Commonwealth of Kentucky
Department of Highways

MODEL STUDY OF FLOW THROUGH CULVERTS

by

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A Report Presented at the Kentucky Highway Conference
University of Kentucky, Lexington, March 29, 1956.

Highway Materials Research Laboratory
Lexington, Kentucky

March, 1956

INTRODUCTION

Within the past four years, the Highway Materials Research Laboratory has expended considerable effort upon investigating and developing new approaches to the problem of estimating the quantity of runoff from small drainage areas. Particular interest has been given to areas of sizes that require culverts or small bridges with less than twenty feet of span. The results of these studies have been included in the Drainage Manual recently adapted for use by the Department of Highways.

In the Drainage Manual, in addition to the emphasis placed on the methods of estimating the quantity of runoff to be anticipated for a culvert design, methods of analyzing the culvert's hydraulic performance are outlined. The manual demonstrates that a knowledge of the hydraulics of the culvert is equally as important as estimating the quantity of runoff, and that the antiquated practice of choosing a specific waterway opening solely on the basis of the size of its drainage area can be highly unrealistic. It is now possible, with adequate hydraulic analysis, to design a structure that will satisfy more economically the conditions of each individual culvert. The limiting conditions at a given site can be included in the designs, thus eliminating the oversimplification and generalization consequent from considering the hydraulics of all culvert types and installations to be the same.

For the proper application of hydraulic principles to the design of culverts a certain amount of basic information on the hydraulic behavior of these structures becomes necessary. It was decided, therefore, that a study be initiated to evaluate the performance of a number of the standard culvert types and to make a detailed study of the efficiency of their operation.

Scale models provide a practical means of studying the hydraulic behavior of structures. This is particularly true in the case of culverts, where such factors as the quantity of runoff, the slope of the culvert barrel, the maintenance condition of the structure, and other variables are highly significant to the performance. In a field study of actual structures it would be impossible to control these variables in order to evaluate their effects. It is also difficult to make a comparison study of the performance of existing structures because of the extreme variations in runoff. Model studies, therefore, permit the only feasible method by which the performance of different types of structures can be compared at identical conditions of slope and runoff.

Model studies are not new in the field of engineering but have been used as far back as the time of Leonardo da Vinci. Hardly a modern dam of any significance has been built without first constructing a scale model and studying its performance under simulated field conditions.

Hence, to permit thorough study of the hydraulics of culvert operation in Kentucky, as well as to study the efficiency of various types of culverts, a model testing apparatus was constructed by the Research Division of the Kentucky Department of Highways. An overall photograph of the apparatus built is shown in Fig. 1.

Description of the Model Testing Device

The model testing apparatus was designed to simulate, as closely as possible, the situations surrounding an actual culvert installation. The layout used was quite like those used by others conducting similar studies, particularly the model research at Oregon State College. A similar layout was used in order to obtain a model setup that would be workable to begin

