COMMONWEALTH OF KENTUCKY

DEPARTMENT OF HIGHWAYS

FRANKFORT

December 16, 1954

ADDRESS REPLY TO

ATTENTION: D. 2. 1. 1.

D. 1. 7.

MEMO TO: D. V. Terrell
Director of Research

Recently the Research Division received from the Division of Design an inquiry about the influence of so-called "roughness factors" in the design of drainage culverts. This is a subject on which a great deal of literature has been published, especially from the standpoint of research conducted by a few well equipped hydraulic laboratories. As a result of this research there is fairly general agreement on the roughness coefficients for different culvert materials, but somewhat less agreement on the way they should be applied.

At the time Mr. Johnson made his inquiry in a telephone conversation with me, it was decided that we should schedule the topic for discussion at the next meeting of the Research Committee. Accordingly, Mr. E. M. West, who as you know has worked on much of our research in the drainage field and has taught two classes in hydraulics for Highway Department employees, was asked to prepare material summarizing various aspects of the subject. It was intended that this merely be suitable for oral discussion, but in the process of organizing his material Mr. West developed a simplified treatment that should be valuable for future reference. For that reason, it has been reproduced for distribution to Committee members.

Fundamentally roughness is one of several factors that determine the hydraulic capacity of culverts. Under some conditions it is the critical factor, and under others it has no influence on the capacity that is achieved. Sometimes it is an advantage to have the material "smooth", and there are conditions under which a high roughness value is an advantage. The most important point is that the design can be balanced to fit all the circumstances - the condition at the site, and materials available, the economics of construction, and the service conditions that are desired. If any one of the hydraulic factors including roughness should be ignored, a design best suited to the circumstances would be achieved only by coincidence.

Although the solutions for an actual design go deeper than Mr. West has gone in his discussion, the relationships would remain as he presents them. Actually, some of the complicated steps in the solution have been simplified through the development of nomographs and other charts relating various factors. These aids, of course, have been made to conform with practical requirements; for example, the sizes of pipe that are produced commercially. Material of this nature has been included in the new Drainage Manual just completed by the Division of Design and intended mainly for use by employees working on drainage problems.

Aside from work on methods for estimating runoff from drainage areas, we have not carried out any of the research contributing to hydraulic solutions. Most of it has come from other organizations and laboratories, some of which Mr. West mentions in the references he recommends for reading by those interested in drainage design. Much more research is needed on certain phases, perhaps the most outstanding need being on coefficients of entrance loss. At present it is known that most of the situations would be represented by coefficients between 0.1 and 0.8, but within that range the conditions must be generalized. Research to establish these as definitely as roughness factors of 0.015 for concrete pipe and 0.021 for corrugated metal pipe would do much to improve the hydraulic solutions. There is a possibility that we can be of help in this respect, through model studies which are now under consideration.

In conclusion, and in answer to the inquiry as it was brought up, we see no possibility of there being a direct and invariable relation between roughness factor and culvert capacity. The relationship is influenced by other factors which should be considered in the design. Under many conditions the capacity will depend on these other factors whether or not they are taken into account in the design. In other words, if these factors are ignored the culvert will never carry as much water as the designer calculates. After all the factors have been considered and the design is set there is, of course, some relation between the roughness and the capacity. The only way to find out what that relation may be, is to solve the problem hydraulically with all the variables taken into account.

Respectfully submitted,

L. E. Gregg
Assistant Director of Research

LEG:ddc
Copies to: Research Committee
Mack Galbreath (3)

M. W. TINDER
COMMISSIONER OF HIGHWAYS

COMMONWEALTH OF KENTUCKY
DEPARTMENT OF HIGHWAYS
FRANKFORT

December 15, 1954   ADDRESS REPLY TO

ATTENTION: D.2.1.1.

MEMO TO: L. E. Gregg
Assistant Director of Research

SUBJECT: Roughness as a Factor in Culvert Hydraulics

In conjunction with the oral discussion of Roughness as a Factor in Culvert Hydraulics, which has been scheduled for the coming meeting of the Research Committee, I have assembled a few notes and diagrams with which you may wish to become familiar. It is intended that this material serve as a guide in a simplified approach to some of the basic considerations in the analysis of culverts, and not to be all inclusive.

Even though this is a simplified version, none of the basic features have been neglected. Instead, I have tried to interrelate all the influencing factors in a general way, and yet avoid numerical calculations and similar details that would take too much time for discussion. More complete treatments of these same relationships are given in the following publications:

"Manual of Drainage for Kentucky", Kentucky Department
of Highways, 1954.

