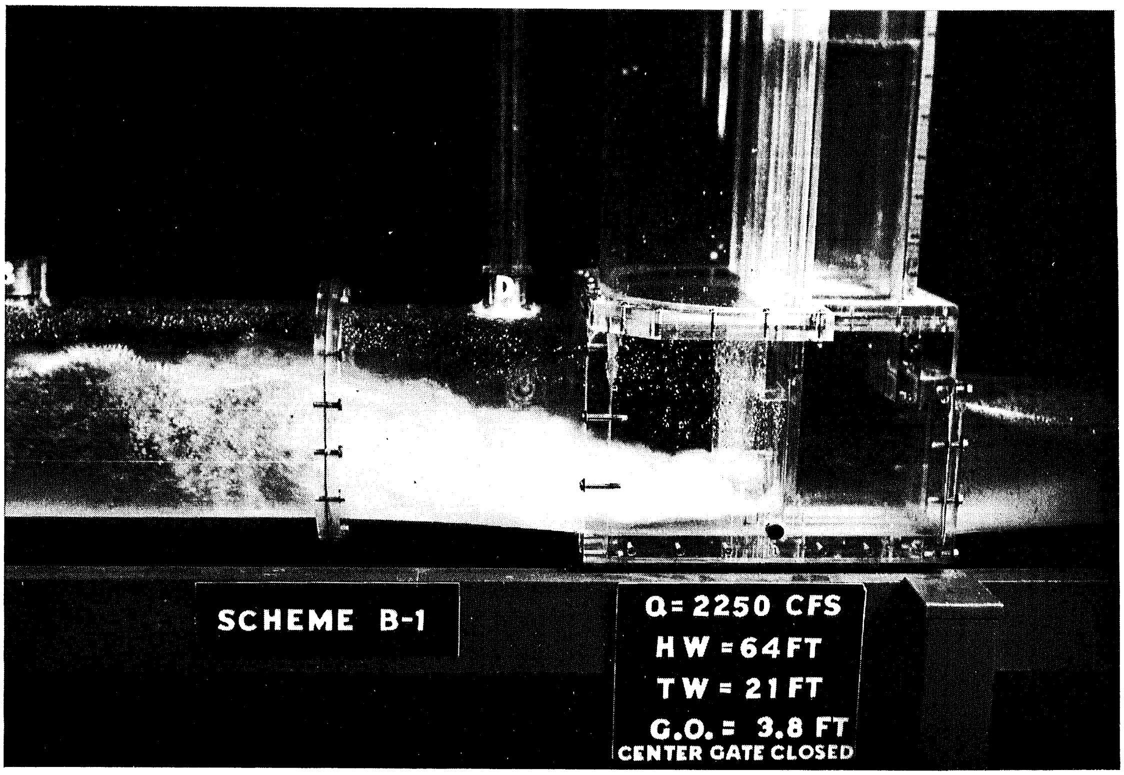

SCHEME B-1
Q= 2250 CFS
HW = 64 FT
TW = 21 FT
G.O. = 3.8 FT
CENTER GATE CLOSED

Photo 16

PHOTO 17 (Serial No. 168-11) Scheme B-1 with air vent at downstream end of air collector. Maximum pressure pulses were largest with the vent in this position. Photo shows the collector full after release of collected air.

PHOTO 18 (Serial No. 168-10) Scheme B-1 with air vent at one-third point of air collector. Gates were closed and tailwater elevation 48 ft. Pressure pulses were reduced to about two-thirds of values obtained with vent at downstream end of collector.

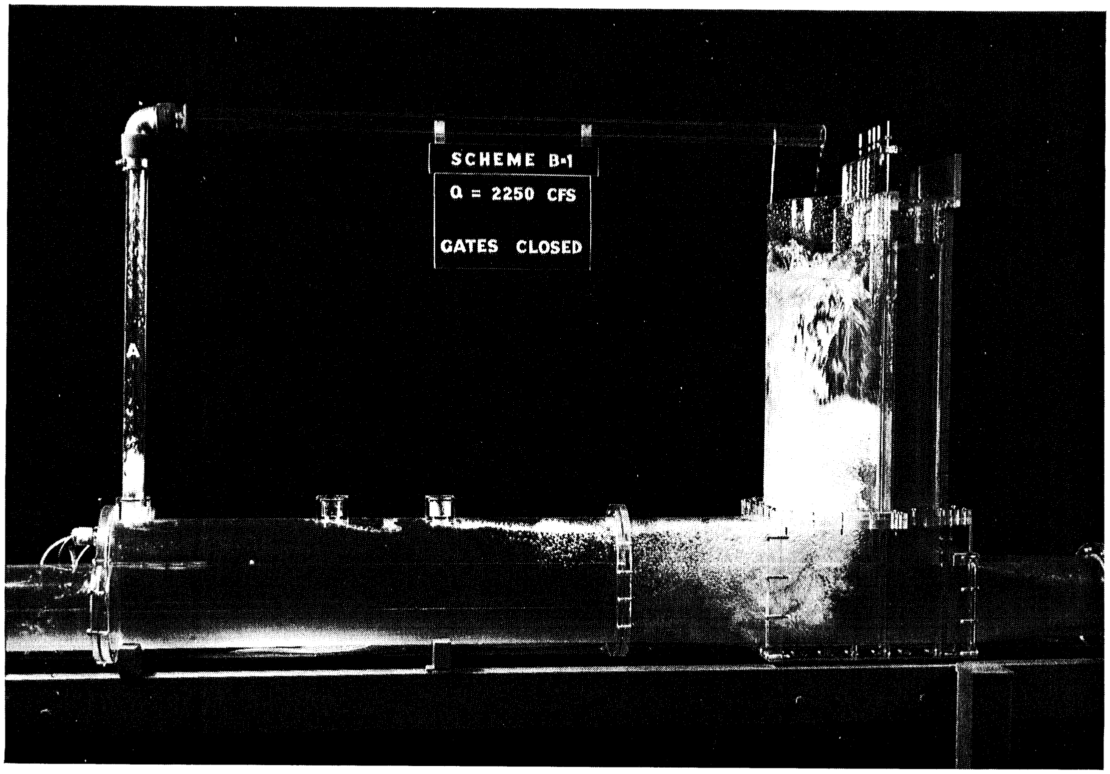


Photo 17

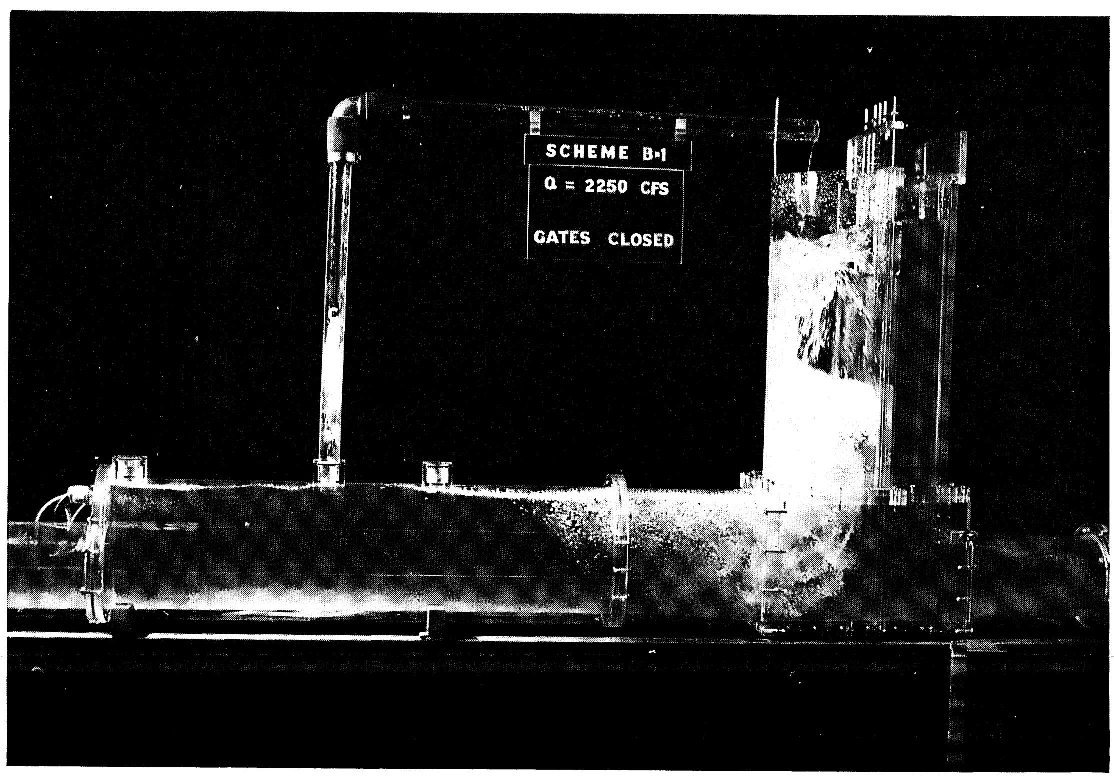


Photo 18

PHOTO 19 (Serial No. 168-9) Scheme B-1 with air vent at midpoint of air collector. The results were similar to those for one-third point shown in Photo 18.

PHOTO 20 (Serial No. 168-16) Scheme B-1 with air vent near gate shaft. The pressure pulses were a minimum at this point and air was more continuously released as it rose to the surface.

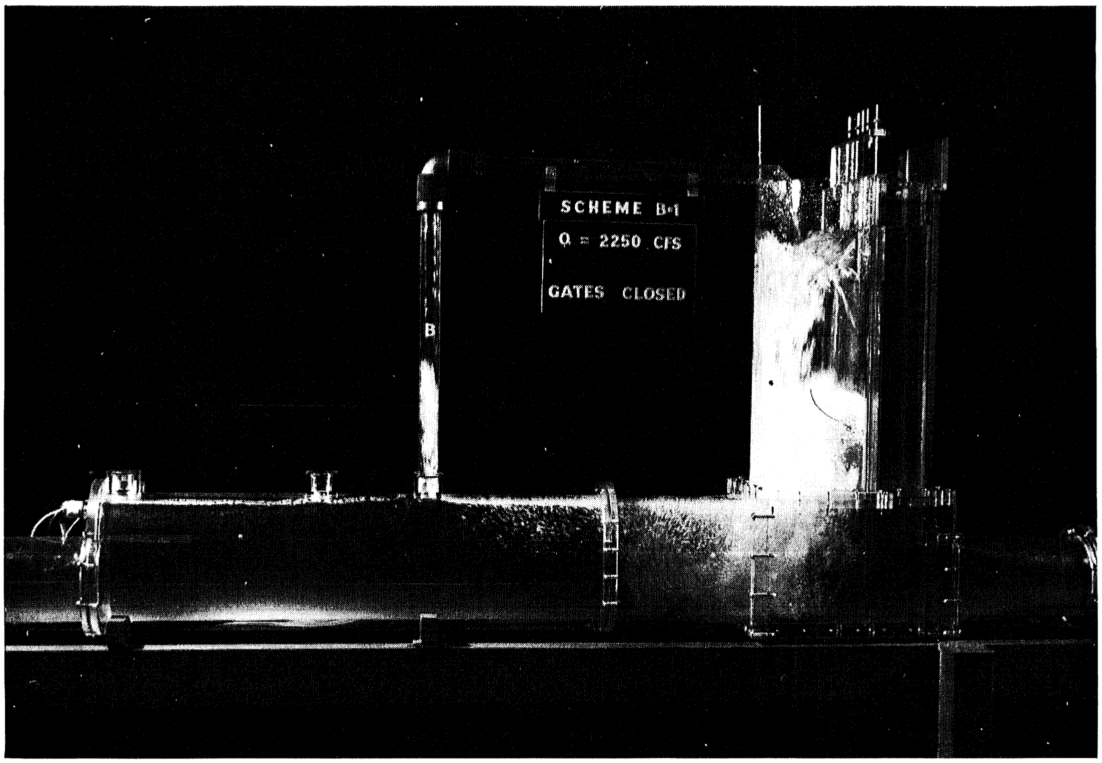


Photo 19

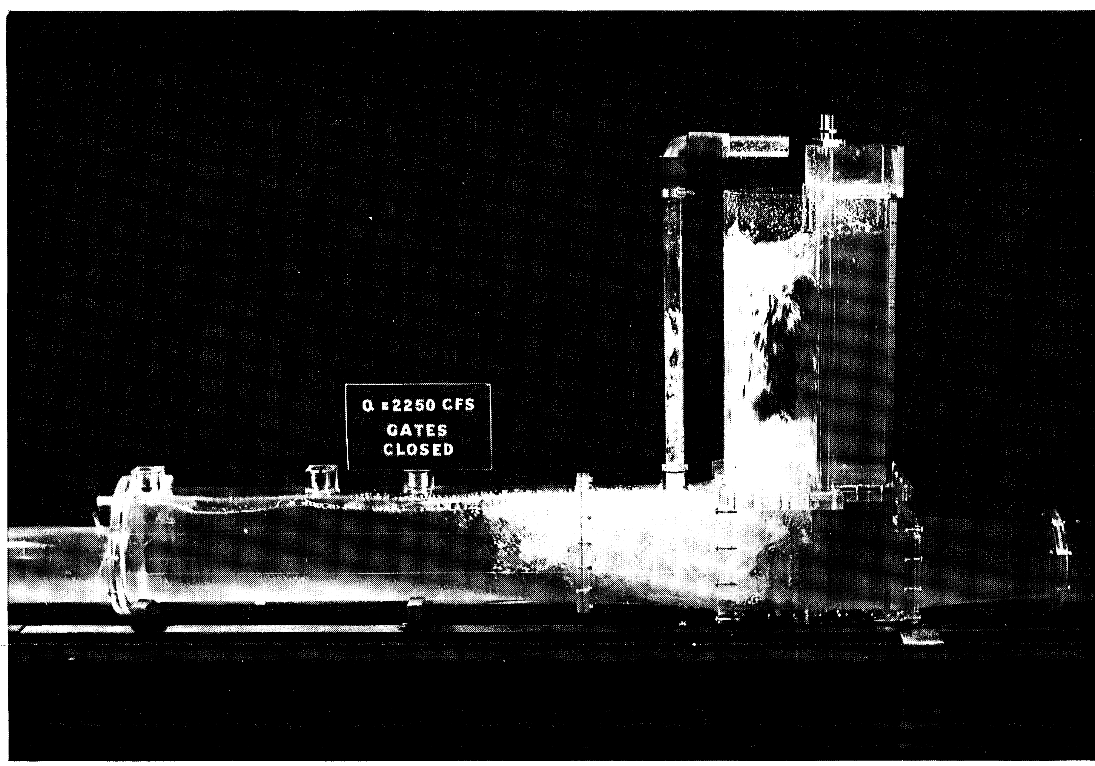


Photo 20

PHOTO 21 (Serial No. 168-29) In this photograph the vent pipe in the gate tower is fully opened to an area 9 sq ft. The relatively free movement of air and water in the vent pipe gives rise to a considerable surging in the air collector downstream of the vent plate. The photograph shows the surging water in the air collector at the moment that the vent area downstream of the plate is completely closed. The tailwater is 48 ft above the invert.

PHOTO 22 (Serial No. 168-30) This photograph is the same as Photo 21 taken at a time that the surge was at the downstream end of the air collector. At this point the vent is almost completely open so that air can escape from the collector. The surging back and forth of the water under these circumstances causes rather large pressure surges in the tunnel proper.

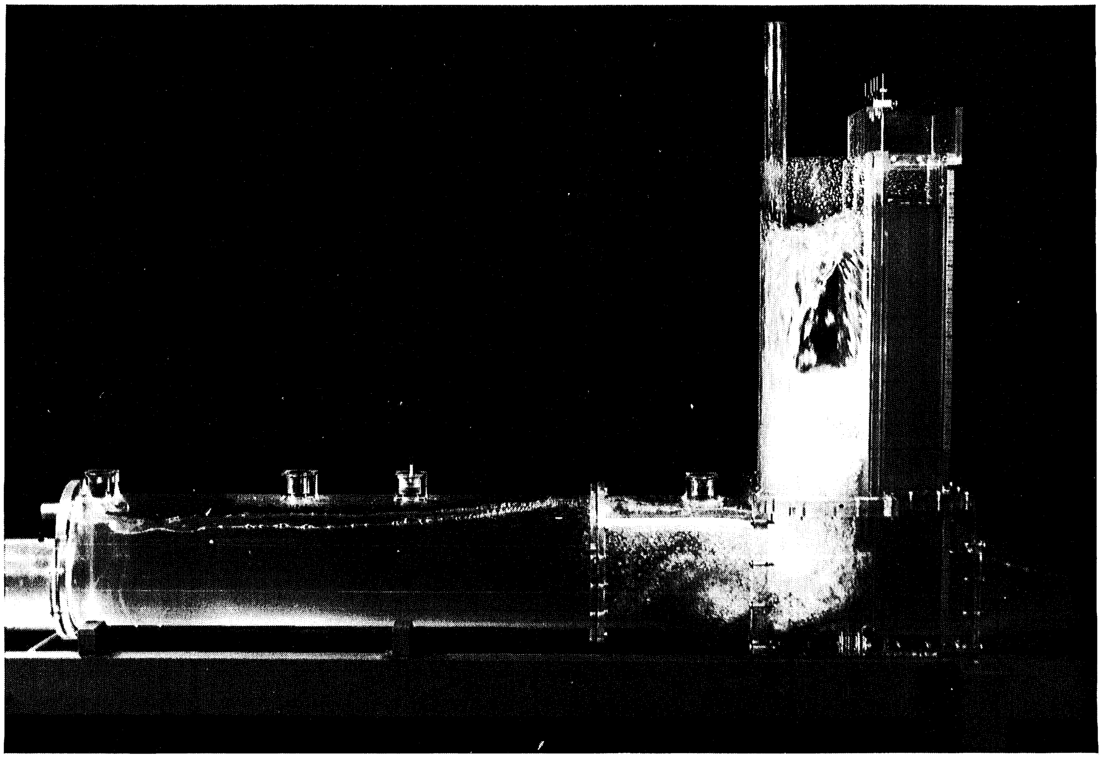


Photo 21

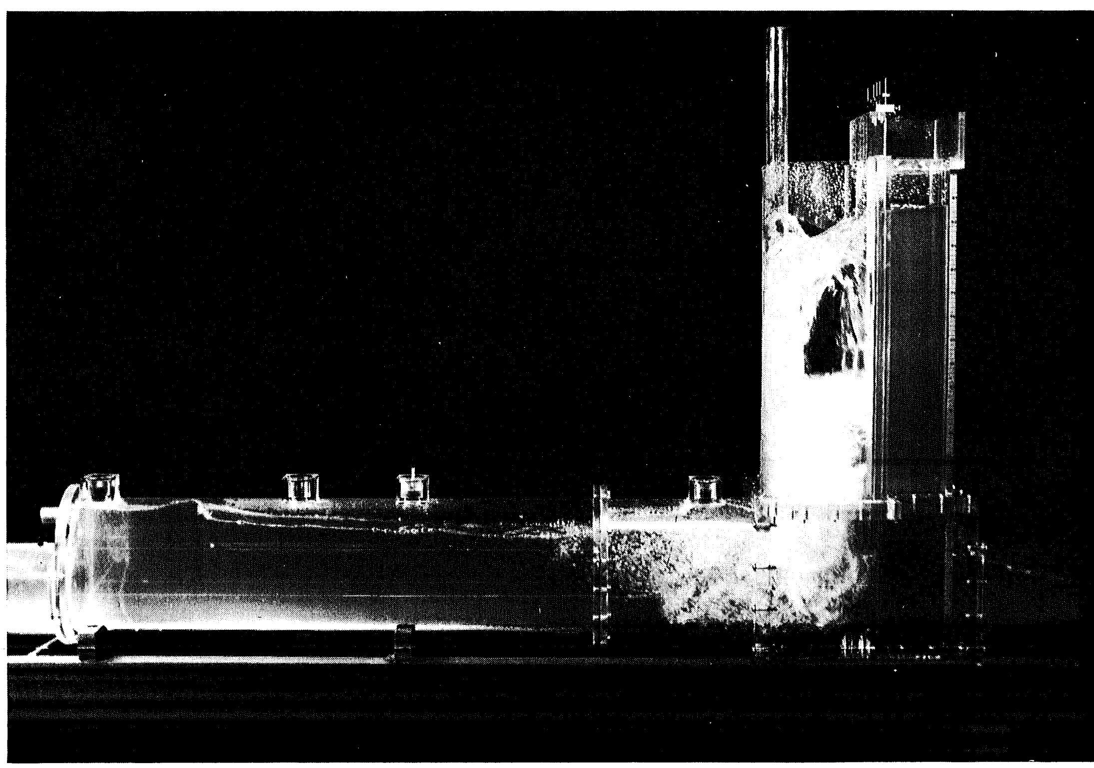


Photo 22

PHOTO 23 (Serial No. 168-33) As a result of the previous experiments with the revised vent, the vent plate has been increased to 50 ft downstream of the gate structure and the pipe in the gate structure has been increased in size to 31 sq ft. The photograph shows a discharge of 2250 cfs over the emergency weirs with the tailwater 33 ft above the invert and the vent area completely opened. This method appeared to work well with less turbulence and pressure fluctuations than were observed in the previous photos.

PHOTO 24 (Serial No. 168-36) In this photograph the vent area was completely closed at exit. The increased pressure in the air collector and the increased volume of air collected before it can get back through the gate structure forces the water surface nearly down to the crown of the tunnel proper. In the photograph the air pocket has increased to approximately 7 ft below the crown of the air collector. The increased pressure due to the closed vent has the effect of smoothing out the pressure fluctuations and dampening the surges somewhat. It is apparent that for this arrangement some type of venting system is necessary.

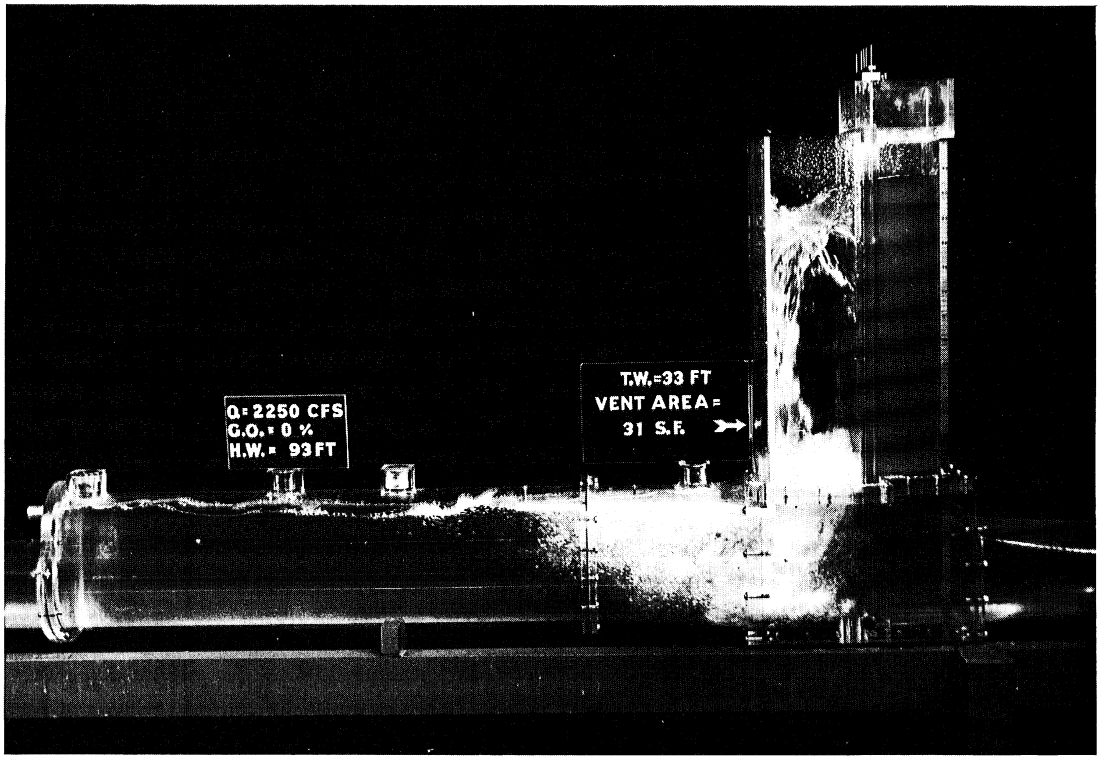


Photo 23

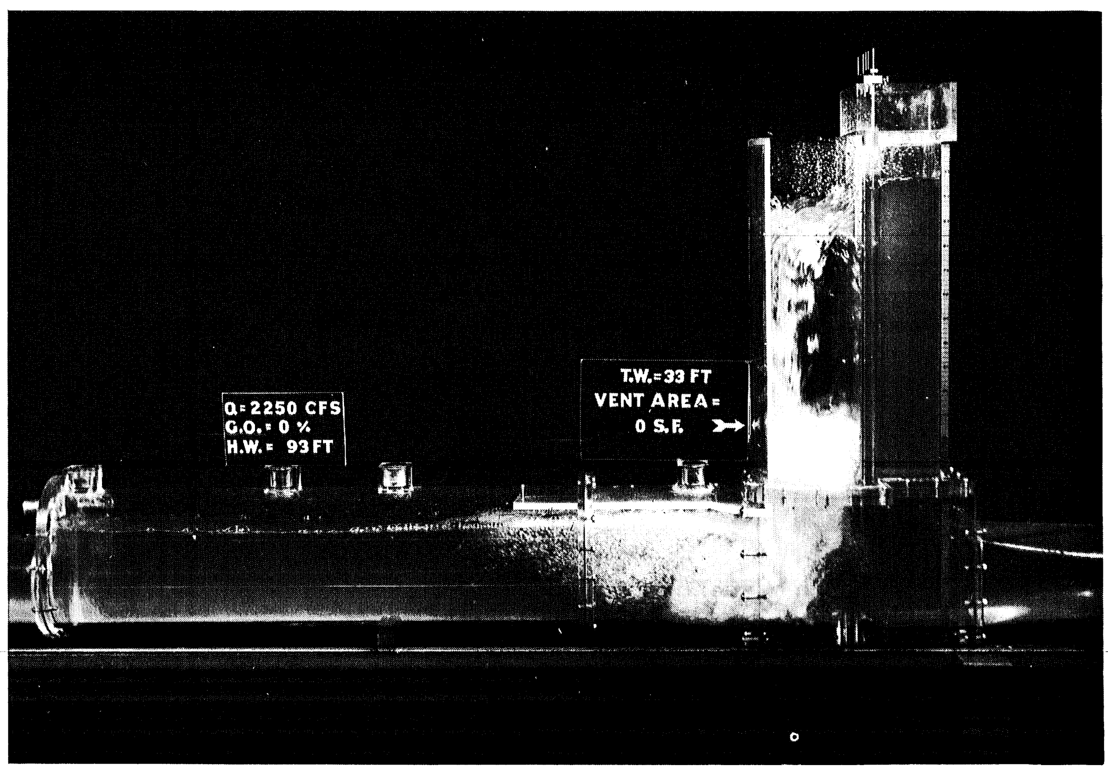


Photo 24

PHOTO 25 (Serial No. 168-65) The jets from the weirs begin to spread out before they impinge on the far side of the drop shaft. The flow then drops straight down into the downstream pool, generating surges of considerable magnitude as well as entraining much air.

PHOTO 26 (Serial No. 168-20) This photograph from the side shows the jets impinging on the side of the drop shaft and plunging into the downstream tunnel. A large amount of air is entrained by the flow. After impinging on the downstream side of the drop shaft, the water falls as a heavy curtain along the wall into the downstream pool. This curtain not only entrains the air but is rather effective in preventing the air in the collecting section from escaping up the shaft.

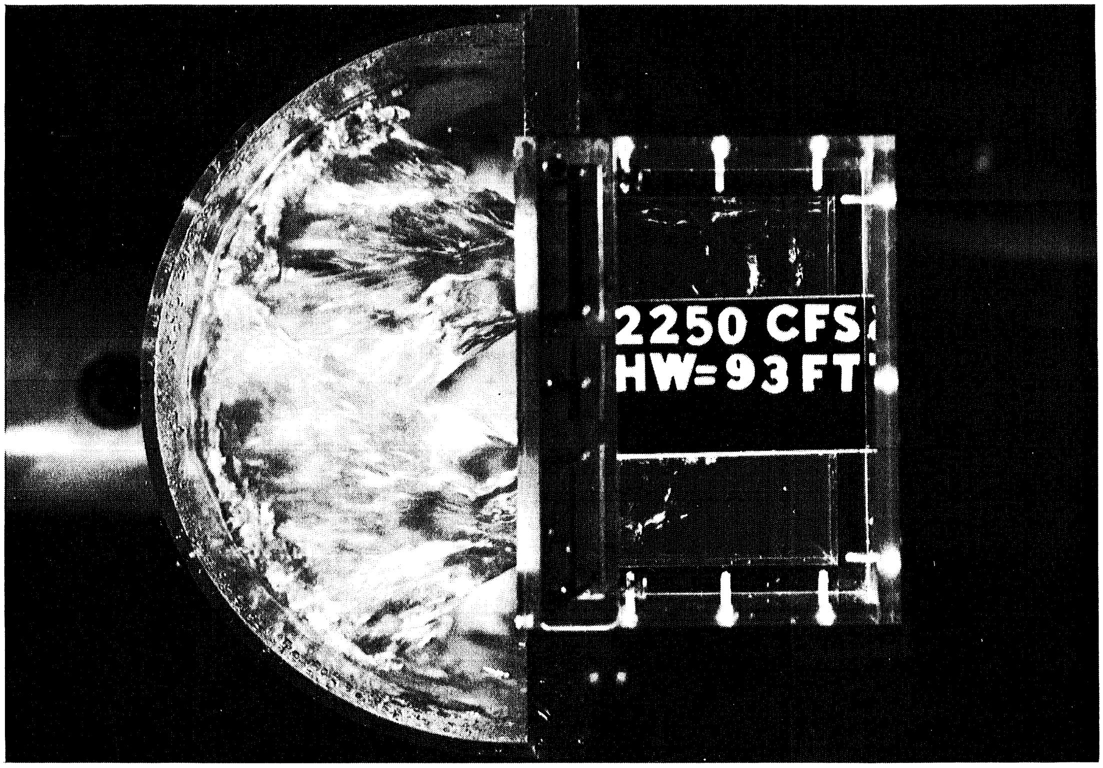


Photo 25

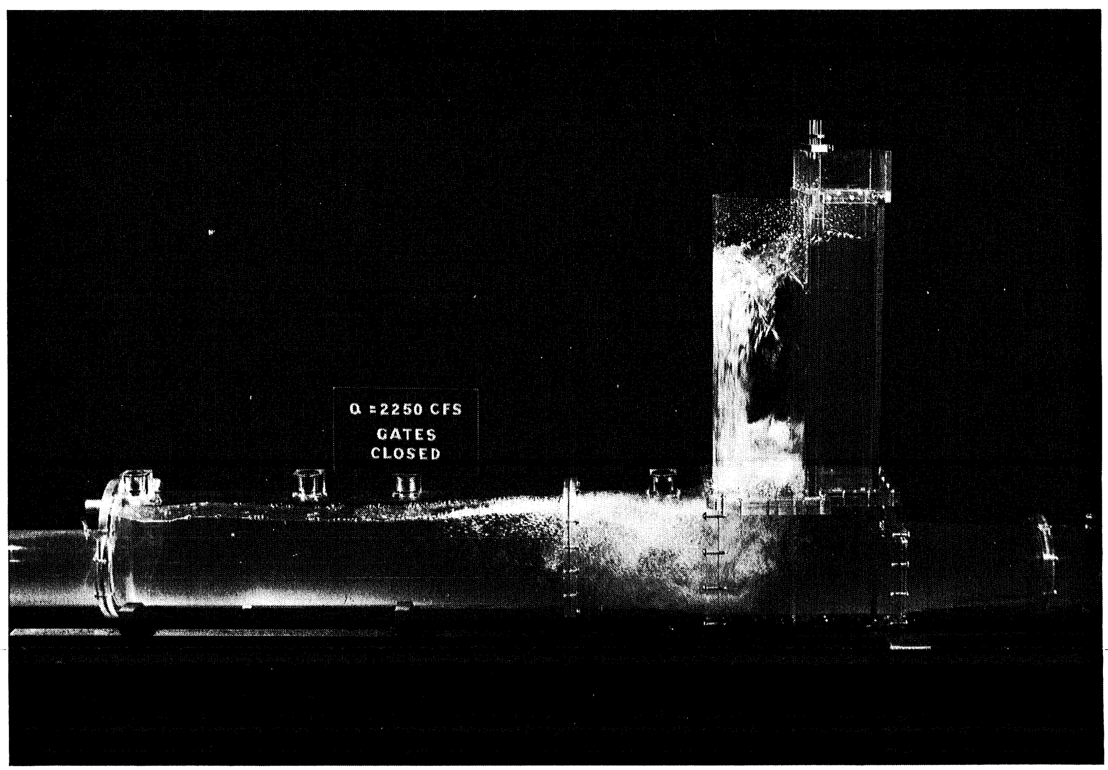


Photo 26

PHOTO 27 (Serial No. 168-63) As a final effort, curved vanes were installed to deflect the flow 90° from its initial direction. The flow pattern is shown in this photograph.

PHOTO 28 (Serial No. 168-64) The 90° curved deflector is still more effective in reducing the amount of air entrained and in spreading the flow around the entire periphery of the drop structure.

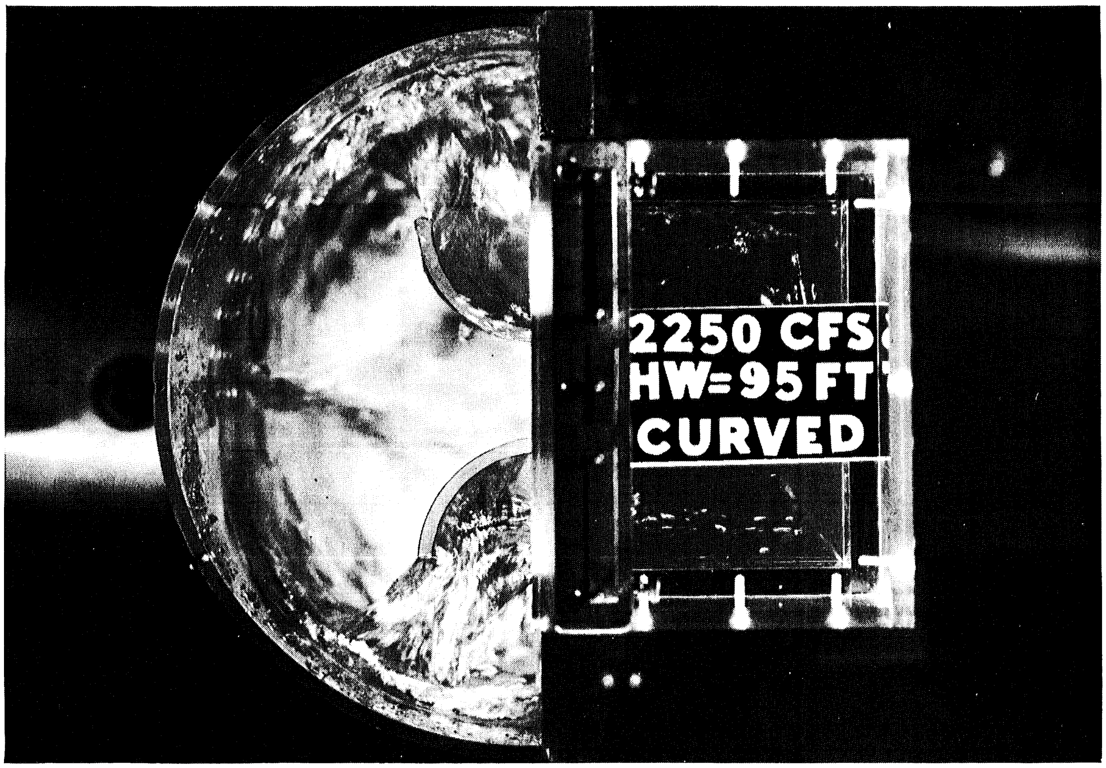


Photo 27

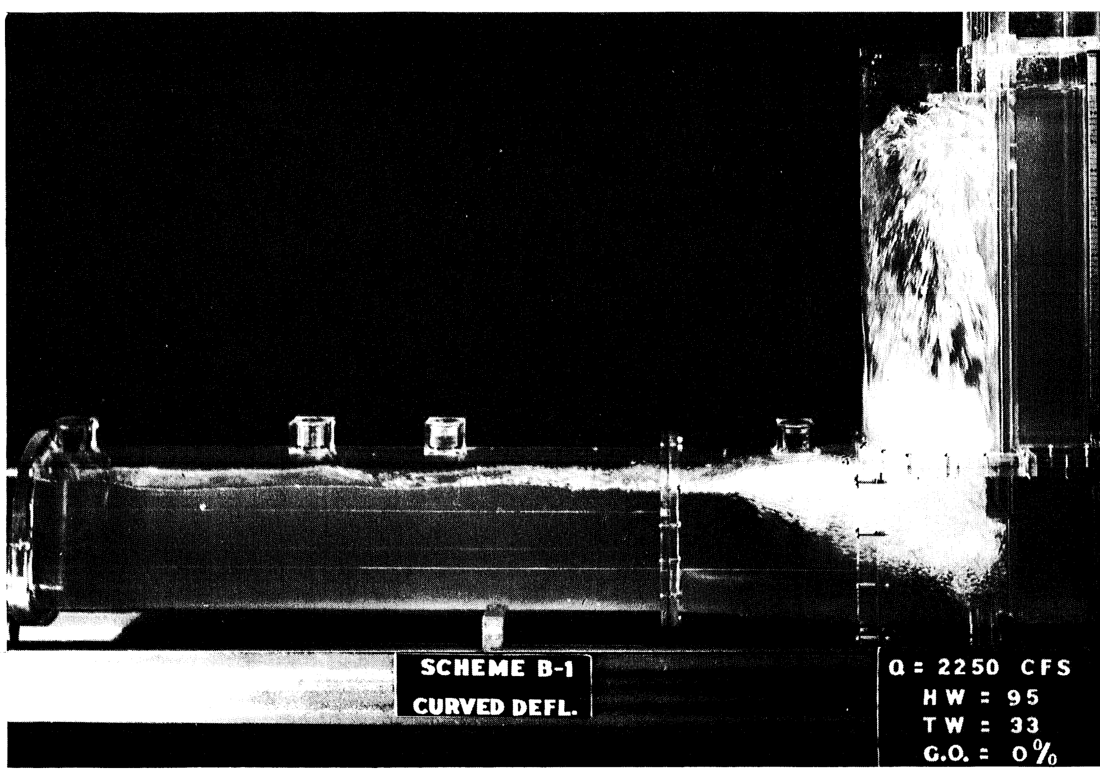


Photo 28

PHOTO 29 (Serial No. 168-73) In order to reduce the surging in the control structure due to flow over the weirs, deflectors were installed in the drop shaft to assist in the dissipation of energy of the jets. These deflectors reduced both the amplitude of the surges and the amount of air entrained.

