Division of Engineering Research on Call Agreement #31796

(Task 8 – Evaluation of Rock Channel Protection Design Procedures)

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for the Ohio Department of Transportation
Office of Statewide Planning and Research

and the
United States Department of Transportation
Federal Highway Administration

March 2021

Final Report

**E.L. Robinson
Engineering of Ohio**

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16. Abstract

A study was undertaken to investigate the source of the Ohio DOT culvert outlet protection design methodology and to compare this method with other State DOTs and FHWA methodologies. The original source of the Ohio DOT methodology was long thought to be a study conducted by The University of Cincinnati (Laushey, 1966). However, a meaningful correlation between the two could not be established. When comparing the Ohio DOT methodology to other State DOT's and FHWA methodologies it is concluded that the Ohio DOT methodology is neither conservation nor unconservative.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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The contents of this report reflect the views of the author(s) who is (are) responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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1 Introduction

1.1 Scope of Work

The Ohio Department of Transportation (ODOT) wishes to investigate the validity of the current method of determining appropriately sized rock channel protection (RCP), often referred to as riprap, at the outlet of culverts and storm sewers to mitigate erosion and dissipate energy.

RCP size and length of application are determined in accordance with Figure 1107-1 of the Location & Design Manual, Volume 2, Drainage Design, see Figure 1. The basis for the figure is believed to be based on the research of Laushey (1966) and developed by the ODOT Hydraulic Section. (Sarikelle, et al., 1980). The figure was subsequently field verified by Sarikelle (1980).

Additional guidance on the selection of appropriate RCP size and length can be found in Federal Highway Administration publication HEC-23 “Bridge Scour and Stream Instability Countermeasures Experience, Selection, and Design Guidance” (2009) and HEC-14 “Hydraulic Design of Energy Dissipators for Culverts and Channels” (Thompson, et al., 2006)

The project goals are:

- Evaluate the current RCP design methodology utilized by ODOT as compared to the current practice of other North American governmental agencies. This was a search of state DOT and provincial governmental agencies drainage design procedures and interviews with select DOT staff. It did not include a survey of State DOTs’.
- Critically assess ODOT methodologies for determining RCP for use as erosion control and velocity dissipation at culvert and storm sewer outlets.
- Propose improvement to the ODOT RCP design methodology considering the current state of the practice.

The following tasks were undertaken to meet the project goals.

- Perform a literature review of State DOTs’ and Canadian Provinces’ requirements for rock channel protection or other erosion control features at outlets of culverts and storm drains.
- The project team will evaluate the current rock channel protection design methods used by the Department as compared to findings from the literature review. This will include a comparison of RCP sizes resulting from differing methodologies.
- Based on the above finding, the project team will propose improvements to the ODOT rock channel protection design methodology.