"Highway Drainage Manual", U. S. Bureau of Public Roads.

"Notes for Short Course in Drainage and Drainage Structure",
Institute of Traffic and Transportation Engineering, University of California.

For still more complete information on the effects of different variables, and some of the research involved in the determination of those effects, the following studies and applications of culvert hydraulics are recommended:

"The Hydraulics of Culverts", F. T. Mavis, Professor and Head of the Civil Engineering Department, Pennsylvania State College.

"Importance of Inlet Design on Culvert Capacity", Lorenz G. Straub, St. Anthony Falls Hydraulic Research Laboratory, University of Minnesota, Tech. Paper No. 13, Series B.

"Experimental Studies Conducted on the Hydraulics of Culverts", Lorenz Straub, St. Anthony Falls Hydraulic Laboratory, for the American Concrete Pipe Association.

"The Long and Short of Conduits", Carnegie Notebook in Civil Engineering, F. T. Mavis, T. E. Stelson and E. H. Miller, Carnegie Institute of Technology.

"Alignment and Grade of Culverts", Wen-Hsiung Li, the John Hopkins University, Department of Civil Engineering, Baltimore Maryland.

All of these are in our library, and probably most of them could be obtained through the University Library by anyone interested in having one or more for a brief period of time. Of course, one or two have been or will be rather widely distributed to employees of the Department.

Slides and diagrams are available to illustrate the different features if questions and comments from others carry the discussion that far. Also, some numerical solutions, such as the ones now under way for three culverts in Bath County, can be reviewed if necessary. Inasmuch as the Drainage Manual is being assembled in Frankfort today, copies of that should be available too.
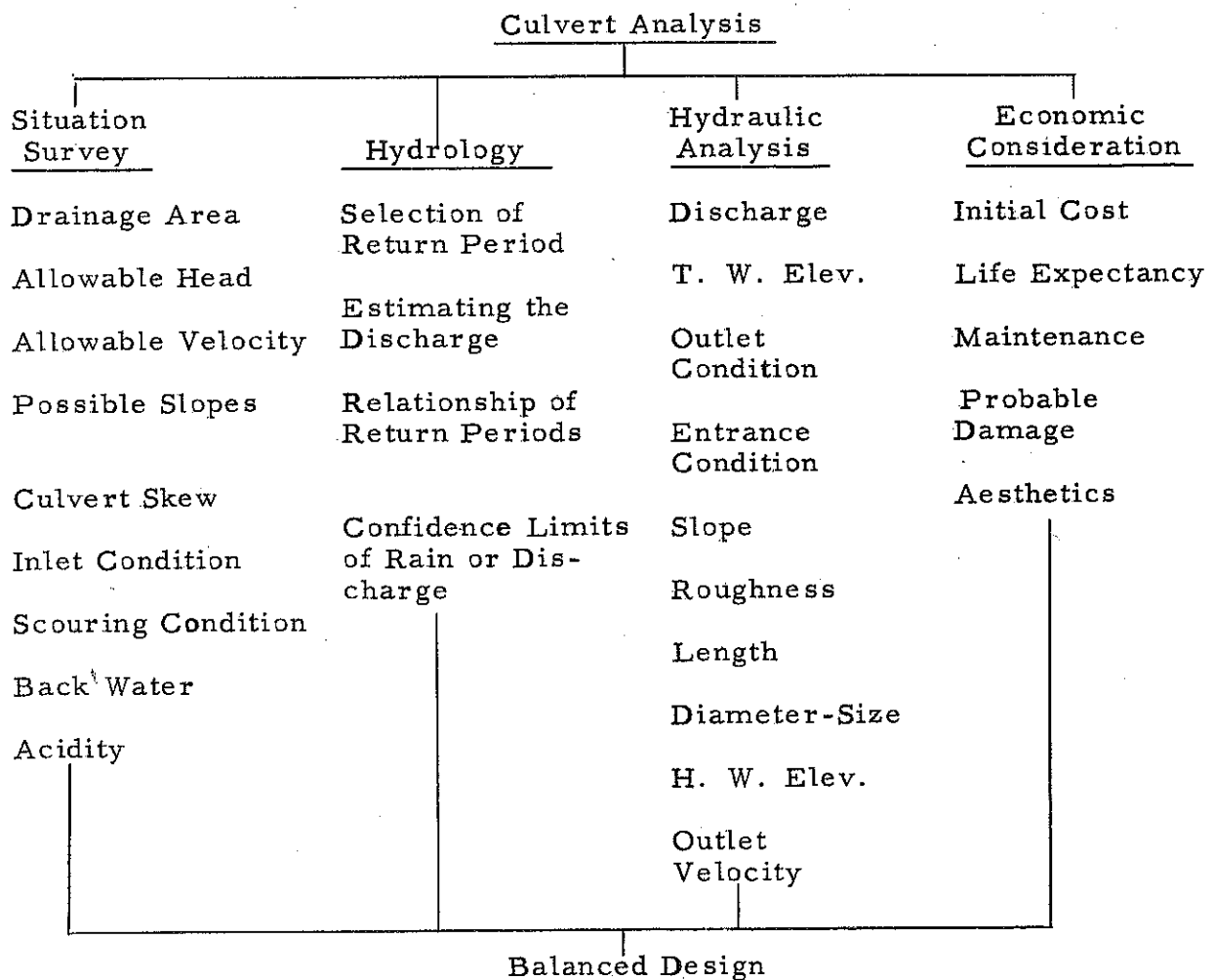
Respectfully submitted,