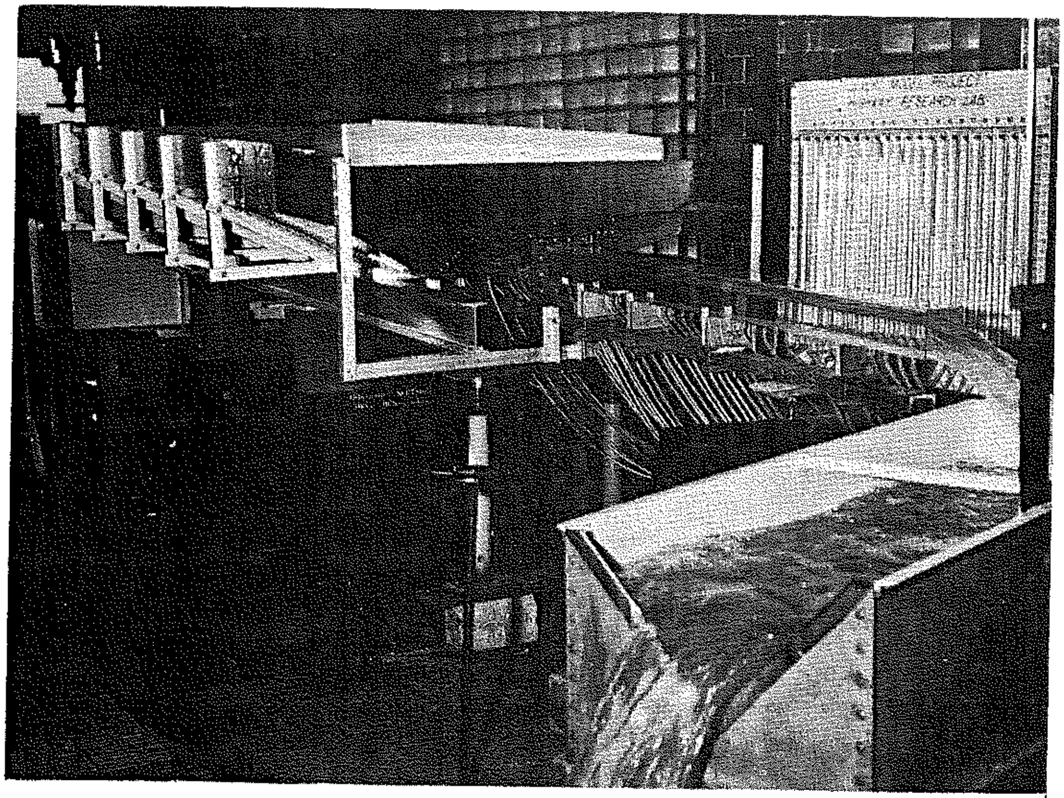


Fig. 1. Model Testing Apparatus, Overall View.

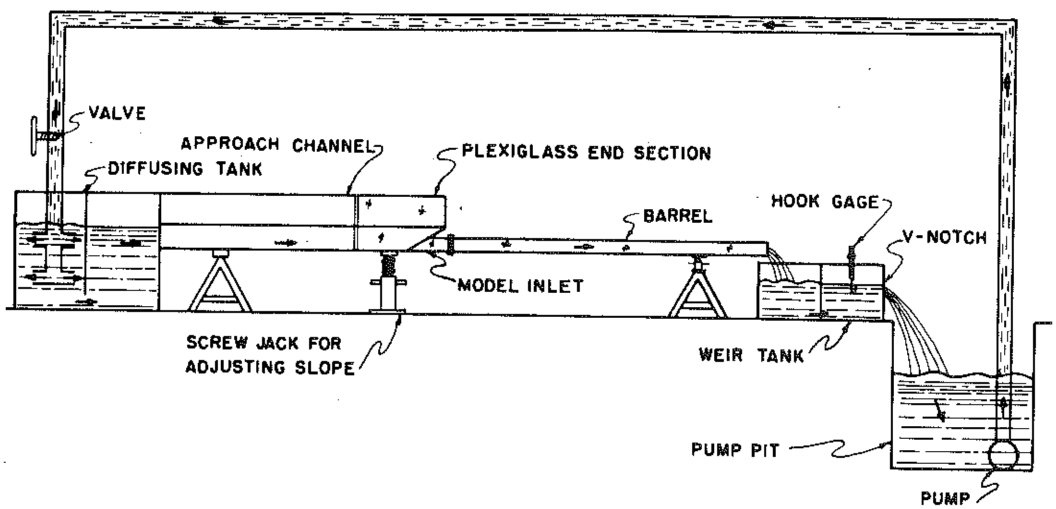


Fig. 2. Schematic Drawing of Apparatus.

with, perhaps eliminating some of the problems in design and construction. Also, it was anticipated that by using this layout, advantage could be taken of the other studies by way of comparison and guidance in the procedures to be used and the data to be taken.

A model-to-prototype scale ratio of one to 12 (the model constructed to be 1/12 the size of the theoretical field situation to be studied) was chosen for these experiments and is considered quite conservative for studies of this type. This choice was made on the basis of hydraulic similarity and the fact that the ratio had been quite commonly used in similar studies conducted by other organizations.

The apparatus (see Fig. 2) consisted of a diffuser tank to dissipate the energy and turbulence in the water from the supply line, a trapezoidal approach channel with a plexiglass end section and flanges to accommodate various types of inlets, a plexiglass culvert barrel section with peizometer connectors located at frequent intervals along the bottom, a receiving tank with a V-notch weir to measure the discharge, and a series of manometers, mounted on boards, to show the head at the various peizometer locations.

The water supply for the tests was taken from the supply pit in the Hydraulics Laboratory by the laboratory pumping system, through a 4-in. diameter line, to the diffuser tank. The quantity of flow (discharge) for the tests was controlled by a gate valve at the diffuser tank.

