New Developments for Erosion Control at Culvert Outlets

GEORGE L. SMITH and DASEL E. HALLMARK, Respectively, Hydraulic Research Engineer, Colorado State University, Fort Collins; Highway Research Engineer, Division of Hydraulic Research, U.S. Bureau of Public Roads, Washington, D.C.

● A PROBLEM which frequently confronts the highway engineer is excessive erosion or gullying at the outlet end of culverts. Nature's method of keeping erosion under control on mild slopes is to spread the runoff over a wide area of the watershed so the flow depths are shallow and resistance to flow rather high. Typically a highway embankment crossing a watershed disrupts the drainage plan of nature in that the runoff from a wide area is funneled to culverts where the flow is concentrated within a small area. This concentration of flow into a culvert greatly increases the erosive ability of the flowing water at the culvert outlet, since the flow has been accelerated (Fig. 1). The accelerated flow must travel some distance before it can fan out again over a wide area after it has passed through the culvert. As time elapses, erosion or gullying increases, and scour control becomes more difficult and expensive. It is no longer realistic to consider only the initial cost of a culvert and ignore future maintenance.

The basic design problem is the dissipation or proper control of the kinetic energy of the jet of water issuing from the culvert outlet. It should be pointed out that not all culverts require special structures to control erosion; for example, where the natural stream channel exhibits a high resistance to erosion, or where the downstream channel control provides adequate depth of flow for energy dissipation of the impinging jet and thereby minimizes erosion of the channel. However, when proper erosion or scour control is needed, it is accomplished by means of an energy dissipator constructed at the downstream end of the culvert. In the past, where this has been done, concrete or stone structures have been employed. Considering the number of culverts involved this type of construction is expensive, both in initial costs and maintenance costs. Therefore, there is a need for a stilling basin that is more economical and yet efficient for use as an energy dissipator. Such a basin, to be economical, should be of simple design, low in construction cost, and require a minimum amount of maintenance. Maintenance in this case would be a measure of the efficiency of the basin.

The purpose of this paper is to present information on a very promising and inexpensive method of controlling erosion at culvert outlets. Sufficient testing has been performed in the laboratory and in the field to demonstrate the effectiveness of the method. In general, the method consists of simply excavating a hole downstream from the culvert outlet and lining it with a graded layer of protective material consisting of coarse sand, gravel and boulders up to a size that will resist erosion at the peak flow. In this report, this method will be referred to as a pre-shaped, armorplated stilling basin. Limitations on applications of the results are presented. Future research needs conclude this paper.

FUNDAMENTAL CONCEPTS OF ENERGY DISSIPATION AND SCOUR CONTROL

Kinetic energy of a jet of water can be dissipated in a stilling basin by one of the following methods (Fig. 2):

1. In the horizontal direction by the hydraulic jump or artificial roughness in the channel;
2. In the vertical direction by jet diffusion and dispersion by the drop structure or manifold, or;
3. In a combination of both directions.

To be effective, the hydraulic jump must be stabilized by a combination of blocks or sills placed on the basin floor and a minimum tailwater depth must be maintained. It is very difficult when the Froude number of the flow is less than two to eliminate completely the waves and some high-velocity flow downstream from the basin. The waves and high-velocity flow as will be demonstrated in another section, are factors which erode the banks and bed at the basin outlet. As the culvert outflow becomes sub-critical, no jump will form but there still may be sufficient energy to create erosion problems at the culvert outlet.