Eugene M. West
Research Engineer

EMW:ddc

NOTES ON ROUGHNESS AS A FACTOR
IN CULVERT HYDRAULICS

Outlined below are the many variables that must be considered in order to arrive at a balanced design for culverts or drinage structures. This is the only way that the best design can be made; the best design being the most practical, most economical structure offering the hydraulic performance required at the site.

Culvert Analysis

Situation Survey	Hydrology	Hydraulic Analysis	Economic Consideration
Drainage Area	Selection of Return Period	Discharge	Initial Cost
Allowable Head		T. W. Elev.	Life Expectancy
Allowable Velocity	Estimating the Discharge	Outlet Condition	Maintenance
Possible Slopes	Relationship of Return Periods	Entrance Condition	Probable Damage
Culvert Skew			Aesthetics
Inlet Condition	Confidence Limits of Rain or Discharge	Slope	
Scouring Condition		Roughness	
Back Water		Length	
Acidity		Diameter-Size	
		H. W. Elev.	
		Outlet Velocity	

Balanced Design

In this discussion the Situation Survey, Hydrology, and Economic Consideration are excluded, not because they have a lesser degree of

importance, but rather to limit the discussion to the hydraulic analysis within which roughness falls.

The principal reason for a hydraulic analysis in the design of a culvert is to make certain the culvert functions to best advantage and offers the greatest capacity at minimum cost. To accomplish this, all the factors must be taken into account even though some may have no influence on the functioning of the culvert that is finally designed and built. For a given situation, a number of alternate structures may be equally satisfactory from the hydraulic standpoint and the choice would then be made on the basis of economic factors such as first cost, durability, or even aesthetic value.

HYDRAULIC ANALYSIS

In the hydraulic analysis for culvert design the first factor to be considered is the stream channel. A culvert placed in a stream does not affect the normal stream characteristics above the ponding area at the inlet; and below the outlet area the distance of influence is short. The extent of this distance is governed by the amount of turbulence or disturbance caused by the structure.

The quantity of water approaching a culvert in a given time is assumed to be uniform and continuous during the peak rate of runoff for which the structure is designed. By this assumption, an equal amount of water must be leaving the culvert location by way of the downstream channel. There may be momentary retardation of flow, lasting until the storage capacity is achieved, but this will be followed by equilibrium between rate of supply and downstream runoff. If sufficient opening in the culvert is not provided, equilibrium will be attained through overflowing of the roadway.
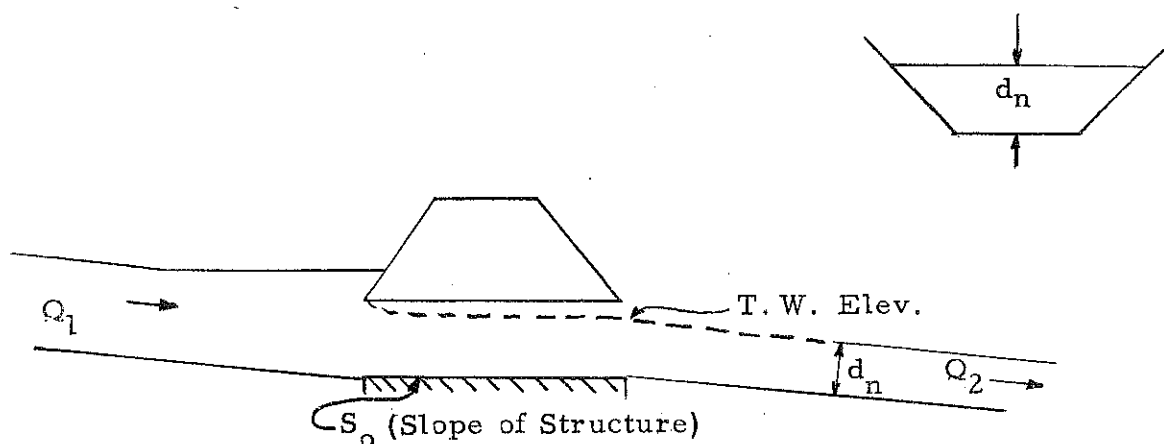
$Q_1 = Q_2$