Quieting of turbulence was gained by positioning baffle boards in the tank and by the design of the tank itself which allowed a sump in the bottom. With this arrangement, no distinguishable turbulence from the supply was carried to the approach channel and there was no definite velocity at the upstream end of the approach channel.

The inlet sections to be tested in this particular study were constructed entirely of 3/16-in. plexiglass, the details and dimensions varying with the type tested. Flanges on both ends of the model provided a bolt connection to the apparatus.

The plexiglass culvert barrel had inside dimensions of 4 in. by 4 in. and was 72 in. long. Piezometer connectors, made from 3/8 -in. round plexiglass stock, were welded to the bottom.

The outlet end of the barrel discharged freely with an unsupported jet into a receiving tank. A hook gage was connected to the side of the tank with a small stilling well around the hook. The tank's end was cut out and flanged to receive a V-notch weir plate in such a way as to permit the flow to discharge from the weir directly into weighing tank, a part of the laboratory equipment.

Provisions for changing the slope of the approach channel and culvert barrel were made by placing screw jacks at the end of the channel and a small machinist's jack under the barrel at the outlet end. The entire length of the approach channel was supported by an aluminum channel beam.

The manometer boards were made of 1/4-in. plywood with places for 44 glass tubes of 1/2 in inside diameter. A white cardboard backing was used, with the gradations ruled in India ink and then sprayed with clear lacquer to prevent water damage. Leveling adjustments were made possible by slots in the boards and leveling screws in the bases. For the connection between the piezometers and the manometers, 1/4-in. inside diameter clear Tygon tubing was used.

Testing Procedure

The choice of the size of the culvert for a specific discharge and other limiting field conditions at the site is dependent upon the headwater depth (H) that can be tolerated and the outlet velocity (V_o) that the channel can stand without severe erosion.

The methods of computing the headwater depth are dependent upon the manner in which the culvert operates. This includes a number of ways - full or part full, with inlet submerged or partially submerged, with outlet submerged or with free fall, and with combinations of these - to give eight general types of operation.

For any of these, the problem of determining the expected headwater depth is basically a problem of evaluating the energy distribution of the water flowing through the culvert. For any specific condition the depth of flow at the outlet end of the model structure can be found. With this known, the energy at the outlet can be evaluated. The energy lost in transmitting the water from the inlet to the outlet of the culvert is used up in overcoming friction in the barrel and in losses in getting the water into the culvert at the inlet end - usually referred to as inlet loss. These losses are evaluated and added to the total energy of the water emerging at the outlet end, and the total energy of the water before entering the culvert is found. This is in the form of potential energy, or head, and thus its value is convertible to water depth (H).

A good deal of work has been done on studies of friction loss in culverts and the methods of application of frictional coefficients are more or less standardized; however, very little is known about entrance losses for various types of structures. Yet the efficiency of operation of culverts is dependent upon the effect of these two specific variables, and furthermore, in most cases the efficiency is directly dependent on the losses.

The major concern, then, in the application of culvert hydraulics, is determining the manner in which a culvert will operate and the losses in energy resultant from its operation, usually referred to as head losses.

In previous drainage studies it has been observed that culverts seldom flow full, even when the water submerges the inlet headwall. In fact, it seems to be rare that a structure will flow full unless submerged by backwater. It has also been observed that some culverts operate more efficiently than others. The degree of efficiency seems to depend on a number of factors, including the slope of the approach channel, the alignment of inlet and barrel, and the design and position of the inlet.

With the model testing apparatus it became possible to observe some of the ways in which a culvert will operate under these varied conditions. Data which showed graphically the actual conditions of flow were taken from photographs of manometer boards (one of which is shown in Fig. 3) and from these data records it was possible to evaluate the efficiency of these operations and to predict the relationship between headwater depth and discharge to be anticipated in actual practice.

