UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

CULVERT HYDRAULICS

A LIBRARY STUDY

Hydraulics Branch Report No. Hyd-489

DIVISION OF ENGINEERING LABORATORIES

OFFICE OF ASSISTANT COMMISSIONER AND CHIEF ENGINEER
DENVER, COLORADO

April 19, 1962

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Denver, Colorado
Date: April 19, 1962

Report No. Hyd-489
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Subject: Culvert hydraulics--a library study

PURPOSE

A library study was conducted to determine the present state of the art of culvert hydraulics, to prepare an annotated bibliography of publications relating to the subject, and to prepare a summary of research still needed in specific areas. Evaluation of construction materials was not a part of this study.

CONCLUSIONS

1. Research work is reasonably complete in the general areas of culvert size, standard inlets, some nonstandard inlets, culvert slopes, and culvert lengths.

2. Additional research is needed for approach conditions, variations of roughness coefficients for culverts flowing partly full, characteristics of different span to height ratios in rectangular and noncircular culverts, further development of economical outlets, and verification or revision of general solutions for nonuniform flow in culverts.

3. Future research should be conducted with large scale models to avoid errors due to scale effects resulting from surface tension, turbulence, configuration, and other causes.

4. Enough information is presently available to compile a comprehensive design manual concerning culvert hydraulics. The writing of such a manual would correlate the previous research work and point out any other areas in which additional research would be profitable. Therefore, the manual should be prepared prior to the conduct of any extended research programs. Careful interpretation of data is important in preparing the manual either from material contained in the bibliography references or material obtained from future research work.

ACKNOWLEDGEMENT

The publications listed in the bibliography were obtained through cooperation by the Technical Library Section, Bureau of Reclamation, Denver, Colorado, and through various laboratories and organizations who were extremely helpful in submitting reports and giving permission for the inclusion of their reports in the bibliography.

INTRODUCTION

Tracing the development of culverts, or even ascertaining when they were first used, is an impossible task. We know that brick culverts were being used in the ancient cities of Harappa and Mohenjodaro in India at least 3,000 years before Christ. By 150 B.C., the Greeks had developed a rudimentary knowledge of relationships between area, velocity, volume, and time for flow in box culverts. Around 100 B.C., the Romans were engaged in the construction of large aqueducts and extensive water conveyance systems. 1/ Even though the Romans were builders of great waterworks, they seemed to be unaware of the principles of hydraulics and of the developments by the Greeks. Since the time of the Romans, culverts have become commonplace items that are installed whenever water must be transported for relatively short distances.

Until the 20th Century, the process of designing culverts was cut and try, accompanied with a few good rules of thumb. However, in the last forty years, great advancements have been made in our basic knowledge of culvert hydraulics. As a result, well-informed engineers do not have to rely on entirely empirical formulas and rules of thumb when solving culvert hydraulic problems, but can attack the problems in a rational manner. Unfortunately, much of the more recent knowledge has not been gathered together, and hence, the information is not being used profitably. To partially overcome this deficiency, a survey was made of the published research work. This report and its appended annotated bibliography presents a summary of the publications surveyed.

1/ "History of Hydraulics," by Hunter Rouse and Simon Ince, Iowa Institute of Hydraulics Research, State University of Iowa, 1957, page 269.

SUMMARY

This report is concerned with culverts in general, and is not intended as an evaluation of construction materials. Foreign language papers which were available have been included in addition to those papers written in English. The results, conclusions, and recommendations of the papers surveyed are summarized under the following topics:

- Culvert Size
- Approach Conditions
- Inlet Details
- Slope of Culvert
- Roughness of Culvert Walls
- Shape of Culvert
- Length of Culvert
- Outlet Details
- Flow Conditions through the Culvert

Culvert Size
(37, 40, 44, 60)*

The three most generally used methods of determining culvert size are:

(1) On the basis of old structures in the vicinity.

(2) Using an empirical formula relating drainage area and culvert size, such as Talbot's formula.

(3) Using hydrologic and physiographic data to determine the quantity of water reaching the culvert, then designing the culvert to pass that quantity of water.

The first two methods are still retained in design handbooks, even though they are the children of antiquity. Their popularity is due to the simplicity of the computations required. The third method requires a consideration of hydrologic factors, drainage area, slope and cover of terrain, as well as knowledge of culvert hydraulics. Two expressions which have attempted to relate these variables are the Burkli-Ziegler Formula and the Rational Formula. Although the third method listed above is the most reasonable approach, exact results are not obtainable because the science of

*Numbers in parentheses refer to references in the appended annotated bibliography.

hydrology is still in its infancy. Engineering experience and judgment indispensible when computing the amount of flow a culvert will be required to pass.

Conclusion: Methods are available to estimate the quantity of water which a culvert will be required to pass. However, researching these methods is the responsibility of the hydrologist and is not a constituent part of this report. The design discharge is assumed known in the discussions which follow.

Approach Conditions
(13, 15, 16, 30, 37, 57, 58)

All of the design methods assume that the water level in the head pool is above the culvert and conditions of negligible approach velocity exist.