PHOTO 30 (Serial No. 168-72) For smaller discharges, the degree of submergence of the weir is reduced and the jets striking the deflectors are more clearly defined. In this photograph, the amount of air entrained in the tunnel appears to be more than that entrained for the maximum discharge.

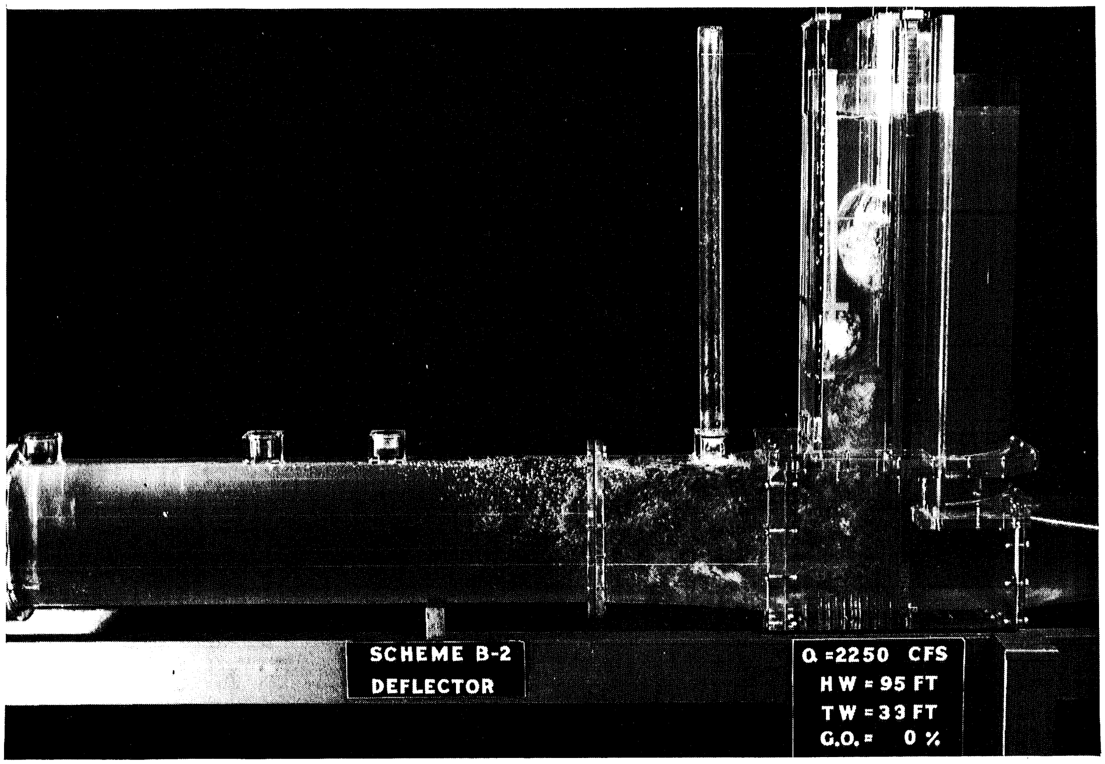


Photo 29

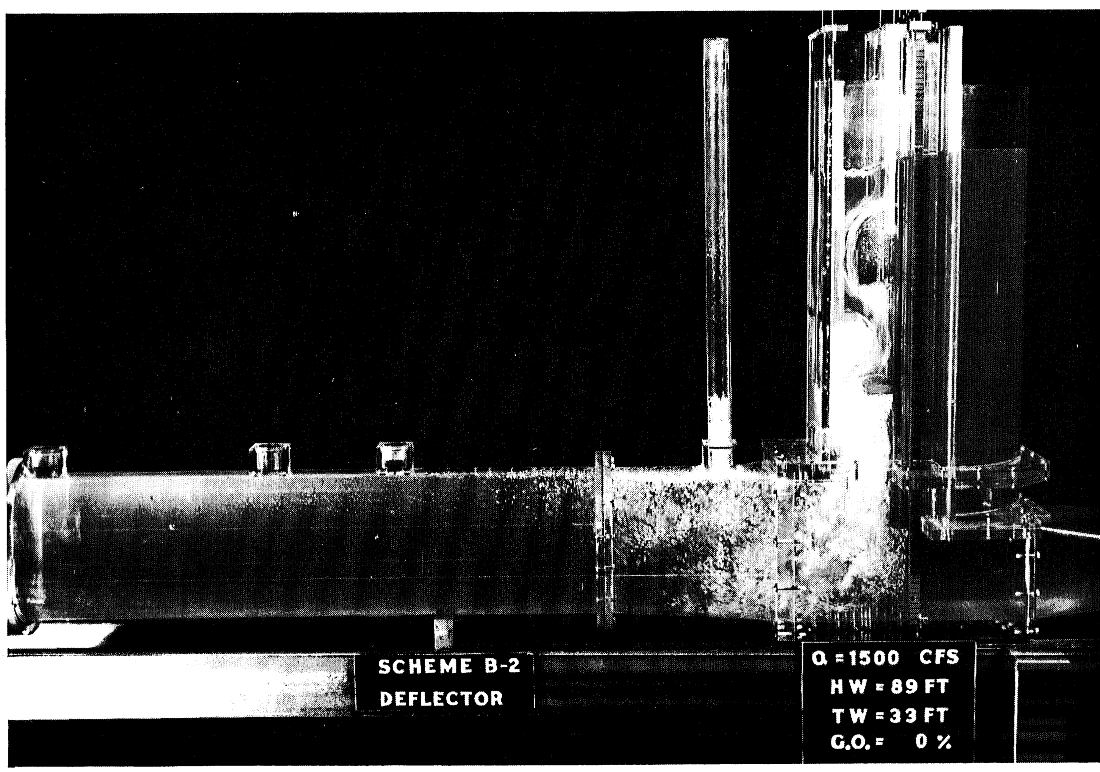


Photo 30

PHOTO 31 (Serial No. 168-79) When the vent area is increased to 9 sq ft, extensive surging exists in the drop structure. This photo shows surging in the drop shaft between the two arrows. This photo was taken when the surge was at the top of its motion. The photograph also shows the surging occurring in the vent pipe at the same time.

PHOTO 32 (Serial No. 168-80) This photograph is similar to Photo 9 except that it was taken at the moment when the surge was at its lowest point in the drop shaft as well as in the vent pipe. The range of surging occurring in this test is shown by the arrows attached to the drop shaft.

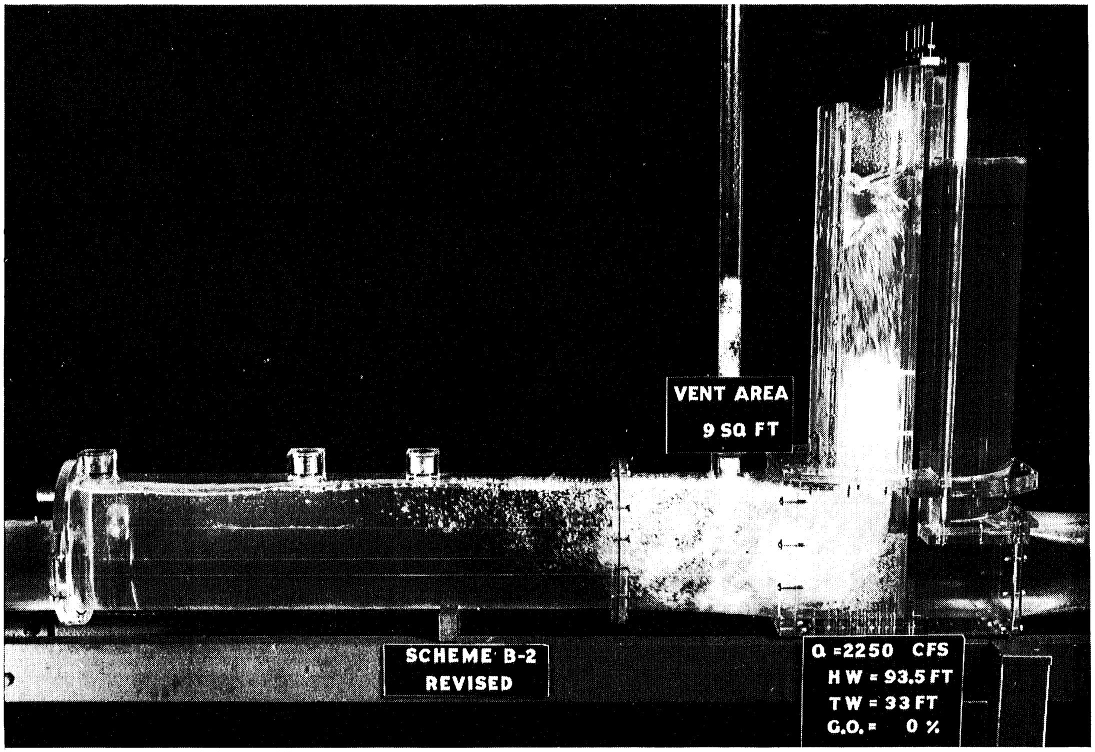


Photo 31

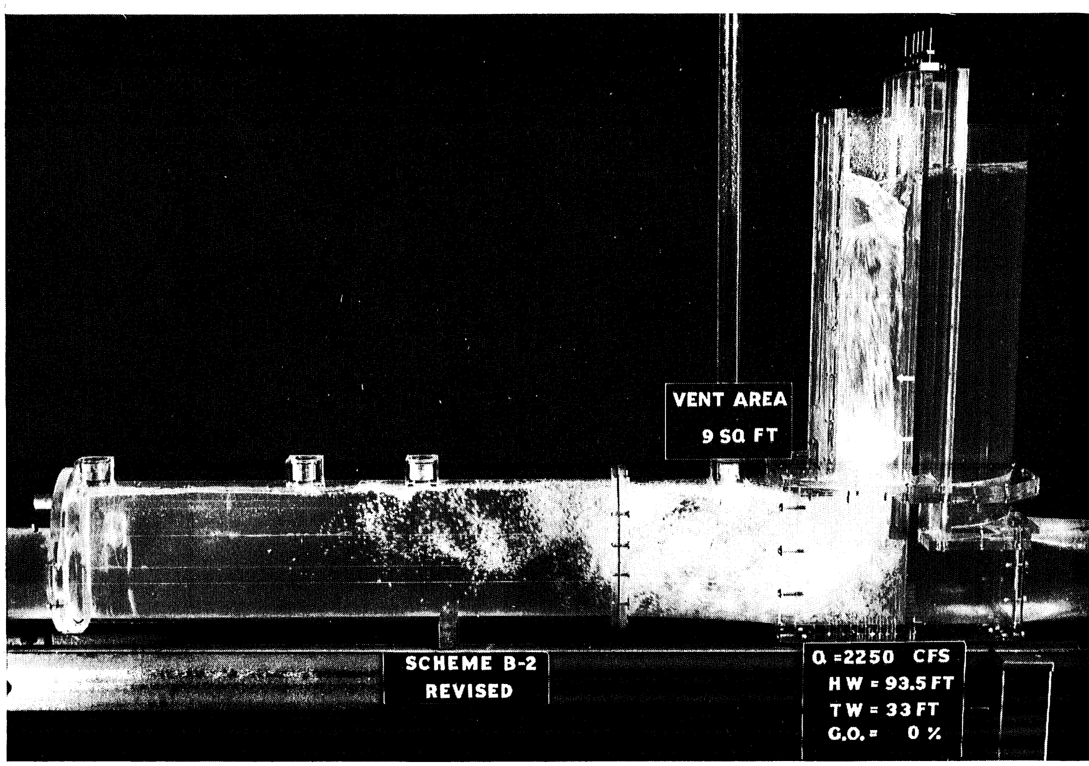


Photo 32

LIST OF CHARTS

CHART 33 (168B459-51) Maximum pressure pulse in terms of orifice size for tailwater elevations of 33 ft and 48 ft above invert for B-1 structure.

CHART 34 (168B459-64) Fluctuating pressure near air vent for B-2 structure for various orifice sizes with tailwater elevation 33 ft above invert.

CHART 35 (168B459-65) Fluctuating pressures near air vent for B-2 structure for various orifice sizes with tailwater elevation 48 ft above invert.

CHART 36 (168B459-66) Maximum pressure pulse in terms of orifice size for tailwater elevations of 33 ft and 48 ft for B-2 structure.

CHART 37 (168B459-36) Comparison of pressure fluctuations in air collector and in downstream segment of tunnel showing transmittal of pressure pulses through tunnel.

CHART 38 (168B459-80) Comparison of pressure fluctuations measured at downstream end of air collector for various positions of air vent, Q = 2250 cfs, T.W. = 48 ft, gates closed.

CHART 39 (168B459-81) Comparison of pressure fluctuations measured at downstream end of air collector for various positions of air vent, Q = 2250 cfs, T.W. = 33 ft, gates closed.

CHART 40 (168B459-67) Dynamic pressure fluctuations in air removal chamber of B-1 structure. Revised vent system along crown and up gate structure. Q = 2250 cfs, downstream submergence 33 ft above invert.

CHART 41 (168B459-68) Dynamic pressure fluctuations in air removal chamber of B-1 structure. Revised vent system along crown and up gate structure. Q = 2250 cfs, downstream submergence 48 ft above invert.

CHART 42 (168B459-59) Dynamic pressure fluctuations in air removal chamber of B-1 structure. Revised vent system along crown and up gate structure showing effect of size of vent on air pressure fluctuations. Q = 2250 cfs, downstream submergence 33 ft and 48 ft above invert.

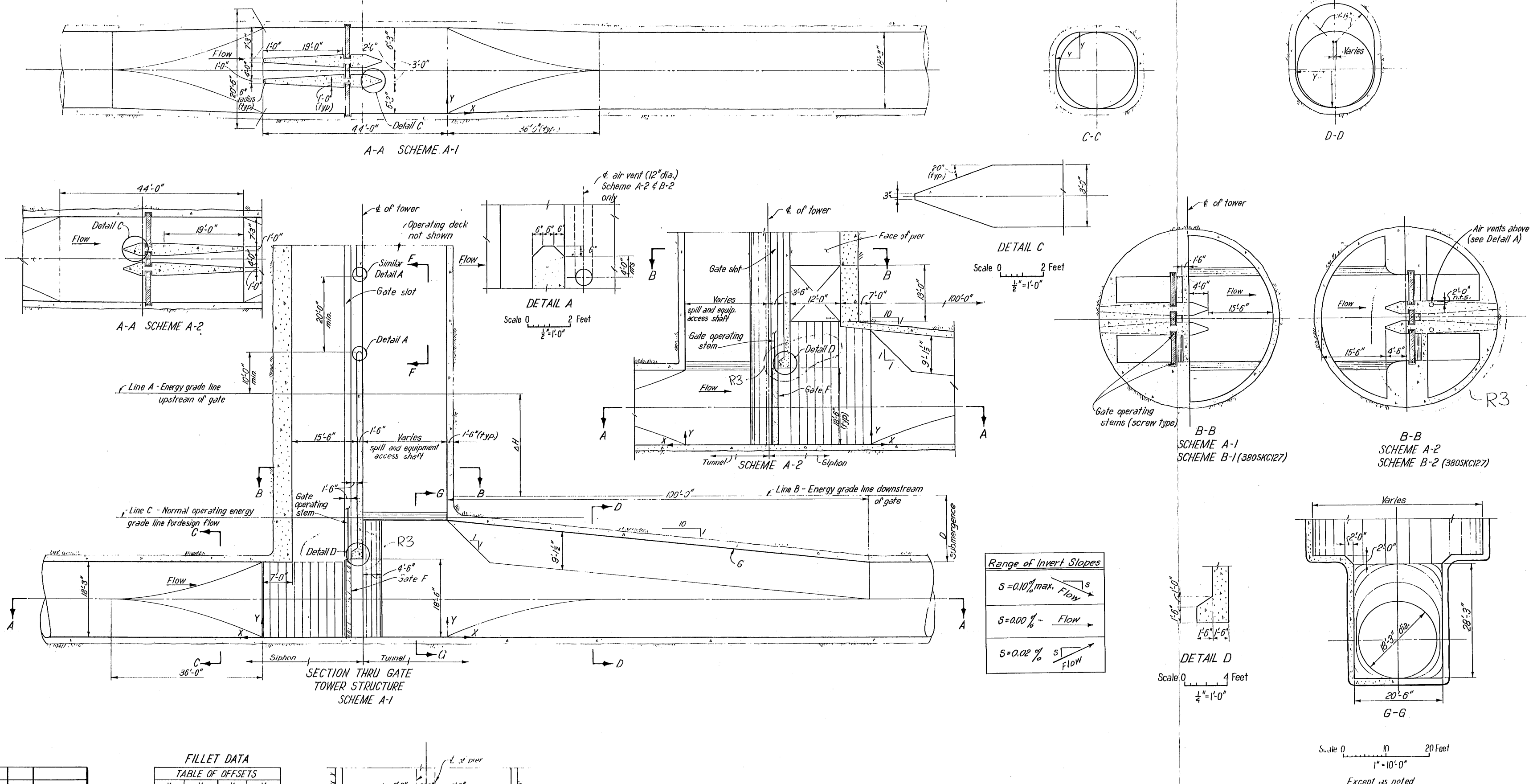
CHART 43 (168B459-41) Magnitude and distribution of pressures on gate shaft wall due to jet issuing from emergency weirs.

CHART 44 (168B459-75) Comparison of surging by discharge from the overflow weir of structure B-1 for various discharges and gate openings.

CHART 45 (168B459-76) Comparison of surging by discharge over overflow weir in structure B-1 with 90° deflector installed for various discharges and gate openings.

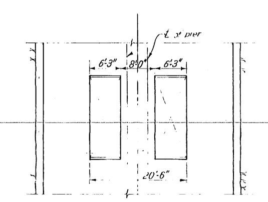
CHART 46 (168B459-79) Comparison of the surges generated in the B-2 structure with and without deflectors in the drop shaft for various discharges and downstream submergence.

CHART 47 (168B459-88) Transient and average pressures in revised B-2 structure with a vent area of 0.5 sq ft for various discharges.



FILLET DATA

TABLE OF OFFSETS			
X	Y	X	Y
0	0	20	6.96
2	1.09	22	7.415
4	1.98	24	7.82
6	2.75	[illegible]	8.175
8	3.45	28	8.48
10	4.12	30	8.75
12	4.735	32	[illegible]
14	5.32	34	9.04
16	5.90	36	[illegible]
18	6.45		



F-F

NOTES:
Work this drawing with 380SKC127

REV. NO.	DATE	NATURE OF REVISION	BY	CHKD.	APPD.
R3	Aug. 9 1966	Removed Detail B, B1, E-E, E1-E1. Revised G-G, B-B & title block; added Detail D	DB	U.K.	
R2	Jan. 24, 1966	Changed center gate + pier; changed pier shape, added conc. hood over valve.	D.B.	WHT	DSK
R1	[illegible] 66	[illegible]	[illegible]	[illegible]	[illegible]

THE METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA

FOOTHILL FEEDER | CONTROL STRUCTURE

GATE TOWER STRUCTURE
SCHEME A

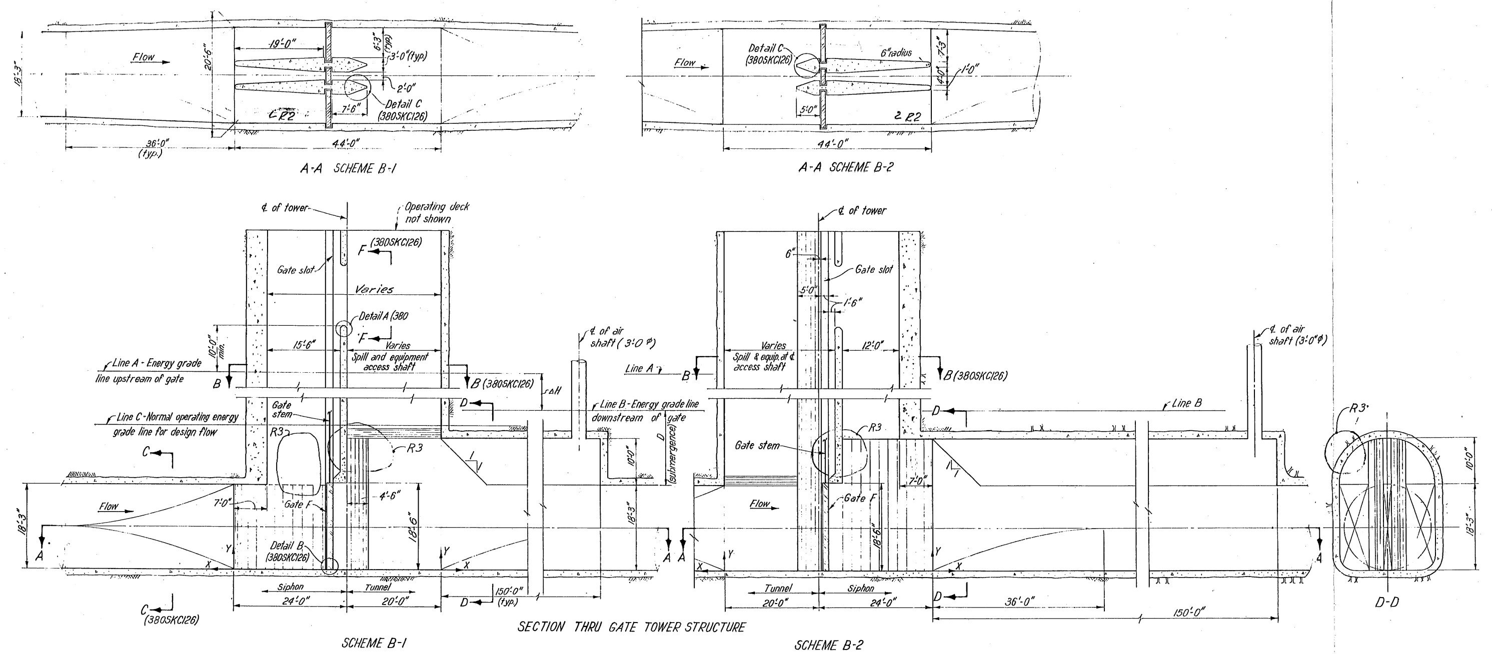
HARZA ENGINEERING COMPANY
APPROVED [signature]
CHICAGO, ILLINOIS | DATE Jan. 11, 1966 | DWG. NO. 380SKC126 R3

DATE	NO	DISTRIBUTION

PRINTS

	BY	DATE	CHKD.	DATE
DSGN.	[illegible]	Jan. 65	L.K.	[illegible]
DWN.	[illegible]	Jan. 65	[illegible]	[illegible]
DEPT.	GROUP LEADER	SECT. HEAD	DEPT. HEAD	
CIVIL	[illegible]		[illegible]	
MECH.				
ELECT.				
PLAN.				
STAFF			CH.ENGR.	

CHART 2



NOTES:
1. Work this drawing with 380SKC126.
2. For location of Line A and B and depth of sumergence D see drawing 380SKC139.

Scale 0 10 20 Feet
1" = 10'-0"

FILLET DATA

TABLE OF OFFSETS			
X	Y	X	Y
0	0	20	6.96
2	1.09	22	7.415
4	1.98	24	7.82
6	2.75	26	8.175
8	3.45	28	8.48
10	4.12	30	8.75
12	4.735	32	8.93
14	5.32	34	9.04
16	5.90	36	9.125
18	6.46		

DATE	NO	DISTRIBUTION	
PRINTS			
	BY	DATE	CHKD. / DATE
DSGN.	W.T.	'65	UK '66
DWN.	D.E.	'66	W.T. '66
DEPT.	GROUP LEADER	SECT. HEAD	DEPT. HEAD
CIVIL	W.T.		D.T.
MECH.			
ELECT.			
PLAN.			
STAFF			CH.ENGR.

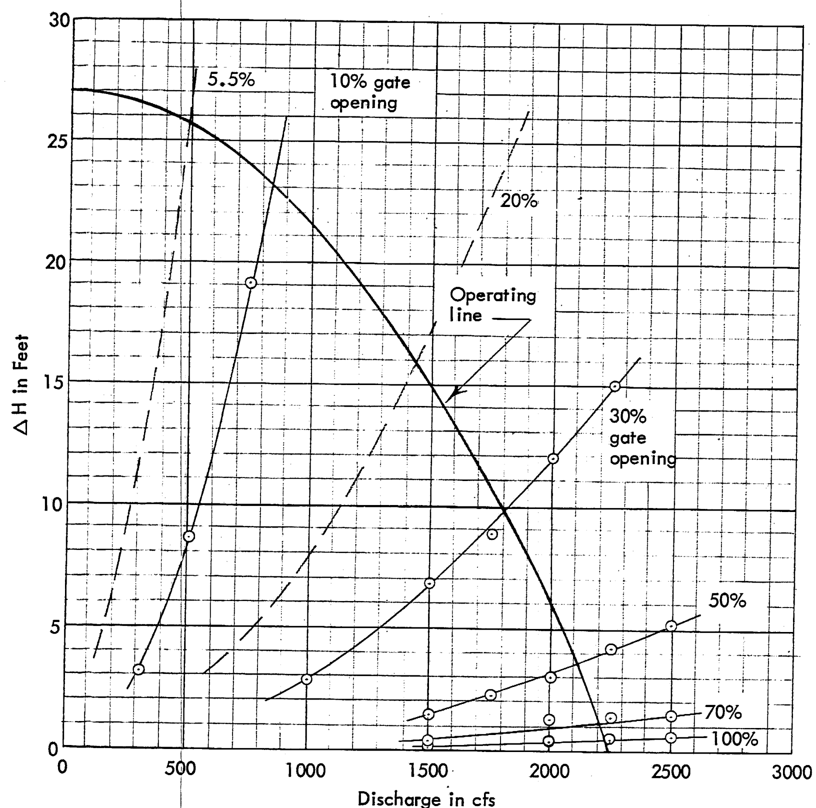
REV. NO.	DATE	NATURE OF REVISION	BY	CHKD.	APPD.
R3	Aug. '84	Removed conc. hood, Howell-Bunger valve and E-E	U.K.	AG	
E2	Jan. 24 66	Changed center gate + pier; changed pier shape, added conc. hood over valve.	D.B.	WHT	DT
E1	[illegible]	[illegible]	D.E.	W.T.	DT

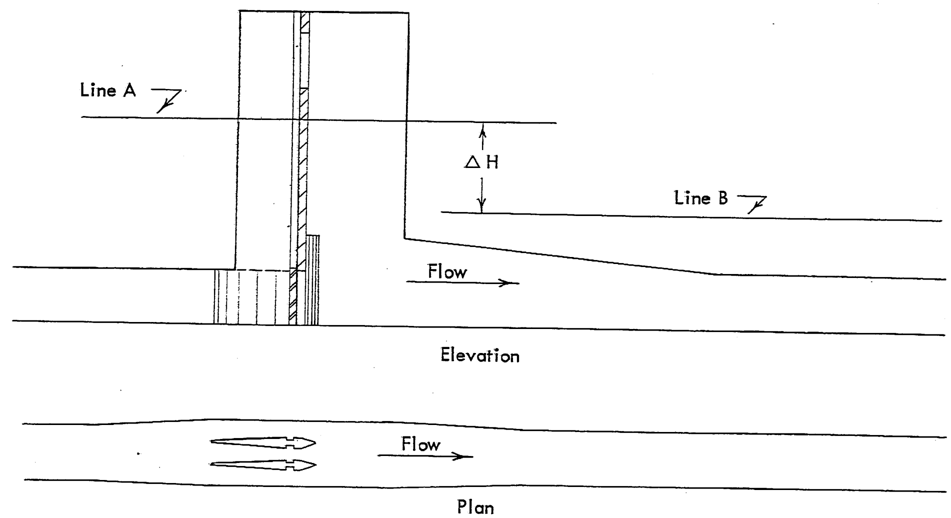
THE METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA

FOOTHILL FEEDER — CONTROL STRUCTURE

GATE TOWER STRUCTURE
SCHEME B

HARZA ENGINEERING COMPANY
APPROVED
CHICAGO, ILLINOIS
DATE Jan. 1, 1966
DWG. NO. 380SKC127.R3





Sketch of Scheme A-1 Model Configuration

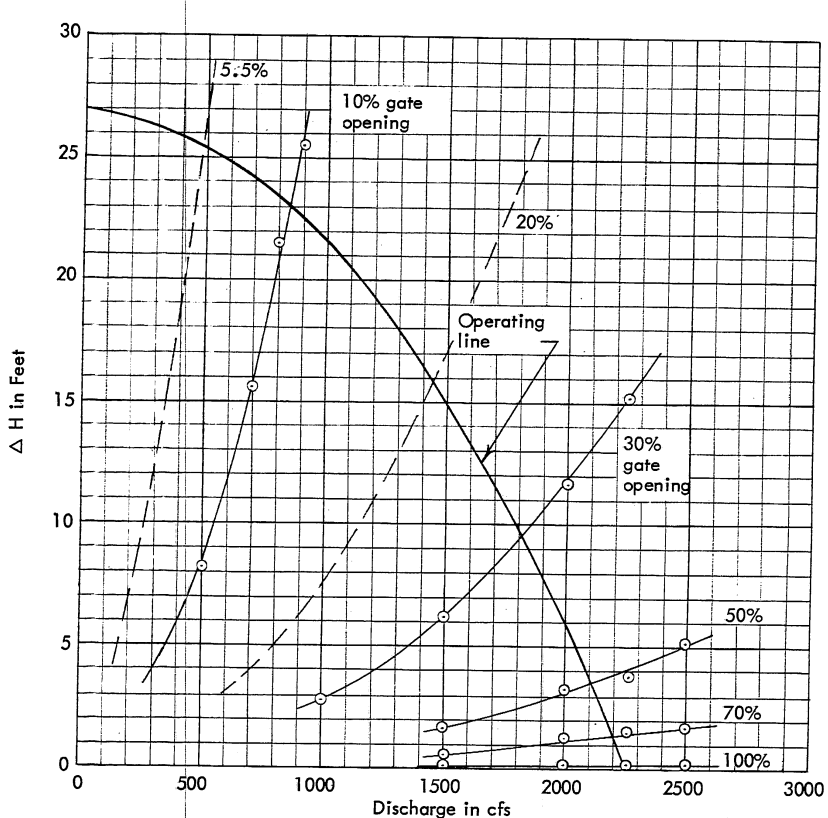
Notes:

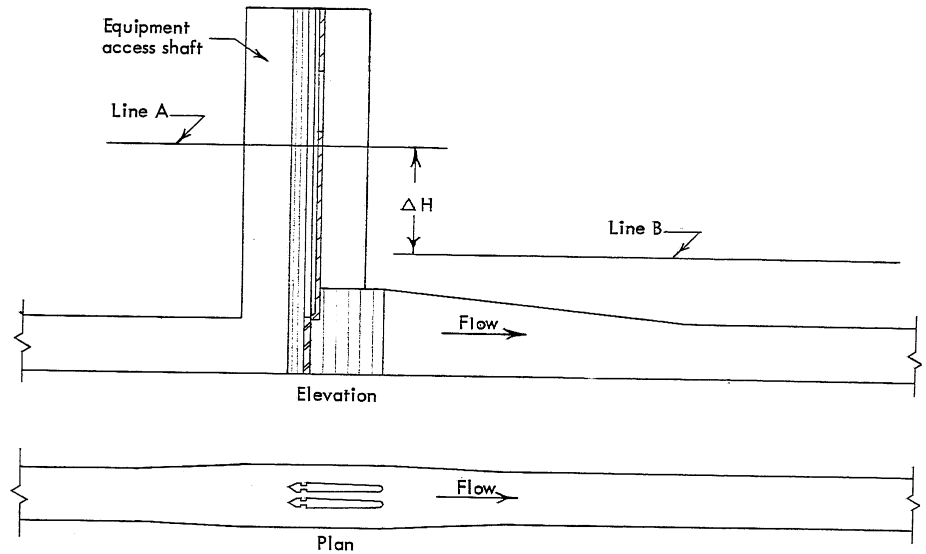
1. Line A is a downstream extension of the Energy Grade Line from upstream of the gate.
2. Line B is an upstream extension of the Energy Grade Line from downstream of the downstream transition.
3. Clear opening between piers was 6 ft 3 in. for the two outside gates and 2 ft 0 in. for the center gate.
4. All gates were open equal amounts for these tests.
5. Operating data obtained from Harza sketch 380 SKC 139.
6. Reference: Harza Engineering Company drawing 380-SKC 127R3.
7. Curves for gate openings of 5.5% and 20% were computed based on data obtained for other openings.

HEAD LOSS CURVES
SCHEME A-1

Model Scale 1:38.3

FOOTHILL FEEDER STUDIES Metropolitan Water District of Southern California		
Harza Engineering Co., Chicago, Ill.		
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA		
DRAWN DJA	CHECKED RMK	APPROVED
SCALE	DATE 7-15-66	NO. 168-B-459-56





Sketch of Scheme A-2 Model Configuration

Notes:

1. Line A is a downstream extension of the Energy Grade Line from upstream of the gate.
2. Line B is an upstream extension of the Energy Grade Line from downstream of the downstream transition.
3. Clear opening between piers was 6 ft 3 in. for the two outside gates and 2 ft 0 in. for the center gate.
4. All gates were open equal amounts for these tests.
5. Operating data obtained from Harza sketch 380 SKC 139.
6. Reference: Harza Engineering Company drawing 380 SKC 127R3.
7. Curves for gate openings of 5.5% and 20% were computed based on data obtained for other openings.