d_n = Normal depth of flow in the channel when discharge (quantity) Q is carried.

Fig. 1

In the process of transmitting a quantity of water (Q) from the upstream channel, through the structure to the downstream channel (Q_2) a number of changes in flow conditions occur (See Fig. 1).

At the upstream reach, the velocity in the channel is normal while further downstream, just above the entrance of the culvert, the velocity becomes zero. The velocity increases just after entering the inlet, and decreases or increases throughout the length of the structure, the magnitude depending upon the hydraulic conditions created by the situation and characteristics of the culvert. The velocity will tend to decrease with increasing friction unless the structure is laid on a slope that is sufficient to overcome friction, while additional increase in slope will result in increased velocity.

At the outlet (or a very short distance beyond the outlet), velocity again decreases due to the increase in cross section from the smaller culvert area to the channel section. Further downstream the velocity

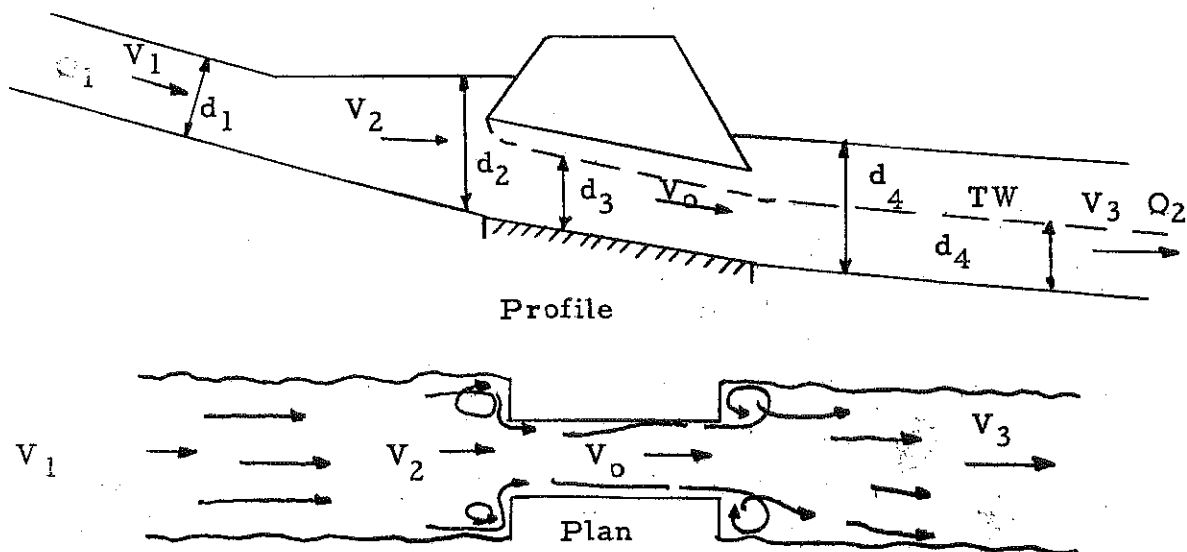

Fig. 2

in the channel will reach its normal condition, the magnitude being the same as if no structure existed.

If the quantity of water is assumed to be continuous, an increase in velocity results in a decrease in depth. Conversely, decreased velocity is accompanied by an increased depth. There is a continual changing of the magnitude of these variables in the hydraulics of flow at the structure site, and abrupt changes in the cross section of flow result in instantaneous changes in velocity and depth.

Wherever the changes are rapid the water becomes turbulent; all the energy can not be converted from velocity to increased depth or vice versa. In this case, energy losses are incurred. (Actually there are friction losses in smooth or laminar flow, but these are negligible in comparison with the losses caused by turbulence).