Some consideration has been given to the approach velocity for those instances in which stagnant conditions do not exist, but only a few experiments have been conducted. These experiments indicate that the approach geometry can have a significant effect on culvert performance. The design handbooks recommend proper alinement of the culvert with the existing watercourse; however, no comments are made concerning corrections to the design when misalinements are necessary.

Conclusion: The effect of approach conditions has been considered and a few tests have been conducted. Additional research in this phase of culvert design would be beneficial.

Inlet Details
(16, 17, 19, 23, 24, 26, 27, 28, 30, 32, 33, 34, 38, 40, 45, 51, 52, 56, 57, 58, 61)

An inlet can have two pronounced effects on the flow through a culvert. First, streamlining of the inlet will reduce the entrance losses; and second, the inlet geometry can cause the culvert to flow full, even though the culvert barrel is placed on hydraulically steep slopes. One or both of these effects were investigated for the following inlet types:

(1) Hooded inlets, both square and triangular

(2) Bellmouth inlets

(3) Tapered inlets on box culverts

(4) Rounded flush inlets

(5) Square-edged flush inlets with parallel, flared, and straight or normal wingwalls

(6) Grooved projecting inlets

(7) Rounded projecting inlets

(8) Thin walled projecting inlets

(9) Gradual transitions

(10) Mitered inlets which conform to embankment slope

(11) Inclined taper and drop inlets

Conclusion: Sufficient research work has been accomplished to accurately predict the effect of standard inlets, as well as a few nonstandard inlets. Further research is required for special inlet configurations that are not listed above.

Slope of Culvert
(9, 26, 28, 30, 34, 40, 44, 47, 52, 58)

The effect of slope has the greatest significance for open channel or partly full flow in culverts. In general, channels which slope downward in the direction of flow may be classified as having a steep, critical, or mild slope. These classifications may be defined as follows:

(1) A steep slope will sustain uniform flow at a supercritical velocity.

(2) A critical slope will sustain uniform flow at a critical velocity.

(3) A mild slope will sustain uniform flow at a subcritical velocity.

(4) Uniform flow is the condition that exists when the water surface is parallel to the channel bottom. 2/

Tests were mainly conducted on steep or mild slopes because critical slopes do not occur very often in practice. By proper

2/Rouse, H., 1959, "Engineering Hydraulics," Wiley and Sons, New York.

application of existing theory, culverts can be designed on any slope.

Nondimensional curves are given to determine the critical depth in circular conduits for various values of Manning's "n." Critical depths for rectangular cross sections can be found in most hydraulic handbooks.3/ The effect of discharge on a change in slope is also presented.

Conclusion: Sufficient research has been conducted to accurately predict the effect of changes in pipe slope on the discharge. Further work is required to determine the critical slope for noncircular and nonrectangular configurations.

Roughness of Culvert Walls

(1, 2, 3, 9, 10, 11, 12, 13, 14, 15, 18, 19, 20, 25, 29, 31, 33, 40, 44, 45, 48, 50, 54, 55, 58, 61)

Probably more time and effort has been expended deriving an accurate expression for pipe friction than on any other phase of culvert design. The subject has been explored through mathematical considerations, as well as through the empirical approach. Various equations, both empirical and rational, have been presented to predict flow in pipes; however, most of the empirical equations can be shown to be special cases of the more recent general resistance relationships. Roughness coefficients, expressed in terms of Manning's "n" have been determined through laboratory and field measurements of various pipe sizes, shapes, and types. A general design assumption is that the roughness coefficient remains constant for the pipes flowing either full or partly full. However, some investigators have found that the roughness coefficient increases for pipes flowing partly full.

Conclusion: Engineers should have the various resistance equations available and know the limitations of the formulas. Additional research should be conducted to determine the variation of Manning's "n" over wide ranges in depth for open channel flow in culverts.

Shape of Culvert

(all references)

Square box culverts and circular culverts are the general culvert shapes that have been studied in detail. Limited data are also

3/ Ibid.

available for inverted egg, pipe arch, and horseshoe shapes. There is very little data concerning variable span to height ratios for rectangular culverts and part circle culverts.

Conclusion: Additional testing is needed for variable span to height ratios of rectangular culverts and noncircular culverts.

Length of Culvert
(1, 13, 14, 15, 30, 33, 34, 46, 58)

The length of the culvert was found to be a significant factor in several cases. For partly full flow and mild slopes, the discharge in long culverts is usually less than in short culverts. On steep slopes, the length of the culvert does not have a significant effect on discharge. For full flow in culverts on mild slopes, the discharge in long culverts is less than in short culverts. However, on steep slopes the discharge in long culverts is greater than in short culverts, due to siphoning action.

Conclusion: The length of the culvert is an important factor in design. Sufficient research has been accomplished to accurately predict the effect of length for different culvert slopes on the discharge.

Outlet Details
(1, 5, 7, 8, 21, 22, 33, 41, 42, 43, 45, 51, 58, 59)

Tests have been conducted with impact-type energy dissipators, flared and submerged outlets, and using adverse hydraulic gradients at the culvert exit. Each of these schemes produced favorable results. Erosion studies have been made for culverts with a cantilevered outlet, and the effect of riprapping the pool into which the outlet discharges has been investigated. Flared outlets similar to a typical inlet shape are not effective in reducing erosion at unsubmerged outlets.