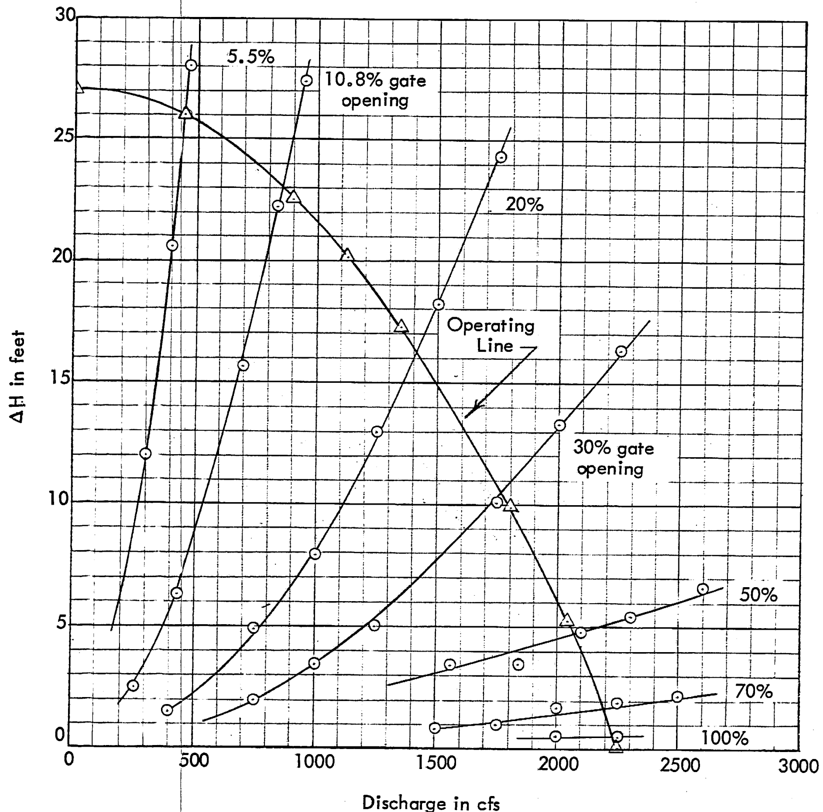
HEAD LOSS CURVES
Scheme A-2
Model Scale 1:38.3

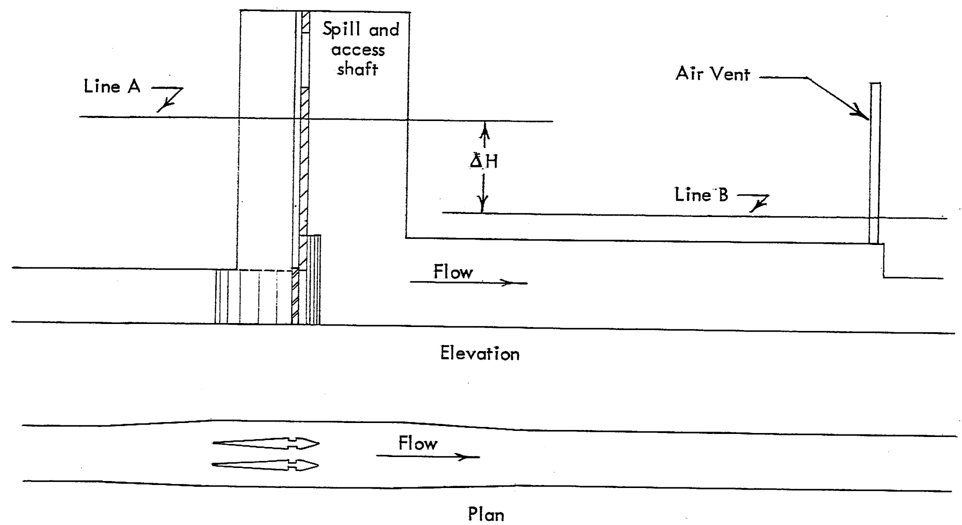
FOOTHILL FEEDER STUDIES
Metropolitan Water District of
Southern California

Harza Engineering Co., Chicago, Ill.

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN DJA	CHECKED RMK	APPROVED
SCALE	DATE 8-1-66	NO. 168-B-459-61





Sketch of Scheme B-1 Model Configuration

Notes:

1) Line A is an extension of the Energy Grade Line upstream of gate.
2) Line B is an extension of the Energy Grade Line downstream of the air vent.
3) Clear opening between piers was 6'3" for the two outside gates and 2'0" for the center gate.
4) All gates were open the same amount in these tests.
5) Operating data obtained from Harza sketch 380 SKC 139.
6) Reference: Harza Eng. Co. drawing 380 SKC 127 R3.

HEAD LOSS CURVES

Scheme B-1

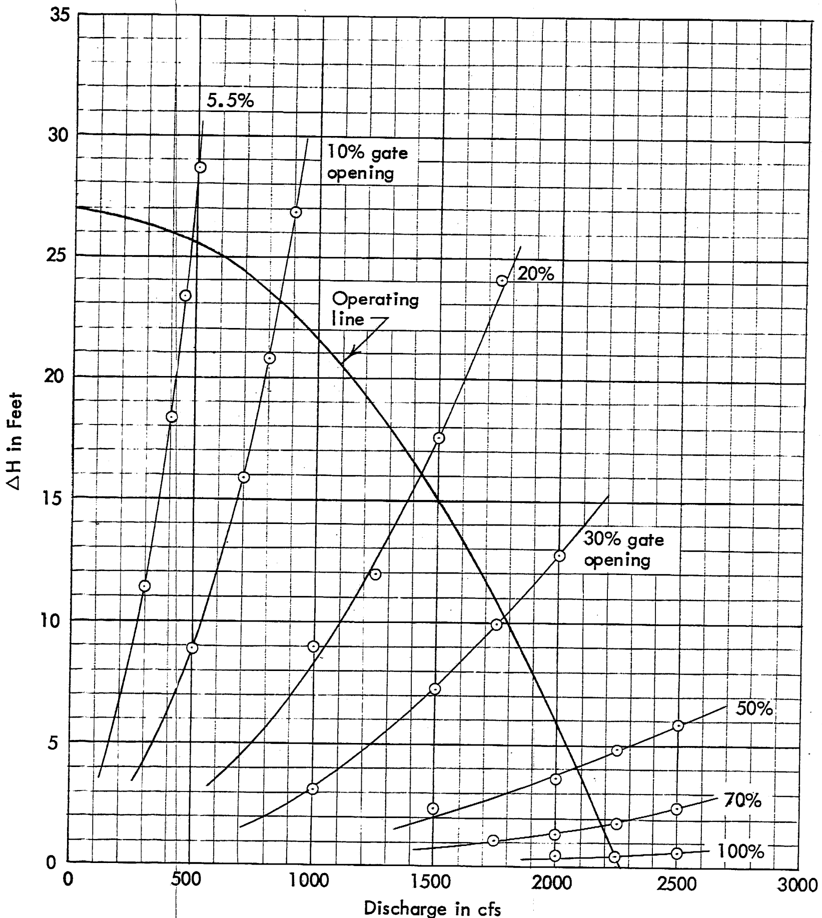
Model Scale 1:38.3

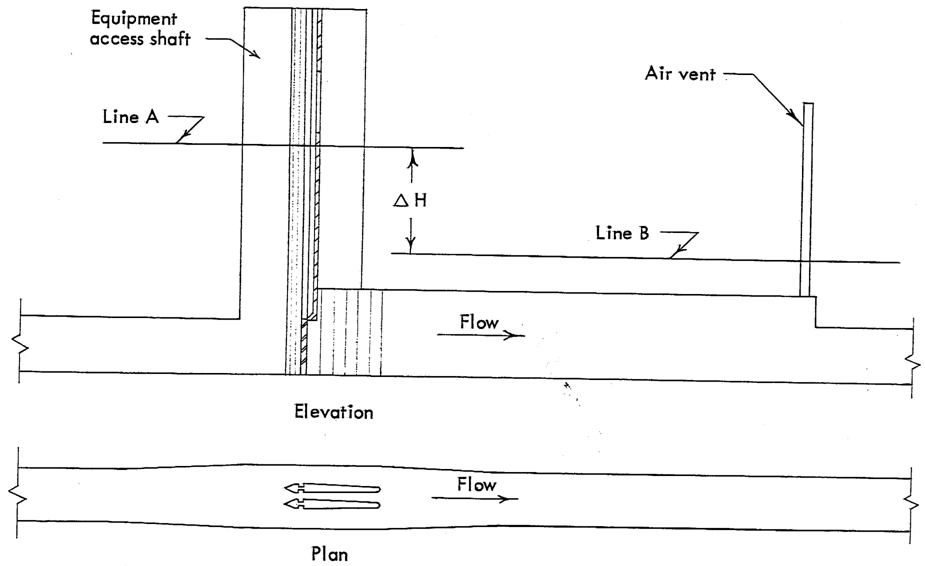
FOOTHILL FEEDER MODEL STUDIES
Metropolitan Water District of Southern California

Harza Engineering Co., Chicago, Ill.

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN DJA	CHECKED RMK	APPROVED
SCALE	DATE 5-3-66	NO. 168-B-459-32





Sketch of Scheme B-2 Model Configuration

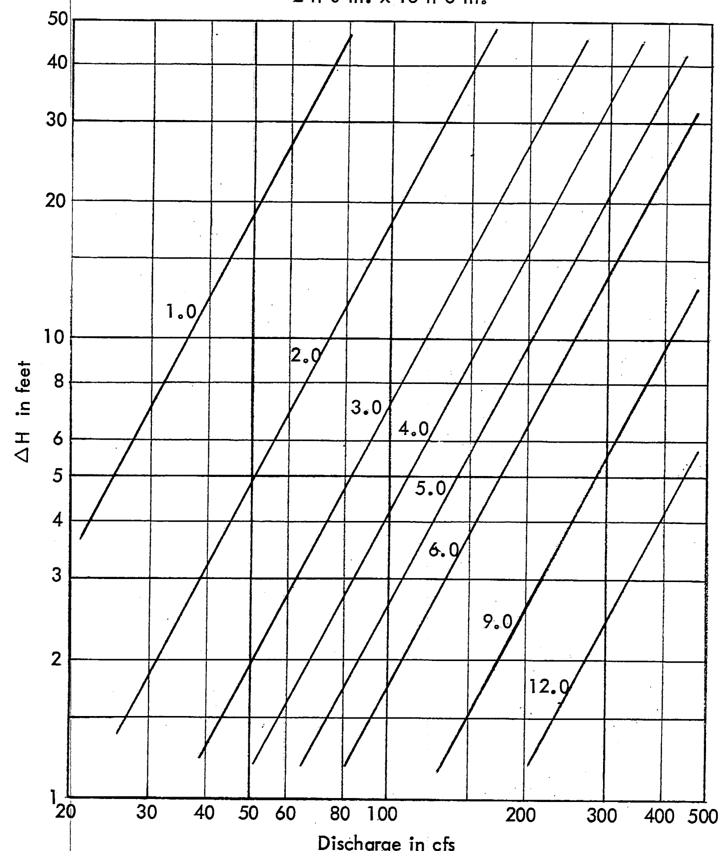
Notes:

1. Line A is a downstream extension of the Energy Grade Line from upstream of the gate.
2. Line B is an upstream extension of the Energy Grade Line from downstream of the downstream transition.
3. Clear opening between piers was 6 ft 3 in. for the two outside gates and 2 ft 0 in. for the center gate.
4. All gates were open equal amounts for these tests.
5. Operating data obtained from Harza sketch 380 SKC 139.
6. Reference: Harza Engineering Company drawing 380 SKC 127R3.

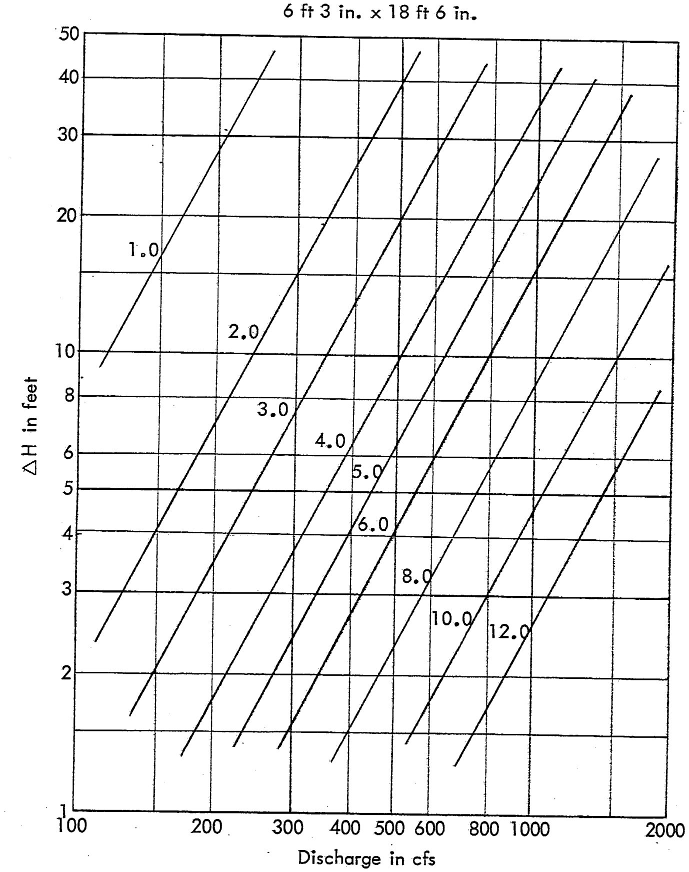
HEAD LOSS CURVES
Scheme B-2
Model Scale 1:38.3

FOOTHILL FEEDER STUDIES Metropolitan Water District of Southern California		
Harza Engineering Co., Chicago, Ill.		
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA		
DRAWN DJA	CHECKED RMK	APPROVED
SCALE	DATE 7-25-66	NO. 168-B-459-57

One Gate
2 ft 0 in. x 18 ft 6 in.



One Gate
6 ft 3 in. x 18 ft 6 in.



Notes:

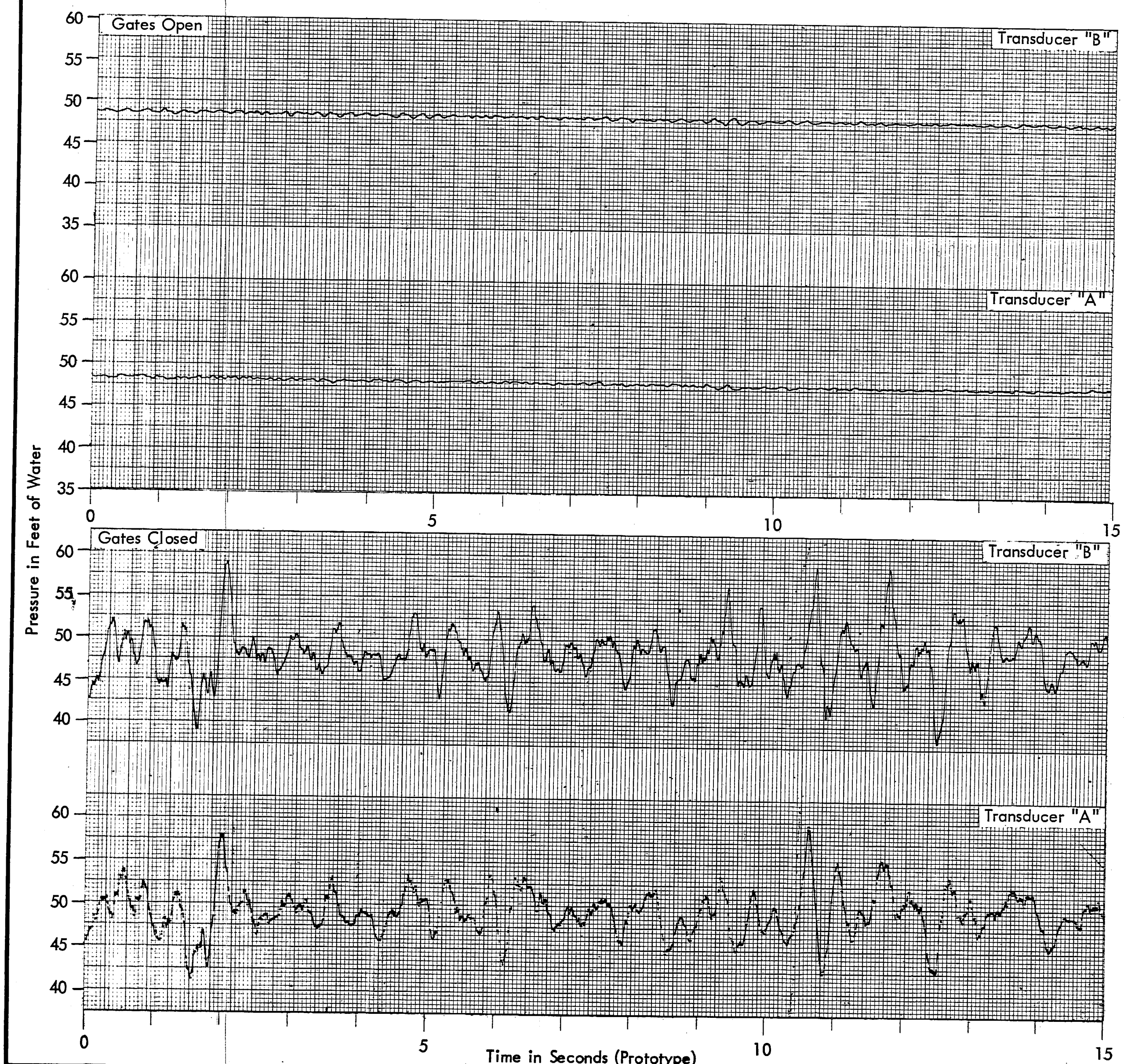
1. Numbers on above curves indicate gate opening in feet.
2. The curves show the headloss incurred when passing a given discharge through any one gate.

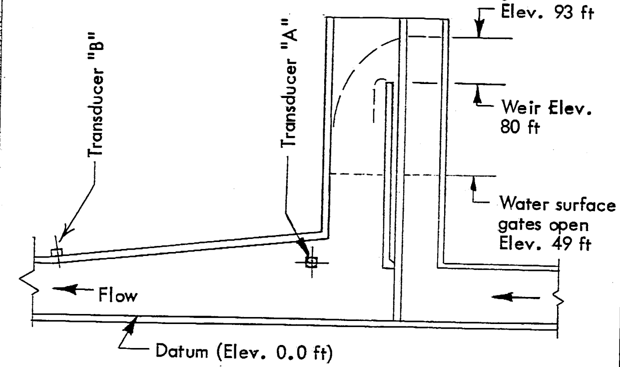
RATING CURVES FOR
SINGLE GATES

Model Scale 1:38.3

FOOTHILL FEEDER STUDIES Metropolitan Water District of Southern California		
Harza Engineering Co., Chicago, Ill.		
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA		
DRAWN DJA	CHECKED	APPROVED
SCALE	DATE 3-22-67	NO. 168-B-459-98

CHART 7





Side view of structure showing location of pressure transducers

Notes:

1. Transducers used were 25 psi C.E.C., chamber mounted type.
2. With gates open, air entrainment and pressure fluctuation are small. With gates closed and flow over weir, air is entrained; the majority of the air returns back up the the trap and out the tower, but some does escape downstream. The irregular fluctuations shown are caused by the entrained air.
3. The maximum magnitude of the pulses is 25 ft of water.

FLUCTUATING PRESSURES IN AIR TRAP OF A-1 TYPE STRUCTURE

Q = 2250 cfs
D.S. Submergence = 48 ft
Gate Opening = 0% and 100%

Model Scale 1:38.3

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Metropolitan Water District of Southern California

Harza Engineering Co., Chicago, Ill.

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

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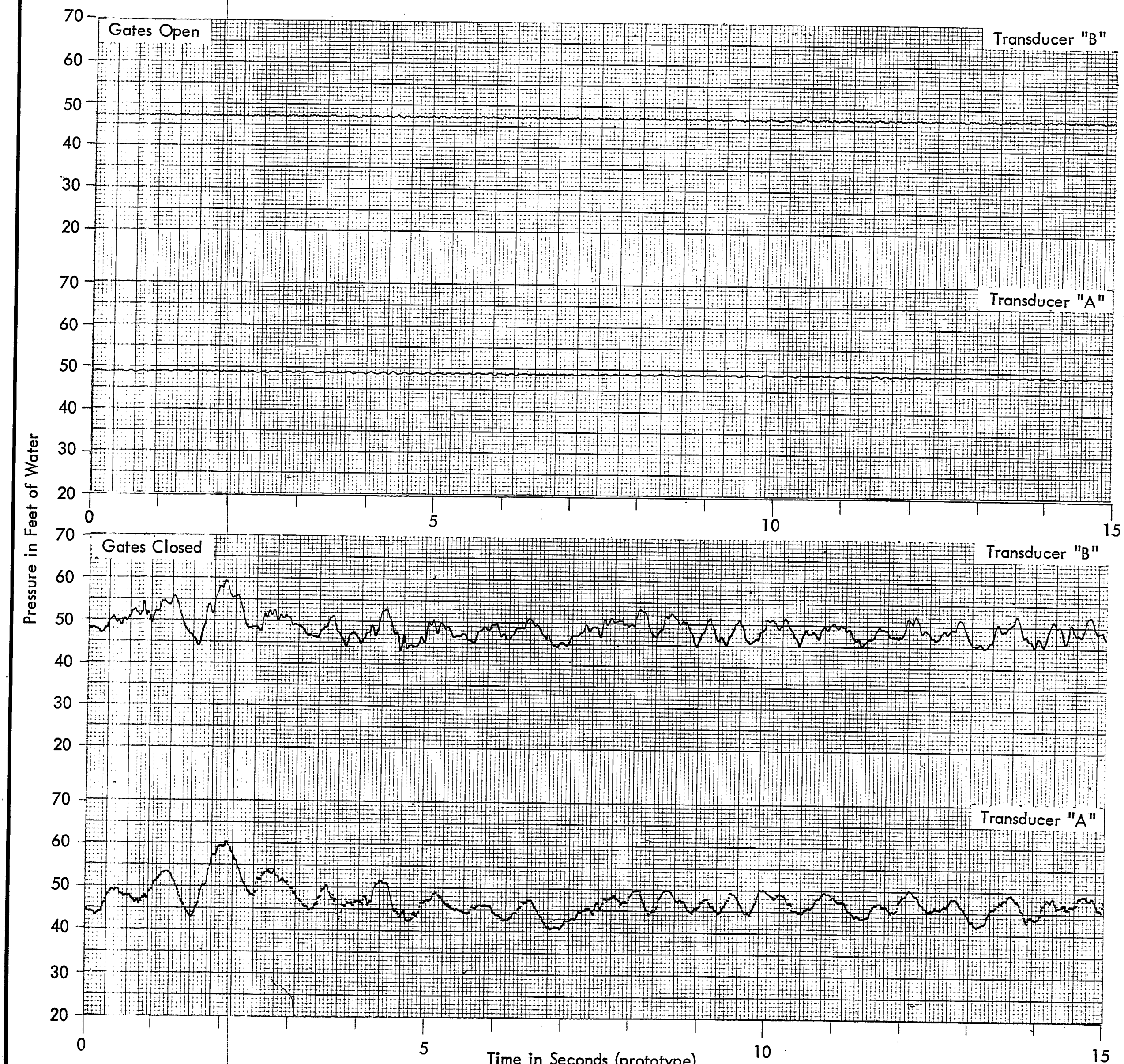
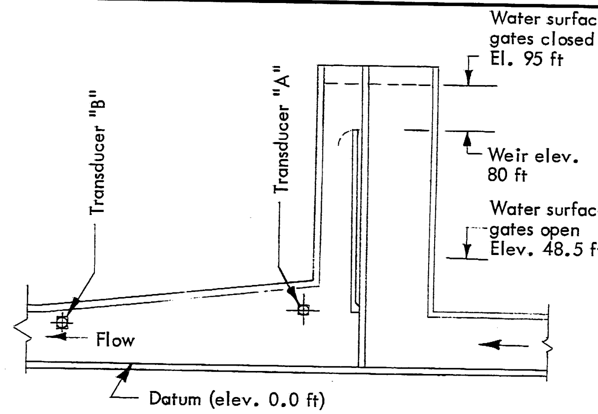
SCALE	DATE 5-13-66	NO. 168-B-459-45

CHART 8





Side view of structure showing location of pressure transducers

Notes:

1. Transducers used were 2.5 psi C.E.C., chamber mounted type.
2. With gates open, air entrainment and pressure fluctuations are small. With gates closed and flow over weir, air is entrained; the majority of the air returns back up the trap and into the tower where it is again entrained. A portion of the entrained air escapes downstream. The irregular fluctuations shown are caused by the entrained air.
3. The maximum magnitude of the pulses is 17 ft of water at transducer "B".

FLUCTUATING PRESSURES IN AIR TRAP OF TYPE A-2 STRUCTURE

Q = 2250 cfs
D.S. Submergence = 48 ft
Gate Opening = 0% and 100%
Model Scale 1:38.3

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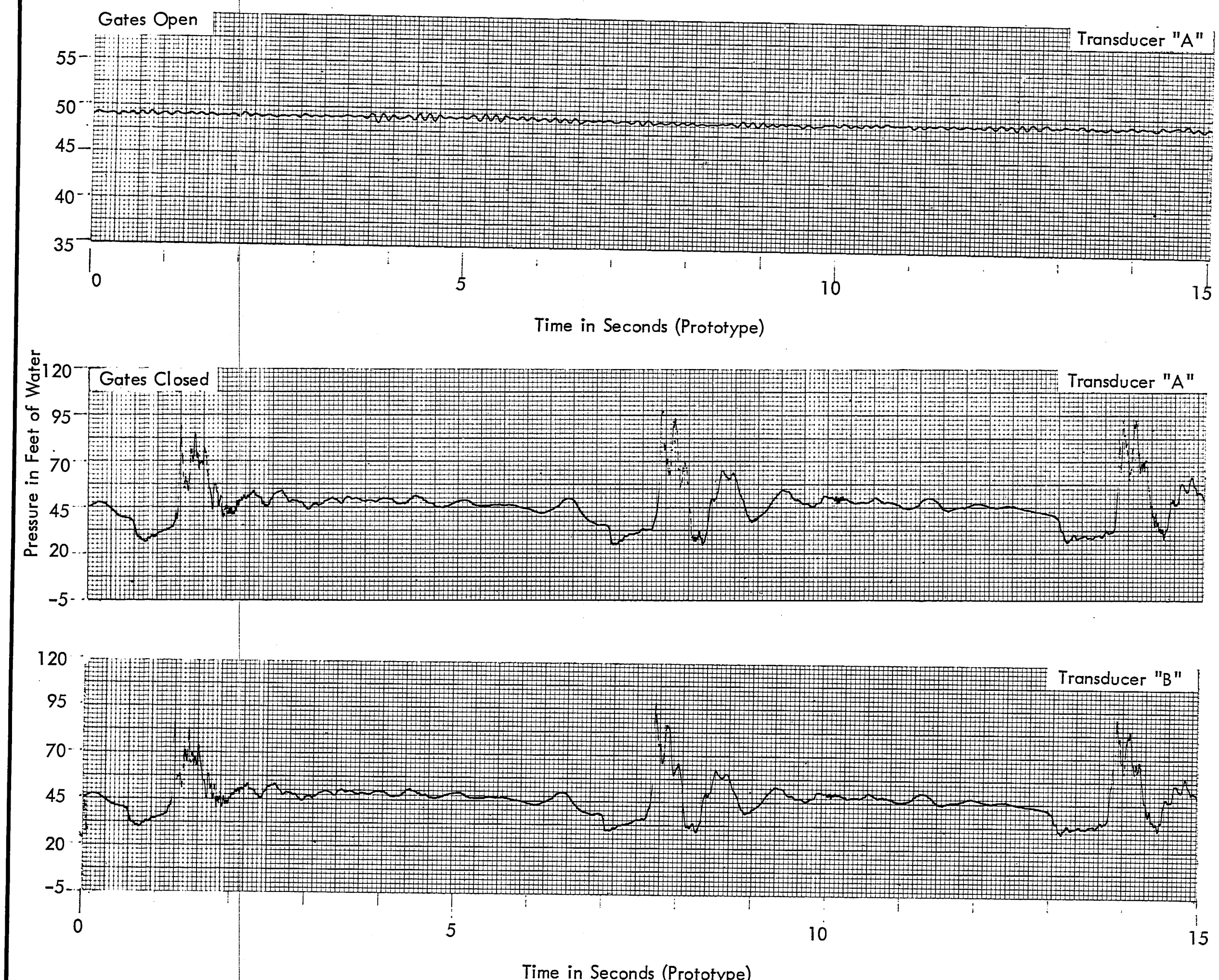
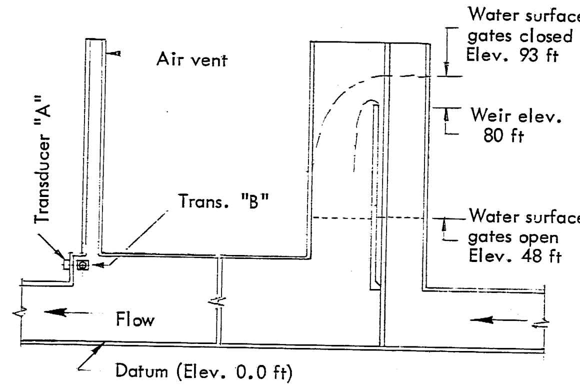
SCALE	DATE 8-1-66	NO. 168-B-459-63





Side view of structure showing location of pressure transducers

Notes:

1. Transducers used were 2.5 psi C.E.C., chamber mounted type.
2. With gates open, air entrainment and pressure fluctuation are small. With gates closed and flow over weir, air is entrained; air escaping through vent results in dynamic pressure oscillation.
3. Ave. period of major pulses = 6.4 sec.
   Ave. magnitude of major pulses = 59 ft
   Max. magnitude of pulses = 90 ft

FLUCTUATING PRESSURES NEAR
AIR VENT IN B-1 STRUCTURE

Q = 2250 cfs
Gate Opening = 0% and 100%
D.S. Submergence = 48 ft
Model Scale 1:38.3

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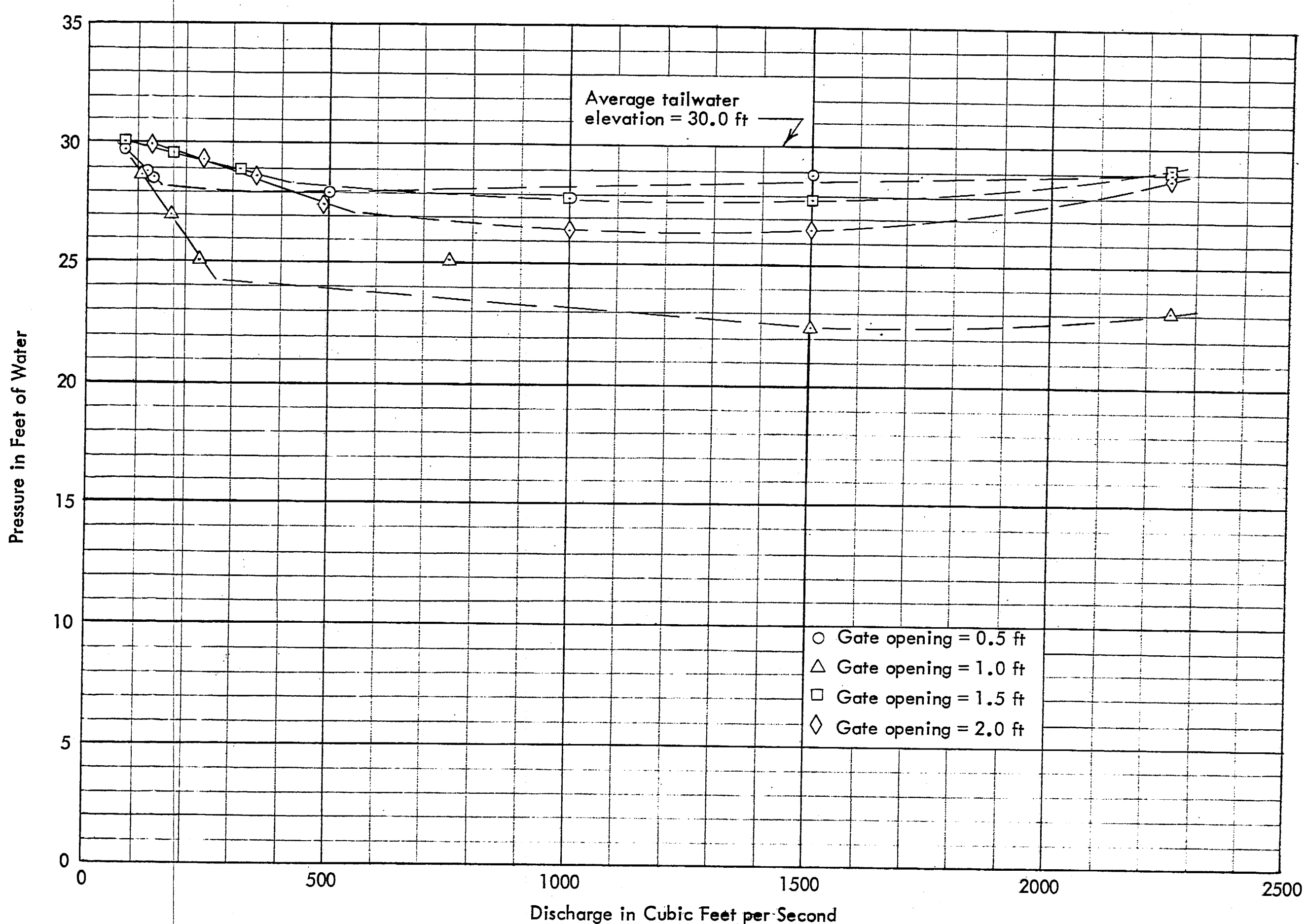
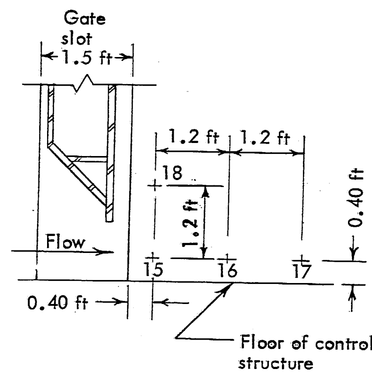
SCALE	DATE 5-4-66	NO. 168-B-459-33





Section view showing positions on right sidewall at which pressures were measured

—— Flow through right gate only

— — Flow through right gate and over the weir

Scheme B-1
MINIMUM AVERAGE PRESSURE
DOWNSTREAM FROM GATE SLOT
Model Scale 1:38.3

Notes:

1. Left and center gates closed and 9 sq ft vent was located 170 ft downstream from gate.
2. For gate openings of 0.5 and 1.0 ft, minimum pressures were recorded at location 15.
3. For gate openings of 1.5 and 2.0 ft, minimum pressures were recorded at location 18.