Outstanding points of energy loss are at the outlet, inlet, and sometimes within the structure. To some extent the losses in the barrel can be offset by changes in the slope of the structure.

Tailwater Elevation

Another primary influence on the flow through a culvert is the elevation of the water surface downstream. Through an analysis of the downstream channel with respect to the design discharge the normal depth of flow in the channel can be calculated by solution of the Manning Formula, or can be read directly from charts prepared for solution of the Manning Formula. From the invert elevation at the outlet of the structure and the normal depth of flow, the tailwater elevation at the outlet end of the structure can be computed.

The significance of tailwater elevation as an influence on performance of the structure depends on whether the structure:

1. Is flowing full at the outlet

2. Is not flowing full at the outlet

A culvert will fall into the first general classification (full flow) if:

(a) laid on its friction slope* or less (Case 1a, Fig. 3)

(b) the outlet end is submerged by the Tailwater Elevation (TW) (Case 1b, Fig. 3)

For conditions where the tailwater depth is less than the height of the culvert and the structure is laid on a slope (moderate to steep)
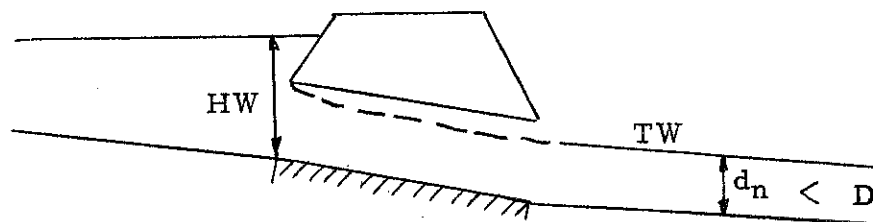
*Friction slope may be defined as the gradient of the structure which produces sufficient increase in velocity head to compensate for the head lost through friction within the structure.
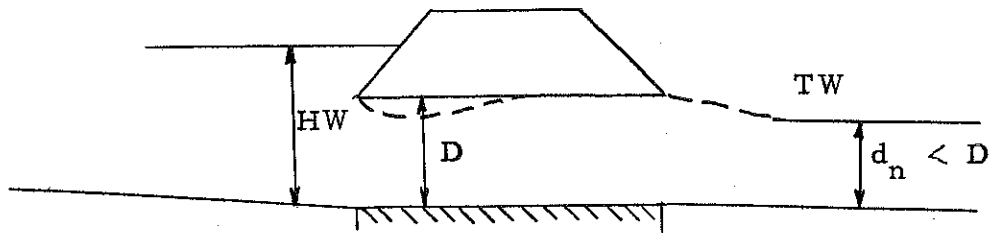
Case Ia
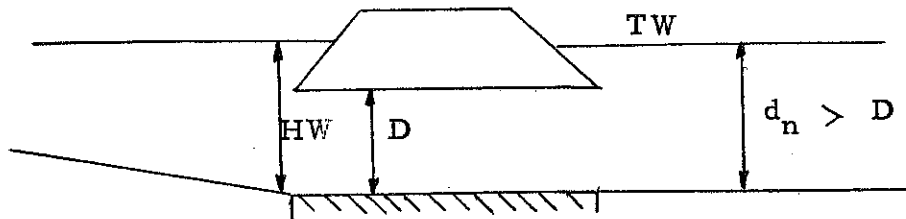
Case 1b

Case 2

Fig. 3

sufficient to overcome friction, the structure will not flow full (Case 2, Fig. 3).

Headwater Elevation - Outlet Velocity

In addition to tailwater elevation, as determined by the downstream channel, there are two limitations which are directly determined by conditions at the site and are generally beyond the province of the designer. These limitations are the permissable headwater elevation and the outlet velocity.

In most instances the permissible maximum headwater elevation is determined by the possibility of damage to the roadway and adjacent property or the extent to which flooding upstream will be objectionable. The permissible outlet velocity is determined by erosion characteristics of stream bed material in the outfall channel.

Conditions controlling headwater elevation are often directly related to those controlling the outlet velocity. In some cases a reduction in outlet velocity may automatically increase the headwater elevation. Likewise, an increase in outlet velocity may decrease the headwater elevation.

Since the principal objective in the design of a culvert is to provide the most economical means of conveying a quantity of water (Q) from the upstream approach channel to the outfall channel in a manner that will give the best hydraulic performance within the limitations of the site, it is often necessary to balance headwater elevation against outlet velocity. This can be accomplished by varying, when possible, some of the other factors involved in the hydraulic performance; (e.g.) slope, inlet conditions, and roughness of the material.