Conclusion: Research should be conducted toward the further development of simple, inexpensive, effective outlets. The research should include the effect of the outlet on scour, energy dissipation, and flow conditions through the culvert.

Flow Conditions through the Culvert
(4, 6, 11, 13, 16, 17, 24, 26, 32, 34, 36, 40, 44, 47, 49, 51, 52, 56, 58)

The flow conditions through a culvert are dependent upon the culvert slope and the respective elevations of the head and tailwater.

For culverts flowing partly full and on a steep slope, the discharge is controlled at the inlet and is determined by orifice or weir considerations, depending upon the headwater depth. For culverts flowing completely full, the discharge is controlled by the difference in head- and tailwater levels and is analyzed according to the standard-pipe-flow conditions. For full flow with a free outlet, data are sparse, but investigators have found the hydraulic gradeline to be below the crown of the pipe. For culverts flowing partly full on mild slopes, outlet control usually exists. For the latter case, discharge computations require that backwater curves be determined and this process is rather tedious. Tests of backwater curves with small models do not always give good results because surface tension and the scale of turbulence tend to modify the surface profile.

Model tests have been conducted for the case of a hydraulic jump in a pipe. Pressure profiles for both rectangular model culverts and full scale circular culverts are available. The effect of a nonuniform velocity distribution is also investigated.

Conclusion: Further research with full scale culverts is desirable to verify or refute general solutions for nonuniform flow in culverts. Present methods for computing headwater for culverts with outlet control appear adequate.

APPENDIX

ANNOTATED BIBLIOGRAPHY
(Chronological Listing)

(1) YARNELL, D. L., NAGLER, F. A., WOODWARD, S. M., 1926, "The Flow of Water Through Culverts," State University of Iowa, Studies in Engineering, Bul. 1, 128 p.

Presentation of the results from 3,301 experiments on the flow of water through short conduits such as pipes and box culverts. Concrete, vitrified clay and corrugated-metal pipes were tested in the following sizes: 12-, 18-, 24-, and 30-inch-diameter in 30-foot lengths. In addition, the 24-inch-diameter pipes were tested with 36-foot lengths. Box culverts up to 4 feet square were tested in lengths of 36 feet. The tests were made on the culverts flowing partially full and full, with both free and submerged outlets for various types of entrances.

(2) NIKURADSE, J., 1932, "Gesetzmässigkeiten der Turbulenten Strômung in Glatten Rohren," (Laws of Turbulent Flow in Smooth Pipes), Verein Deutscher Ingenieure, Forschumgsheft 356.

Investigation of the laws of turbulent flow in smooth pipes at high values of Reynolds number. Work done by Stanton, Bazin, Prandtl, and V. Karman is found to compare favorably.

(3) NIKURADSE, J., 1933, "Strômungsgesetze in Rauhen Rohren," (Laws of Flow in Rough Pipes), Verein Deutscher Ingenieure, Forschungsheft 361.

Development which shows similitude relationships for model pipes which are roughened with sand grains. Relationships also found for friction factor and Reynolds number for six different pipe roughnesses.

(4) KINDSVATER, C. E., 1937, "The Hydraulic Jump in Enclosed Conduits," State University of Iowa, Master's Thesis.

The thesis presents the results of 35 tests, made in a 6-inch transparent pipe, with hydraulic jumps produced by artificial constrictions of three sizes. Curves are presented to show comparisons between theory and observation. The tests indicate a general confirmation of the theory, with certain qualifications for special cases.

(5) BLAISDELL, F. W., 1941, "Tests of a Standard Culvert Outlet for Use with Drop Inlet Culverts," U. S. Department of Agriculture, Preliminary Report No. 2, Project MN-R-3, 10 p.

Tests were conducted to determine the degree of scour and the effect of sills and baffles in reducing scour for a standard flared outlet. Standards are developed for depths of cutoff walls, and wingwall installation.

(6) STREETER, V. L., 1942, "The Kinetic Energy and Momentum Correction Factors for Pipes and for Open Channels of Great Width," Civil Engineering V 12, n4, April, pp. 212-213.

Derivation of Kinetic Energy and Momentum Correction Factors for a nonuniform velocity distribution based on von Karman's universal logarithmetic velocity distribution law. Curves of the correction factors are given for various values of the Darcy roughness coefficient.

(7) BLAISDELL, F. W., 1943, "Tests of Culverts and Flume Outlet Structures," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis 14, Minnesota.

(8) BLAISDELL, F. W., 1943, "The SAF Stilling Basin," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis 14, Minnesota.

(9) MAVIS, F. T., 1943, "The Hydraulics of Culverts," Pennsylvania State College, Engineering Experiment Station, Bulletin No. 56.

Tests were conducted on model pipes constructed from cast iron, lucite, and transite. The cast iron pipe was 6 inches in diameter and 60 inches long laid on a 3.05 - percent slope. The lucite pipes were tested for diameters between 3 and 5.85 inches with lengths of 44.0 to 53.2 inches laid on slopes between 0.05 and 6.57 percent. The transite pipe was 12 inches in diameter and 155 inches long laid on slopes between 1.22 and 2.96 percent.