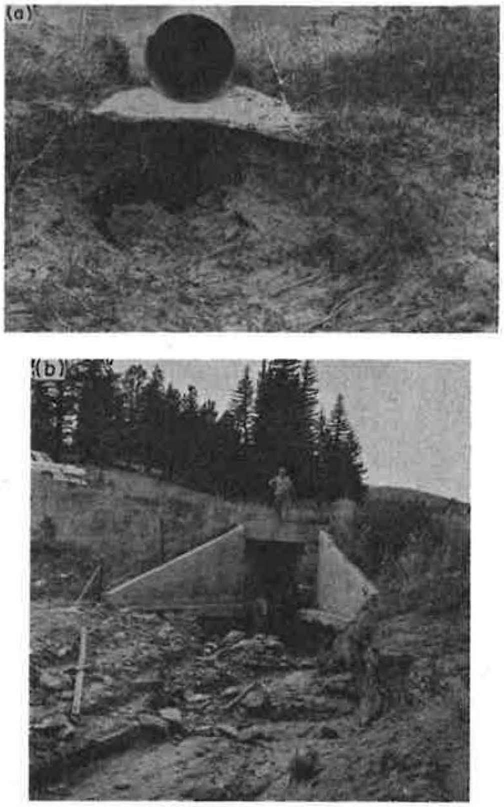

Figure 1. Erosion at culvert outlets caused by accelerated flow; (a) pipe culvert, and (b) box culvert.

Effective dissipation of energy in the vertical direction requires that the jet of water be diffused by the surrounding flow or tailwater. Also, it is essential that a minimum depth of tailwater be maintained in the stilling basin in order that the jet diffusion will be sufficient to prevent high energy waves from emanating from the stilling area. However, this method has the distinct advantage of confining the energy dissipation to a relatively small area, compared to the hydraulic jump, by quickly bringing the water into a state of high-intensity turbulence, transforming the bulk of the flow energy into heat and fine-grain turbulence.

Recent hydraulic laboratory tests by Hallmark (1) and Smith (2) at Colorado State University have demonstrated that the kinetic energy of a freely falling jet of water can be effectively dissipated in the vertical direction by means of a pre-shaped, armorplated stilling basin. For either the box culvert outlet (Fig. 3) or the pipe culvert outlet (Fig. 4) the basin in the alluvial bed is an excavated hole which is lined with a graded layer of protective material consisting of coarse sand, gravel, and boulders up to a size that will resist erosion at the peak flow.

The function of the pre-shaped stilling basin is to provide a large enough stilling pool so that the kinetic energy of the freely falling jet is dissipated by diffusion within the pool. The function of the graded gravel is to act essentially as an armorplate lining for the pre-shaped basin controlling erosion. The armorplate material must be of such size that the velocity of the deflected and diffused jet leaving the stilling basin will not carry the armorplate particles from the scour hole. Armorplate effectiveness depends on its gradation; that is, it must be uniformly graded from the maximum size of the stream bed material up to that of the largest size armorplate material. With uniform gradation, each particle of armorplate is protected by smaller particles underneath so that it will not be undermined. For example, the armorplating material acts in a manner similar to the "Terzaghi" graded filter (3). Separation and placement of separate size material is not required for the armorplate material to be effective.

A criterion for maximum size and gradation has not been determined either experimentally or theoretically. However, Peterka (4) gives an empirical expression based on the bottom velocity of channel flow for determining the maximum size of armorplate that will resist erosion. Lane (5) in his stable channel design theory