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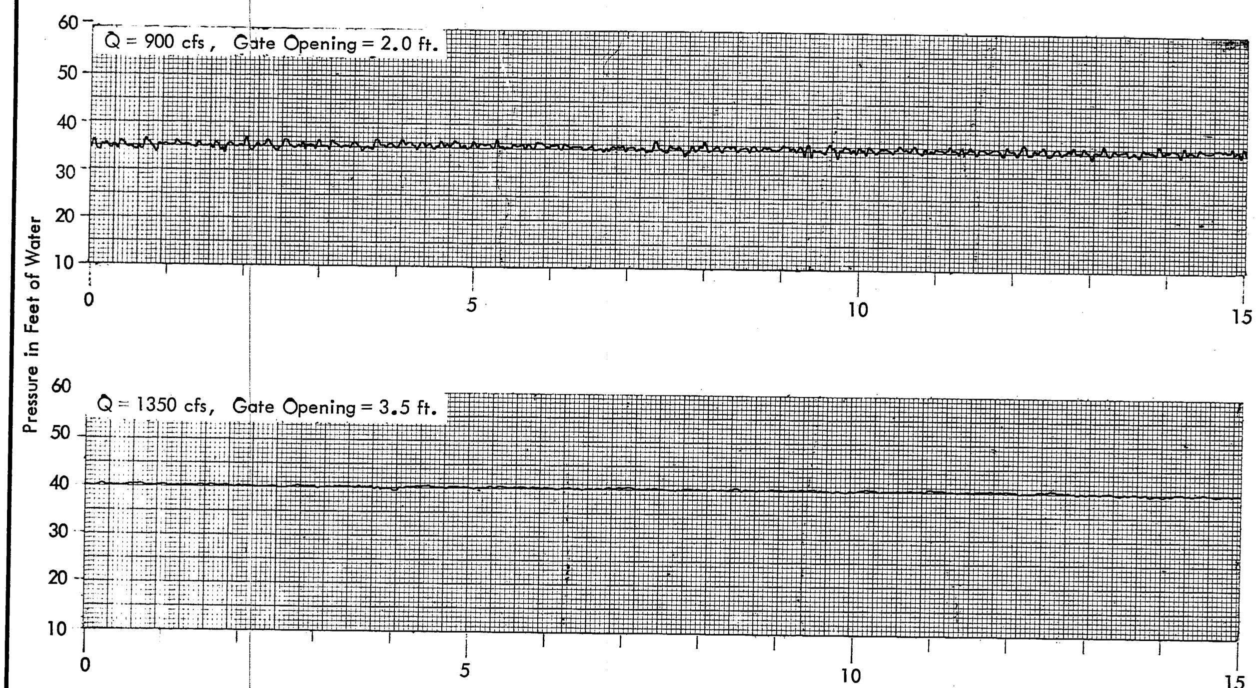
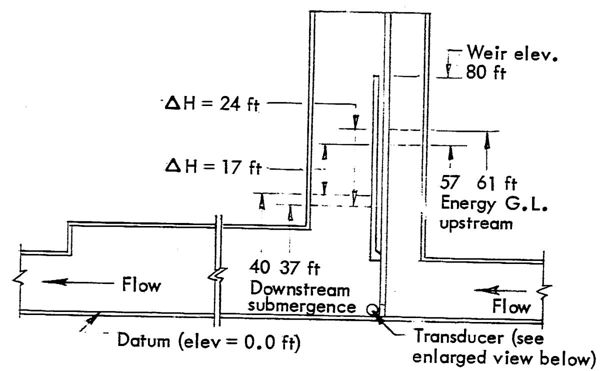
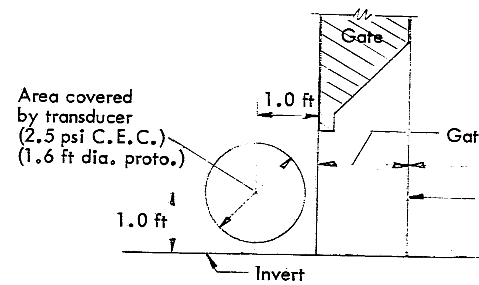
SCALE	DATE 6-17-66	NO. 168-B-459-46





Side view of structure showing location of transducer at side wall



Enlarged view of transducer location

Notes:

1. The tests were made to determine possibility of cavitation in vicinity of gates.
2. A gate opening less than 2.0 ft was not attempted because of pressure transducer dimensions. A flush mounted type was used rather than a chamber mounted type which was eliminated because the chamber mounted system decreased the natural frequency. This low natural frequency made it impossible to accurately measure pressures at the opening of the chamber.
3. The flow conditions were obtained from Harza sketch 380-SKC-139. The upstream E.G.L. was set by varying the downstream E.G.L. The head loss in the model did not correspond to that in the sketch.
4. The minimum pressures found were: Q = 900 cfs, min. press. = 34 ft water
   Q = 1350 cfs, min. press. = 39 ft water

Q (cfs)	Gate opening (ft)	U.S.-E.G.L. (ft)	D.S.-E.G.L. (ft)
900	2.0	61	37
1350	3.5	57	40

DYNAMIC PRESSURE OSCILLATIONS DOWNSTREAM OF GATE AT SIDE WALLS OF B-1 STRUCTURE

Model Scale 1:38.3

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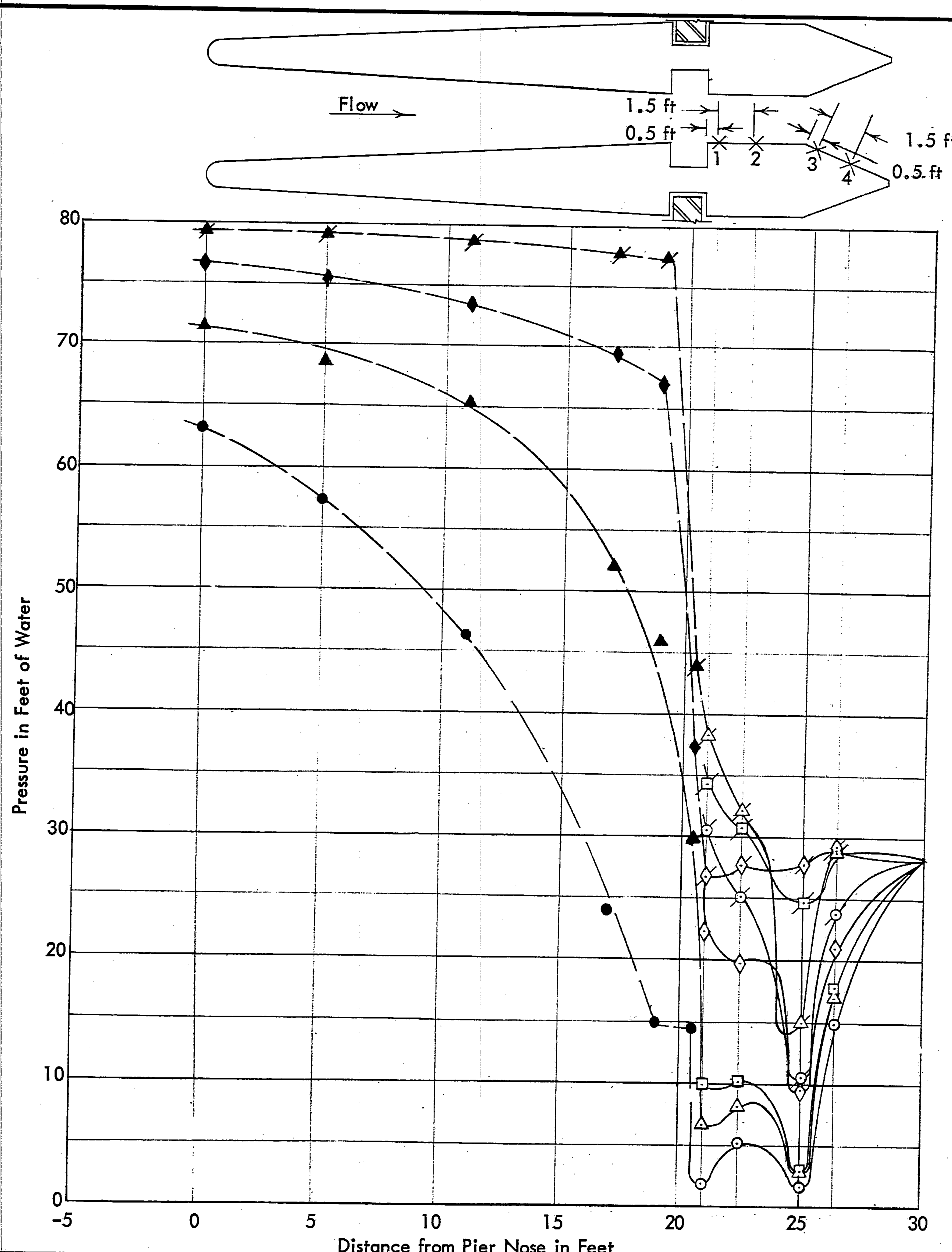
SCALE	DATE 7-13-66	NO. 168-B-459-55



Notes:

1. Two outside gates closed, center gate open, no vent.
2. Pressures measured at positions shown in sketch, 0.4 ft above floor of control structure.
3. This series of tests was run in order to determine the lowest average pressure on the pier walls, assuming that this low pressure condition occurs with a large ΔH through the gates, a constant H.W. = 80 ft and a constant D.S. Submergence = 28.3 ft were used throughout the tests.
4. For a gate opening of 0.5 ft the lowest pressure cannot be measured since the vena contracta depth is less than 0.4 ft.
5. The lowest pressure recorded was 1.8 ft of water at Q = 2400 cfs and a gate opening of 18.5 ft.
6. The solid symbols represent computed values for the pressure at certain distances upstream from the gate slot. These values were determined by subtracting the velocity head at a point from the 80 ft of head available.

	Discharge cfs	Gate Opening ft	Minimum Pressure ft of water
⊙	2400	18.5	1.8
△	1700	15.0	3.0
⊡	1470	13.0	3.0
◇	1050	10.0	9.5
⊙̸	840	8.0	10.6
△̸	480	5.0	15.0
⊡̸	205	2.0	24.8
◇̸	53	0.5	26.8

SCHEME B-1
AVERAGE MINIMUM PRESSURES ON PIER WALL WITH ONLY CENTER GATE OPEN
H.W. = 80 ft
D.S. Submergence = 28.3 ft
Model Scale 1:38.3

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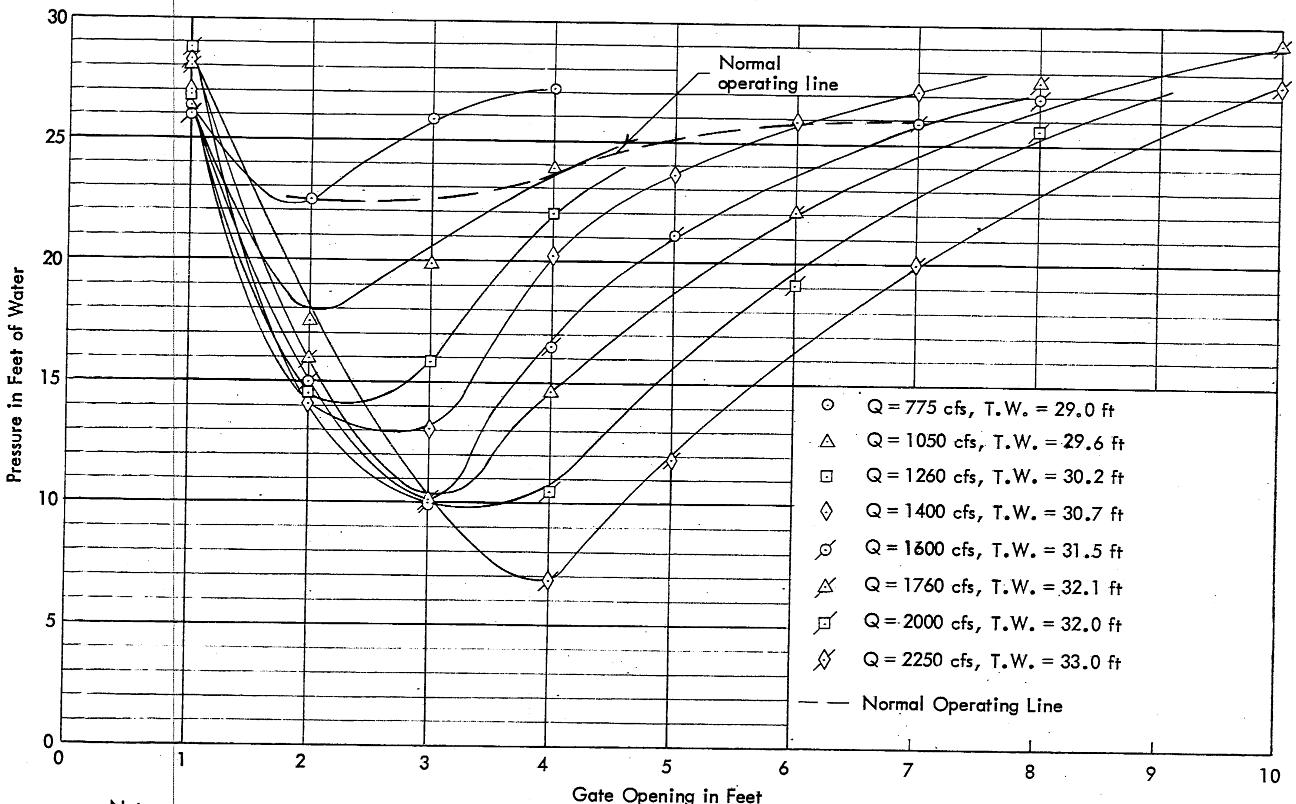
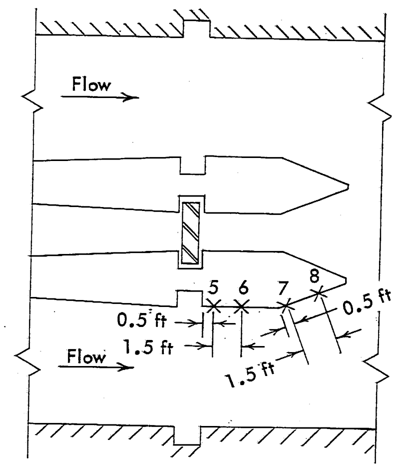
SCALE	DATE 7-8-66	NO. 168-B-459-52





Plan view showing the positions on pier wall at which pressures were measured

Notes:

1. Center gate closed, left and right gates open equally, no vent.
2. Pressures were measured at positions shown in sketch, 0.4 ft above floor of control structure.
3. Tailwater elevation established using Harza sketch 380-SKC-139.
4. Minimum pressure occurred at location 7 for each condition tested.
5. ΔH across gates ranged up to 57 ft. Large values of ΔH necessitate some weir flow.
6. Minimum pressure of 6.8 ft of water occurred when ΔH = 47 ft, Q = 2250 cfs, T.W. = 33.0 ft, gate opening = 4 ft.

SCHEME B-1
MINIMUM AVERAGE PRESSURE
ON PIER WALL DOWNSTREAM
FROM GATE SLOT WITH
TWO 6 FT 3 IN. GATES OPERATING

Model Scale 1:38.3

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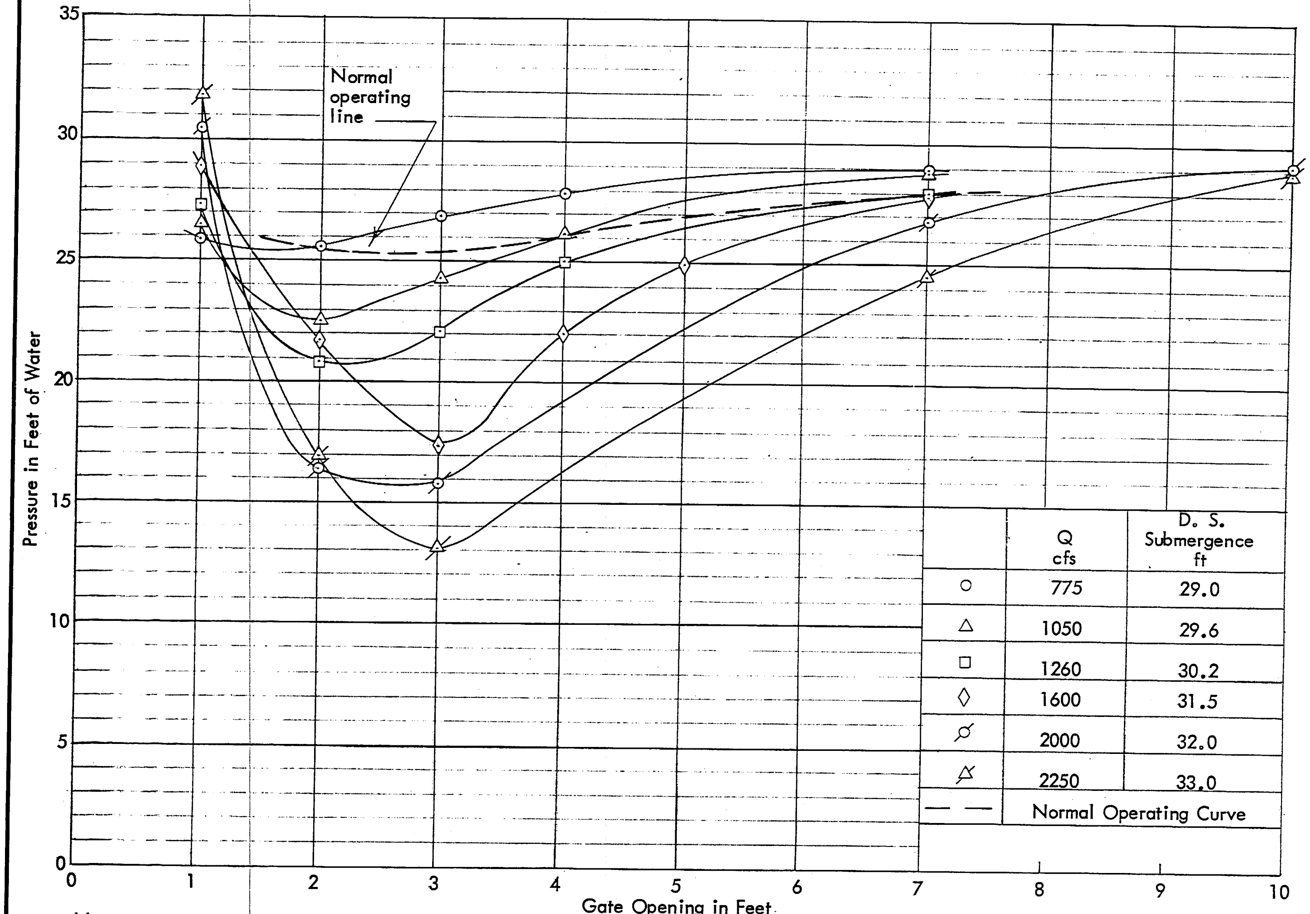
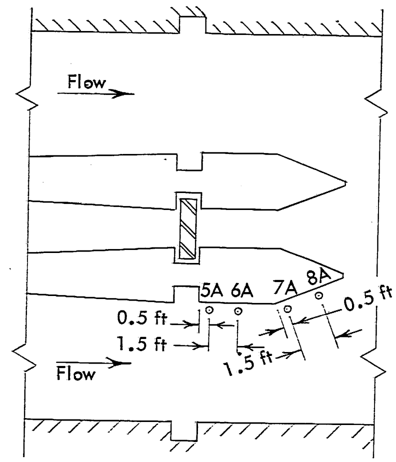
SCALE	DATE 7-5-66	NO. 168-B-459-47

CHART 14



	Q cfs	D. S. Submergence ft
○	775	29.0
△	1050	29.6
□	1260	30.2
◇	1600	31.5
⌀	2000	32.0
⍋	2250	33.0
— —	Normal Operating Curve	



Plan view showing positions on floor of control structures at which pressures were measured

Notes:

1. Center gate closed, left and right gates open equally, no vent.
2. Pressures were measured at positions shown in sketch, 0.4 ft from pier wall.
3. Tailwater elevation established using Harza sketch 380-SKC-139.
4. Minimum pressure occurred at location 7A for each condition tested.
5. ΔH across gates ranged up to 58 ft. Large values of ΔH necessitate some weir flow.
6. Minimum pressure of 13.1 ft of water occurred when ΔH = 48 ft, Q = 2250 cfs, T.W. = 33.0 ft, gate opening = 4.0 ft.
7. Pressures were measured using piezometers.

SCHEME B-1
MINIMUM AVERAGE PRESSURE ON FLOOR GATE OF STRUCTURE DOWNSTREAM FROM GATE SLOT WITH TWO 6 FT 3 IN. GATES OPERATING

Model Scale 1:38.3

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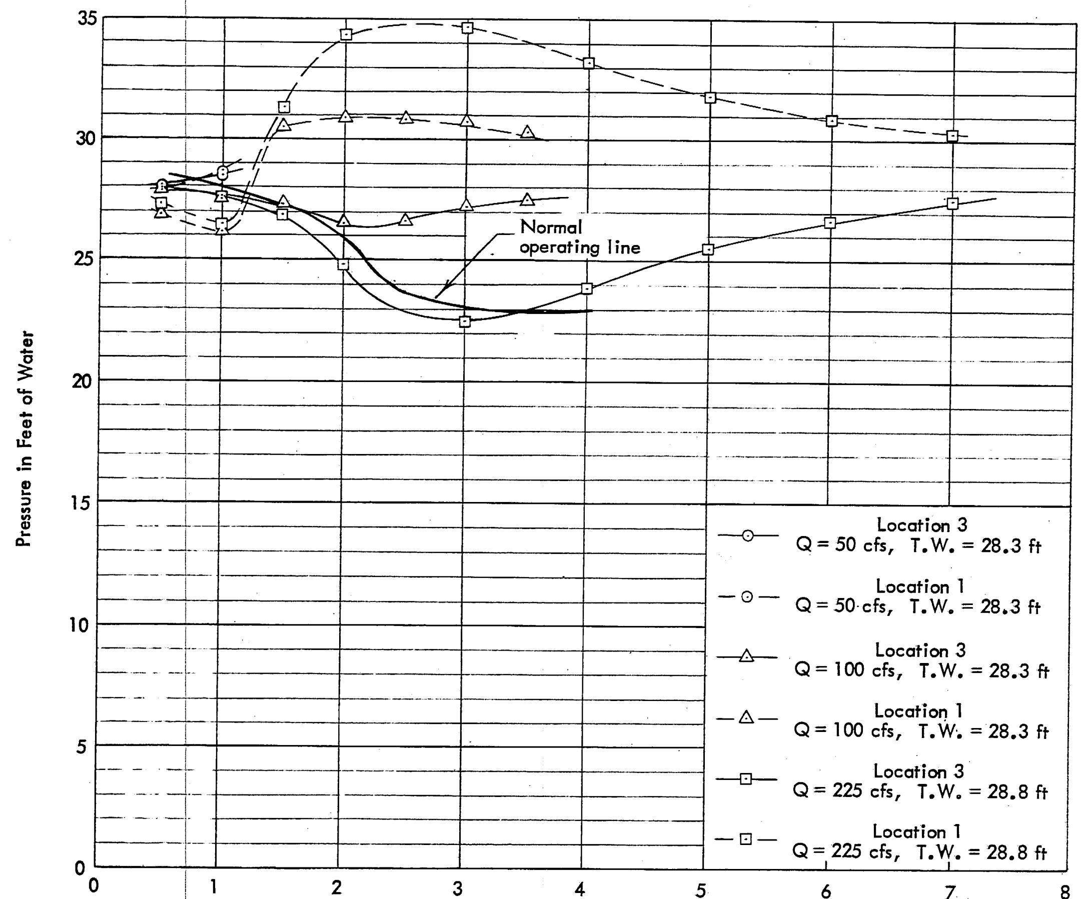

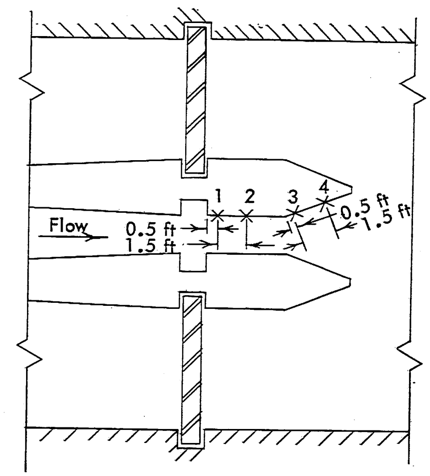

Plan view showing the positions on pier wall at which pressures were measured

SCHEME B-1
AVERAGE MINIMUM PRESSURES ON PIER WALL WHEN ONLY CENTER GATE IS OPERATING

Model Scale 1:38.3

Notes:

1. Side gates closed, center gate open, no vents.
2. Pressures were measured at positions shown in sketch, 0.4 ft above floor of control structure.
3. Tailwater elevation established using Harza sketch 380-SKC-139.
4. ΔH across gates ranged up to 54 ft. Large values of ΔH necessitate some weir flow.
5. Minimum pressure of 22.5 ft of water occurred when ΔH = 32.5 ft, Q = 225 cfs, T.W. = 28.8 ft, gate opening = 3 ft.
6. For each discharge the gate was opened and pressures were recorded up to the gate opening for which the lowest pressure equaled the T.W. pressure.

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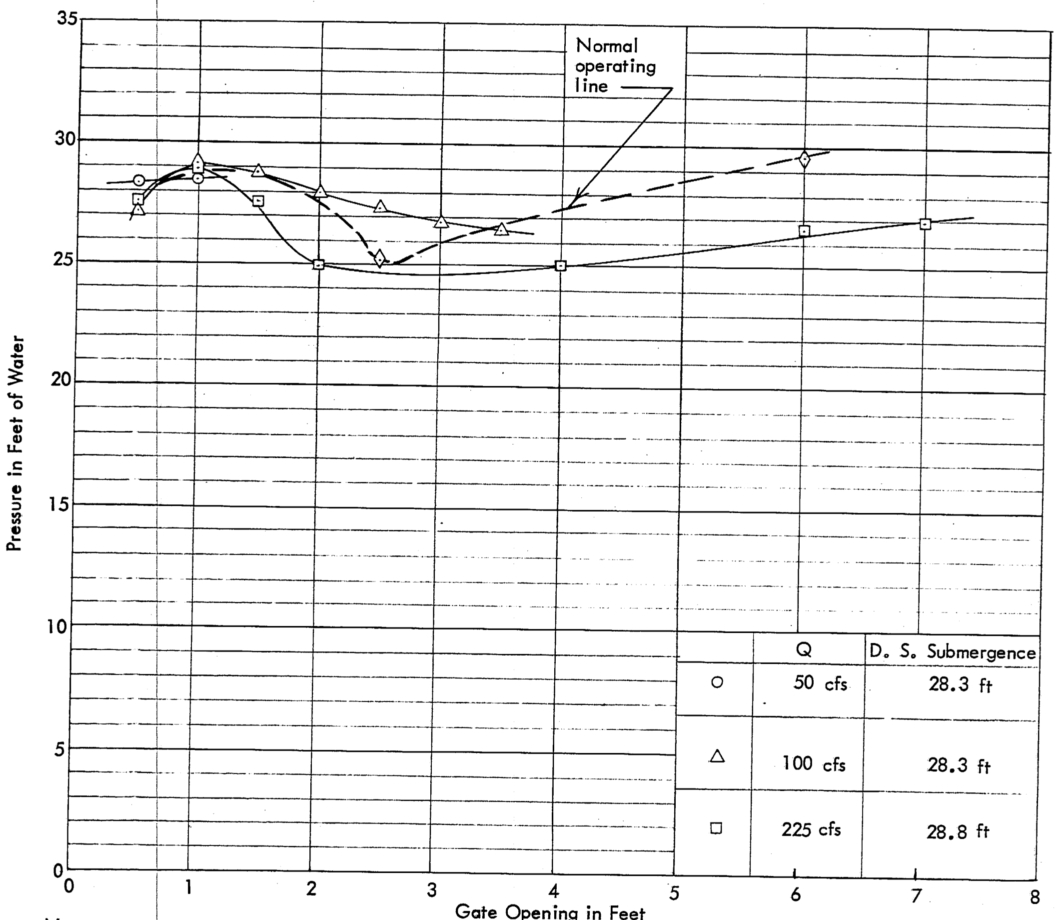
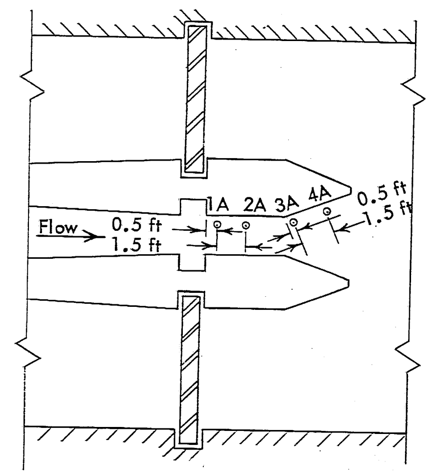
SCALE	DATE 7-5-66	NO. 168-B-459-48



	Q	D. S. Submergence
○	50 cfs	28.3 ft
△	100 cfs	28.3 ft
□	225 cfs	28.8 ft



Plan view showing the positions on control structure floor at which pressures were measured

Notes:

1. Side gates closed, center gate open, no vents.
2. Pressures were measured at positions shown in sketch, 0.4 ft from pier wall.
3. Tailwater elevation established using Harza sketch 380-SKC-139.
4. ΔH across gates ranged up to 53 ft. Large values of ΔH necessitate some weir flow.
5. Minimum pressure of 24.9 ft of water occurred when ΔH = 52 ft, Q = 225 cfs, T.W. = 28.8 ft, gate opening = 2.0 ft.
6. Pressures were measured using piezometers.
7. Minimum pressure occurred at location 3A for each case tested.

SCHEME B-1
AVERAGE MINIMUM PRESSURES ON GATE STRUCTURE FLOOR WHEN ONLY CENTER GATE IS OPERATING

Model Scale 1:38.3

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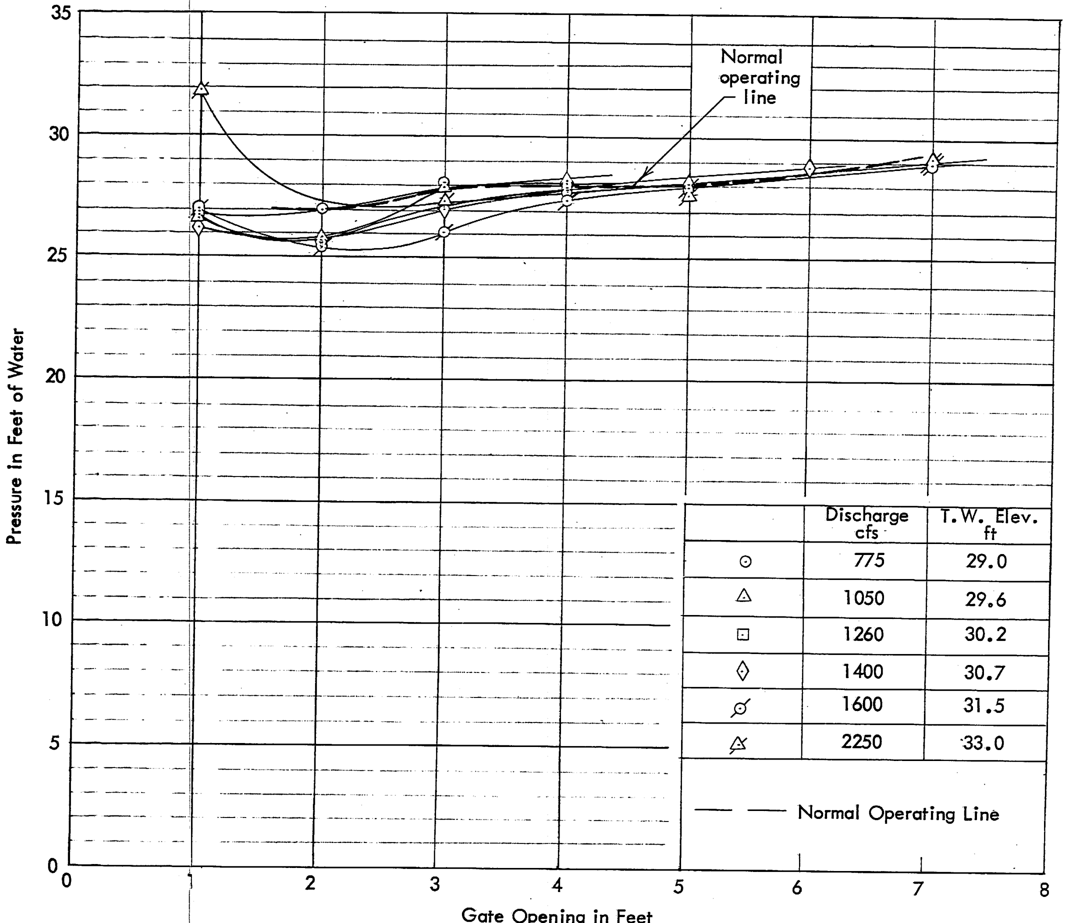
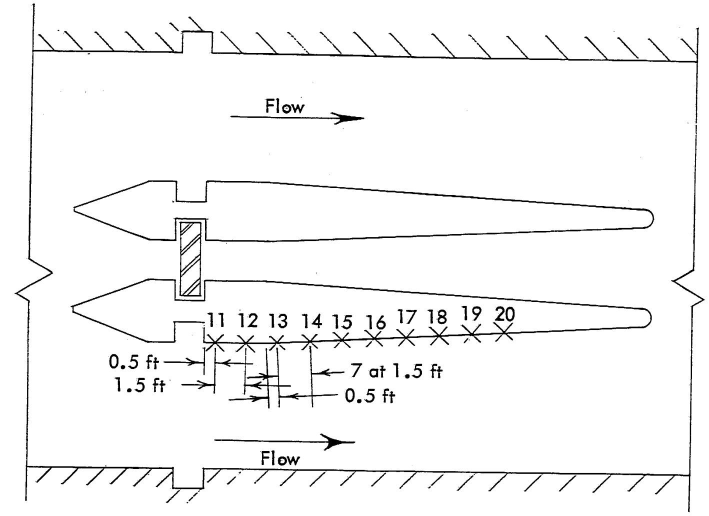


	Discharge cfs	T.W. Elev. ft
⊙	775	29.0
△	1050	29.6
⊡	1260	30.2
◊	1400	30.7
⌀	1600	31.5
△̸	2250	33.0

— — Normal Operating Line



Plan view showing the positions on pier wall at which pressures were measured

For any particular test condition, the pressures along the pier wall (location 11 to 20) varied by approximately 1 ft of water.

SCHEME B-2
MINIMUM AVERAGE PRESSURE ON PIER WALL DOWNSTREAM FROM GATE SLOT WITH TWO OUTSIDE GATES OPERATING
Model Scale 1:38.3

Notes:

1. Center gate closed, left and right gates open equal amounts, no air vent in air collector.
2. Pressures were measured by piezometers at positions shown in sketch, 0.4 ft above floor of control structure.
3. Tailwater elevation is the minimum found on Harza sketch 380-SKC-139.
4. Minimum pressure occurred at location 11 for 1 ft gate opening, 13 for 2 ft gate opening, and 20 for gate openings of 3 or more feet.
5. ΔH across gates ranged up to 58 ft. Large values of ΔH necessitate some weir flow.
6. Pressures were measured using piezometers.
7. Minimum pressure of +25.2 ft of water occurred when $\Delta H = 52$ ft, Q = 1600 cfs, T.W. = 31.5 ft, gate opening = 2 ft.

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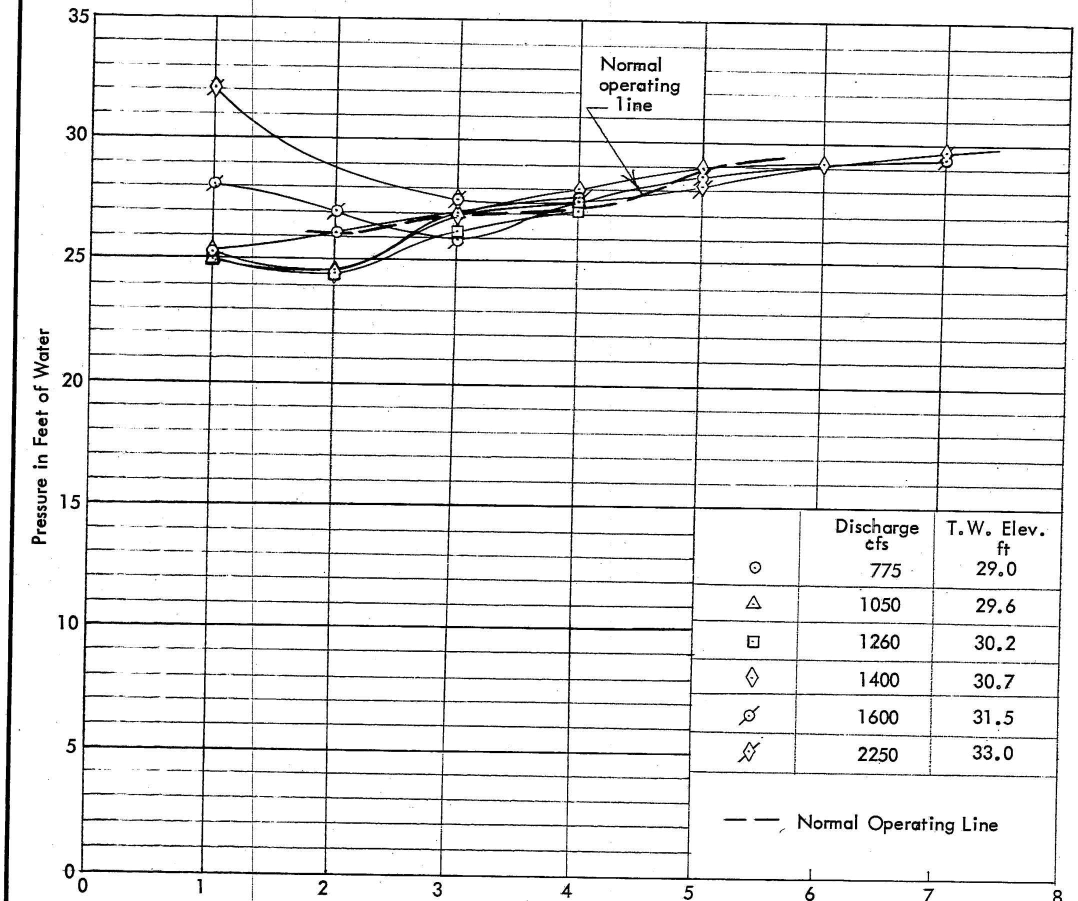

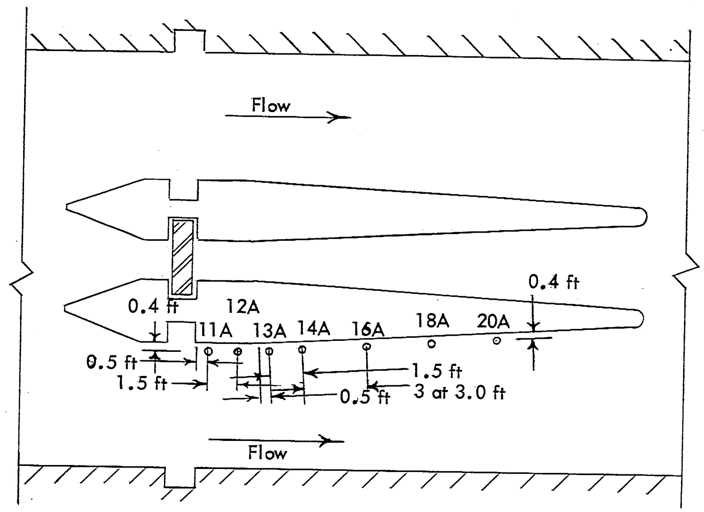

Plan view showing positions on floor of control structure at which pressures were measured

SCHEME B-2

MINIMUM AVERAGE PRESSURE ON FLOOR OF GATE STRUCTURE DOWNSTREAM FROM GATE SLOT WITH TWO OUTSIDE GATES OPEN

Model Scale 1:38.3

Notes:

1. Center gate closed, outside gates open, no air vent in air collector.
2. Pressures were measured by using piezometers at positions shown in sketch, 0.4 ft from pier wall.
3. Tailwater elevation is the minimum found on Harza sketch 380-SKC-139.
4. Minimum pressure occurred at location 13A for gate openings of 1, 2, and 3 ft and at location 16A for gate openings of more than 3 ft.
5. ΔH across gates ranged up to 57.5 ft. Large values of ΔH necessitate some weir flow.
6. Minimum pressure of +24.5 ft of water occurred when $\Delta H = 52$ ft, Q = 1260 cfs, T.W. = 30.2 ft, gate opening = 2 ft.