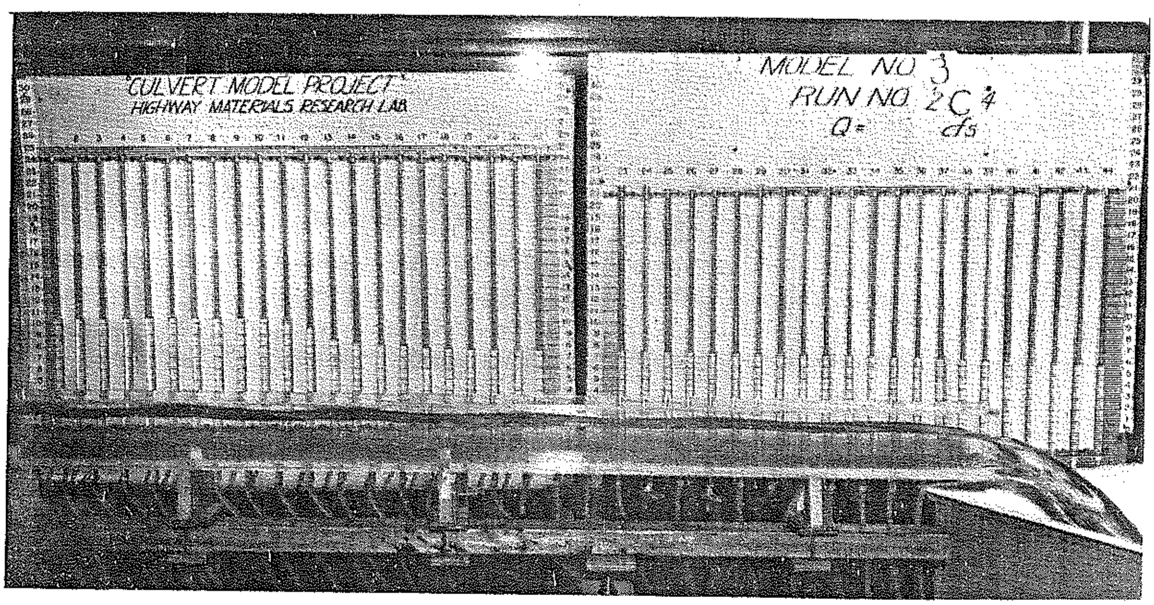


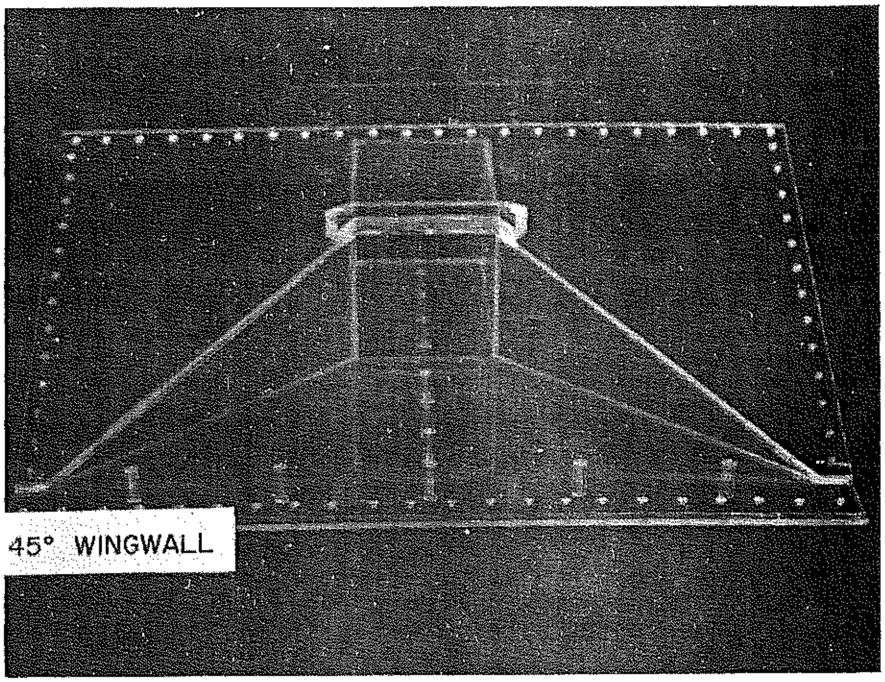
Fig. 3. Sample Data Record Taken Photographically from Manometer Boards.

Two models of standard type culvert inlets were tested, with 30-deg. and with 45-deg. wingwalls. (The models, which were made from sheet plexiglass, are shown in Fig. 4). The test indicated that the efficiency of the standard 45 deg. wingwall culvert was slightly greater than that of the 30 deg. This greater efficiency of the wider spread opening was apparently due to the spreading out of the area of constriction at the inlet. This result of the tests suggested an immediate means by which the efficiency of a culvert might be improved - specifically, of how it might be made to flow full - and a hood arrangement was made to be added to the inlet, with the intention of spreading out of the area of constriction even further.