ROCK CHANNEL PROTECTION AT CULVERT AND STORM SEWER OUTLETS	1107-1
	REFERENCE SECTION 1107.2

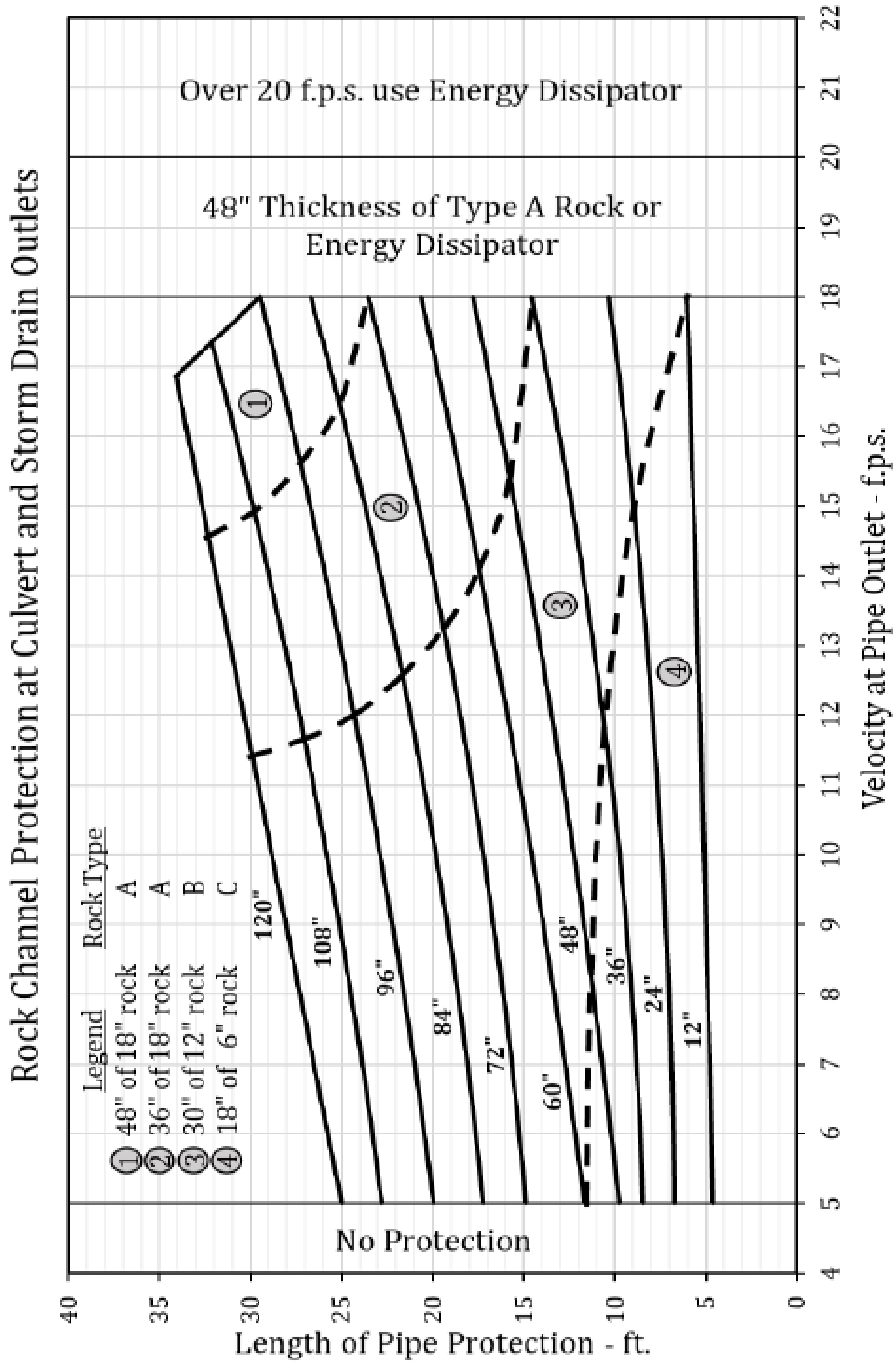


Figure 1 – ODOT Rock Channel Protection

1.2 Outline of the Report

Chapter 2 provides the literature search results which focused on a review of current practices within different state DOTs' and Canadian Provincial DOTs'. The identified literature was reviewed and assembled in a summary which includes key references. The project literature review focused on the State DOT design specifications for rock channel protection.

Summaries of relevant review findings of other State DOTs' are provided in Chapter 2 with links to key reference material. Many of the State DOTs' refer to FHWA HEC-14 as their primary reference for design and do not have a specific independent design methodology.

Chapter 3 presents an investigation into the source of the current ODOT methodology as well as a comparison of the current ODOT methodology with the FHWA HEC-14 methodology. This includes a comparison of RCP sizes resulting from differing methodologies.

Chapter 4 summarizes the results, offers recommendations regarding the use of RCP in Ohio, and provides suggestions for future research.

2 Literature Review

2.1 Introduction

The literature review focused on a review of current practices within different state DOTs' and Canadian Provincial DOTs'. Summaries of relevant review findings of other State DOTs' are provided in the following subsections and include references to key information. Many of the State DOTs' refer to FHWA HEC-14 as their primary reference for design and do not have a specific independent design methodology.

2.2 Summary of State Reviews

Information on the design of energy dissipation at the outlet of culverts or storm sewers was obtained for 42 of the 49 U.S. States (excluding Ohio). Information was not directly available for Florida, Hawaii, Iowa, Louisiana, Maine, Mississippi or New Hampshire. Information on RCP design could not be located for any of the Canadian Provinces.

Of the remaining 42 states, 23 make direct reference to HEC-14 without modification, 12 use HEC-14 with limitations or modifications, 4 utilize in-house equations or nomographs, one state, Texas, uses structural modifications within the pipe network, or HEC-15 (Kilgore, et al., 2005), and one state requires energy dissipation design to be reviewed on a case-by-case basis (Idaho).

See Figure 2 for a summarization of these results.