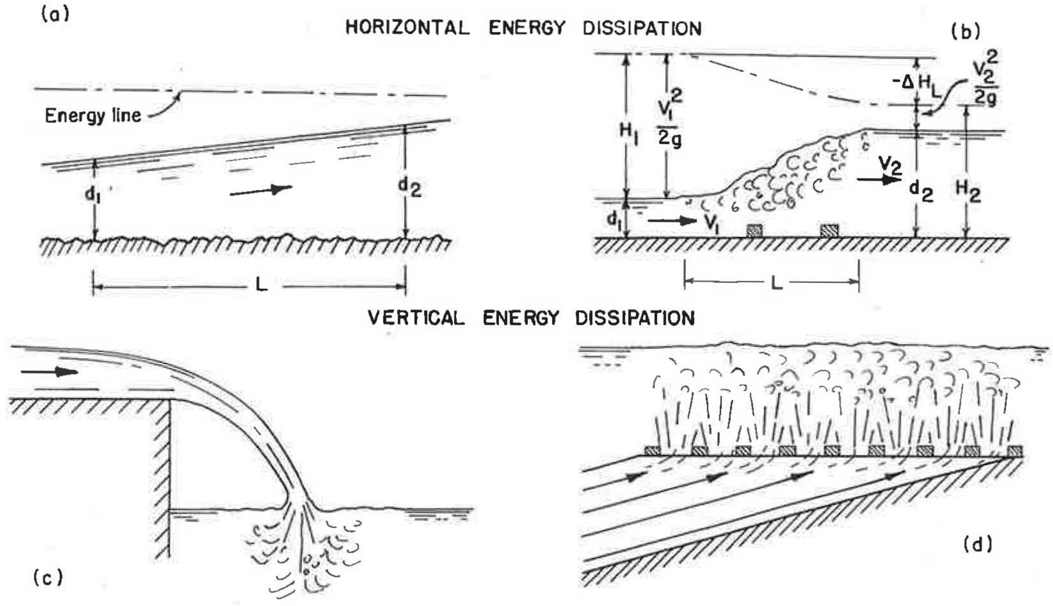

Figure 2. Methods of dissipation of kinetic energy; (a) channel resistance, (b) hydraulic jump and form resistance, (c) downward—vertical jet diffusion downstream of a drop structure, and (d) upward—vertical jet diffusion above a manifold outlet.

provides a trial and error method of estimating a maximum size of armorplate for bank protection. In the laboratory tests 1-in. maximum material was used in varying amounts and according to Figure 5 a small percentage of armorplate gave adequate erosion control.

These studies demonstrated that erosion control depends not only on the use of

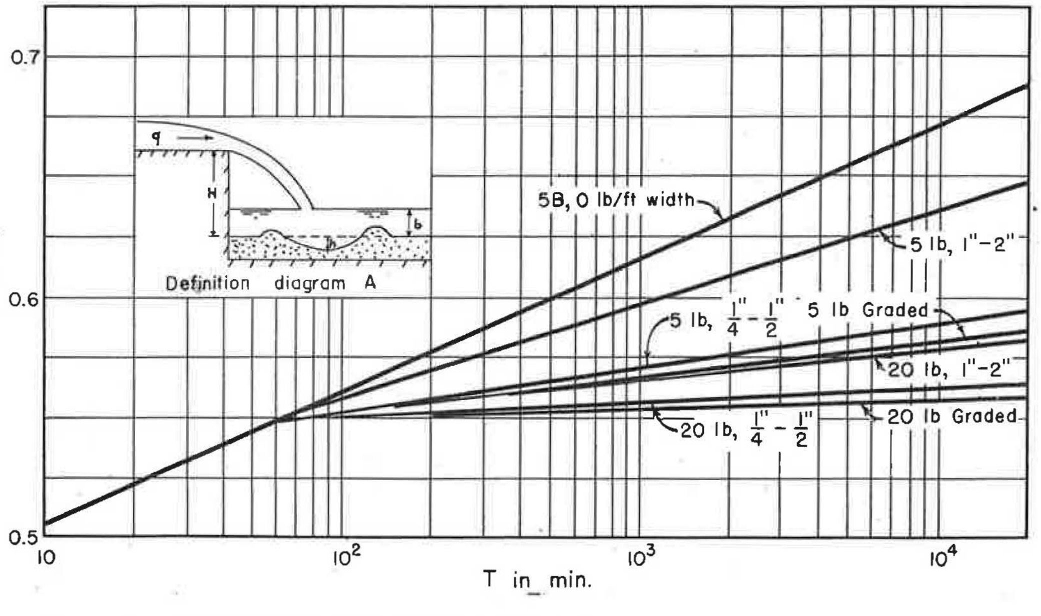

Figure 3. Variation of rate of scour with size and quantity of armorplate.