The culverts were operated under the following conditions:

(a) Partly full with free outfall.

(b) Partly full with outfall partially submerged.

(c) Full with outfall completely submerged.

(d) Full with outfall partially submerged.

(e) Full with free outfall.

On the basis of these tests, a satisfactory engineering analysis can be made of the flow of water through conduits of intermediate length and circular cross section for the above conditions. The paper presents diagrams and examples of computations to compute the flow under the five types of flow as given above.

(10) JOHNSON, C. F., 1944, "Determination of Kutter's "n" for Sewers Partly Filled," ASCE Trans., Vol. 109, pp. 223-47.

Tests were made in sewers whose shapes were inverted egg, horseshoe, and circular for various depth of flow up to 0.4 D. The discussions add further data for culverts made from other materials. The circular culvert in the paper was constructed from brick.

(11) HINDS, 1946, "Comparison of Formulas for Pipe Flow," Journal of the American Water Works Association, Vol. 38, No. 11, Nov., pp. 1226-1252.

A review of the 6 or 8 formulas available or in current use for computation of discharges in the design of water supply systems.

The following conclusions were reached: (1) Old pipe formulas are imperfect and limited in scope, (2) new pipe formulas for laminar flow and smooth pipes are accurate beyond practical needs, (3) for water the Colebrook formula for turbulent flow is ideal in conception, but needs substantiation, (4) research should collect friction data on new kinds of pipe and develop new formulas or substantiate old formulas.

(12) BARBE, R., 1947, "La Mesure dans un Laboratoire des Dertes de Charge de Conduites Industrielles" (Laboratory Measurement of Head Losses in Commercial Pipelines). La Houille Blance, Vol. 2, pp. 191-203. Also in Waterways Experiment Station Translation No. 51-10, 25 p.

Tests were made on pipes 800 mm in diameter and 200 m long for the range of Reynolds number 5 X 10^5 to 2 X 10^6. The types of pipes were (a) centrifugally cast concrete (b) prestressed concrete (c) cast iron, with a very smooth lining

of centrifugally cast, "Bitumastic" (d) steelplates, completely welded.

The results all fall close to the mean curve of Nikuradse for smooth pipes. The series of tests which were closest to the Nikuradse curve were those of the cast iron pipe lined with "Bitumastic." Steelplate and prestressed concrete are nearly equivalent. The most deviation was found in the centrifugally cast concrete pipe.

(13) KEULEGAN, G. H., 1948, "Friction Losses in Short Pipes and Culverts Flowing Full," National Bureau of Standards, not published.

(14) KEULEGAN, G. H., 1948, "Theory of Flow Through Short Tubes with Smooth and Corrugated Surfaces and with Square Edged Entrances," National Academy of Sciences, National Research Council, Highway Research Board, Research Report 6-B.

The theoretical form of discharge formulas for flow in short culverts is derived, as well as the criteria for determining the hydraulic length of a culvert. Experimental results are shown to agree satisfactorily with theoretical computations.

(15) LARSON, C. L., MORRIS, H. M., 1948, "Hydraulics of Flow in Culverts," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Project Report N6.

(16) CHAPUS, E. E., 1949, "Entrance Losses in Short Circular Conduits," University of Minnesota, Master's Thesis, Nov.

Measurements of head loss at the entrance to a circular pipe were made to determine the effect of Reynolds number, head over crown, shape of entrance lip, and width of approach channels on entrance coefficients. A 4-inch Lucite pipe was used.**

(17) SCHILLER, R. E., Jr., 1949, "The Flow of Water Through Box Culvert Models," Texas A & M College, Engineering Experiment Station, Master's Thesis, June.

**Paper was not available for review. The abstract was obtained from other sources.

Tests were conducted on plexiglas models of box culverts with straight wingwalls to determine relative capacities and flow characteristics. A flared wingwall design was discovered that should, with sufficient heads, flow full under all conditions. Discharges under free outfall conditions could be increased as much as 30 percent.**

(18) HARRIS, C. W., 1950, "An Engineering Concept of Flow in Pipes," ASCE Trans., Vol. 115, pp. 909-958.

An analysis of existing formulas concerning flow in smooth and rough pipes. The relations between the pipes are expressed by correlated equations rather than by separate empirical formulas. Correlation is shown between artificially prepared random roughness and a variety of commercial pipes. A method is furnished for distinguishing surface losses from localized losses. All the equations are related through simple algebraic expressions. Considerable discussion.

(19) STRAUB, L. G., MORRIS, H. M., 1950, "Hydraulic Data Comparison of Concrete and Corrugated Metal Culvert Pipe," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Technical Paper No. 3, Series B.

Tests were conducted on concrete and corrugated-metal pipes, and on corrugated-metal pipe arches for the purpose of determining pipe friction and entrance loss coefficients. Manning's "n" was also determined for culverts flowing part full. The culverts were new and installed with excellent alinement. They ranged in size from 18 to 36 inches in diameter, each with an overall length of approximately 193 feet. Except for the 24-inch concrete pipe and the 24-inch corrugated pipe arch, all culverts were tested with the inlet projecting 2 feet into the headwater pool and with the inlet flush with the headwall. The two exceptions were only tested with the inlets projecting.