Possibilities for variation fall within three general extremes, which are represented by the following examples:

Example 1 - A structure could be laid on the slope of the channel and made of sufficient size to prevent any headwater on the structure, and yet have the outlet velocity equal to the normal channel velocity established by nature. (Normally are uneconomical an undesirable design).

Example 2 - A structure could be made with small cross-sectional area and near perfect inlet conditions, consist of a very smooth material, and be placed on a slope that would cause very high outlet velocities. Such an arrangement would assure adequate capacity with a minimum head on the structure, only to the point where permissible outlet velocities were exceeded.

Example 3 - A structure could be made with small cross sectional area, consist of a rough material, be laid on a flat slope and have poor inlet conditions. A design such as this would provide adequate capacity with low outlet velocity only to the extent that maximum headwater elevations would permit. The capacity would be adequate only if a very high headwater elevation is tolerable.

Somewhere within the limits of the conditions of these examples, a balanced design can be worked out hydraulically, provided all of the appropriate variables are considered with regard to their respective magnitudes and proper relations to each other. By this means, a culvert can thus be "tailored" to accommodate almost any headwater and outlet velocity condition.

Inlet Conditions

The importance of inlet conditions is encompassed by the simple statement that the amount of water that will flow through the barrel of a structure is limited by the amount that can enter the inlet end. Because of orifice action (or "necking down") at the inlet, an appreciable amount of velocity head is lost before the water starts to flow within the structure. The velocity head lost is a function of the geometry of

the inlet, the amount of turbulence caused by the orifice action, and the increase in velocity that accompanies the change in cross sectional area of the water at this point.

Naturally the best inlet conditions are those that create minimum amounts of turbulence in company with the increase in velocity. In effect, this permits the flowing water to retain the greatest percentage of its energy (velocity head), and in doing so it makes possible the passage of greater quantities under a given head. Stated differently, it eliminates the need for a higher headwater elevation to push a given quantity of water through the structure.

The effects of various inlet conditions have been expressed as mathematical coefficients, with the numerical values depending upon the portion of the head lost through interference to flow under specific inlet conditions. These coefficients have been determined experimentally in hydraulic laboratories for some general cases as well as some extreme conditions. The extreme values have been found to be 0.1 of the velocity head for good conditions, and 0.8 of the velocity head for poor conditions. For the many situations in between, it is necessary to estimate the inlet coefficient.

Considerable work is being done to determine experimentally the value of coefficients for different conditions and to improve the hydraulic efficiency of inlets in order to conserve velocity energy. Some outstanding examples of improved inlet efficiency were demonstrated in research carried out by Oregon State College, where the inlet design for the Oregon State Highway Department standard box culvert was revised, and a 100 percent increase in capacity was attained.

Outlet Conditions

Under certain conditions, the amount of water that can flow through a culvert is controlled by the amount that can be discharged at the outlet end. Retardation of flow at this point can be brought about either by backwater from the downstream channel or by poor transition from barrel flow to channel flow. The smoothest possible transition should be made so that the reduction in velocity head is minimized. As noted in the earlier discussions of tailwater elevation and outlet velocity, the headwater elevation may be increased by reduction in velocity head.

Roughness

Characteristics of material within the barrel of the structure always influence the flow, but the extent to which they exert an influence depends on several things. Under any circumstance, however, the head lost through friction (roughness) is a function of the area exposed - or, the wetted area - and the velocity at which water flows through the barrel. The wetted area is determined by the length and size of the structure.

The portion of energy lost due to friction or roughness may be expressed as a loss in velocity head in the following equation:

$$h_f = f_n \frac{l}{R} \frac{V^2}{2g}$$

where

h_f = velocity head lost due to friction,

f_n = a function of the roughness coefficient "n",

l = length of structure,

R = hydraulic radius, expressed as a ratio of wetted area to perimeter or A/P,

V = representative velocity of flow in the barrel,

and   g = acceleration due to gravity = 32.2 ft./sec.^{2}

Therefore, the effect of friction varies directly with the length (1), inversely with the hydraulic radius (R), and directly with the normal, or for this purpose, representative velocity of flow (V).

Since the normal velocity for a given size structure carrying a known discharge quantity (Q) is determined by a function of the slope of the structure, the effect of roughness (n) also varies directly with a function of the slope. Slope, then, is an outstanding variable determining the effect of roughness (n).