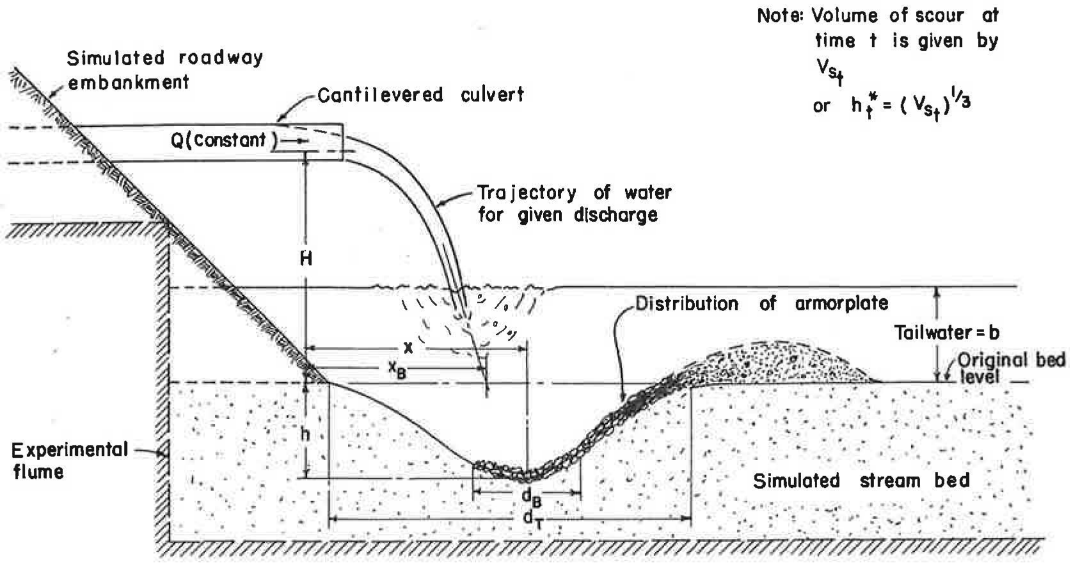

Figure 4. Schematic diagram showing some of the variables that can affect the rate of scour caused by outflow from a cantilevered culvert into a rectangular channel with rigid sides and an alluvial bed. (Note: Geometry of pre-shaped basin is included.)

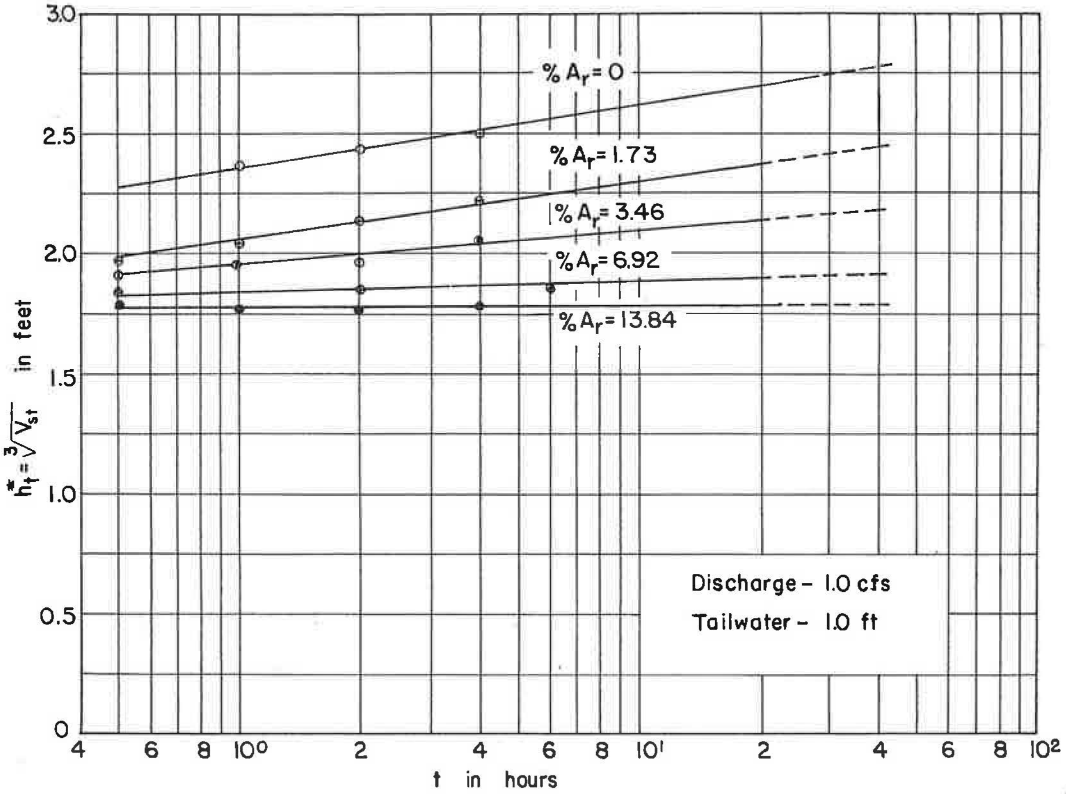

Figure 5. Variation in rate of scour as influenced by quantity of armorplate, discharge and tailwater depth.

armorplating a pre-shaped stilling basin and along the channel banks but also on the proper control of the energy line of the channel downstream of culvert outlets. Control of the energy line as related to tailwater depth may be accomplished by the use of a series of drops, whose crest is higher than the upstream lip of the stilling basin. However, in most cases the position of the total energy line of the downstream channel in relation to the culvert outlet will permit the use of a stilling basin at the culvert outlet without requiring controls further downstream in the channel.