This paper includes the salient test results for both concrete and corrugated-metal culverts as reported in papers No. 4 and 5, Series B.

**Ibid.

(20) STRAUB, L. G., MORRIS, H. M., 1950, "Hydraulic Tests on Corrugated Metal Culvert Pipes," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Technical Paper No. 5, Series B.

(21) VENEGAS, L. E., 1950, "Study of Flaring Outlet End of Culvert to Increase Rate of Discharge," Louisiana State University and A & M College, Master's Thesis, Aug.

(22) SMITH, R. A., 1951, "The Effect of Length on Performance Characteristics of Diffusers," Louisiana State University and A & M College, Master's Thesis, Aug.

This study resulted as a generalization of "Study of Flaring Outlet End of Culvert to Increase Rate of Discharge." (See Reference 21).

(23) EKERDT, G. A., 1952, "Headwall Angle Effect on Box Inlet Discharge," University of Wisconsin, Master's Thesis, c/o Dr. Arno T. Lenz.

An 8-inch-wide (W) box culvert with lengths L = 1/2W, W, and 2W, and depths D = W, 1/2W and 1/4W was tested for heads up to 0.7L with wingwall angles from 45° to 90°.**

(24) ANONYMOUS, 1953, "Culvert Hydraulics," National Academy of Sciences, National Research Council, Highway Research Board, Research Report 15-B.

The report consists of two papers, "Model Studies of Tapered Inlets for Box Culverts," by SHOEMAKER, R. H., Jr., and CLAYTON, L. A.; and "Importance of Inlet Design on Culvert Capacity," by STRAUB, L. G., ANDERSON, A. G., and BOWERS, C. E.

The first paper had the following purposes: (1) clarify the theory of operation of box culverts, and (2) modify the Oregon State Highway Standard inlet in order to increase the overall effectiveness of the culvert as a drainage structure. The test data were taken from a 1:12 scale model of a 4- by 4-foot box culvert 82 feet long. The testing consisted of: (1) analyzing standard inlets with no flare, inlets with a taper in the sides and top of 1 to 10, and inlets designed for operation under inlet control in nonsubmerged states; (2) operation of the standard inlet as a sluice gate; and (3) full-flow operation of the standard and tapered inlets.

**Ibid.

The second paper is discussed in Reference (27).

(25) GUSTAVSBURG, O. K., 1953, "Der gegenwärtige Stand unserer Erkenntnisse uber die Rohrreibung" (Present knowledge on Pipe Friction), Sonderdruck aus GWF "Das Gas-und Wasserfach," 94., Heft 16/18, Wasser.

The first part of this paper is concerned with the foundations of turbulent theory on which Prandtl's work is based. The second part is concerned with the compilation of tables of roughness as accurately as possible, and the inclusion of special cases which still do not fit in the framework of common irregularities.

(26) MONOHAR, M., 1953, "Entrance Effects on Part-Full Flow in a Model Culvert Pipe," University of Minnesota, Master's Thesis, July.

Tests were conducted on a 4-inch-diameter culvert with a length of 35 feet; a square and a well-rounded inlet were used. Head-discharge relationships, pressures, and related data were obtained for variations in discharge and slope.**

(27) STRAUB, L. G., ANDERSON, A. G., BOWERS, C. E., 1953, "Importance of Inlet Design on Culvert Capacity," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Technical Paper No. 13, Series B, 27 p.

Tests were made on a 4-inch-diameter model to determine the advantage of rounded entrances over square-edged entrances. These tests do not consider beveled, bellmouth, protruding or sloping headwalls at the mouth of the culvert nor wingwalls and warped transitions.

Limited bibliography.

(28) KARR, M. H., CLAYTON, L. A., 1954, "Model Studies of Inlet Designs for Pipe Culverts on Steep Grades," Oregon State University, Engineering Experiment Station, Bul. 35, 39 p.

Report on experiments to observe the behavior of a number of typical culvert installations that did not flow full, and the

**Ibid.

evolution of hoods on the inlet as a simple method to force culverts to flow full under field conditions.

(29) ANONYMOUS, 1955, "Friction Losses in Corrugated Metal Pipe," Corps of Engineers, Portland District, Report N 40-1, Bonneville Hydraulic Laboratory, Bonneville, Oregon, July.

See Reference (50).

(30) FRENCH, L., 1955, "Hydraulic Characteristics of Commonly Used Pipe Entrances," First Progress Report on Hydraulics of Short Pipes, National Bureau of Standards, not published.

Determination of head-discharge relationship for commonly used nonrectangular culvert inlets under various slopes, lengths, and degrees of roughness. Factors controlling the regime of flow for various inlets and the development of improved inlets are also discussed. An explanation is given concerning the importance of approach conditions and the effects of different approach geometries.

(31) MORRIS, H. M., Jr., 1955, "Flow in Rough Conduits," Trans. ASCE, Vol. 120, pp. 373-410.