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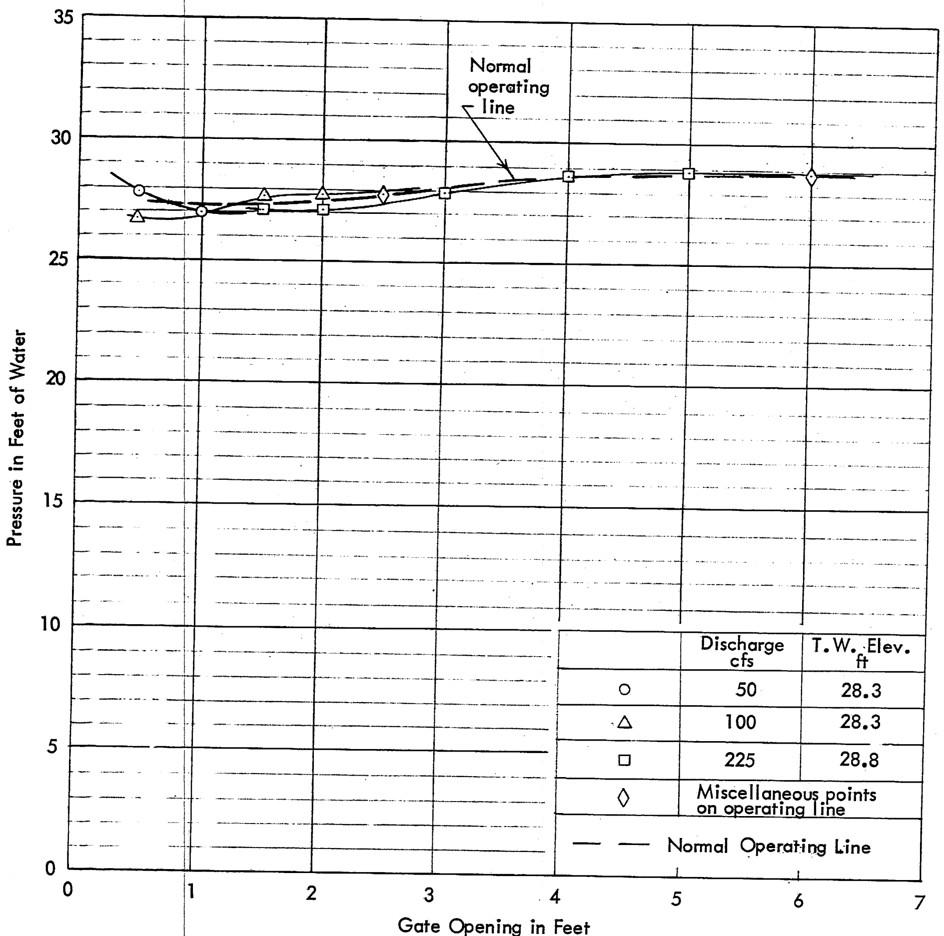

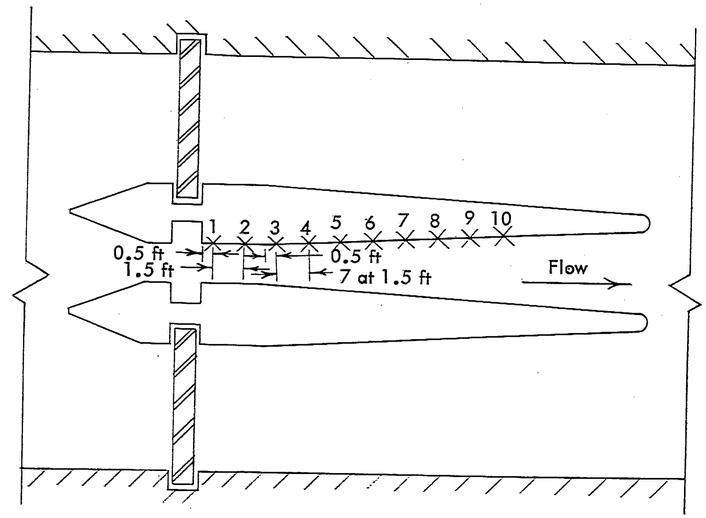

Plan view showing the positions on pier wall at which pressures were measured

For any particular test condition, the pressures along the pier wall (location 1 to 10) varied by approximately 1 ft of water.

SCHEME B-2
MINIMUM AVERAGE PRESSURE ON PIER WALL DOWNSTREAM FROM GATE SLOT WITH ONLY CENTER GATE OPEN

Model Scale 1:38.3

Notes:

1. Center gate open, outside gates closed, no air vent in air collector.
2. Pressures were measured by piezometers at positions shown in sketch, 0.4 ft above floor of control structure.
3. Tailwater elevation is the minimum found on Harza sketch 380-SKC-139.
4. Minimum pressure occurred at location 1 for 0.5 ft and 1 ft gate openings, and at location 3 for gate openings of 1.5 or more feet.
5. ΔH across gates ranged up to 53 ft. Large values of ΔH necessitate some weir flow.
6. Pressures were measured using piezometers.
7. Minimum pressure of +26.7 ft of water occurred when ΔH = 53 ft, Q = 100 cfs, T.W. = 28.3 ft, gate opening = 0.5 ft.

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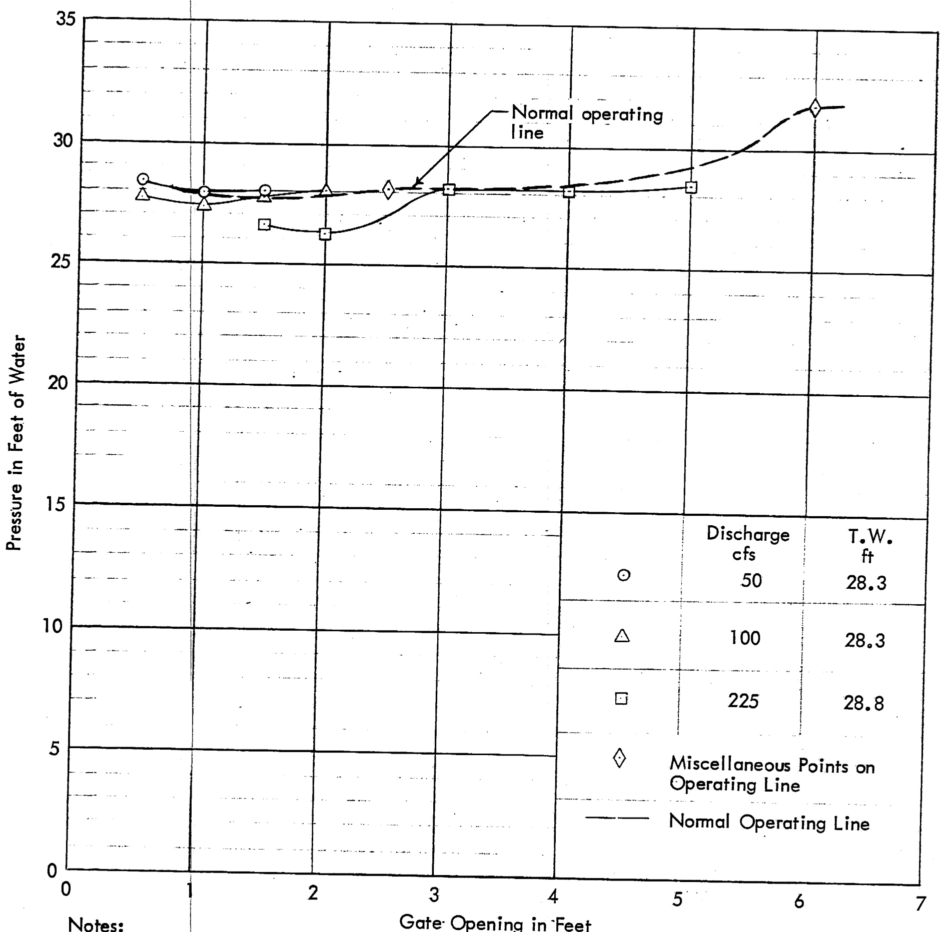

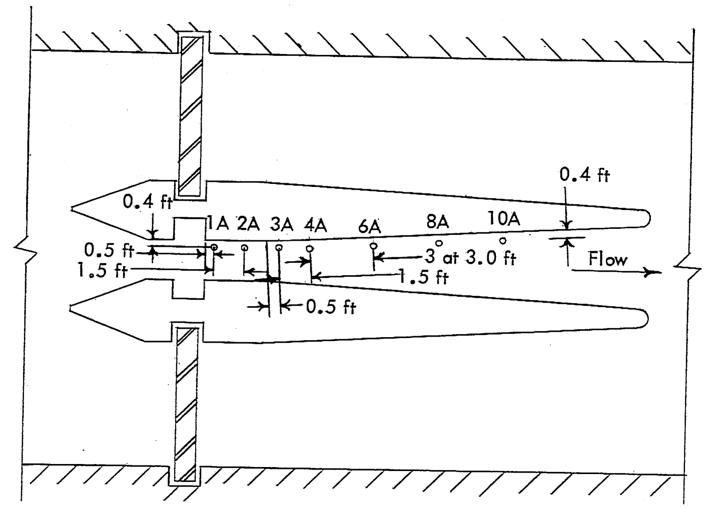

Plan view showing the positions on the floor of the control structure at which pressures were measured

Notes:

1. Center gate open, outside gates closed, no air vent in air collector.
2. Pressures were measured by using piezometers at positions shown in sketch, 0.4 ft from pier wall.
3. Tailwater elevation is the minimum found on Harza sketch 380-SKC-139.
4. Minimum pressure occurred at location 4A for all gate openings at 50 cfs and for 0.5 ft gate opening at 100 cfs, and at location 6A for all other conditions tested.
5. ΔH across gates ranged up to 53 ft. Large values of ΔH necessitate some weir flow.
6. Minimum pressure of +26.6 ft of water occurred when ΔH = 52.5 ft, Q = 225 cfs, T.W. = 28.8 ft, gate opening = 1.5 ft.

SCHEME B-2

MINIMUM AVERAGE PRESSURE ON FLOOR OF GATE STRUCTURE DOWNSTREAM FROM GATE SLOT WITH ONLY CENTER GATE OPEN

Model Scale 1:38.3

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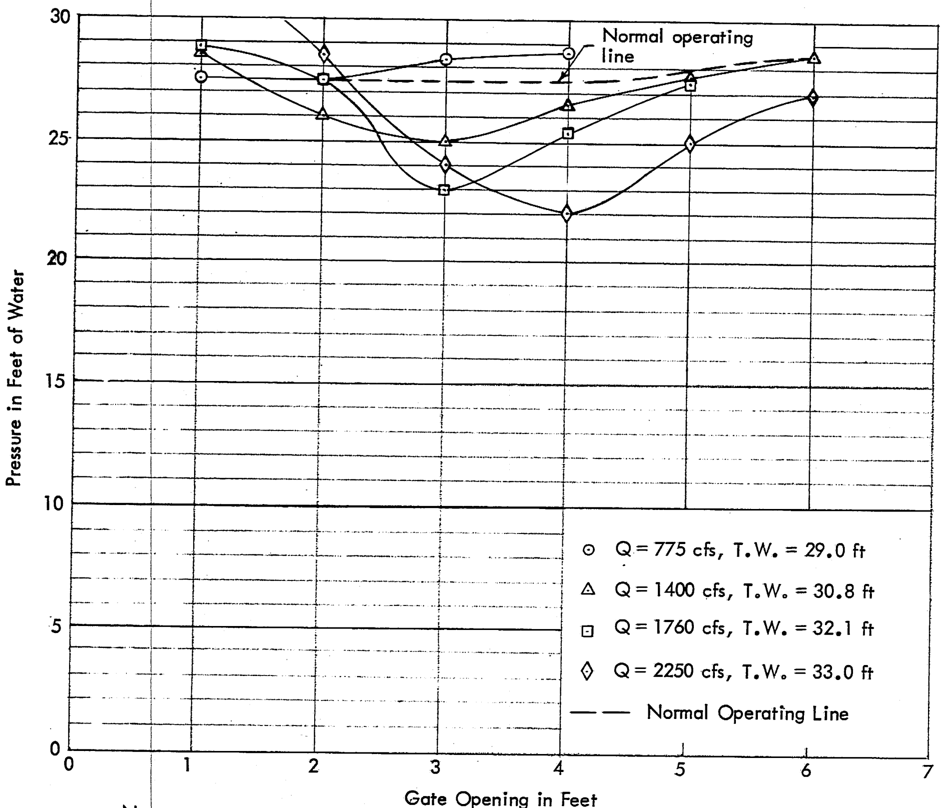

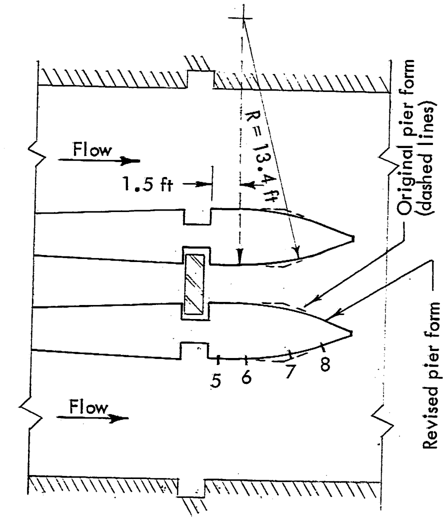

Plan view showing the positions on pier wall at which pressures were measured

Notes:

1. Center gate closed, left and right gates open equally, no vent.
2. Pressures were measured at positions shown in sketch, 0.4 ft above floor of control structure.
3. Tailwater elevation established using Harza sketch 380-SKC-139.
4. Minimum pressure occurred at location 7 for each condition tested.
5. ΔH across gates ranged up to 57 ft. Large values of ΔH necessitate some weir flow.
6. Minimum pressure of 22 ft of water occurred when $\Delta H = 46$ ft, Q = 2250 cfs, T.W. = 33 ft, gate opening = 4 ft.

SCHEME B-1
(Revised Pier Nose)
MINIMUM AVERAGE PRESSURE ON PIER WALL DOWNSTREAM FROM GATE SLOT WITH TWO 6 FT 3 IN. GATES OPERATING

Model Scale 1:38.3

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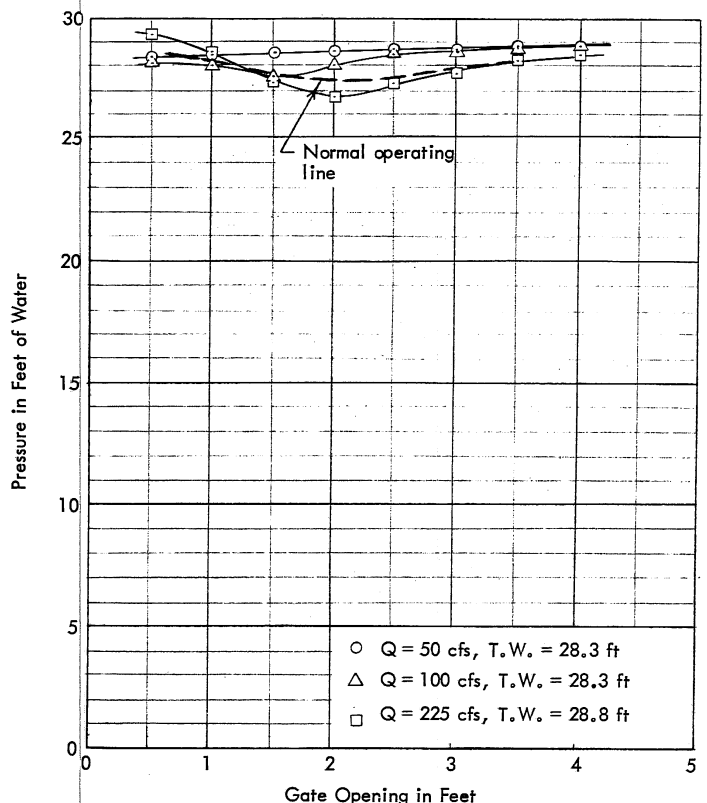
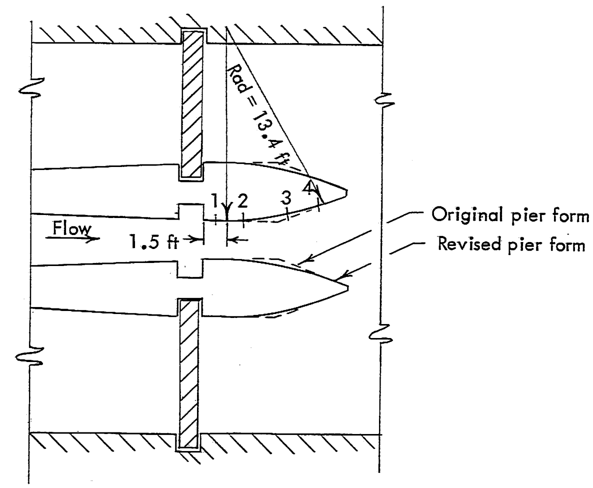
DRAWN JRB	CHECKED DDG	APPROVED
SCALE	DATE 12-27-66	NO. 168-B-459-91





Plan view showing the positions on pier wall at which pressures were measured

SCHEME B-1
(Revised Pier Nose)
MINIMUM AVERAGE PRESSURE ON PIER WALLS WHEN ONLY CENTER GATE IS OPERATING

Model Scale 1:38.3

Notes:

1. Side gates closed, center gate open, no vents.
2. Pressures were measured at positions shown in sketch, 0.4 ft above floor of control structure.
3. Tailwater elevation established using Harza sketch 380-SKC-139.
4. ΔH across gates ranged up to 53.5 ft. Large values of ΔH necessitate some weir flow.
5. Minimum pressure of 26.7 ft of water occurred when $\Delta H = 52.2$ ft, Q = 225 cfs, T.W. = 28.8 ft, gate opening = 2 ft.

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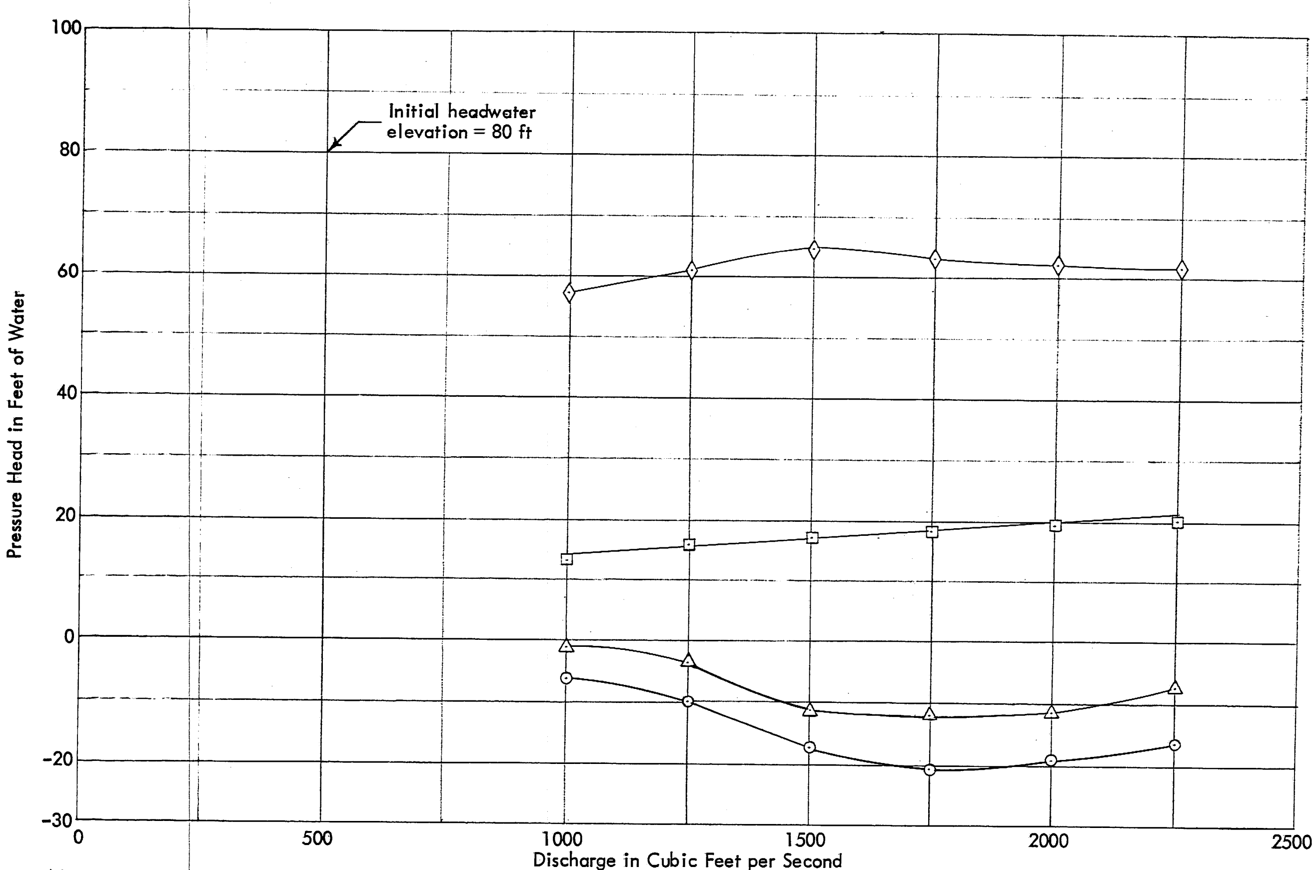
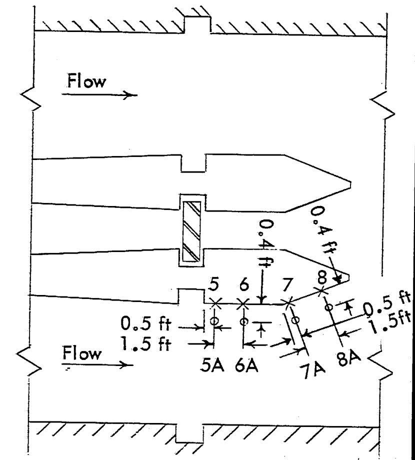
SCALE	DATE 12-28-66	NO. 168-B-459-93





Plan view showing the positions on pier wall and on floor of control structure at which pressures were measured.

○ Pressure at location 7

△ Pressure at location 7A

□ D. S. Submergence after sweepout

◊ H. W. Elevation after sweepout

Notes:

1. Center gate closed, left and right gates open equally, no vents.
2. Pressures on pier wall were measured at positions 5, 6, 7, and 8 shown in sketch, 0.4 ft above floor of control structure.
3. Minimum pressure occurred at location 7 for each condition tested.
4. Test procedure was as follows:
   a. A given discharge was established.
   b. The left and right gates were opened equally so that the H.W. = 80 ft.
   c. The D.S. submergence was decreased until sweepout occurred, i.e., until the hydraulic jump was no longer submerged and had moved into the transition downstream from the gates.
   d. Data presented on this drawing were then recorded.
5. Minimum pressure of -20.5 ft of water occurred with a Q = 1750 cfs, D.S. submergence = 18.5 ft, gate opening = 3.1 ft.

SCHEME B-1
MINIMUM AVERAGE PRESSURE ON PIER WALL AND ON FLOOR OF GATE STRUCTURE DOWNSTREAM FROM GATE SLOT WITH OUTSIDE GATES OPERATING

Model Scale 1:38.3

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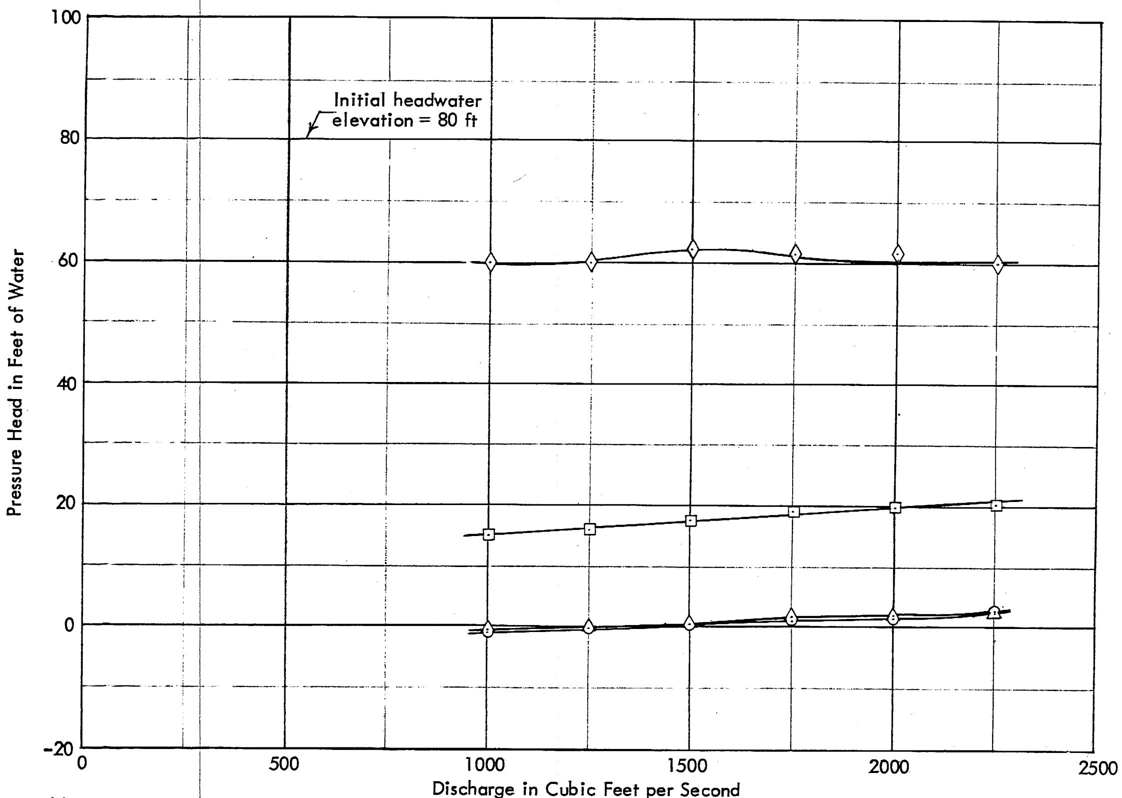
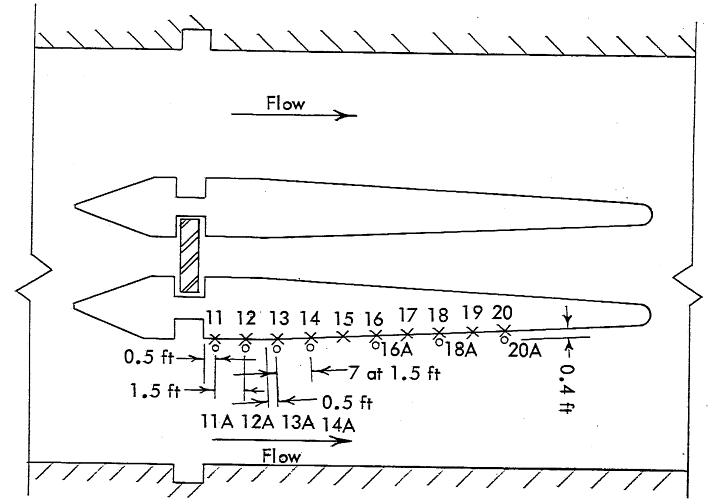
DRAWN JRB	CHECKED DJa	APPROVED
SCALE	DATE 8-15-66	NO. 168-B-459-53R1





Plan view showing the positions on the pier wall and on the floor of the control structure at which pressures were measured

○ Minimum pressures on floor

△ Minimum pressures on pier

□ D. S. Submergence at sweepout

◇ H. W. Elevation after sweepout

Notes:

1. Center gate closed, left and right gates open equally, no vent in air trap.
2. Pressures were measured by using piezometers at locations 11 through 20 on pier wall 0.4 ft above floor of control structure and at locations 11A, 12A, 13A, 14A, 16A, 18A, and 20A on floor of control structure 0.4 ft from pier wall.
3. Minimum pressure occurred at locations 13 and 13A for discharges up to and including 1500 cfs and at locations 20 and 16A for discharges greater than 1500 cfs.
4. Test procedure was as follows:
   a. A given discharge was established.
   b. The left and right gates were opened equally so that the H.W. = 80 ft.
   c. The D.S. submergence was decreased until sweepout occurred, i.e., until the hydraulic jump was no longer submerged and had moved into the transition downstream from the gates.
   d. Data presented on this drawing were then recorded.
5. Minimum pressure of -1.0 ft of water occurred when Q = 1000 cfs, D.S. submergence = 15 ft, gate opening = 1.8 ft.

SCHEME B-2
MINIMUM AVERAGE PRESSURE AT POINT OF SWEEPOUT ON PIER WALL AND ON FLOOR OF GATE STRUCTURE DOWNSTREAM FROM GATE SLOT WITH OUTSIDE GATES OPERATING

Model Scale 1:38.3

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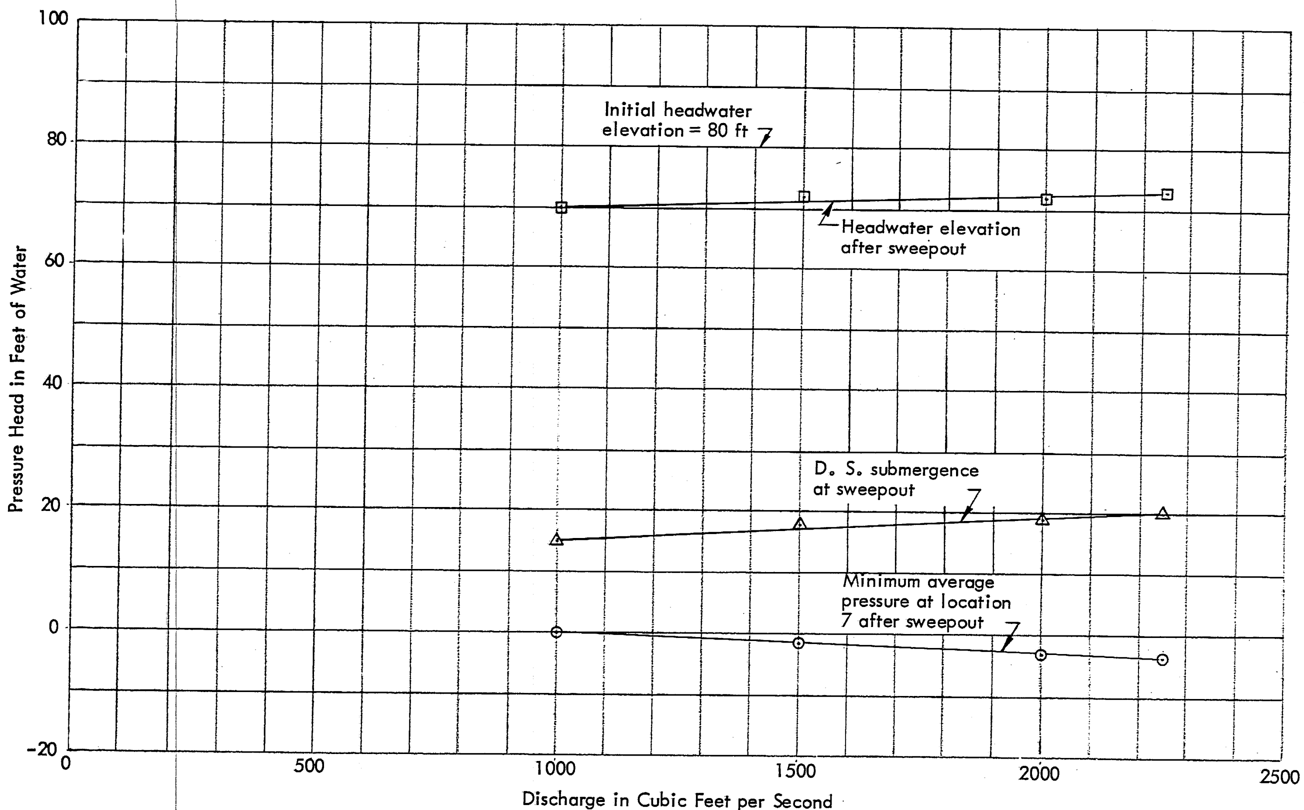
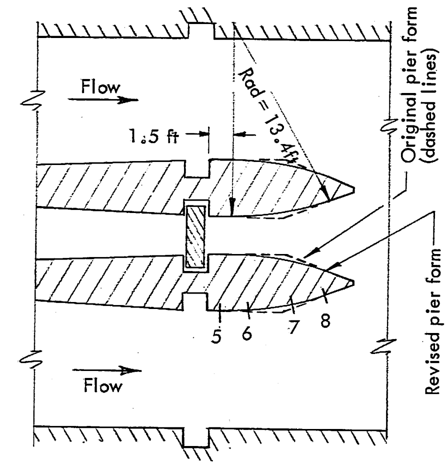
DRAWN DJA	CHECKED RMK	APPROVED
SCALE	DATE 8-18-66	NO. 168-B-459-71





Plan view showing the positions on pier wall at which pressures were measured

Notes:

1. Center gate closed, left and right gates open equally, no vents.
2. Pressures were measured at positions shown in sketch, 0.4 ft above floor of control structure.
3. Minimum pressure occurred at location 7 for each condition tested.
4. Test procedure was as follows:
   a. A given discharge was established.
   b. The left and right gates were opened equally so that the H.W. elev. = 80 ft.
   c. The D.S. submergence was decreased until sweepout occurred, i.e. until the hydraulic jump was no longer submerged and had moved into the transition downstream from the gates.
   d. Data presented on this drawing were then recorded.
5. Minimum pressure of -3.5 ft of water occurred with Q = 2250 cfs, D.S. submergence = 20 ft, gate opening = 3.5 ft.

SCHEME B-1
(Revised Pier Nose)
MINIMUM AVERAGE PRESSURE ON PIER WALLS WHEN SWEEPOUT OCCURS

Model Scale 1:38.3

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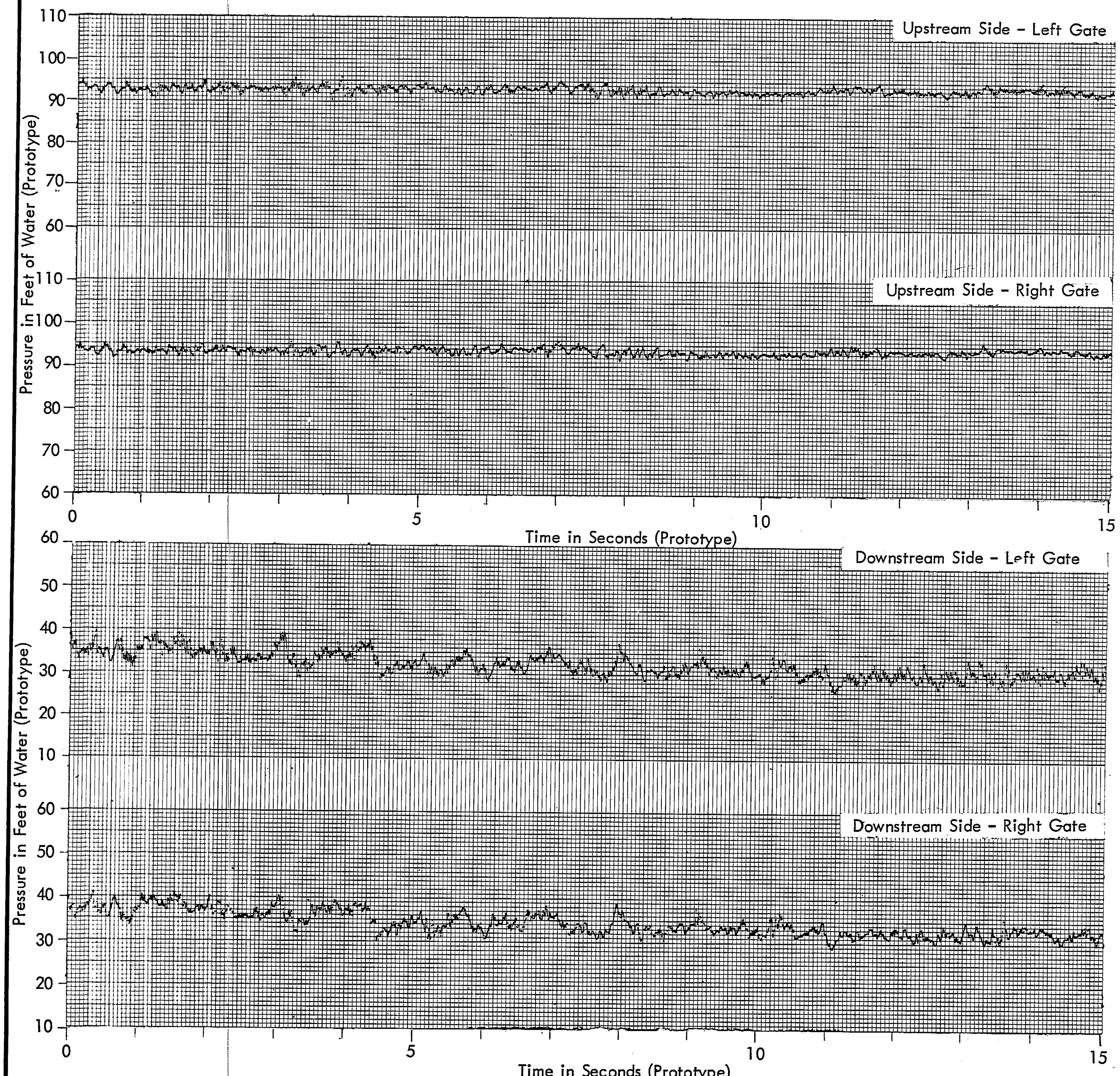
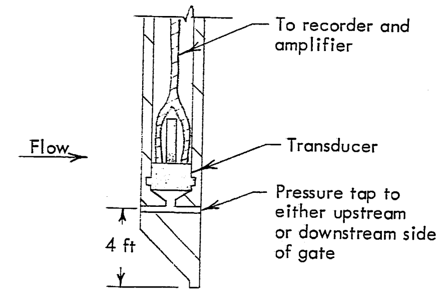
DRAWN RMK	CHECKED AQ	APPROVED
SCALE	DATE 12-27-66	NO. 168-B-459-92

CHART 26





Section view of gate showing transducer location

Notes:

1. Transducers used were 2.5 psi C.E.C., chamber mounted type.
2. Gates closed, flow over the weir.
3. The records at left show the similarity of pressure patterns recorded simultaneously on either the upstream or downstream side of the two outside gates.