DEVELOPMENT OF AN ARMORPLATED, PRE-SHAPED STILLING BASIN

To develop design criteria for a pre-shaped, armorplated stilling basin, a research program was conducted at Colorado State University (6). The hydraulic laboratory tests were made for a limited range of flow conditions, boundary geometry, and sediment characteristics. The sediment characteristics for armorplating were selected to be representative of those materials found in sand-gravel-cobble deposits. The research program was conducted as follows:

1. An experimental investigation was made of the scour phenomenon caused by a freely falling jet of water impinging into an alluvial bed.
2. The geometry of a standard scour hole (pre-shaped stilling basin) was determined for the three-dimensional jet by an analysis of the scour data.
3. The effect of quantity of graded gravel (armorplate) on the rate of scour was investigated.
4. The most effective point of placement and the minimum effective quantity of armorplate needed for the pre-shaped basin were obtained by an analysis of experimental data.

In making an investigation of the problem of scour in alluvial stream bed caused by a freely falling jet of water, it is important first to consider the various factors affecting such scour. Besides the energy of the jet, which at the pool surface can be expressed in terms of discharge, density and height of fall or velocity, there is the extent of jet disintegration and jet diffusion before it impinges upon the erodible bed. Thus the distance the jet travels in the air, and the depth of tailwater, as well as lateral extent of the pool are important. Finally, the sediment characteristics of the alluvial bed must be considered. Rouse (7) had demonstrated that for completely alluvial material, the geometric mean fall velocity and the standard deviation of this fall velocity about the mean adequately characterize the erodibility of granular sediment. These variables together with the sediment density, completely describe the sediment.

Because of the many factors that can have an effect on scour (Fig. 4) the experimental investigations were limited in the following manner:

1. The jet issued from a source sufficiently close to the bed so that air resistance was negligible ($H = 4.0$ ft, $Q = 0.5$ to 2.0 cfs).
2. The depth of tailwater above the original bed was varied in discrete increments ($b = 0.5$ to 1.5 ft).
3. One size of bed material ($d_m = 2.6$ mm) having a narrow size range ($\sigma_d = 1.35$ mm) was used.
4. During any single test run, the discharge from the jet was held constant and the elevation of the tailwater remained fixed.
5. The channel at the culvert outlet was rectangular in cross-section with rigid sides and alluvial bed.
6. The size of the pre-shaped basin used for testing the armorplate was based on the size of scour hole that would be developed by a given discharge for a given tailwater depth and time of scour, which for both cases was approximately one hour.

In order to design an armorplated, pre-shaped stilling basin downstream from a culvert outlet, it is necessary to have criteria for determining: (a) the design dimensions of the pre-shaped basin; (b) the orientation of the basin relative to the culvert outlet; (c) the minimum size of armorplate that will resist erosion at peak design flow;

(d) the location or point of placement of the armorplate; and (e) the quantity size distribution of armorplate needed.

From an analysis of experimental data for the three-dimensional case (cantilevered culvert), the following criteria were obtained for a pre-shaped basin in a rectangular channel with rigid sides and alluvial bed:

$$d_t = 2.38\ h_t^* \tag{1}$$

$$h\ = 0.50\ h_t^* \tag{2}$$

$$d_B = 0.65\ h_t^* \tag{3}$$

in which

d_t = the diameter of the pre-shaped basin at the surface of the stream bed,
h = the maximum depth of the pre-shaped basin,
d_B = the diameter of the pre-shaped basin at the depth h, and
h_t^* = the cube root of the volume (V_{st}) of the basin at time t, = $(V_{st})^{1/3}$

For example, if as in the laboratory the discharge is 1 cfs and the tailwater depth will be maintained at 1.0 ft, then from Figure 5 for 1 hr the value for $h_t^* = 2.35$. In Figure 5, A_r is the armorplate expressed as a percent of the total volume of the pre-shaped basin. The dimensions of the pre-shaped basin would be $d_T = (2.38)\ (2.35) = 5.6$ ft; $h = (0.50)\ (2.35) = 1.2$ ft; and $d_B = (0.65)\ (2.35) = 1.5$ ft.