The description for isolated-roughness, wake-interference and quasi-smooth or skimming flow are given. Equations are derived for the three flow types and experimental plots are made which confirm the equations. The data comes from many different sources. Consideration is given to the effect of corrugations on the flow.

(32) FRENCH, J. L., 1956, "Pressure and Resistance Characteristics of a Model Pipe Culvert," Second Progress Report on Hydraulics of Culverts, National Bureau of Standards, not published.

Piezometric grade lines were determined from suitably located piezometer taps. These provided a means of computing the effective head at the outlet, resistance coefficient in the zone of established flow, and the resistance coefficient in the entrance length or zone of flow establishment.

(33) ANONYMOUS, 1956, "Culvert-Flow Characteristics," National Academy of Sciences, National Research Council, Highway Research Board, Bul. 126, 23 p.

The bulletin consists of two papers, "Demonstration of Possible Flow Conditions in a Culvert," by CARSTENS, M. R., and HOLT, A. R., and "Tests on Circular-Pipe-Culvert Inlets," by SCHILLER, R. E., Jr.

The first paper deals with model tests conducted on a rectangular culvert 0.300 foot high, 0.167 foot wide and 3.00 feet long. The majority of possible flow profiles within a highway culvert were photographed; classified by the position of the control section; and analyzed in detail. From this qualitative study, the effects of entrance streamlining, barrel length and roughness, and outlet submergence are readily visualized.

The second paper deals with tests on the following type inlets: (a) square-edged flush inlets with flared, straight and parallel wingwalls; (b) thin-walled projecting inlet; (c) mitered sharp-edged inlet (1-1/2 to 1 slope); (d) mitered rounded inlet (r/d = 0.125); (e) tongue and groove projecting inlet; and (f) rounded projecting inlet (r/d = 0.15). The tests were conducted on models 69 inches long, with the exception of the square-edged entrances which were 52 inches long. The pipe diameter was 5 inches. All tests were run under free or unsubmerged outfall conditions only.

(34) WEST, E. M., HUGHES, R. D., 1956, "Development and Use of Hydraulic Models in Study of Culvert Performance," Kentucky University Engineering Experiment Station, Bul. N 41, Vol. 11, N 1, Sept., 56 p.

The tests were run on a 4-inch square plexiglas box culvert. The tests reaffirm that culverts with standard inlets operate under entrance control when the outlet is nonsubmerged and the slope is sufficient to overcome friction; and that under entrance control they will not flow full, regardless of the amount of head on the inlet or the slope of the structure.

Results indicate a definite increase in carrying capacity is attained by the addition of a hood under conditions where entrance control would prevail if using a standard entrance.

The types of entrances tested were 30° and 45° wingwall inlets, with and without hoods. The hoods were proportioned so that the area of waterway opening at their upstream face was twice that of the culvert barrel.

(35) FRENCH, J. L., 1956, "Pressure and Resistance Characteristics of a Model Pipe Culvert," National Bureau of Standards, not published.

(36) LI, W. H., PATTERSON, C. C., 1956, "Free Outlets and Self-Priming Action of Culverts," Proc. ASCE, Vol. 82 (J Hyd Div) No. HY3, June, Paper 1009, 22 p.

Tests were conducted to determine the effective position of the hydraulic gradeline for full-flowing culverts with free outlets. Priming on models was also investigated.

(37) SPINDLER, W. H., 1956, "How to Design and Install Culverts," Public Works, Vol. 87, No. 1, Jan., pp. 83-90.

Determining waterway requirements, size, modifying conditions, placement, gradeline, length, and installation of culverts. Based on author's book, "Handbook of Drainage and Construction Products," 1955, revised 1958.

See reference (44).

(38) BABCOCK, H. A., SIMMONS, W. P., Jr., 1957, "Flow Characteristics in a Pipeline Downstream from a Square Cornered Entrance," U.S. Bureau of Reclamation, Division of Engineering Laboratories, Denver, Colorado, Laboratory Report No. HYD-422, 8 p.

The investigations present basic data on the flow conditions and pressure distribution downstream from a square cornered pipe entrance under various conditions of submergence, approach shape, and Reynolds number. The information is intended for use as reference material in the calibration of meter gates.

(39) FRENCH, J. L., 1957, "Effect of Approach Channel Characteristics on Model Pipe Culvert Operation," Third Progress Report on Hydraulics of Culverts, National Bureau of Standards, not published.

Experimental data on the effect of approach channel characteristics on the operation of pipe culverts at supercritical slopes are presented. Approach flow turbulence level and velocity distribution are shown, for the four different inlet geometries investigated, to significantly influence regime change phenomena; and it is concluded that general reproducibility of experimental results requires full consideration and control of approach flow conditions.**

**Ibid.

(40) HENDRICKSON, J. G., 1957, "Hydraulics of Culverts," American Concrete Pipe Association.

A manual for the design of culverts including location, allowable loads, determining runoff, and culvert hydraulics. Charts and tables are included to aid the engineer in computations. Bibliography is limited to noncontroversial topics.