SIMULTANEOUS PRESSURES ON THE TWO OUTSIDE GATES

Q = 2250 cfs
D.S. Submergence = 35 ft
H.W. Elev. = 93 ft
Gate Opening = 0%

Model Scale 1:38.3

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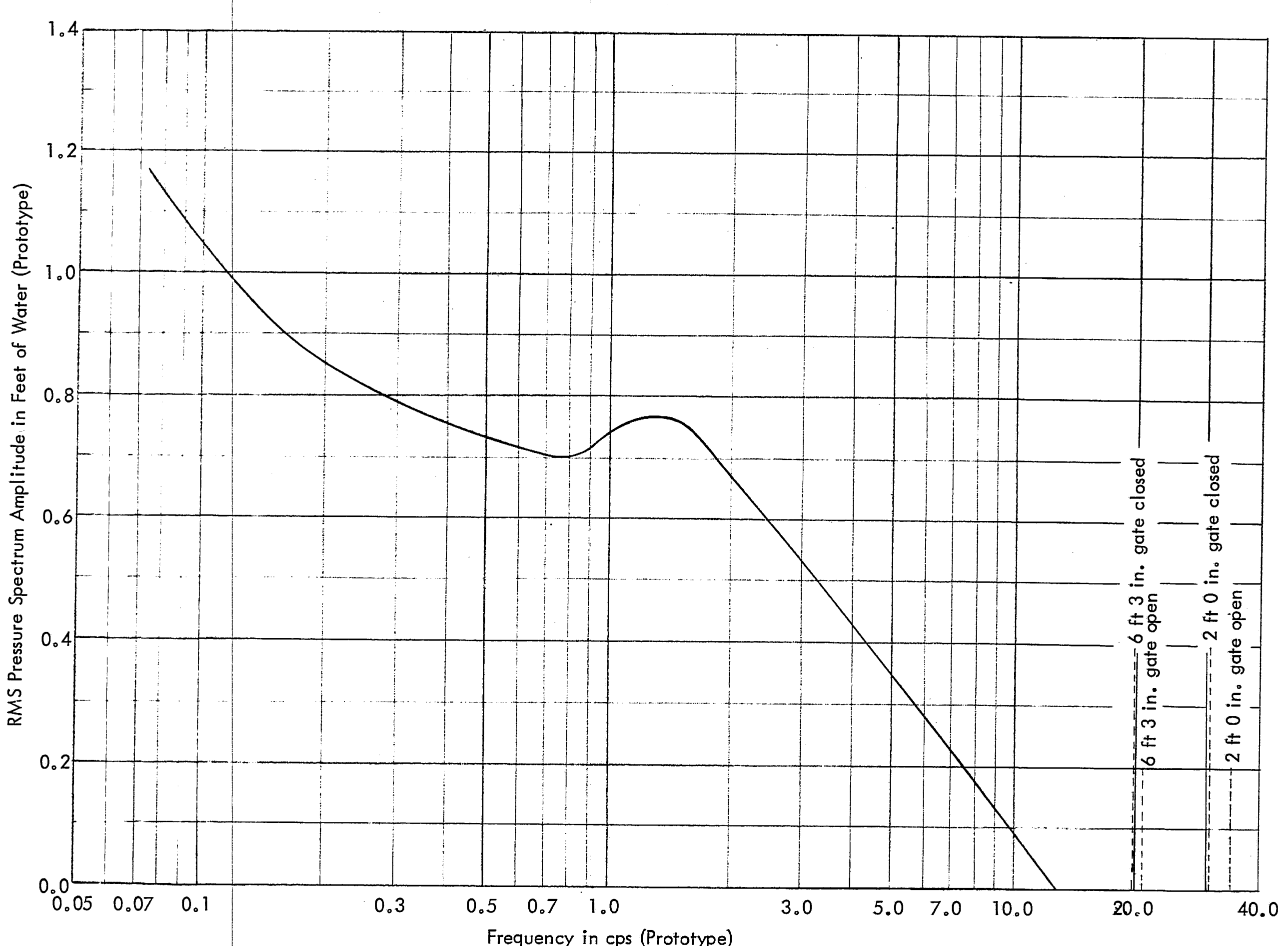
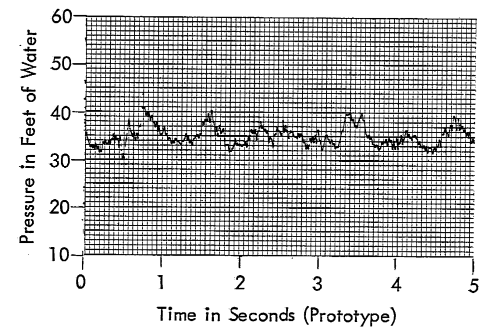
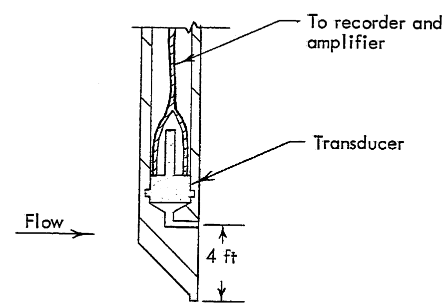
SCALE	DATE 1-11-67	NO. 168-B-459-96





Typical record of pressure fluctuations



Sketch of gate showing transducer location

HARMONIC WAVE ANALYSIS OF THE PRESSURE PULSES OCCURRING ON THE DOWNSTREAM SIDE OF THE GATE

Q = 2250 cfs
Gate Opening = 0%
D.S. Submergence = 35 ft

Model Scale 1:38.3

Notes:

1. Transducers used were 2.5 psi C.E.C., chamber mounted type.
2. Gates closed, flow over the weir.
3. The transducer was mounted so as to record fluctuating pressures 4 ft above the bottom of the gate.
4. The spectrum was obtained by analysis of records similar to that shown (above right). The graph above is a plot of the Root Mean Square of the amplitude of the various pressure pulses which occur on the face of the gate in terms of the frequency with which these pulses occur.
5. Dashed lines on graph indicate natural frequency of gates as designed by Harza Engineering Co. and shown on Harza drawings 380-SKC-165 and 166.

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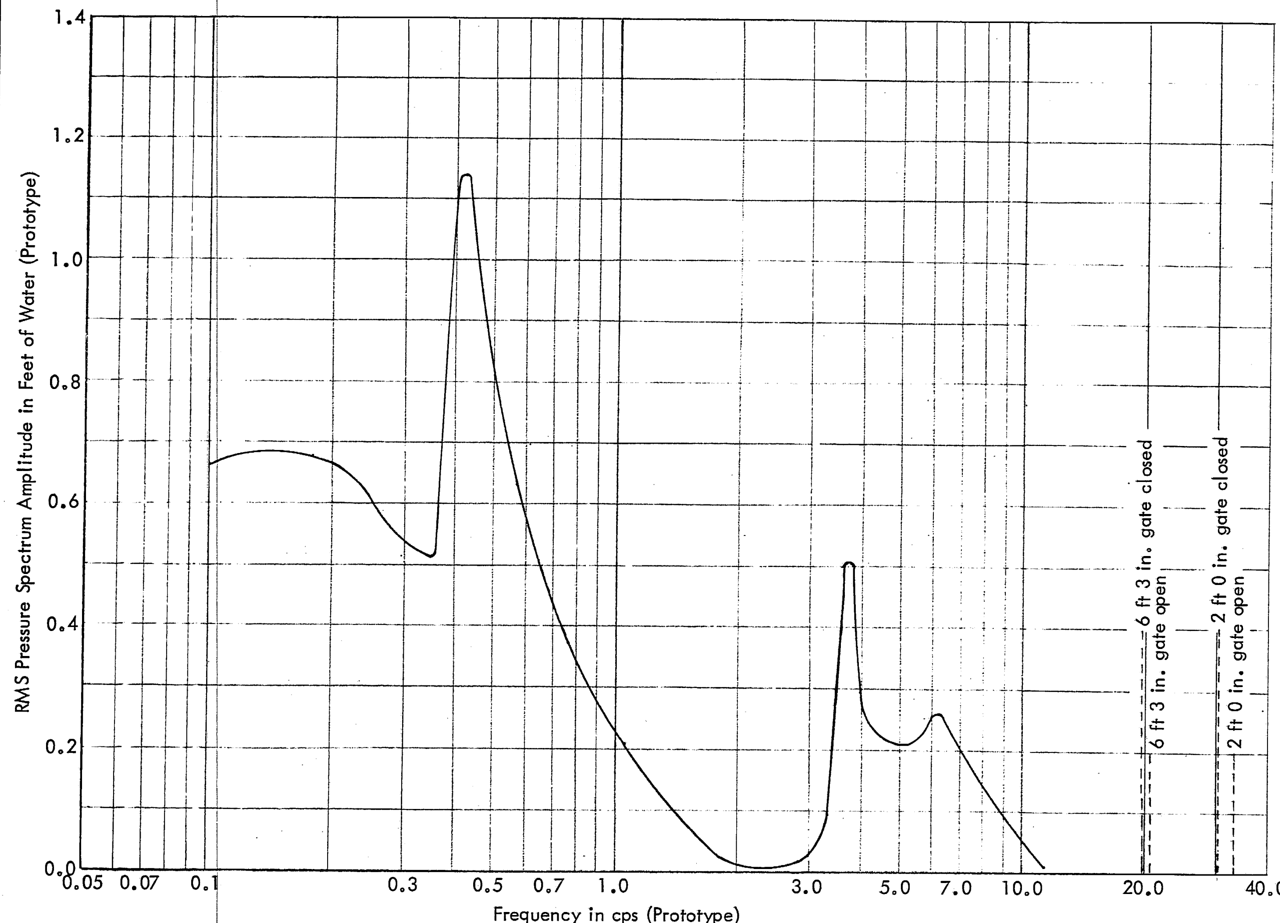
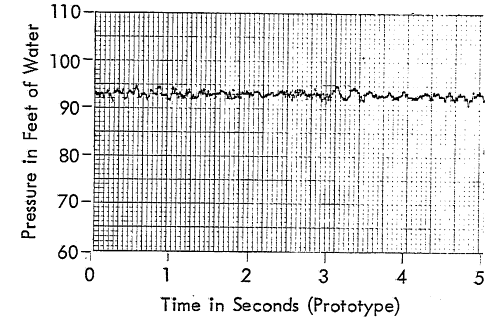
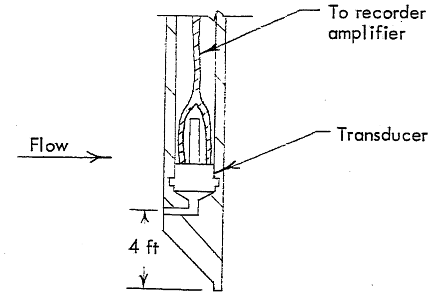
DRAWN DJA	CHECKED RMK	APPROVED
SCALE	DATE 1-10-67	NO. 168-B-459-95





Typical record of pressure fluctuations



Sketch of gate showing transducer location

HARMONIC WAVE ANALYSIS OF THE PRESSURE PULSES OCCURRING ON THE UPSTREAM SIDE OF THE GATE

Q = 2250 cfs
Gate Opening = 0%
D.S. Submergence = 35 ft
Model Scale 1:38.3

Notes:

1. Transducers used were 2.5 psi C.E.C., chamber mounted type.
2. Gates closed, flow over the weir.
3. The transducer was mounted so as to record fluctuating pressures 4 ft above the bottom of the gate.
4. The spectrum was obtained by analysis of records similar to that shown (above right). The graph above is a plot of the Root Mean Square of the amplitude of the various pressure pulses which occur on the face of the gate in terms of the frequency with which these pulses occur.
5. Dashed lines on graph indicate natural frequency of gates as designed by Harza Engineering Co. and shown on Harza drawings 380-SKC-165 and 166.

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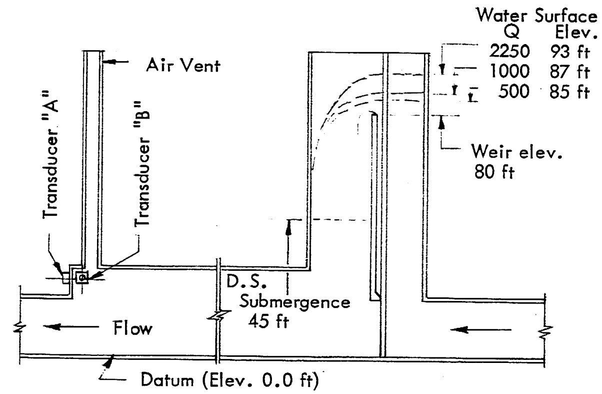
DRAWN DJA	CHECKED RMK	APPROVED
SCALE	DATE 1-10-67	NO. 168-B-459-94



Side view of structure showing location of pressure transducers

Notes:

1. Transducers used were 2.5 psi C.E.C., chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. In this test, the period and magnitude of pressure pulses were measured for 3 different discharges with constant d.s. submergence.

Discharge (cfs)	500	1000	2250
Period (Seconds)	17	10	6.4
Maximum magnitude of pressure pulses (ft water)	16	62	90

VARIATION OF FLUCTUATING PRESSURES NEAR AIR VENT IN B-1 STRUCTURE DUE TO VARIED DISCHARGE
Q = 500, 1000, 2250 cfs
D.S. Submergence = 45 ft
Gate Opening = 0%
Model Scale 1:38.3

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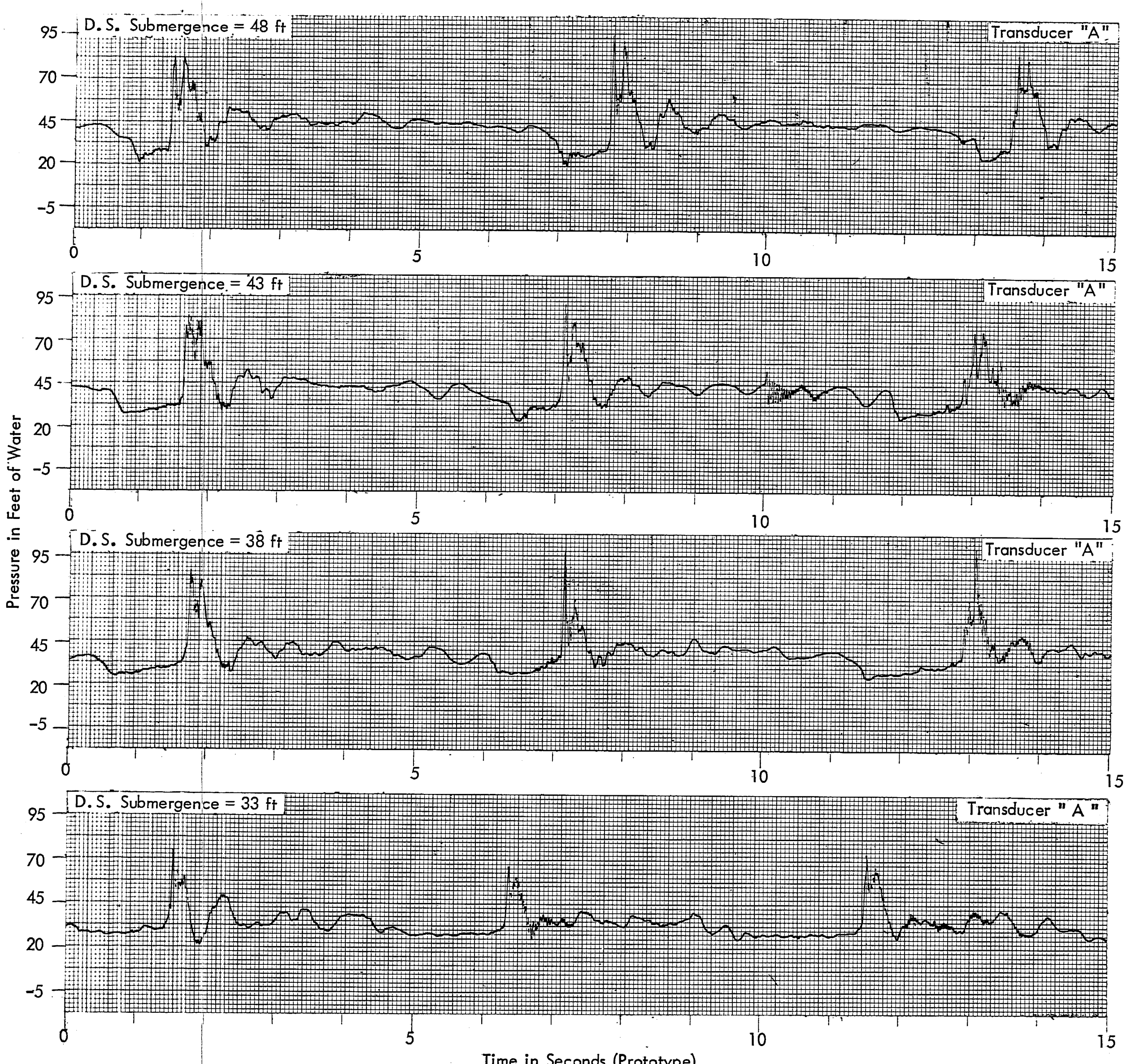
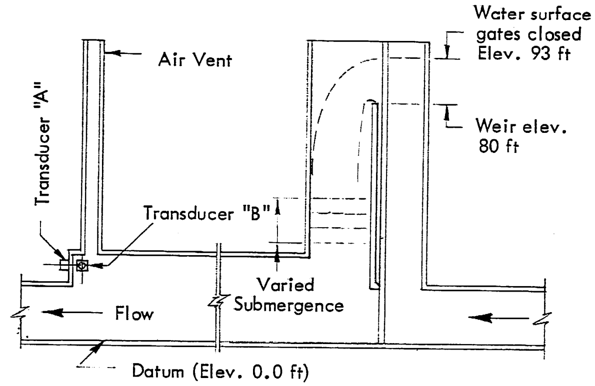
SCALE	DATE 5-5-66	NO. 168-B-459-34





Side view of structure showing location of pressure transducers

Notes:

1. Transducers used were 2.5 psi C.E.C., chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. In this test, the downstream submergence was varied, causing a difference in period and magnitude of pulses.

D.S. Submergence	33 ft	38 ft	43 ft	48 ft
Ave. Period (in seconds)	5.3	5.6	5.9	6.4
Maximum magnitude of pulses (ft water)	58	75	75	90

VARIATION OF FLUCTUATING PRESSURES NEAR AIR VENT OF B-1 STRUCTURE DUE TO CHANGE IN D.S. SUBMERGENCE

Q = 2250 cfs
Gate Opening = 0%
D.S. Submergence: 33 ft to 48 ft
Model Scale 1:38.3

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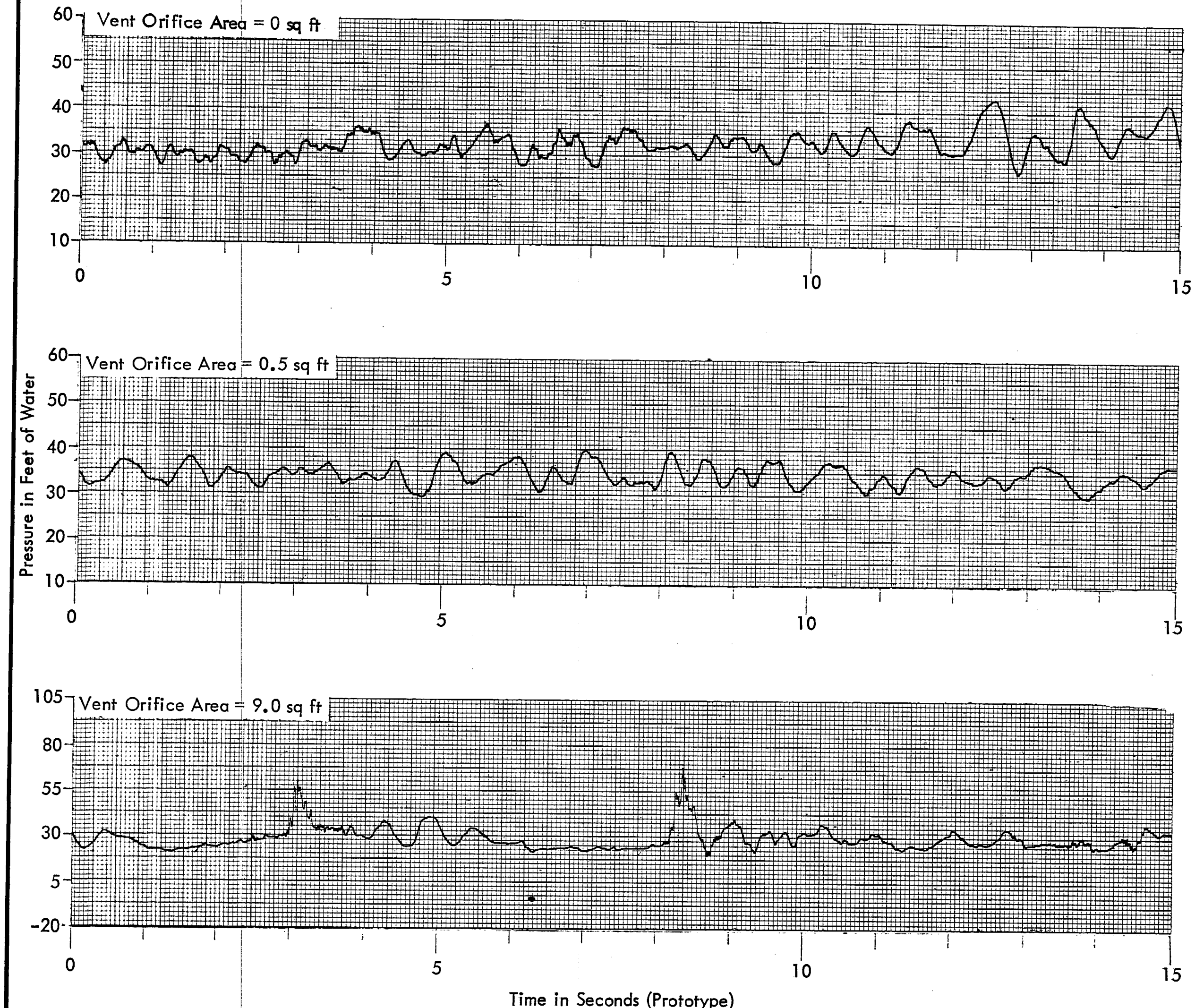

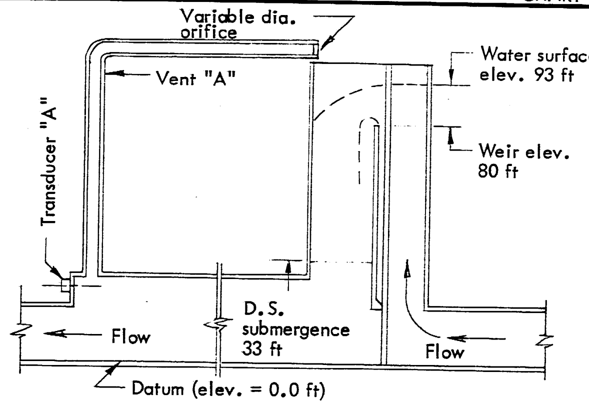

Side view of structure showing location of transducer and vent

Notes:

1. Transducer used was a 2.5 psi C.E.C. chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. The reduction in vent area causes a higher pressure air pocket in the trap. This pressurized air reduces the turbulence in the trap and thus reduces the magnitude of the pulses.

Vent area (sq ft, proto.)	0	0.1	0.25	0.5	1.0	2.0	4.5	9.0
Max. pressure pulse (ft water)	21	13	13	14	18	26	42	58

COMPARISON OF FLUCTUATING DYNAMIC PRESSURES IN AIR TRAP OF B-1 STRUCTURE WITH VARIATION OF VENT CROSS-SECTIONAL AREA

Q = 2250 cfs
D.S. Submergence = 33 ft
Gate Opening = 0%
Model Scale 1:38.3

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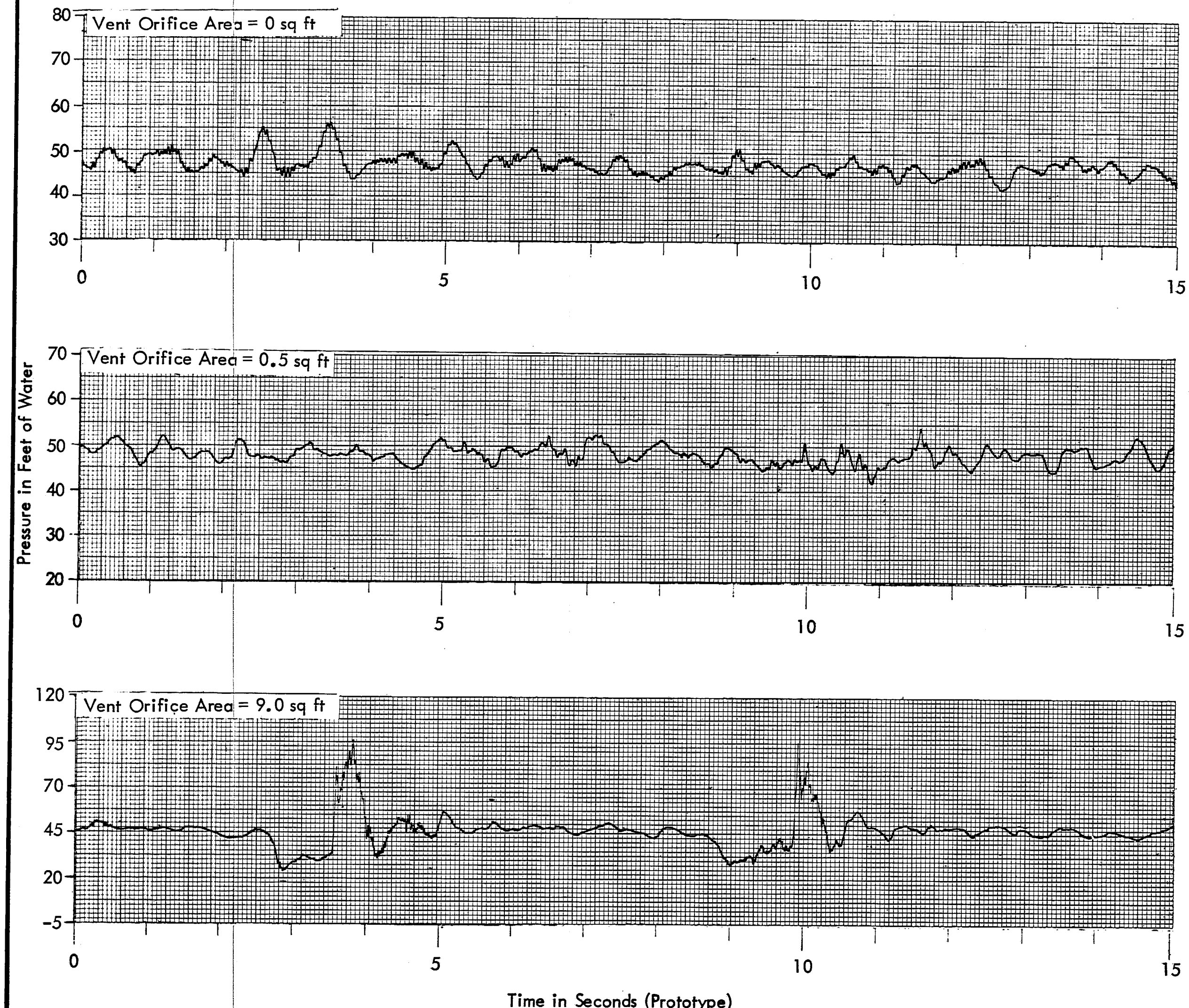

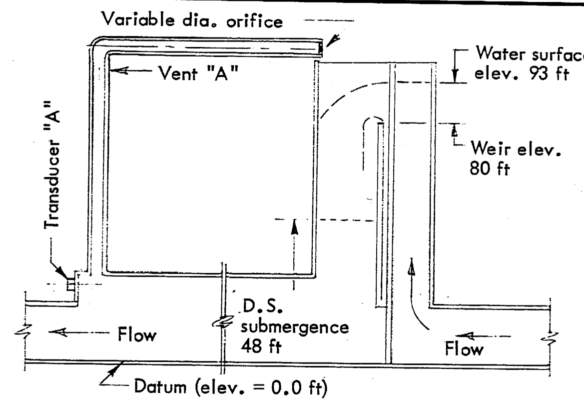

Side view of structure showing location of transducer and vent

Notes:

1. Transducer used was a 2.5 psi C.E.C. chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. The reduction in vent area causes a higher pressure air pocket in the trap. This pressurized air reduces the turbulence in the trap and thus reduces the magnitude of the pulses.

Vent area (sq ft, proto.)	0	0.1	0.25	0.5	1.0	2.0	4.5	9.0
Max. pressure pulse (ft water)	20	12	12	16	26	57	78	90

COMPARISON OF FLUCTUATING DYNAMIC PRESSURES IN AIR TRAP OF B-1 STRUCTURE WITH VARIATION OF VENT CROSS-SECTIONAL AREA

Q = 2250 cfs
D.S. Submergence = 48 ft
Gate Opening = 0%
Model Scale 1:38.3

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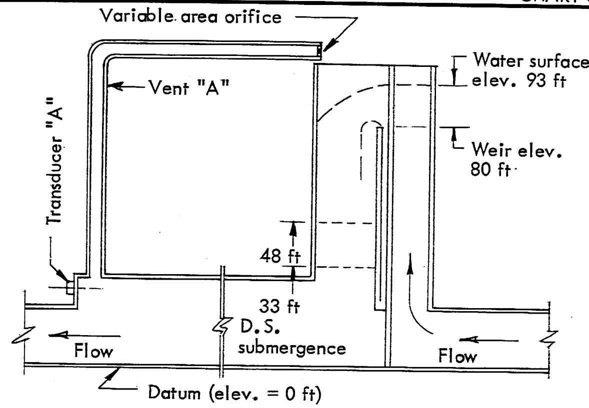
SCALE	DATE 6-28-66	NO. 168-B-459-50

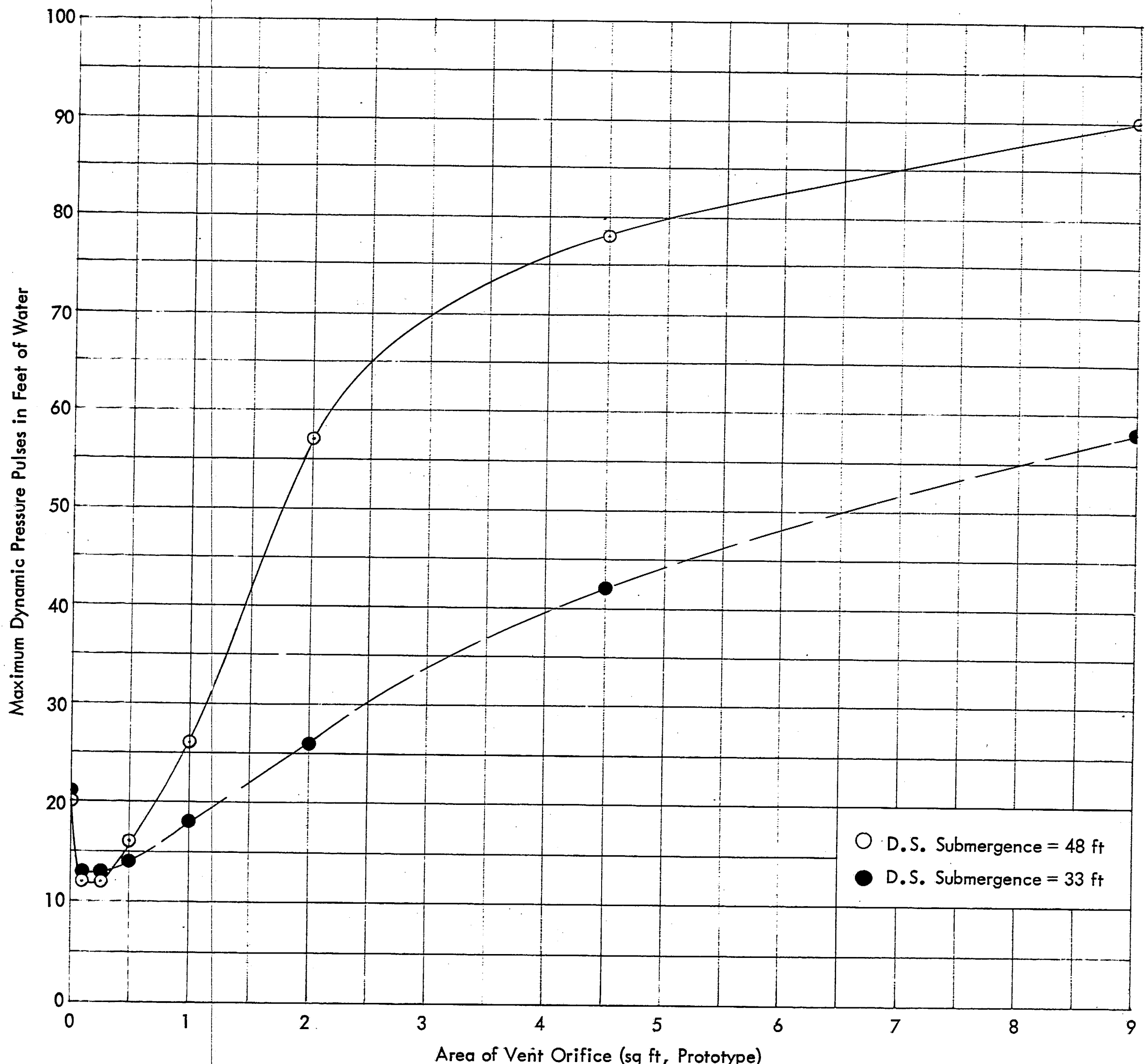
CHART 33



Side view of structure showing location of transducer and vent

Notes:

1. Dynamic pressures were measured with 2.5 psi C.E.C. transducers, chamber mounted type.
2. Vent area was varied by installing assorted dia. orifices at the end of the vent tube.
3. With the gates closed and flow over the weir, air is entrained. Air escaping through the vent causes dynamic pressure oscillations. With the use of a small diameter vent, the escaping air is throttled, causing a higher pressure air pocket at the crown of the trap. The pressurized air pocket reduces fluctuations of the water surface, thus reducing the pressure pulses.