No criterion for maximum size of armorplate has been determined. However, experimental tests showed that the effective point of armorplate placement is at a distance equal to X_B from the outlet. The quantity of armorplate in cubic feet is determined by

$$V_{ar} = 0.19\ (h_t^*)^2 D \tag{4}$$

in which D is the maximum diameter of armorplate in inches.

Also of significance to the field engineer would be the quantity of graded armorplate expressed as a percent of the total volume of the pre-shaped basin. Eq. 4 can be written as

$$\%Ar = \frac{V_{ar}}{V_{st}} \times 100 = \frac{19\ D}{h_t^*} \tag{5}$$

For the experimental tests D = 1 in. was used; therefore, the percent of armorplate for this example is

$$\%Ar = \frac{19}{2.35} = 8.1$$

or

$$V_{ar} = 1.05\ ft^3$$

As indicated by Figure 5, the %Ar as determined by Eq. 5 would be sufficient to provide for an effective armorplated, pre-shaped stilling basin for this particular example. The 8.1 percent line would also lie between the 6.92 and 13.84 percent lines with nearly a zero increase in size basin, h_t^* as time continues.

To make the design criteria applicable to field conditions such as illustrated in Figure 1, it was necessary to investigate scour as influenced by boundary geometry at the culvert outlet.

INFLUENCE OF BOUNDARY GEOMETRY ON SCOUR

Any consideration of the effect of boundary geometry on scour in the pre-shaped must start with the simplest boundary form. A channel that is rectangular in cross-section is of this type. By keeping the sides rigid, the effect of channel width, B, on the rate of scour was investigated.

The results of these tests indicated that as the channel becomes wider, the rate of scour increases for any given increment of time. This increase in scour is due in part to the standing eddy which develops between the impinging jet and the channel sides. As the channel becomes wider, the eddy increases in both magnitude and stability.

The standing eddy exerts a shear force along the bed surface and with a decreasing pressure gradient normal to the bed, lifts into suspension the fine sediment particles. As it rotates, the suspended particles are carried into the jet flow and eventually to a point of deposition downstream.

The effect of the channel sides is to destroy the energy of the eddy by providing frictional resistance to the rotating fluid. As the channel sides approach the impinging jet, there is an increase in the energy transfer to small scale turbulence. This small scale turbulence is then dissipated in the form of heat.

Another important factor to be studied was the effect of side slopes of the channel bank on scour. For this case the channel cross-section was of a trapezoidal shape. In the field, rigid channel boundaries are seldom encountered at culvert outlets;