(41) SMITH, G. L., 1957, "Scour and Energy Dissipation Below Culvert Outlets," Colorado Agricultural and Mechanical College, Fort Collins, Colorado, CER No. 57GLS16, 122 p.

The paper includes a discussion of the principles of energy dissipation, contributions of engineering experience, and the types of structures now employed for energy dissipation.

Experimental work was conducted with a cantilevered outlet. Investigations included the effects of tailwater depth, armor-plating, and energy of the jet on scour.

(42) ANONYMOUS, 1958, "Hydraulic Design of Stilling Basins and Bucket Energy Dissipators," U.S. Department of the Interior, Bureau of Reclamation, Engineering Monograph No. 25, 114 p.

Various types of energy dissipators are presented for both large and small outlet structures. Sufficient data are available to determine the necessary outlet dimensions over a wide range of discharges and heads.

(43) ANONYMOUS, 1958, Article in "The Local Government Engineer," Department of Public Works, Sydney, N.S.W., Australia, Feb.

Studies on two models of a standard 4-foot 6-inch-diameter pipe culvert to a 1:13 scale. One model having a large moveable bed of sand for scour comparison tests, the other being a half section model for investigating vertical distribution of flow in stilling basins.**

(44) SPINDLER, W. H., 1958, "Handbook of Drainage and Construction Products," Armco Drainage and Metal Products, Incorporated, Middletown, Ohio, 529 p.

**Ibid.

A manual for the design of culverts including location, allowable loads, runoff, and culvert hydraulics. The hydraulic design curves are based on work done at the University of Iowa.

(45) BAUER, W. J., 1959, "Improved Culvert Performance through Design and Research Studies," Civil Engineering, Vol. 29, pp. 167-169, March.

This article presents a method of improving culvert performance by (1) providing a gradual transition at the inlet, (2) reducing friction losses by smoothing the conduit, and (3) utilizing a flared outlet or by using an adverse hydraulic grade near the exit.

Discussion follows by BLAISDELL, F. W., in Civil Engineering, Vol. 29, p. 492, July 1959 and by BAUER in Civil Engineering, Vol. 29, p. 650, September 1959.

(46) HAN, L. S., 1959, "Hydrodynamic Entrance Lengths for Incompressible Laminar Flow in Rectangular Ducts," ASME, Journal of Applied Mechanics, Paper 59-A-82, 7 pp.

The problem of determining the hydrodynamic entrance length in a rectangular channel is solved by the method of linearizing the Navier Stokes equation. The resulting equation is regarded as an equation to generate a mathematical expression for the axial velocity in the entire region, making smooth transition from a uniform profile to the fully developed one. From this expression, the entrance length, defined as where 99 percent of the fully developed centerline velocity is attained, is calculated for channels of six aspect ratios. The pressure drops are also calculated and presented herein. A comparison is made with the limited amount of experimental and theoretical data.

(47) METZLER, D. E., ROUSE, H., 1959, "Hydraulics of Box Culverts," State University of Iowa, Studies in Engineering, Bul. 38, 34 pp.

Culverts placed on a mild slope, and on a steep slope are considered with inlet conditions unsubmerged, partially submerged and fully submerged. The design characteristics and operational characteristics are given for culverts placed on a discontinuous slope. All results are from laboratory measurements of hydraulic models. The authors state that repeating the inlet shape at the outlet is of no use hydraulically and that it is doubtful that a gentle outlet flare effectively reduces the erosive effect of the outflow.

(48) MOORE, W. L., 1959, "Relationships Between Pipe Resistance Formulas," ASCE Proc., Vol. 85 (J. HYD Div), No. HY3, March, pp. 25-41.

The relationship between modern concepts of pipe resistance and the older empirical formulas is clarified, and a simple procedure developed to derive an exponential formula applicable to a known range of flow conditions. Limitations of the equivalent pipe length concept are discussed. Data on resistance measurements in water mains in service indicate that the head loss varies with the discharge to a power nearly equal to 2.0 rather than 1.85 as commonly assumed.

(49) OWEN, H. J., SOOKY, A., HUSAIN, S. T., DELLEUR, J. W., 1959, "Hydraulics of River Flow Under Arch Bridges," A progress report, Purdue University No. CE166, 12 pp.

The hydraulic characteristics of flow under arch bridges are considered. Nondimensional curves of discharge coefficients and backwater profiles are given for semicircular wiers and a semicircular bridge model.

(50) WEBSTER, M. J., METCALF, L. R., 1959, "Friction Factors in Corrugated Metal Pipe," ASCE Proc., Vol. 85 (J. HYD Div), No. HY9, September.

Tests were conducted on corrugated-metal pipes 3, 5, and 7 feet in diameter and 180, 251, and 350 feet long, respectively, in order to determine friction coefficients for flow. The tests were also concerned with pressure distributions along the corrugations.

(51) ARGUE, J. R., 1960, "New Structure for Roadway Pipe Culverts," (Single Pipe Culvert Investigation), The Journal of the Institute of Engineers, Australia, Vol. 32, No. 6, pp. 23-29.