In the case of a culvert where a steady uniform flow of water is maintained, the water surface is parallel to the bottom of the barrel. The slope of the barrel, the slope of the water surface, and the slope that represents the rate at which velocity head is being used up to overcome friction, are all the same.

When flowing water partly fills a culvert and the structure is laid on a slope sufficient to maintain uniform flow parallel to the bottom, the structure is laid on the so-called friction slope, as mentioned on page 5. An increase in roughness of the culvert material would thereby necessitate an increase in the friction slope assuming that all other conditions are to be maintained.

For example: If a 36-in. diameter pipe with a roughness of 0.015 is designed to carry 30 cfs at a depth of 2/3 full, the friction slope required would be 0.8 percent. For a factor of roughness of 0.021, the required slope would be 1.4 percent. And under those conditions there

would be no change in headwater elevation, outlet velocity, or any of the
other factors important in culvert design. If the slope were increased
above this amount, the depth of flow would decrease; and conversely,
if the slope were decreased, an increased depth of flow would result -
once again assuming that none of the other features changes.

Thus, for structures laid on slopes less than friction slope, an
increase in roughness would produce a slower velocity and greater depth
of flow. If the culvert slope is flat enough, and the culvert is of suffi-
cient length, a reduction in velocity due to friction would cause an in-
crease in the headwater elevation up to whatever point is necessary to
create sufficient energy for the necessary quantity of flow.

However, when a culvert is laid on its friction slope (or greater),
and the tailwater elevation is below the crown at the outlet end, increased
friction will not affect the headwater elevation except in a rare case of
near perfect inlet conditions. Whenever friction slope (or greater) can
be maintained, there is possibility of advantage being derived from a
material with relatively high roughness because of its tendency to reduce
outlet velocity without increasing headwater elevation.

The sketches on the following page show how various conditions
of flow are developed. Each case is a situation within itself, but in some
instances the condition can be brought about by changes in relationships
applying to one or more of the other cases. In brief, the situations and
their relationships to roughness factors are as follows:

Case 1 - The structure is not flowing full; the slope is less than
critical slope*. An increase in roughness would increase the depth of

* Critical slope is that slope of the channel bed or conduit which under a
given set of conditions is just sufficient to maintain a fixed quantity of flow
at the minimum depth or at a minimum energy content.
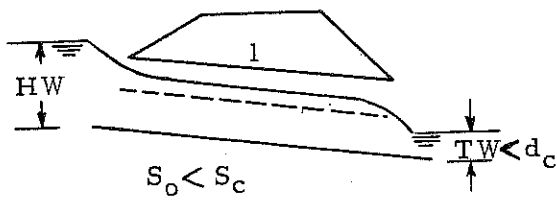
TYPICAL CONDITIONS UNDER WHICH CULVERTS OPERATE

Low Heads
$HW \leq 1.4 D$

High Heads
$HW > 1.4 D$

$$HW = d_c + \frac{V_o^2}{2g} + h_e + h_f - S_oL$$

$$HW = H$$
1042, 1043

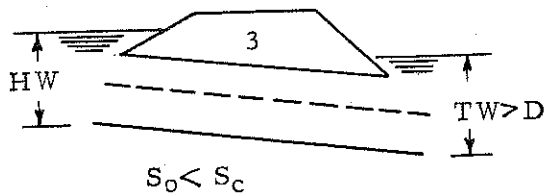(figure 1) $S_o < S_c$, $TW < d_c$

(figure 1A) $S_o < S_c$, $TW < D$

$$HW = d_{TW} + \frac{V^2_{TW}}{2g} + h_e + h_f - S_oL$$

$$HW = H + D - S_oL$$
1041

(figure 2) $S_o < S_c$, $TW > d_c$ $< D$

(figure 1B) $S_o < S_c$, $TW < D$
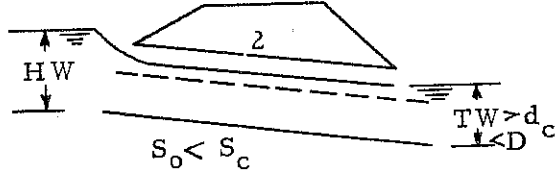
$$HW = H + TW - S_oL$$
1041