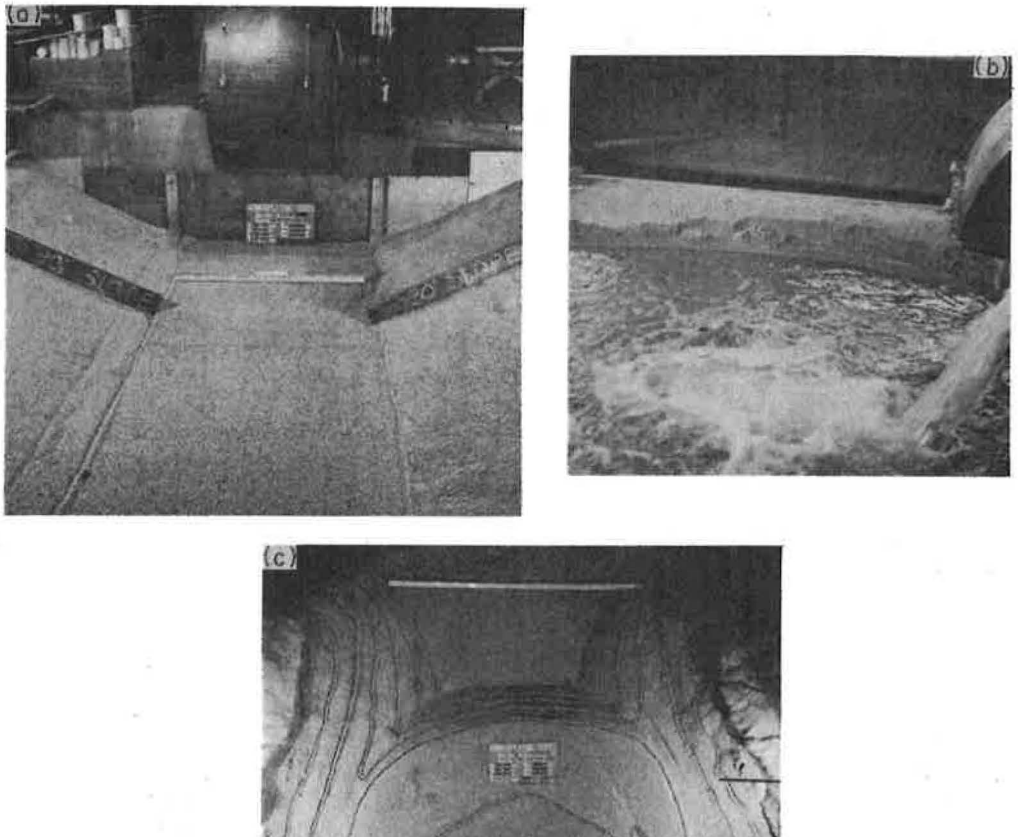

Figure 6. Scour in an alluvial channel at a culvert outlet without armorplate protection. Discharge 1 cfs, tailwater 1 ft, and time of scour 8 hr; (a) initial bed condition, (b) flow pattern, and (c) final scour pattern.

therefore for this study the alluvial banks, whose slopes were made equal to the natural angle of repose of the material composing the banks, were studied.

To stabilize an alluvial bank, it is necessary that those flow characteristics causing its erosion be determined. Keeping the channel width constant (Fig. 6), a study was made of the flow phenomenon causing disintegration of an alluvial bank.

During the laboratory tests it was noted that the waves emanating from the stilling pool area constantly attacked the channel banks. The impact of the wave on the bank dislodged the fine soil particles, which were then carried away by the receding or reflected wave as suspended material. This suspended material was carried into the main stream flow by the action of the standing eddy between the bank and the center of the stilling pool. As the soil particles were removed, sloughing of the bank occurred under the action of gravity and wave forces, and the exposed raw bank provided a fresh source of fine soil particles. As the banks eroded, the stilling area increased in diameter. There was a decrease in the amplitude of the waves reaching the bank, and an increase in size of the standing eddy. Kinetic energy in one form or another was constantly attacking the channel banks. From the results of this study it can be inferred that stability of the channel at the culvert outlet would require not only an armorplated, pre-shaped basin for protection of the channel bed against erosion by the energy of the impinging jet of water, but also armorplating of the channel banks against erosion by wave action. This is demonstrated in Figure 7 which shows the effect of armorplate as a means of protection against erosion of an alluvial channel of a trapezoidal shape downstream of a cantilevered culvert outlet.

SUMMARY

The problem of erosion control at culvert outlets depends on dissipation of kinetic energy in the horizontal direction, vertical direction, or combination of both directions. Dissipation of kinetic energy may be controlled in the vertical direction by use of a pre-shaped armorplated stilling basin.

Systematic experiments upon the rate of scour and scour control in an alluvial bed by a jet of freely falling clear water have indicated the following essential facts:

1. A graded gravel has proved to be extremely effective as protection against erosion from high-velocity flow and waves. It is important, however, that the gravel be graded so that the larger size material is protected from undermining by the smaller size material underneath. The maximum size of the gravel material must be sufficient to resist movement from the stilling basin.