Without the hood it had been impossible to get the culvert barrel to flow full, regardless of the amount of headwater that accumulated on the embankment slope or the grade at which the barrel was set. In almost all cases except on a flat slope, it was impossible to get more than 2/3 full barrel flow and often the flow was considerably less.

When the hood was added, the barrel began immediately to flow full. Subsequent testing demonstrated that this full flow would prevail whenever the headwater submerged the inlet by a depth of about 1.2 times the height of the barrel. These tests were preliminary; however, they showed a dramatic increase in efficiency gained by using the hood. Fig. 5 illustrates the increase, showing the flow of water through the barrel before and after adding the hood, under conditions of constant slope and quantity of supply.

The increased efficiency was recorded on movie film. The hood was removed and the maximum head possible was allowed to fill the approach channel. It was noted that the barrel was flowing only approximately 2/3 full. The hood was then added, without changing the quantity of water coming into the system. The barrel immediately began to flow full and the headwater



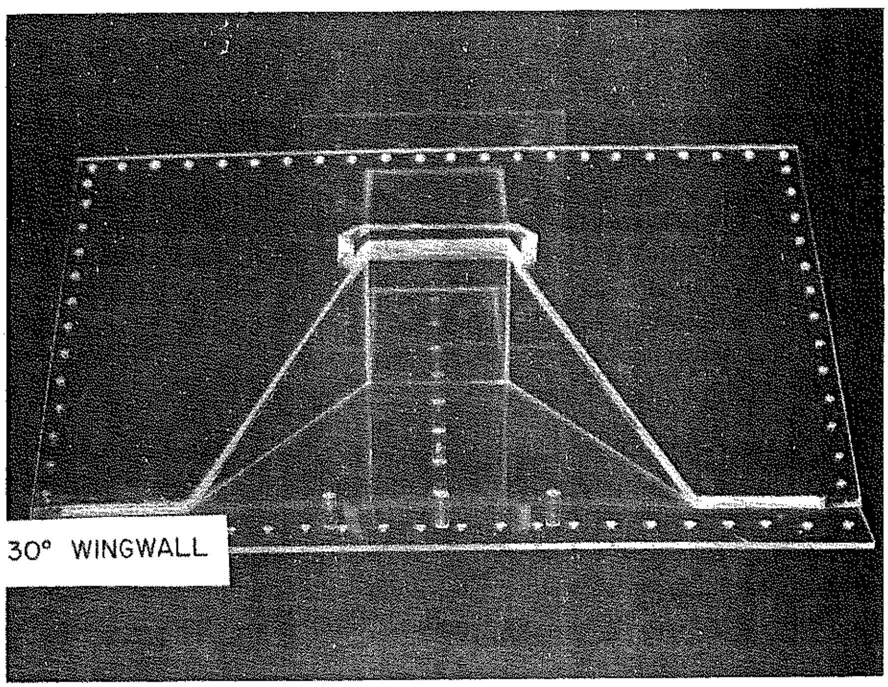


Fig. 4: Plexiglass Models of Kentucky Standard Type Inlets.