Development of a hooded entrance to make pipe flow full and a concrete outlet structure that holds a hydraulic jump. Utilized rock riprap at inlet and outlet to reduce scour and standardization of outlet structures.

(52) BLAISDELL, F. W., 1960, "Hood Inlet for Closed Conduit Spillways," ASCE Proc., Vol. 86 (J. HYD Div), No. HY5, May, pp. 7-31.

Concerned with experimental tests performed on a model having different inlet conditions. A hood inlet with two different anti-Vortex arrangements were tested. The use of a hood inlet causes the pipe to fill with little or no submergence of the inlet crown. This filling occurs even though the pipe is laid on a steep slope.

(53) O'LOUGHLIN, E. M., 1960, "Culvert Investigations by Hydraulic Models," Department of Public Works, Sydney N.S.W., Australia, July.

(54) STRAUB, L. G., BOWERS, C. E., PILCH, M., 1960, "Resistance to Flow in Two Types of Concrete Pipe," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Technical Paper No. 22, Series B, 148 pp.

Experimental studies were performed on 24- and 36-inch concrete culvert pipes to determine the effect of interior surface finishes and joint irregularities on the frictional resistance of pipe. Cast and vibrated pipe and machine-tamped pipe were used in the tests. Numerical values were obtained for Manning's "n" and Darcy's "f."

Limited analyses were also made concerning velocity distribution, elevation of the gradeline at the outlet of the pipe, losses produced by a small pipe passing transversely through the pipe, local friction factors based on the velocity distribution near the wall of the pipe.

(55) WHITTINGTON, R. B., 1960, "Friction Factors in Smooth and Rough Pipes," Institution of Water Engineers, J. v. 14, N 4, July, pp. 301-306.

A simple expression is derived for layer thickness which is applicable for all values of Reynolds number by reversing Prandtl's concentration upon turbulent "core" at the expense of exact velocity-gradients in the laminar layer. A new simple empirical expression is proposed for calculation of friction factor for rough pipes instead of using Nikuradse's original formula.**

(56) BOSSY, H. G., 1961, "Hydraulics of Conventional Highway Culverts," Paper presented at the Tenth National Conference, Hydraulics Division, ASCE, Urbana, Illinois, 63 pp., not published.

**Ibid.

Discussion of the various phases of culvert design. It is concluded that the methods now available for determining the relation between culvert dimensions and inlet-edge type, discharge rate, and head in inlet control are adequate for conventional culverts of nonrectangular barrel cross section. Methods for computing headwater for culverts with outlet control appear to be adequate.

(57) FRENCH, J. L., 1961, "Hydraulics of Improved Inlet Structures for Pipe Culverts," National Bureau of Standards, Fourth Progress Report on Hydraulics of Culverts, not published.

Experimental data for a group of improved culvert inlets of simple geometry are presented. The effects of vortex action over the inlet are examined and it is concluded that subatmospheric pressures in the inlet region are subject to ventilation by air-carrying vortices and hence that flow regimes in the culvert dependent upon such pressures cannot be assumed. The minimum performance of the culvert structure under adverse conditions is shown to approximate the performance of the inlets in entrance control. The significance of various aspects of the inlet geometry on the location of the applicable inlet control section is demonstrated. Effects of drop inlets, channel depressions upstream from the inlet, and inclined tapered inlets are examined; and it is concluded that significant improvement in culvert performance may be secured by such means.

(58) NEILL, C. R., 1961, "Hydraulic Investigations Related to Large Corrugated--Metal Culverts," Master's Thesis, Department of Civil Engineering, Edmonton, Alberta, Canada, 108 pp.

Previous research in the United States and Canada dealing with culvert hydraulics is reviewed and the findings compared with existing design information and practice. Full-scale tests were run on a 60-inch-diameter structural plate corrugated-metal pipe, 72 feet long. The pipe was tested on slopes of 0, 1, 2, and 3.3 percent with the following types of entrances: inlet-level flush, square projecting, hood, and projected level. The maximum inlet submergence was $H/D = 1.7$.

(59) SMITH, G. L., 1961, "Scour and Scour Control Below Cantilevered Culvert Outlets," Colorado Agricultural and Mechanical College, Fort Collins, Colorado, CER 61 GLS 14, Feb.

(60) CHOW, V. T., 1962, "Hydrologic Design of Culverts," ASCE, Journal of the Hydraulics Division, Vol. 88, No. HY2, Mar., Part 1, pp. 39-56.

Various methods for determining the design discharges of small watersheds are presented. A simple and practical method is presented to determine the peak discharge by considering climatic and physiographic factors. An example illustrates the method.

(61) HARTNETT, J. P., KOH, J. C. Y., McCOMAS, S. T., 1962, "A Comparison of Predicted and Measured Friction Factors for Turbulent Flow Through Rectangular Ducts," Trans., ASME, Journal of Heat Transfer, Feb., pp. 82-88.

The friction coefficient for both laminar and turbulent flow through rectangular channels was analytically and experimentally studied. It was found that the circular-tube correlation accurately predicts the friction coefficient for flow through rectangular ducts of any aspect ratio for Reynolds numbers between 6×10^3 and 5×10^5.

AUTHOR INDEX

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