COMPARISON OF FLUCTUATING DYNAMIC PRESSURES IN AIR TRAP OF B-1 STRUCTURE WITH VARIATION OF VENT CROSS-SECTIONAL AREA

Q = 2250 cfs
D.S. Submergence = 33 ft and 48 ft
Gate Opening = 0%
Model Scale 1:38.3

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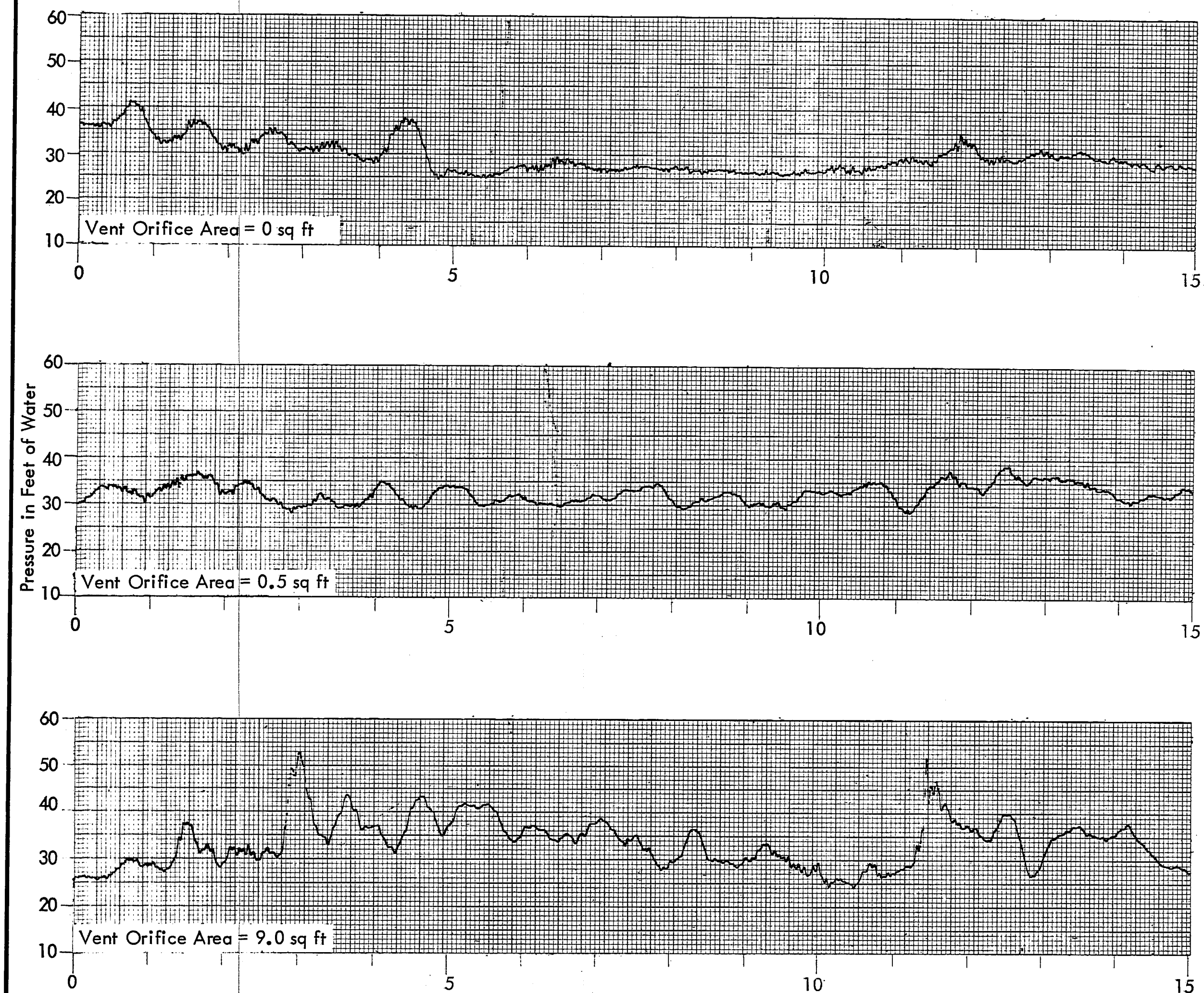
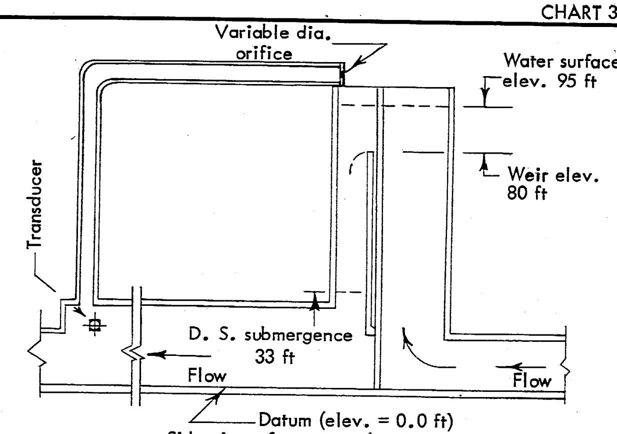
SCALE	DATE 6-30-66	NO. 168-B-459-51





Side view of structure showing location of transducer and vent

Note: The average value of the fluctuating pressures on the recordings does not always agree with the d.s. submergence noted because of the presence of long period surges d.s. of the gates. See Drawing No. 168-B-459-72 for details.

Notes:

1. Transducer used was a 2.5 psi C.E.C. chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. The reduction in vent area causes a higher pressure in the trap. This pressurized air reduces the turbulence in the trap and thus reduces the magnitude of the pulses.

Vent area (sq ft, proto.)	0	0.25	0.5	1.0	2.0	4.5	9.0
Max. pressure pulse (ft water)	13	10	10	15	18	27	27

COMPARISON OF FLUCTUATING DYNAMIC PRESSURES IN AIR TRAP OF B-2 STRUCTURE WITH VARIATION OF VENT CROSS-SECTIONAL AREA

Q = 2250 cfs
D.S. Submergence = 33 ft
Gate Opening = 0%
Model Scale 1:38.3

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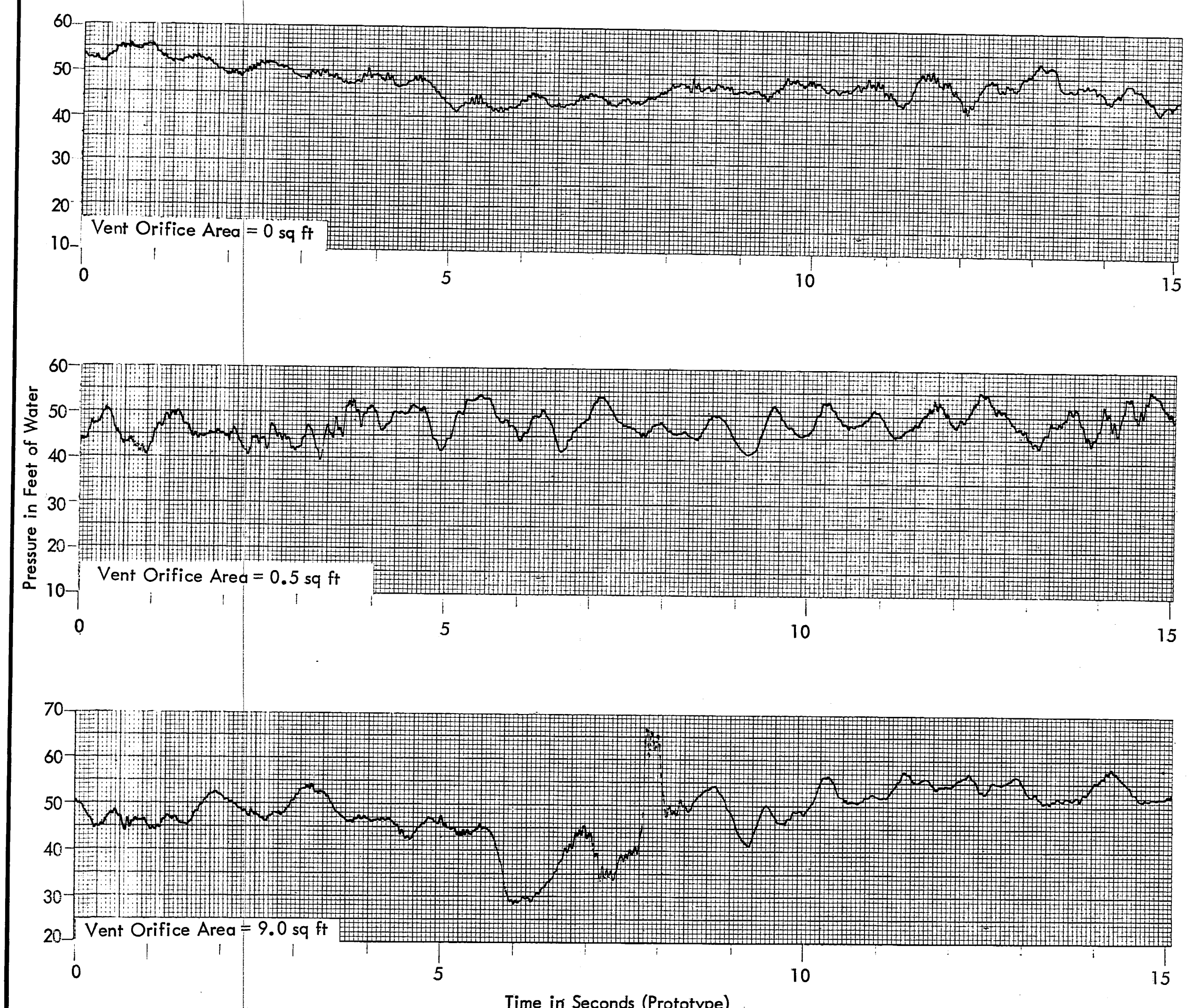
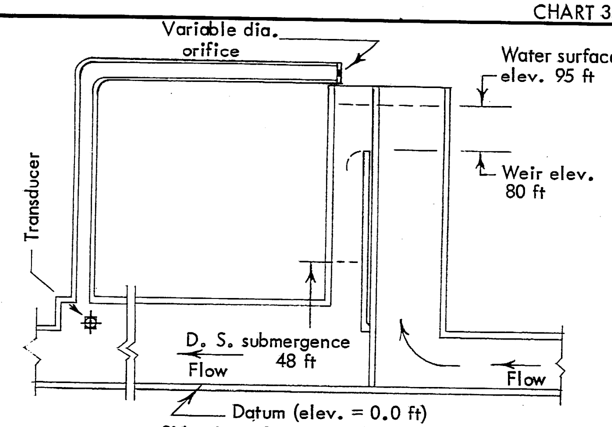
SCALE	DATE 8-2-66	NO. 168-B-459-64



Note: The average value of the fluctuating pressures on the recordings does not always agree with the d.s. submergence noted because of the presence of long period surges d.s. of the gates. See Drawing No. 168-B-459-72 for details.



Side view of structure showing location of transducer and vent

Notes:

1. Transducer used was a 2.5 psi C.E.C. chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. The reduction in vent area causes a higher pressure in the trap. This pressurized air reduces the turbulence in the trap and thus reduces the magnitude of the pulses.

Vent area (sq ft, proto.)	0	0.25	0.5	1	2	4.5	9.0
Max. pressure pulse (ft water)	13	15	16	24	36	47	45

COMPARISON OF FLUCTUATING DYNAMIC PRESSURES IN AIR TRAP OF B-2 STRUCTURE WITH VARIATION OF VENT CROSS-SECTIONAL AREA

Q = 2250 cfs
D.S. Submergence = 48 ft
Gate Opening = 0%
Model Scale 1:38.3

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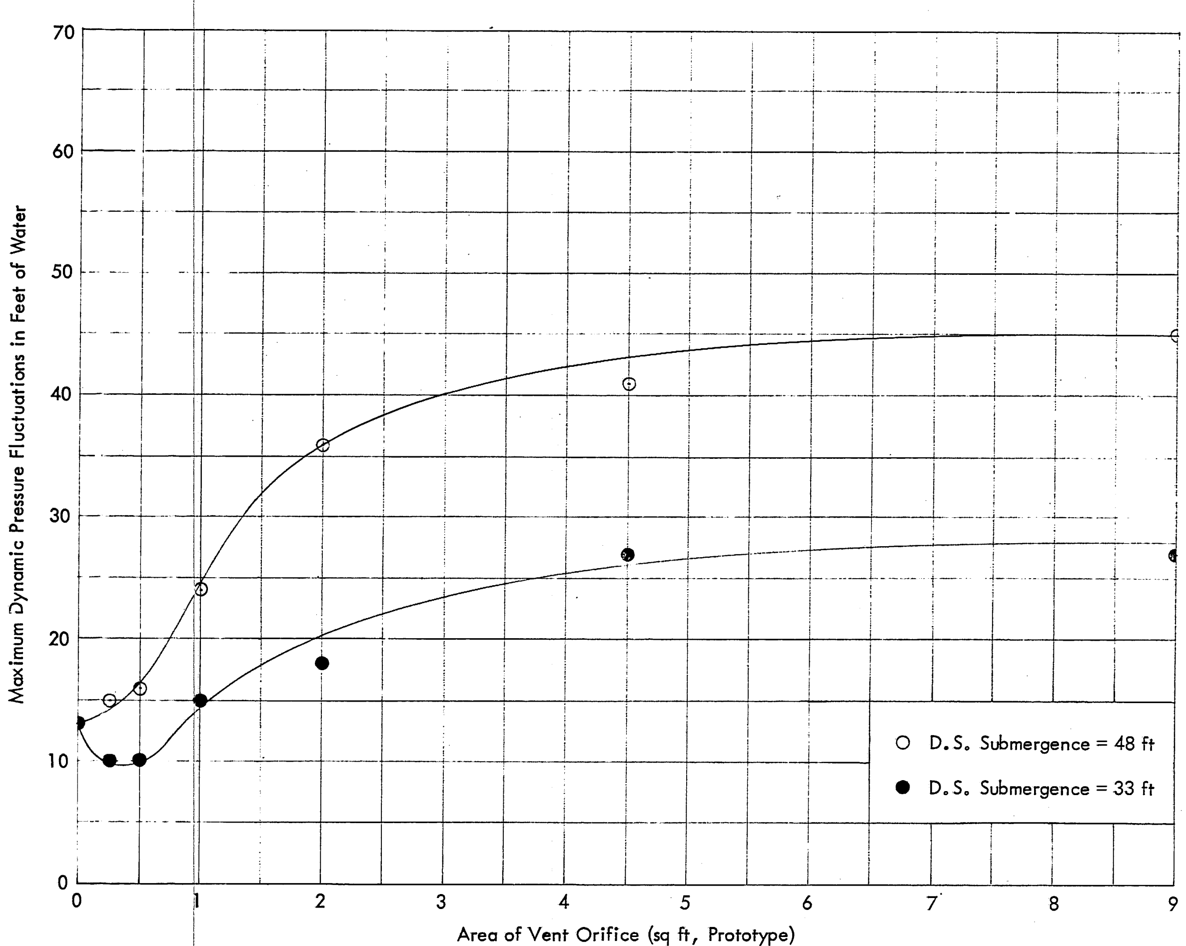
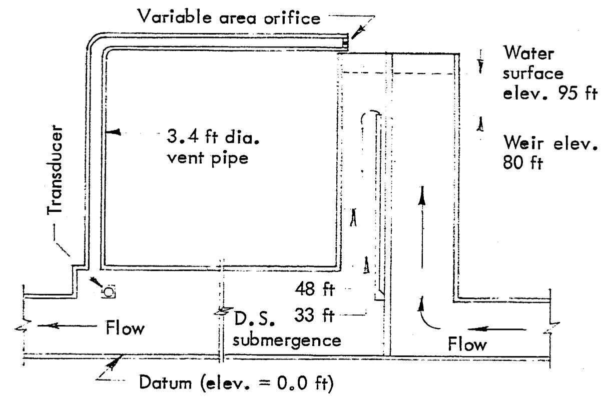
DRAWN DJA	CHECKED RMK	APPROVED
SCALE	DATE 8-2-66	NO. 168-B-459-65





Side view of structure showing location of transducer and vent

Notes:

1. Dynamic pressures were measured with 2.5 psi C.E.C. transducers, chamber mounted type.
2. Vent area was varied by installing assorted dia. orifices at the end of the vent tube.
3. With the gates closed and flow over the weir, air is entrained. Air escaping through the vent causes dynamic pressure oscillations. With the use of a small diameter vent, the escaping air is throttled, causing a higher pressure air pocket at the crown of the trap. The pressurized air pocket reduces fluctuations of the water surface, thus reducing the pressure pulses.

COMPARISON OF FLUCTUATING DYNAMIC PRESSURES IN AIR TRAP OF B-2 STRUCTURE WITH VARIATION OF VENT CROSS-SECTIONAL AREA

Q = 2250 cfs
D.S. Submergence = 33 ft and 48 ft
Gate Opening = 0%
Model Scale 1:38.3

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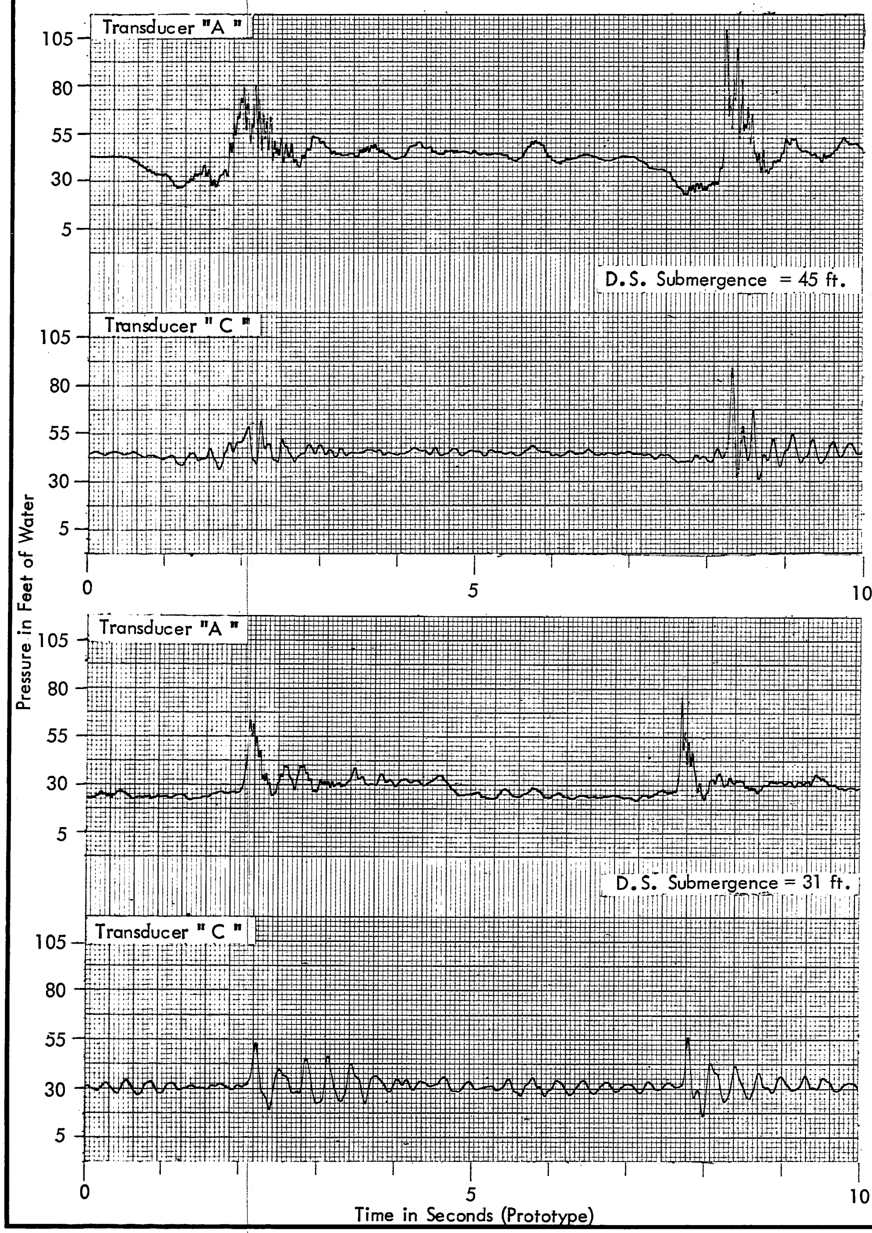
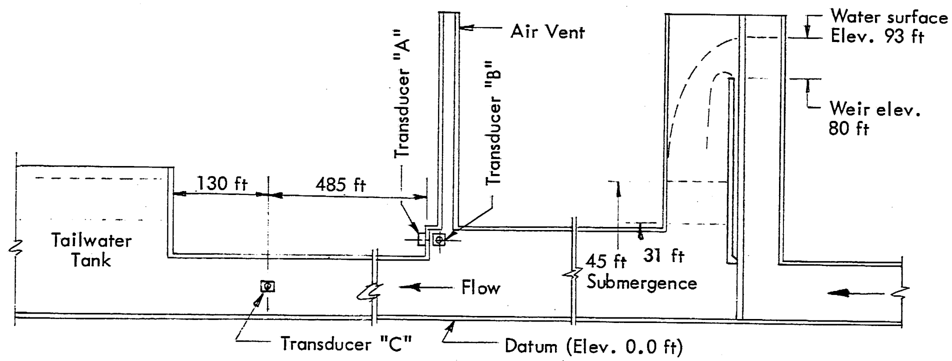
SCALE	DATE 8-2-66	NO. 168-B-459-66





Side view of structure showing location of transducers

Notes:

1. Transducers used were 2.5 psi C.E.C., chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. In this test a transducer was installed 485 ft (prototype) downstream of the air trap near the tailwater tank. Objective of the test was to check pressure fluctuations at this point and phase relationship relative to fluctuations near air vent (transducer "A").
4. Pressures were in phase within a small fraction of a second but decreased in magnitude with distance from the vent. Apparently there were no significant fluctuations due to small amount of air entering tailwater tank.

COMPARISON OF FLUCTUATING PRESSURES NEAR AIR VENT WITH DOWNSTREAM PRESSURES IN B-1 STRUCTURE

Q = 2250 cfs
Gate Opening = 0%
D.S. Submergence = 31 ft and 45 ft

Model Scale 1:38.3

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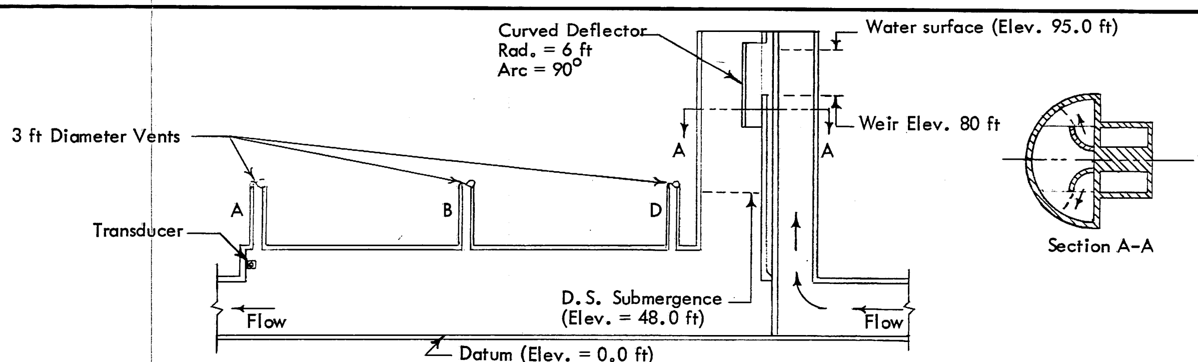
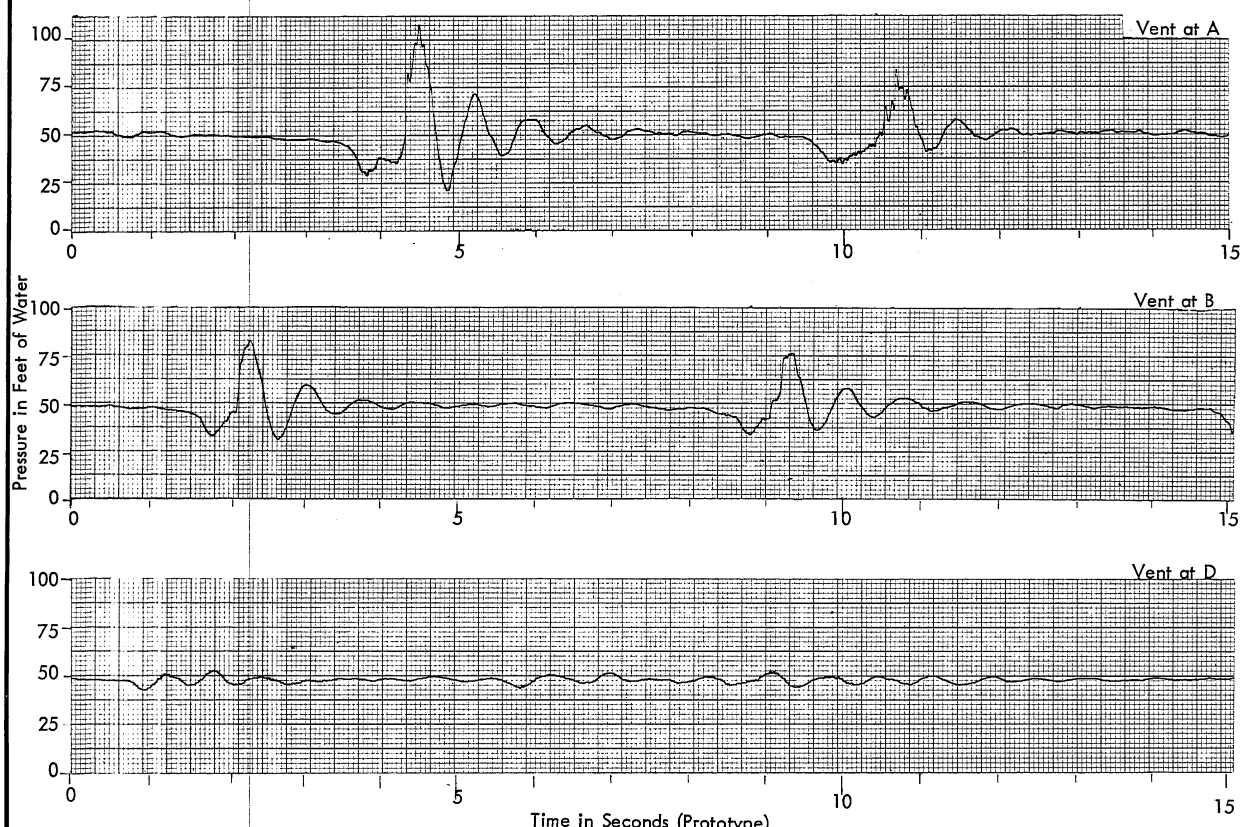
DRAWN RMK	CHECKED	APPROVED
SCALE	DATE 5-5-66	NO. 168-B-459-36



Side View of Structure



Vent Position	Dist. Downstream from Gate (ft)	Maximum Pulse (ft water)	Period (sec)
A	170	82	6
B	100	77	6
D	35	15	-

Notes:

1. Transducers used were 2.5 psi C.E.C., chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. In this test, the position of the 3 ft diameter vent was changed in order to find that vent location which will cause the smallest pressure oscillations.

VARIATION OF FLUCTUATING PRESSURES NEAR DOWNSTREAM END OF AIR TRAP OF B-1 STRUCTURE WITH DEFLECTORS DUE TO CHANGE IN VENT LOCATION

Q = 2250 cfs
D.S. Submergence = 48 ft
H.W. = 95 ft
Gate Opening = 0%
Model Scale 1:38.3

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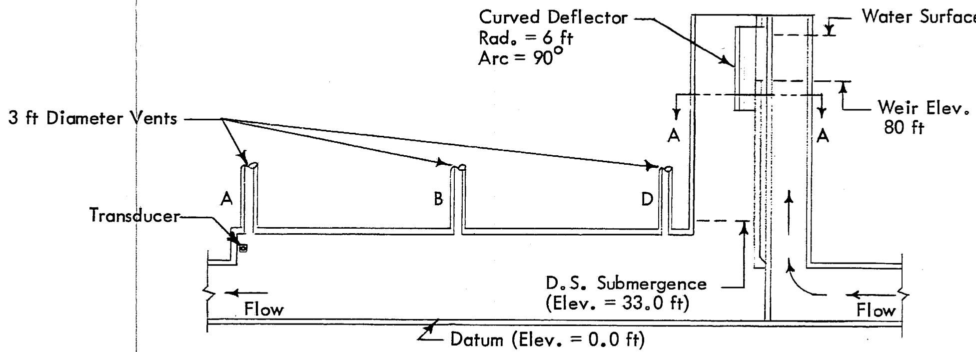
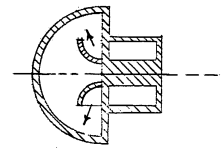
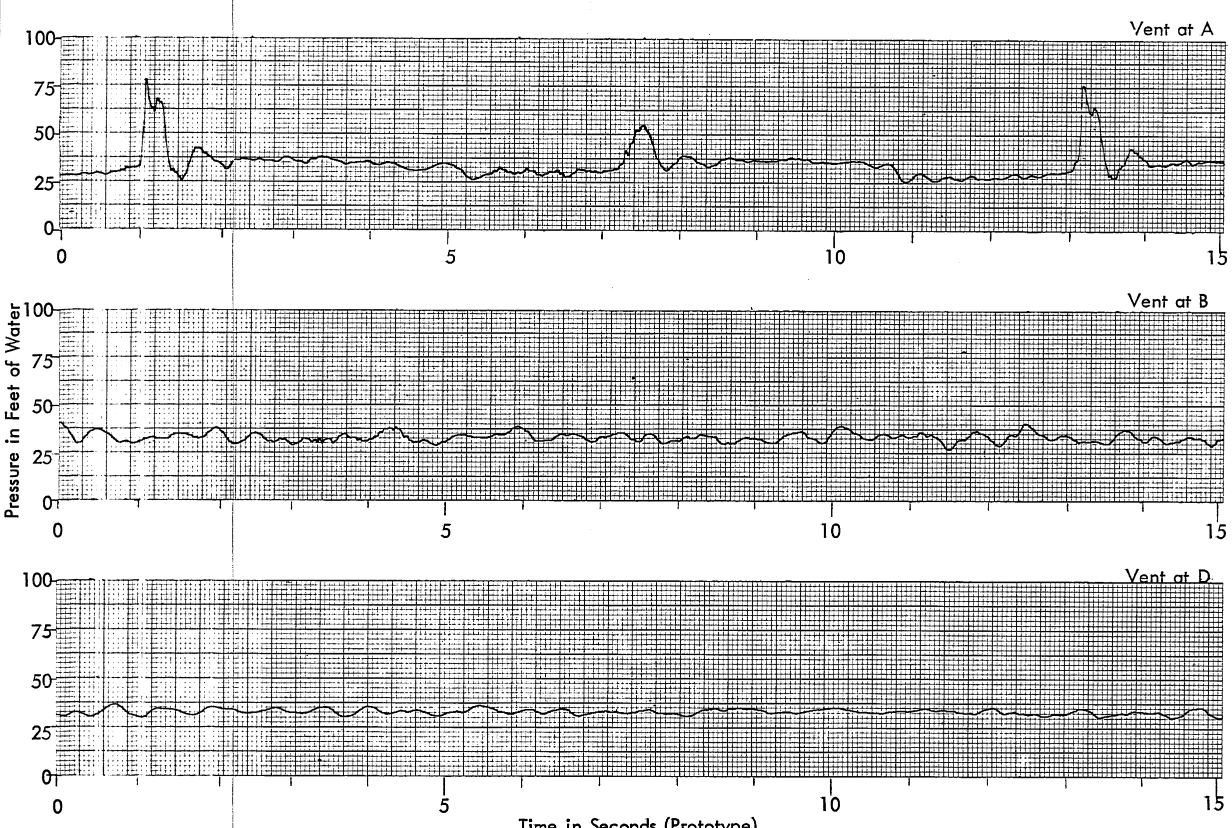
DRAWN JRB	CHECKED DVA	APPROVED
SCALE	DATE 9-1-66	NO. 168-B-459-80





Section A-A

Vent Position	Dist. Downstream from Gate (ft)	Maximum Pulse (ft water)	Period (sec)
A	170	62	6
B	100	12.5	-
D	35	10	-



Notes:

1. Transducers used were 2.5 psi C.E.C., chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. In this test, the position of the 3 ft diameter vent was changed in order to find that vent location which will cause the smallest pressure oscillations.

VARIATION OF FLUCTUATING PRESSURES NEAR DOWNSTREAM END OF AIR TRAP OF B-1 STRUCTURE WITH DEFLECTORS DUE TO CHANGE IN VENT LOCATION

Q = 2250 cfs
D.S. Submergence = 33 ft
H.W. = 95 ft
Gate Opening = 0%
Model Scale 1:38.3

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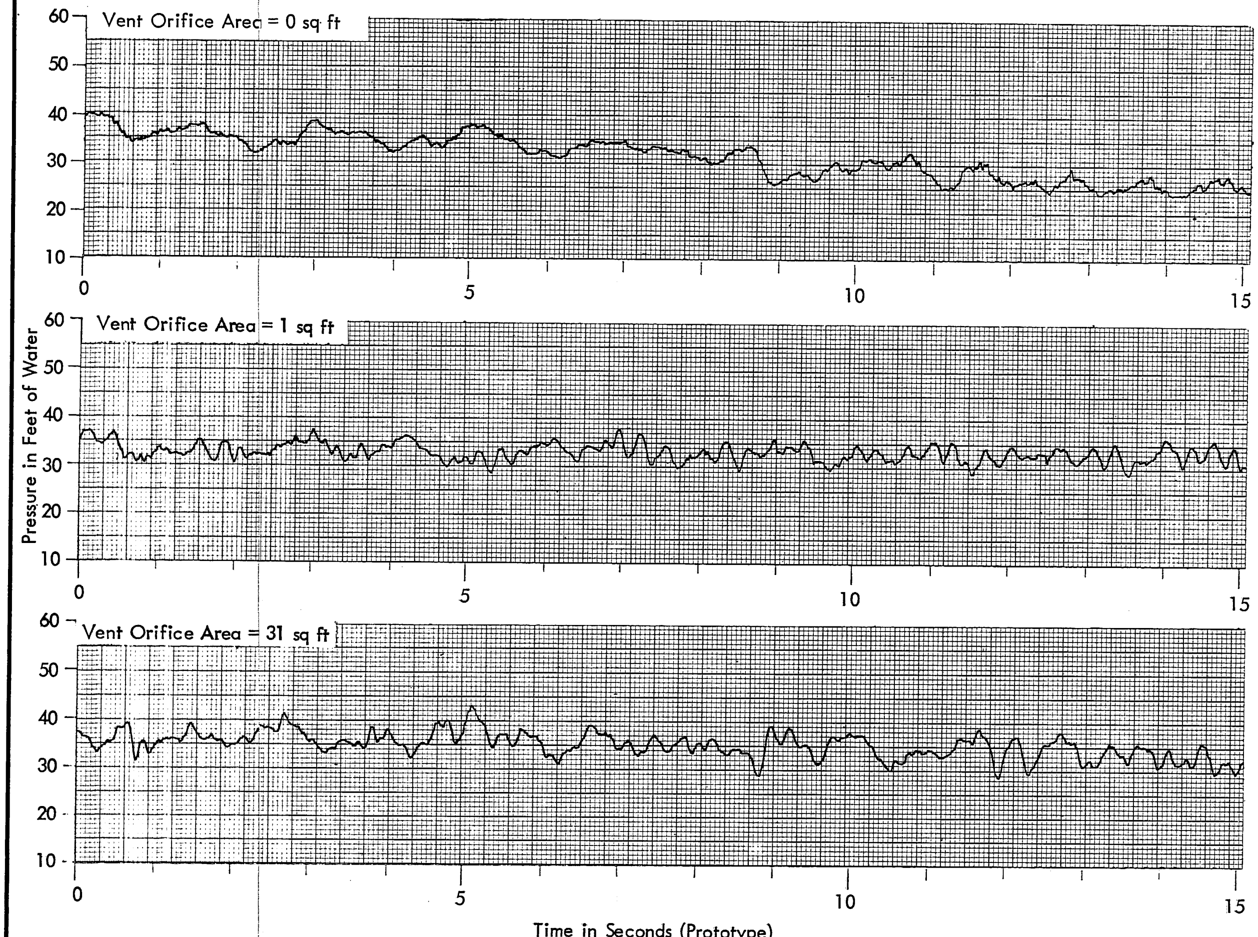
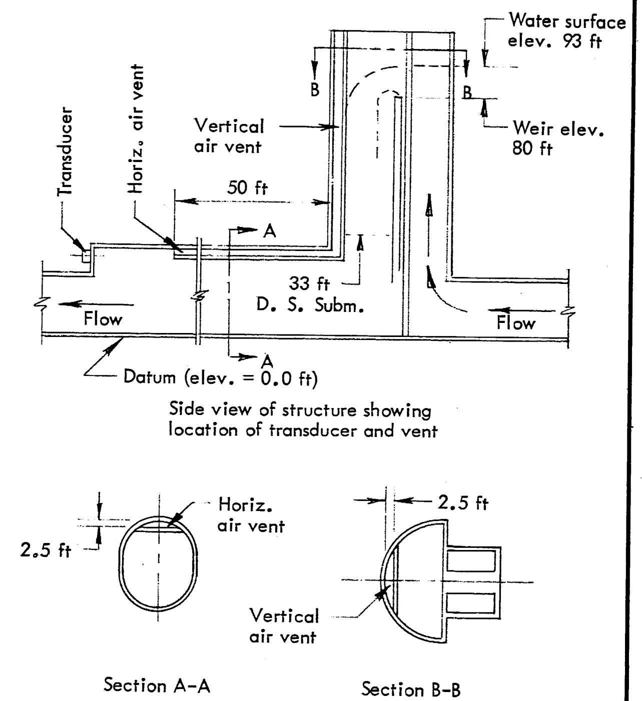
SCALE	DATE 9-1-66	NO. 168-B-459-81





Vent area (sq ft, proto.)	0	1	5	10	20	31
Max. pressure pulse (ft water)	10	8	16	18	18	19

Notes:

1. Transducer used was a 2.5 psi C.E.C. chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. This test was similar to test shown on Drawing No. 168-B-459-54 except the horiz. plate was 2.5 ft below the crown and extended 50 ft d.s. of the tower. The vertical vent was enlarged to a max. cross-sectional area of 31 sq ft and equipped with variable area orifices.
4. The recordings shown are typical for the conditions noted, consequently the values shown in the tables are not necessarily from these recordings. The values in the table are plotted on Drawing No. 168-B-459-59.