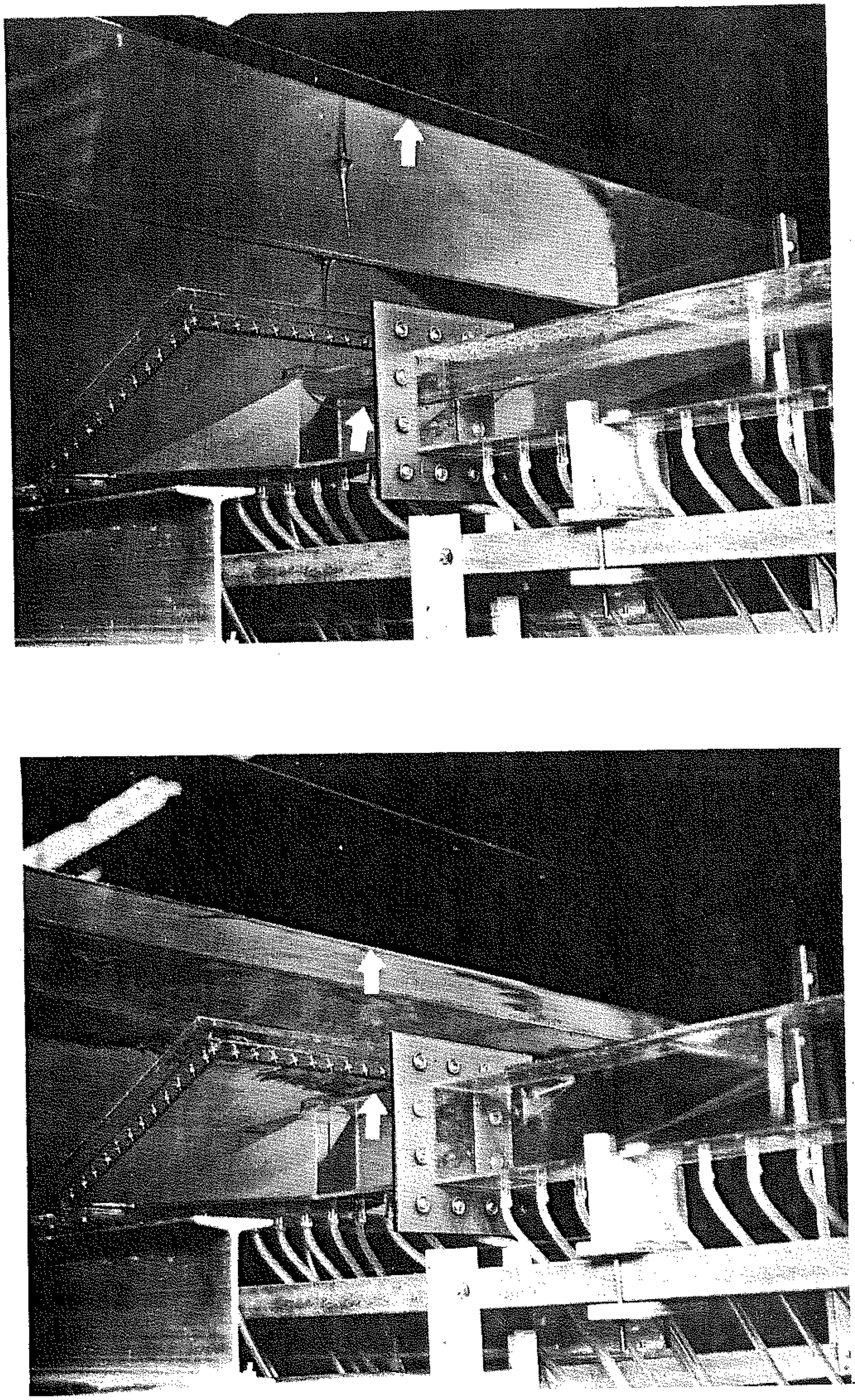


Fig. 5. Photographs of Approach Channel, Inlet, and Barrel Taken before and Almost Immediately after Adding the Hood. Upper Arrow shows Headwater Depth, Lower Arrow Indicates Water Level in the Barrel.

depth began decreasing rather rapidly, down to where it barely submerged the inlet. At this point the system became stabilized.

The hood was then removed and the culvert automatically snapped back to part full flow and the headwater depth began rising, back to its original height of the top of the flume.

With this demonstrated increase in efficiency, (which is somewhere in the neighborhood of 100 percent when the hood is wide enough to develop an inlet opening area of twice the barrel area) a reduction in the size of many structures to be built in the future may be brought about, reflecting a tremendous savings in cost. Hoods could also be adapted to some structures that are undersized at present and causing undesirable headwater elevations. With the decrease in head produced by the hoods, they could cause an unsatisfactory structure to function satisfactorily.

Conclusion

These are but a few of the uses planned for the model testing equipment. Additional studies will be made to investigate other ways of improving culvert performance. The apparatus can be used to study the effects of skew, multiple barrels, various barrel shapes, and possibly of scour.

A problem anticipated with the accelerated construction of four or more lane highways is the problem of grades for the drainage structures. Even at present with relatively narrow rights of way and limited lengths of culverts, when a structure is on a stream with a steep gradient it becomes necessary to "stand the culvert on end" or bury the inlet and leave the outlet to have a gun barrel effect. With the model device, studies of means for avoiding this, such as drop inlets and broken-back structures, can be made to determine the most effective possible placement and designs. It is planned that the model testing device will be kept in operation for a considerable time in the future, in order to continue the study of many present problems and those certain to arise in the hydraulic design of drainage structures.