$$HW = H$$
1042, 1043

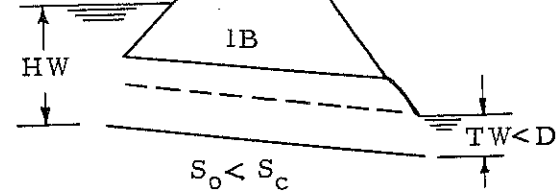(figure 3) $S_o < S_c$, $TW > D$

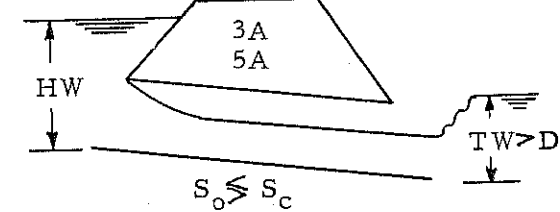(figure 3A 5A) $S_o \lessgtr S_c$, $TW > D$

$$HW = H$$
1042, 1043

$$HW = H$$
1042, 1043

(figure 4) $S_o > S_c$, $TW < D$

(figure 4A) $S_o > S_c$, $TW < D$

$$HW = H$$
1042, 1043

$$HW = H + D - S_oL$$
1041

(figure 5) $S_o > S_c$, $TW > D$

(figure 4B) $S_o > S_c$, $TW < D$, H
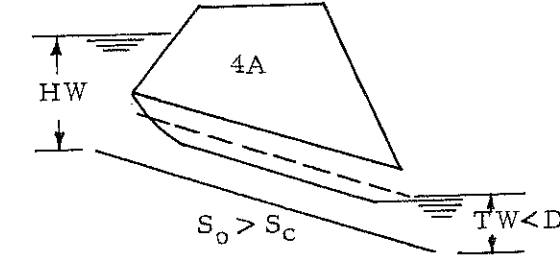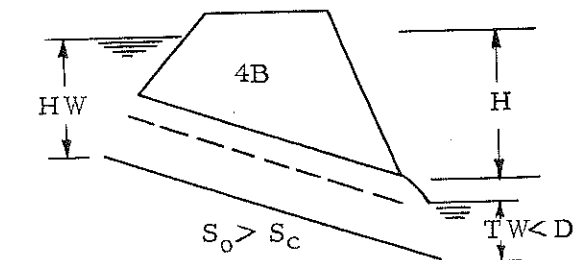
(Adopted From Bureau of Public Roads Drainage Manual)

flow and would cause an increase in headwater elevation.

Case 1A - When the headwater depth in Case 1 has increased an amount sufficient to submerge the inlet of the structure, the inlet end becomes the controlling section, and an increase in roughness would have no effect on the headwater elevation. An increased roughness would increase the depth of flow. However, the amount of flow is controlled by the amount that can be admitted at the inlet.

Case 1B - If a perfect inlet was provided for structures 1A and 1B, or if the relationship of length to diameter became very large and the slope approached zero gradient, the structure would flow full. Under conditions of full flow, an increase in the roughness of the material would cause a decrease in velocity. Since the pipe would be flowing full, this decrease in velocity could not be compensated for by an increase in depth of flow. Therefore, an increase in headwater elevation would result.

In general, with prevailing inlets and the length-diameter ratios normally encountered in highways. This case seldom applies. Tendencies toward wider roadways and higher fills are bringing the situation into greater prominence.

Case 2 - The slope is less than critical, and the pipe is not flowing full. Control is in the barrel or at the inlet section. For this depth, an increase in roughness would cause a greater depth of flow and would increase the headwater elevation. However, when the headwater submerges the inlet of the structure, the operation becomes similar to Case 1A or 1B, depending upon the inlet condition and the slope-length ratio.

Case 3 - The slope is less than critical and the outlet of the structure is submerged. An increase in roughness would cause a decrease in velocity which could not be offset by greater depth of flow. Thus, an increase in headwater elevation would result.

Case 3 or 5A - Conditions are the same as in Case 3, except that poor inlet conditions, shorter length, a smaller length-diameter ratio, or possibly greater slope prevent the structure from flowing full. In these cases the control is at the inlet. The inlet conditions control the amount of flow by controlling the amount of water that can get into the barrel. An increase in roughness would cause a greater depth of flow but would not influence the headwater elevation so long as these conditions prevailed.

Cases 4, 4A, 5 and 5A - In these cases the structures are laid on slopes that are equal to, or greater than, critical slope. Any increase in roughness would cause greater depth of flow, but it would have no bearing on the headwater elevation since there is no provision for full-depth flow.

Case 4B - The slope is greater than critical slope. The inlet conditions are assumed to be excellent, and the ratio of length to diameter large. Roughness of the material is great enough to make flow dependent on conditions in the barrel. With roughness the controlling factor, any increase in this factor would result in an increased headwater elevation.