Q = 2250 cfs
D.S. Submergence = 33 ft
H.W. = 93 ft
Gate Opening = 0%
Model Scale 1:38.3

DYNAMIC PRESSURE FLUCTUATIONS IN AIR TRAP OF B-1 STRUCTURE - REVISED VENT SYSTEM ALONG CROWN AND UP GATE STRUCTURE

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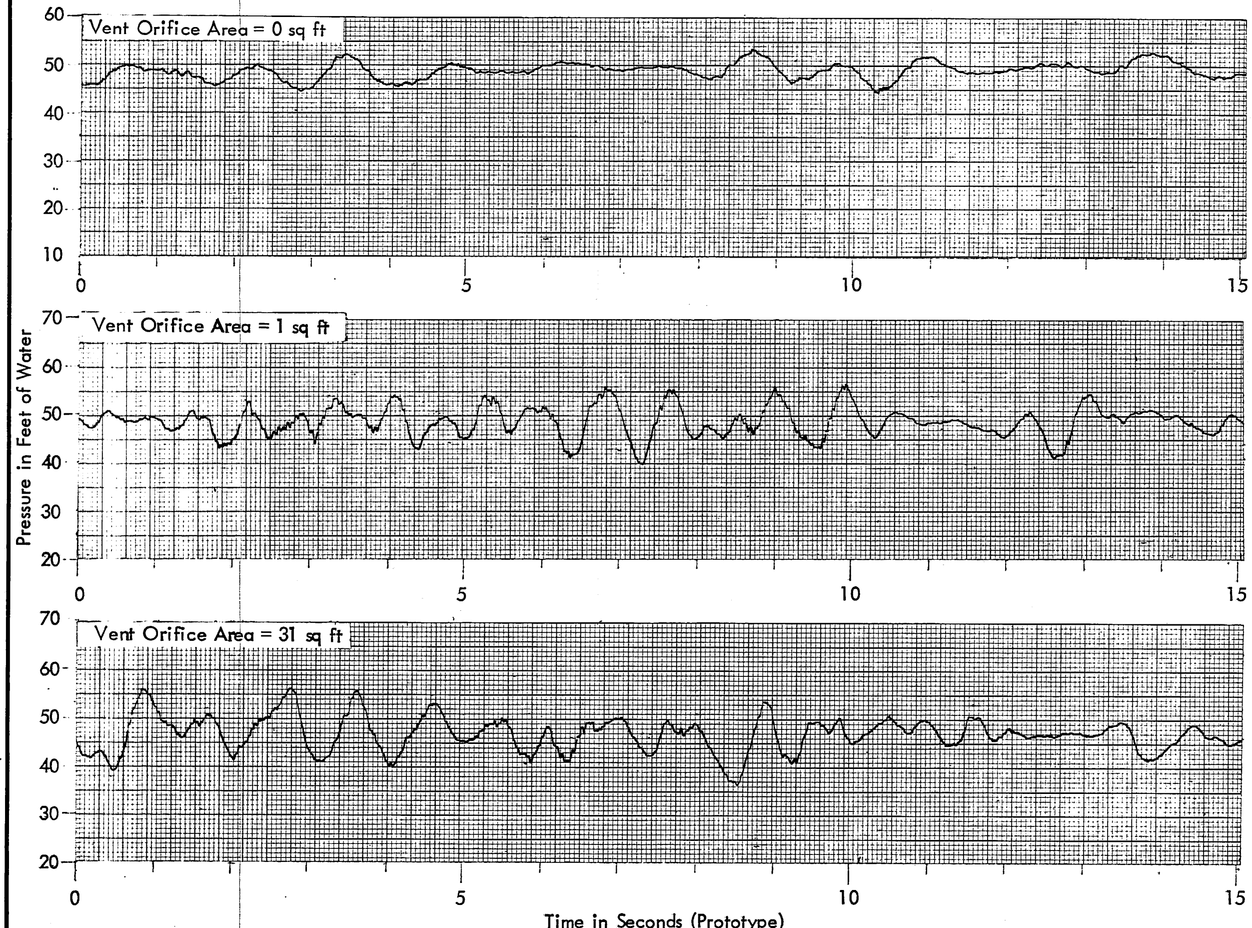
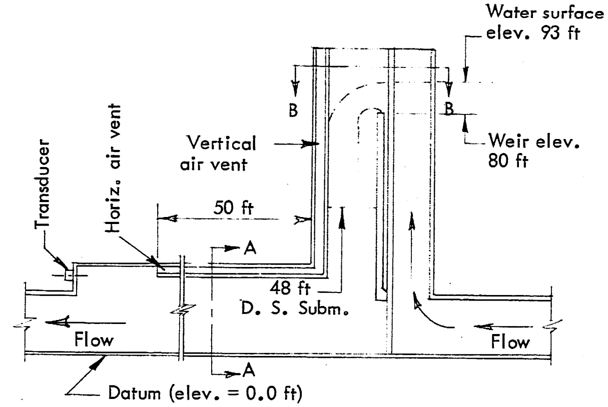
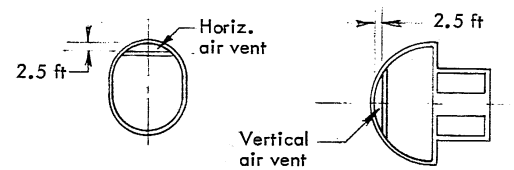
DRAWN RMK	CHECKED DQa	APPROVED
SCALE	DATE 8-3-66	NO. 168-B-459-67





Side view of structure showing location of transducer and vent



Section A-A

Section B-B

Vent area (sq ft, proto.)	0	1	5	10	20	31
Max. pressure pulse (ft water)	16	18	22	26	29	32

DYNAMIC PRESSURE FLUCTUATIONS IN AIR TRAP OF B-1 STRUCTURE - REVISED VENT SYSTEM ALONG CROWN AND UP GATE STRUCTURE

Notes:

1. Transducer used was a 2.5 psi C.E.C. chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. This test was similar to test shown on Drawing No. 168-B-459-54 except the horiz. plate was 2.5 ft below the crown and extended 50 ft d.s. of the tower. The vertical vent was enlarged to a max. cross-sectional area of 31 sq ft and equipped with variable area orifices.
4. The recordings shown are typical for the conditions noted, consequently the values shown in the tables are not necessarily from these recordings. The values in the table are plotted on Drawing No. 168-B-459-59.

Q = 2250 cfs
H.W. = 93 ft
Gate opening = 0%
D. S. Submergence = 48 ft
Model Scale 1:38.3

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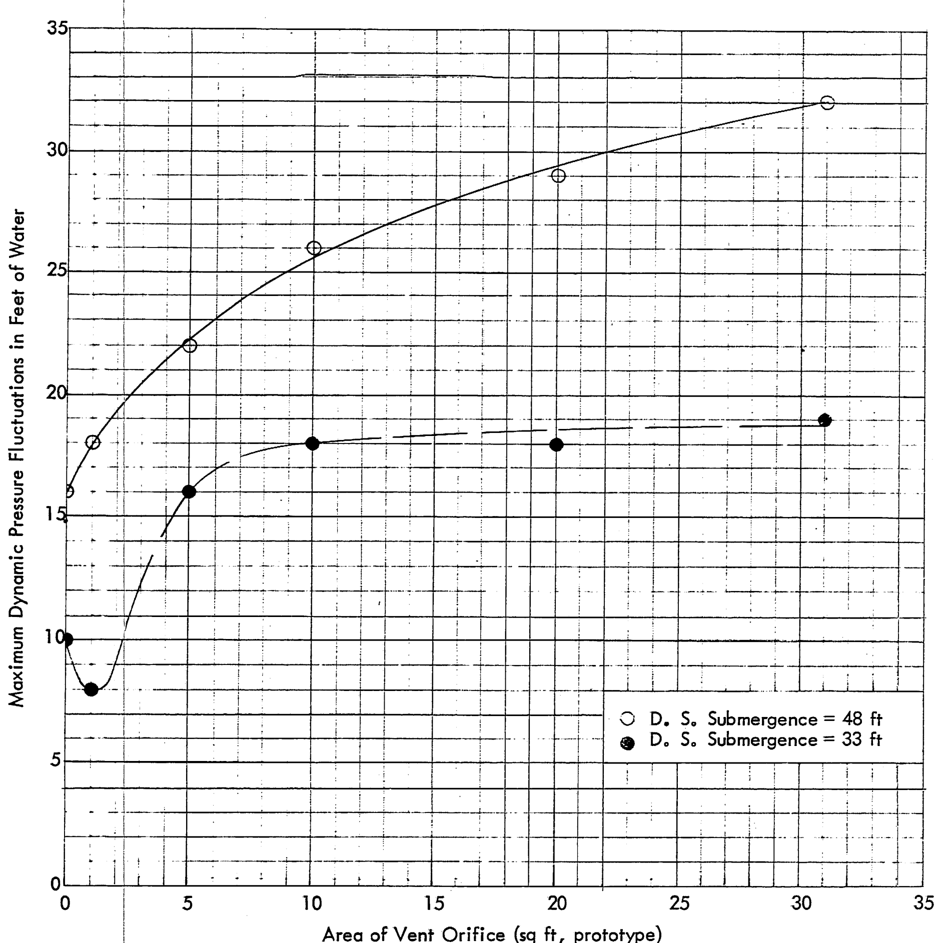
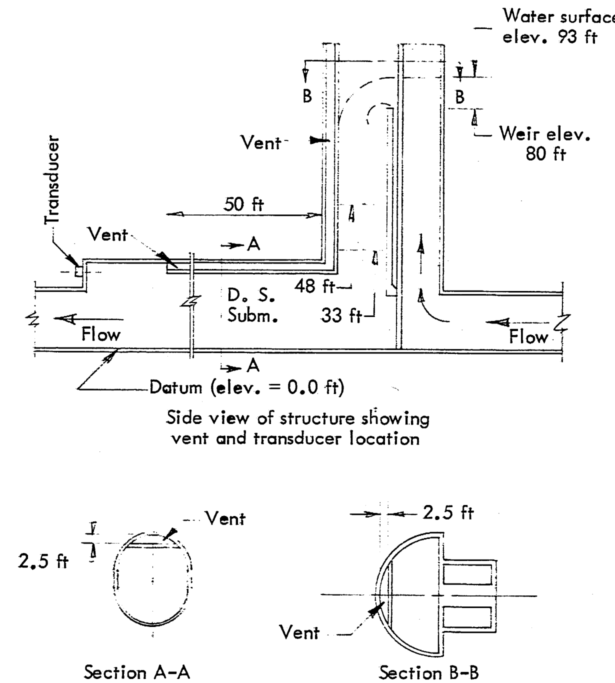
DRAWN RMK	CHECKED DQa	APPROVED
SCALE	DATE 8-2-66	NO. 168-B-459-68





Notes:

1. Transducer used was a 2.5 psi C.E.C. chamber mounted type.
2. With gates closed and flow over weir, air is entrained; air escaping through vent causes dynamic pressure oscillations.
3. This test was similar to test shown on Drawing No. 168-B-459-54 except the horiz. plate was 2.5 ft below the crown and extended 50 ft d.s. of the tower. The vertical vent was enlarged to a max. cross-sectional area of 31 sq ft and equipped with variable area orifices.
4. The values shown on the curves were taken from Drawings No. 168-B-459-67 and 68.

Q = 2250 cfs
H.W. = 93 ft
G.O. = 0%
D. S. Submergence = 33 ft and 48 ft

DYNAMIC PRESSURE FLUCTUATIONS IN AIR TRAP OF B-1 STRUCTURE - REVISED VENT SYSTEM ALONG CROWN AND UP GATE STRUCTURE

Model Scale 1:38.3

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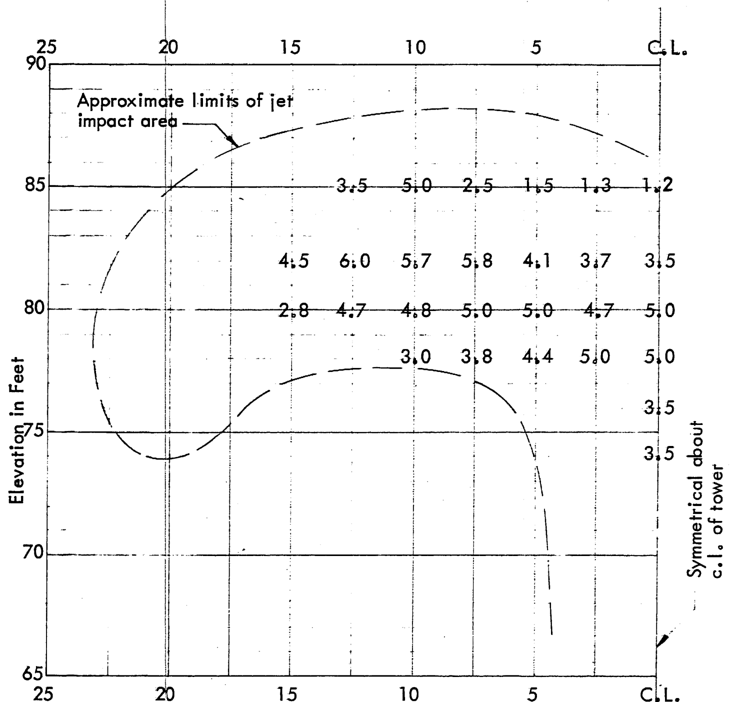
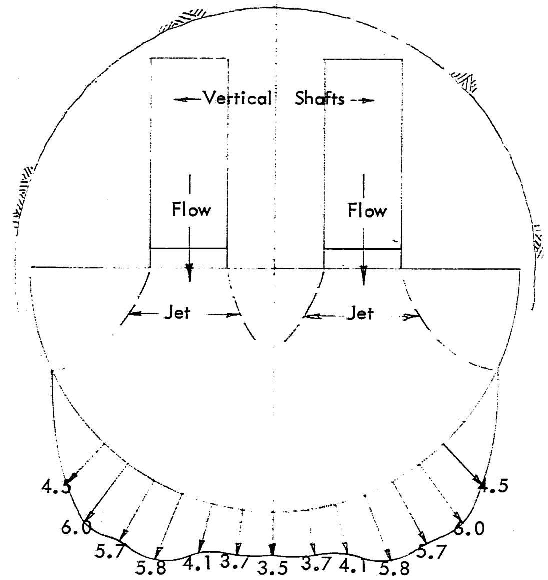
SCALE	DATE 7-28-66	NO. 168-B-459-59



Distance Along Circumference of Tower in Feet
Front View of Tower at Jet Impact Area (Looking U.S.)



Section at Elevation 82 ft Showing Horizontal Pressure Distribution

MAGNITUDE AND LOCATION OF FORCE ON TOWER WALL DUE TO JET ISSUING FROM OVERFLOW WEIR

Model Scale 1:38.3

Note:

1. Figures shown are pressures in feet of water.
2. Pressures measured by use of piezometers at locations shown by figures.
3. Q = 2250 cfs, H.W. = 93 ft
   Weir elevation = 80 ft

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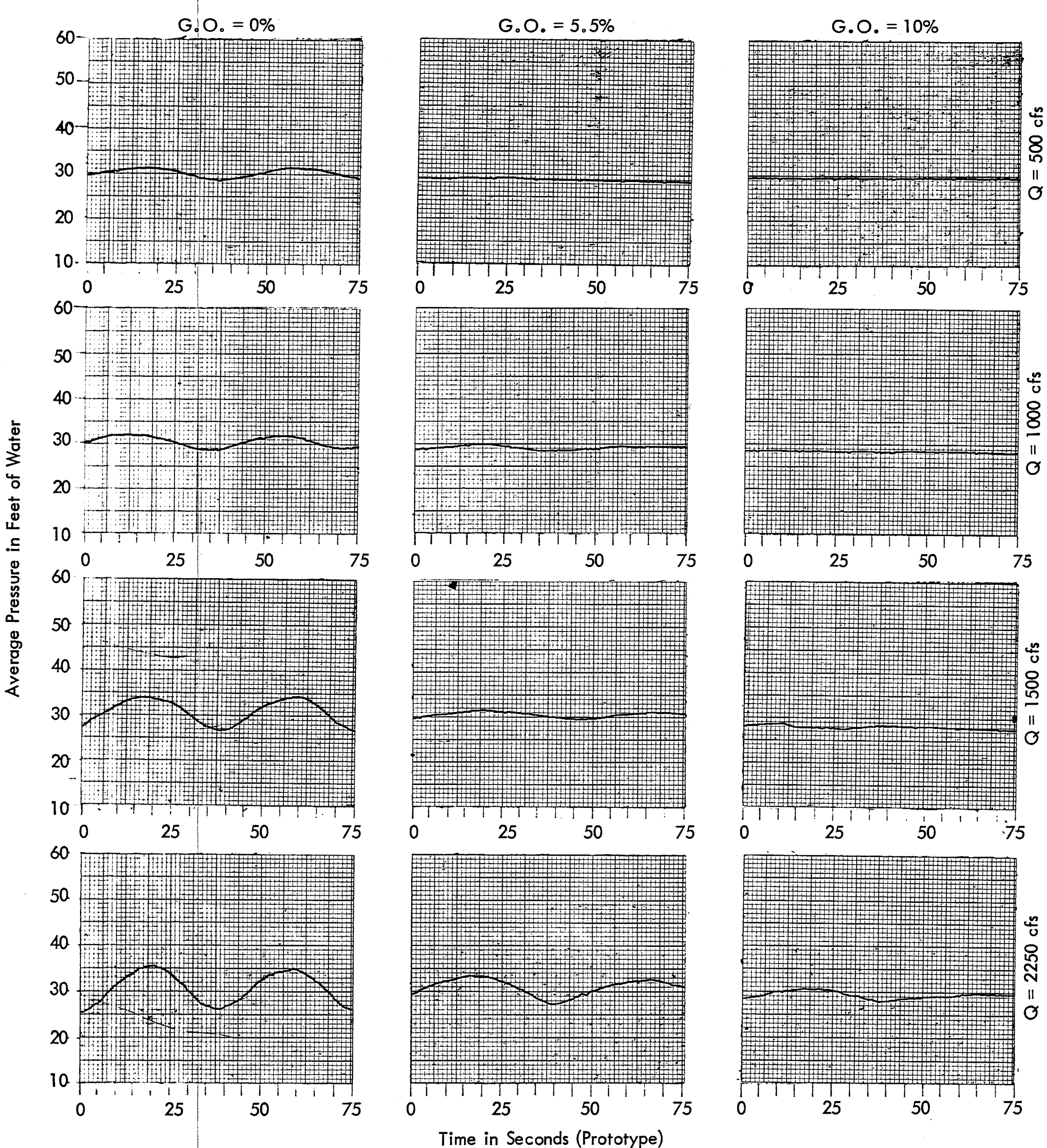
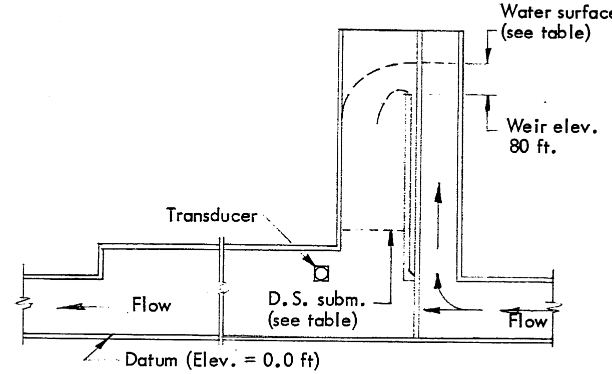
DRAWN RMK	CHECKED	APPROVED
SCALE	DATE 6-8-66	NO. 168-B-459-41





Side view of structure

Notes:

1. Average pressures were measured with a 2.5 psi C.E.C. transducer, chamber mounted type.
2. No vents were used in these tests.
3. The long period surges shown at the left are caused by the flow over the weir striking the d.s. pool. When the H.W. elev. is below the weir, it is noted that the surging ceases.

Q(cfs)	500			1000			1500			2250		
Gate Opening (%)	0	5.5	10	0	5.5	10	0	5.5	10	0	5.5	10
H.W. (ft)	84	61	39	88	84	66	90	87	83	93	91	88
D.S. Submerg. (ft)	29	29	29	30	30	30	31	31	31	33	33	33
Surge Magnit. (ft)	3	0	0	3	1.5	0	8	2	1	10	5	2.5
Surge Period (sec)	47	0	0	42	44	0	39	45	0	37	45	44

COMPARISON OF SURGING IN B-1 STRUCTURE WITH VARIATION OF DISCHARGE AND GATE OPENING

Model Scale 1:38.3

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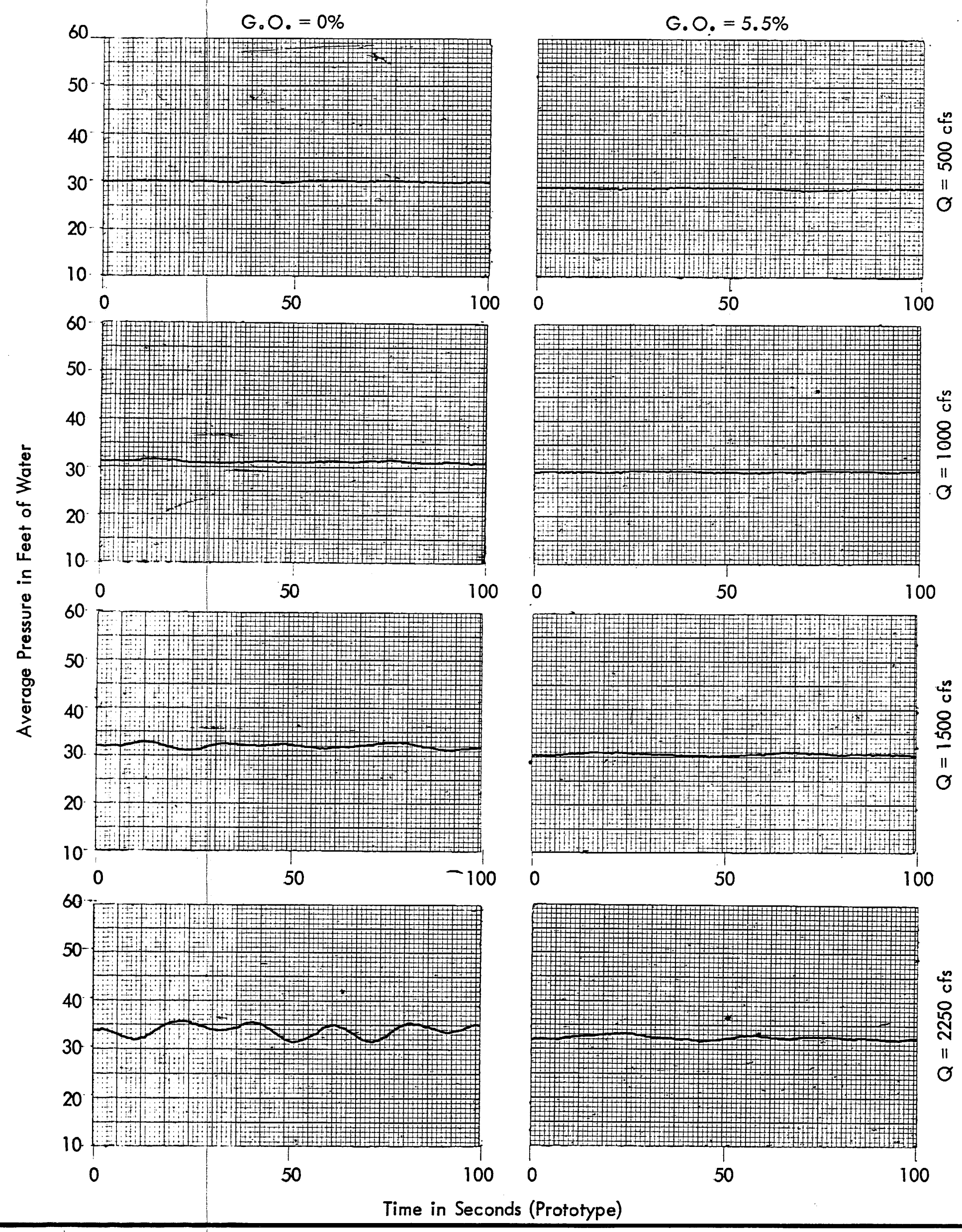
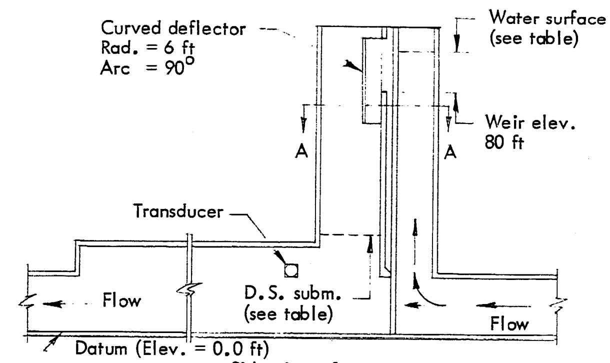
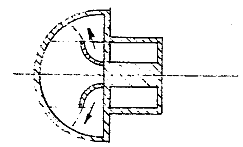
DRAWN RMK	CHECKED	APPROVED
SCALE	DATE 8-15-66	NO. 168-B-459-75





Side view of structure

Q (cfs)	500		1000		1500		2250	
Gate opening (%)	0	5.5	0	5.5	0	5.5	0	5.5
H.W. (ft)	85	61	88	84	90	87	95	92
D.S. submerg. (ft)	29	29	30	30	31	31	33	33
Surge magnit. (ft)	0.5	0	0.5	0	2	0.5	4	1.5
Surge period (sec)	0	0	0	0	12	52	21	32



Section A-A

Notes:

1. Average pressures were measured with a 2.5 psi C.E.C. transducer, chamber mounted type.
2. No vents were used in these tests.
3. In these tests, the long period surges shown on Drawing No. 168-B-459-75 were reduced or eliminated by the use of deflectors installed at the weir as shown above. The deflectors changed the flow direction of the overflow so it did not fall directly onto the d.s. pool, but instead struck the horiz. slab outside of the channel at elev. 30.25 ft.

COMPARISON OF SURGING IN B-1 STRUCTURE WITH VARIATION OF DISCHARGE AND GATE OPENING REVISED DESIGN WITH DEFLECTORS INSTALLED AT OVERFLOW WEIRS

Model Scale 1:38.3

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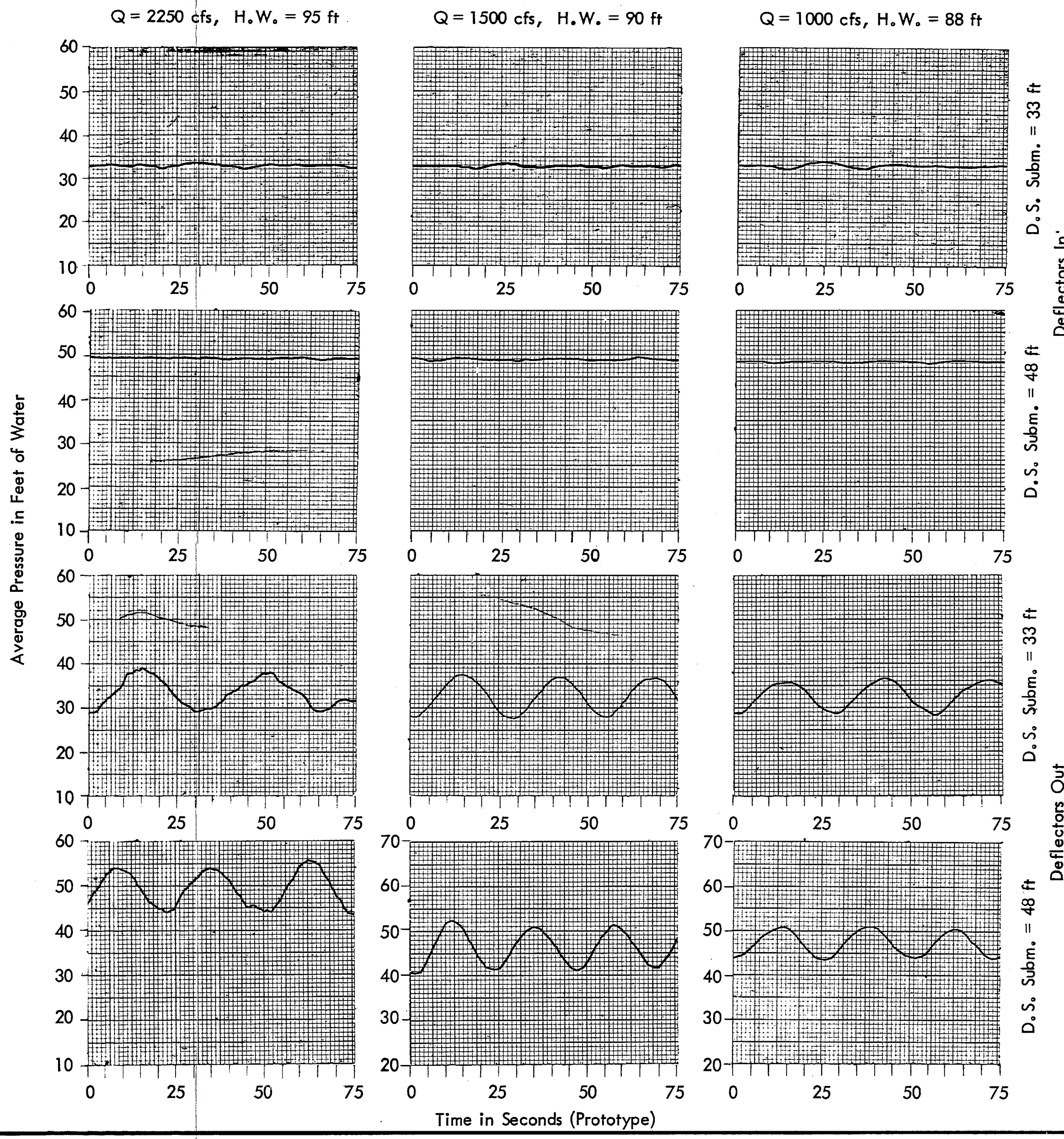
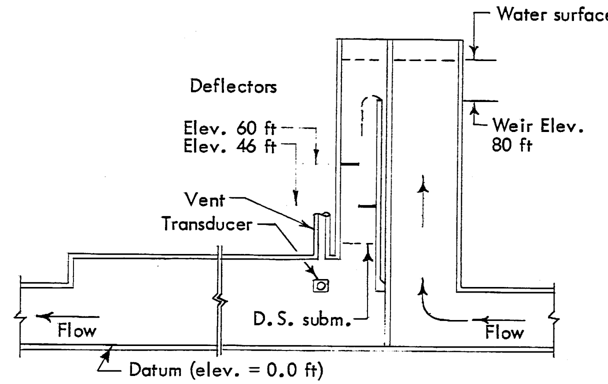
DRAWN RMK	CHECKED	APPROVED
SCALE	DATE 8-16-66	NO. 168-B-459-76





Side view of structure

Notes:

1. Transducer used was a 2.5 psi C.E.C. chamber mounted type.
2. Step type deflectors were installed in d.s. tower to dissipate energy in order to eliminate long period surges in structure. Comparison of recordings with deflectors in place with those previous to installation shows that the efficiency of the deflectors is good.
3. A vent was found to be necessary near upper end of air collector to rid structure of entrained air in discharges of 1000 and 1500 cfs.
4. Gate opening = 0% in all tests.

SURGING IN B-2 STRUCTURE - COMPARISON OF ORIGINAL DESIGN WITH REVISION USING STEP TYPE DEFLECTORS IN DOWNSTREAM SECTION OF TOWER

Model Scale 1:38.3

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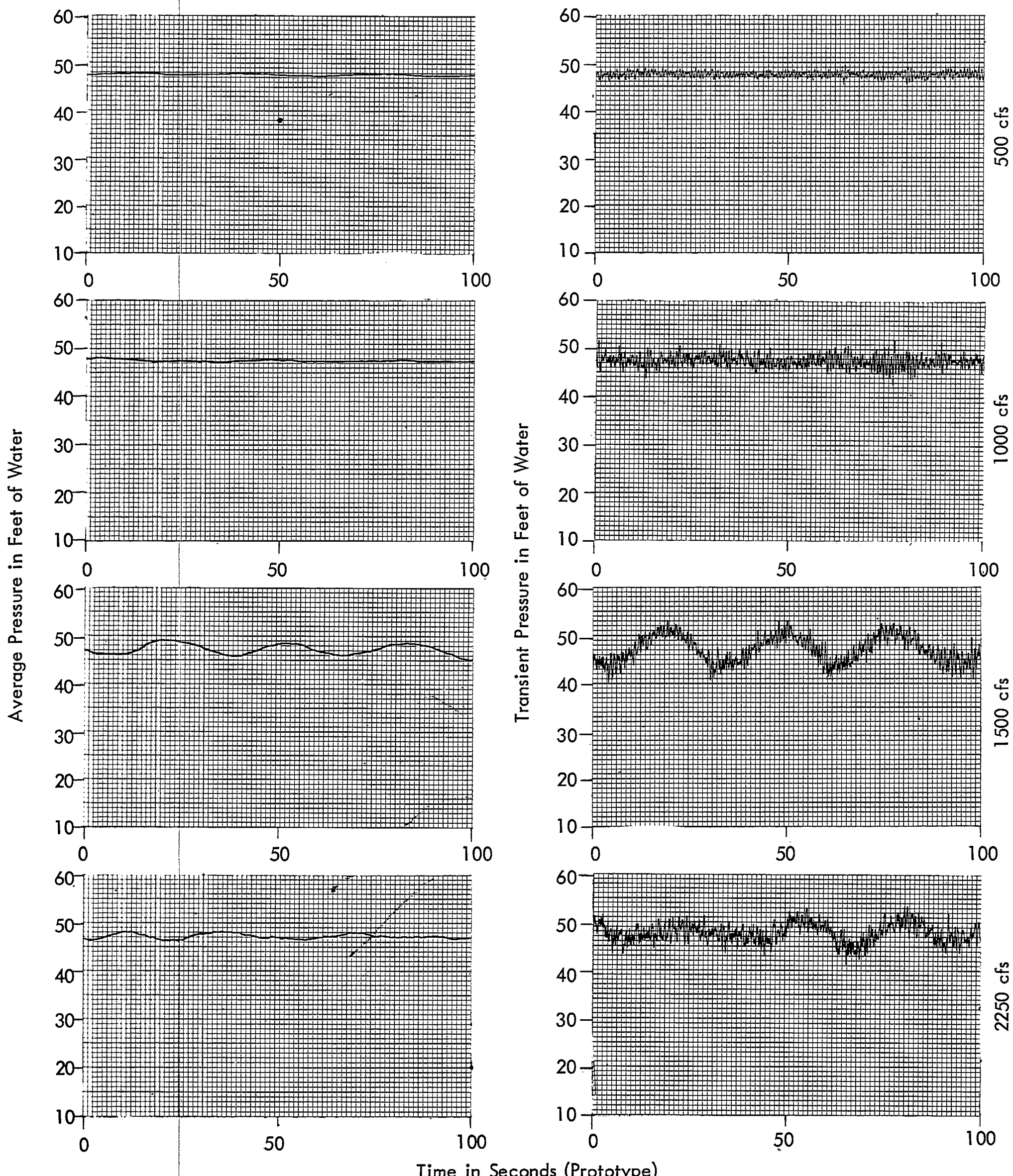
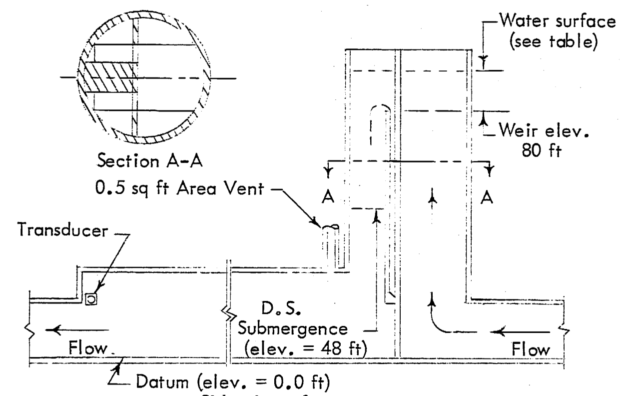
SCALE	DATE 8-22-66	NO. 168-B-459-79





Side view of structure

Q (cfs)	500	1000	1500	2250
H.W. (ft)	84	87	89.5	93.5
Maximum Surge (ft)	-	-	4	3
Maximum Pulse (ft)	4	9	9	8.5
Surge Period (sec)	-	-	24	21

Notes:

1. Dynamic pressures were measured with a 2.5 psi C.E.C. transducer, chamber mounted type.
2. With the gates closed and flow over the weir, air is entrained. Air escaping through the vent causes dynamic pressure oscillations. With the use of a small diameter vent, the escaping air is throttled, causing a higher pressure air pocket at the crown of the trap. The pressurized air reduces fluctuations of the water surface, thus reducing the pressure pulses. With the vent throttled to 0.5 sq ft of area, tests indicate that the transient pressure pulses and the long period surges are effectively reduced.

COMPARISON OF AVERAGE AND TRANSIENT PRESSURES IN REVISED B-2 STRUCTURE WITH 0.5 SQ FT AREA VENT AT "D" DUE TO VARIATION OF DISCHARGE

D.S. Submergence = 48 ft
Gate Opening = 0%
Model Scale = 1:38.3

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DRAWN JRB	CHECKED [illegible]	APPROVED
SCALE	DATE 9-21-66	NO. 168-B-459-88