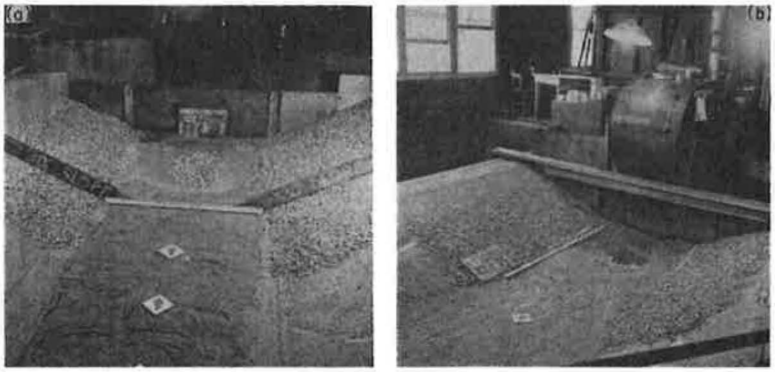

Figure 7. Scour in an alluvial channel at a culvert outlet with armorplate protection. Discharge 1 cfs, tailwater 1 ft, and time of scour 8 hr; (a) initial bed condition, and (b) final scour pattern.

2. Wave action and standing eddies at culvert outlets are two important factors in causing erosion of alluvial banks. An increase in channel width near the culvert outlet causes an increase in the rate of scour.
3. Armorplate protection must be provided to the channel banks within the stilling basin area to provide protection from waves and eddies.

Under the laboratory test conditions the characteristics of a standard pre-shaped stilling basin in terms of h_t^* are given by

$$d_T = 2.38\ h_t^*$$
$$h = 0.5\ h_t^*$$
$$d_B = 0.65\ h_t^*$$

in which h_t^* is the cube root of the volume of scour, $(V_{st})^{1/3}$ developed by a jet of water in t hours of scouring action. Furthermore, for the laboratory conditions a minimum of 10 percent armorplate based on the volume of scour hole at one hour of scour effectively controlled the erosion process. In the report (6) an analysis is made to determine h_t^* and size of armorplate material for a range of flow and stream bed material characteristics.

ADDITIONAL STUDY REQUIRED

Practical results of importance to highway engineers will result from fundamental research investigations regarding the dynamics of the kinetic energy of a jet of fluid and its proper control. In general, in order to obtain improved design criteria for stilling basins at culvert outlets, it will be necessary to study and understand the mechanics of scour and energy dissipation more thoroughly. Although research advances made in the last few years have been very fruitful, some of the studies that will still need to be conducted are:

1. The influence of various types of natural bed materials—cohesive and non-cohesive soils—on the performance of an armorplated, pre-shaped stilling basin.
2. The effect of the degree of overlap of material size between armorplating material and bed material on the rate and control of scour.
3. To determine maximum size and gradation of armorplate for varied flow conditions to control scour.
4. The effect of discharge and height of fall of the jet on the scour phenomenon in the stilling basin.
5. The influence of channel boundary conditions as they relate to channel width and slope of channel sides downstream from the culvert outlet.
6. Investigation of the influence of a rising and falling hydrograph on the design criteria for a pre-shaped basin.
7. A research study using results previously obtained, on low cost armorplating scour control for culverts laid on the natural grade of the stream bed.

REFERENCES

1. Hallmark, Dasel E., "Scour at the Base of a Free Overfall." Master's Thesis, Colorado A and M College (1955).
2. Smith, George L., "An Analysis of Scour Below Culvert Outlets." Master's Thesis, Colorado State University (1957).
3. Terzaghi, Karl and Peck, Ralph B., "Soil Mechanics in Engineering Practice." John Wiley and Sons, Inc., New York, p. 50 (1948).
4. Peterka, A. J., "Stilling Basin Performance Studies on Aid in Determining Riprap Size." Hyd. Lab. Report No. HYD 409, Bureau of Reclamation (Feb. 23, 1956).
5. Lane, E.W. and Carlson, E.J., "Some Factors Affecting the Stability of Canals Constructed in Coarse Granular Materials." Proc. Minnesota International Hydraulics Convention, Minneapolis (Sept. 1-4, 1953).

6. Smith, George L., "Scour and Scour Control Below Cantilevered Culvert Outlets." Colorado State University Research Foundation Report No. CER61GLS14.
7. Rouse, Hunter, Editor, Engineering Hydraulics. Proceedings of Fourth Hydraulic Conference, Iowa Institute of Hydraulic Research, John Wiley and Sons, Inc., New York (1949).

HRB: OR-420