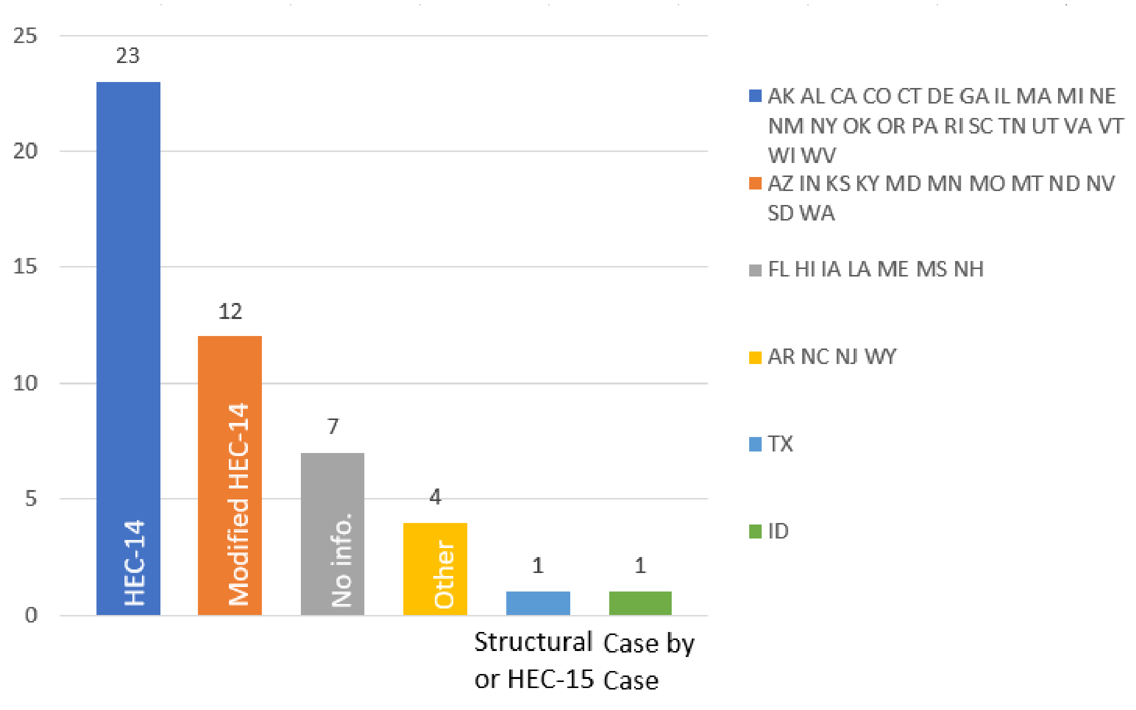


Figure 2 – RCP Design Methodology

2.3 Existing ODOT Research

ODOT has sponsored two research projects concerning the design of culvert outlet protection. The first was a study conducted in 1966 by the University of Cincinnati (Laushey, 1966). The project consisted of scale model testing of pipe culverts utilizing uniform, mostly spherical gravel as outlet protection material. The study investigated the parameters related to scour hole formation, as well as the time-dependent growth of the formed scour hole; the final size of the scour hole at equilibrium; and the material size necessary to resist incipient bed erosion.

Scour hole geometry for uniform spherical particles is defined using the following equations:

$$h = 0.53\ \sqrt[3]{Vol} \qquad (1)$$

$$h = 0.46R \qquad (2)$$

where:

h = depth of scour hole (ft.)

Vol = volume of scour hole (ft.^{3})

R = radius of scour hole (ft.)

A similar equation is provided for gravel material:

$$h = 0.48\ \sqrt[3]{Vol} \qquad (3)$$

The ultimate equilibrium scour volume for a full-flow pipe can be calculated from:

$$\frac{Vol_\infty}{D^3} = \frac{2.54\ (V - V_c)}{gd} \qquad (4)$$

where:

Vol_∞ = maximum volume of scour hole (ft.^{3})

D = pipe diameter (ft.)

d = mean material size (ft.)

g = gravitational acceleration (ft/sec^2)

V = outlet velocity (ft/sec)

V_c = incipient scour velocity (ft/sec) calculated as:

$$V_c = \frac{20.8\ d^{1.5}}{D} \qquad (5)$$

It is not clear in the report how the length, width, and depth of rock are determined. However, if the length of the scour hole is estimated as $2R$, by substitution and mathematical manipulation the length of the scour hole can be calculated as:

$$L = 2.30\left(\frac{2.54(V - V_c)D^3}{gd}\right)^{1/3} \qquad (6)$$

where:

L = length of scour hole (ft.)

The University of Akron performed a follow-up study focused on validating the field performance of rock channel protection designed in accordance with Figure 1 (Sarikelle, et al., 1980). The report also compared the length of RCP designed using the ODOT method versus other methods used at the time. A key conclusion from the study is that “Although the lengths of rock channel protection schemes used in Ohio are shorter than the lengths designed by other accepted procedures for a given design flow, it was determined that the actual number of sites which had scour problems at the end of the rock was small, therefore, the Ohio design lengths have proved adequate.” However, the authors also noted that the culverts had generally not yet experienced a significant flood event.

2.4 FHWA Hydraulic Engineering Circular Number 14

The FHWA publication HEC-14 includes a design method for “Riprap Aprons” which is a “commonly used device for outlet protection for culverts 60 in or smaller” (Thompson, et al., 2006). The method for determining the required size of rock is based on the work of Fletcher and Grace (1972) and is as follows:

$$D_{50} = 0.2\,D\left(\frac{Q}{\sqrt{g}D^{2.5}}\right)^{4/3}\left(\frac{D}{TW}\right) \qquad (7)$$

where:

D_{50} = rock size (ft.)

D = pipe diameter (ft.)

Q = design discharge (ft^3/sec)

g = gravitational acceleration (ft/sec^2)

TW = tailwater depth. Generally limited to 0.4D to 1.0D (ft.)

It is interesting to note that the terms in this equation are similar to those in Equation 5 above.

If the flow in the pipe is expected to be supercritical, the pipe diameter is adjusted by the following factor:

$$D' = \frac{D + y_n}{2} \quad (8)$$

where:

D' = adjusted pipe diameter (ft.)

D = pipe diameter (ft.)

y_n = normal supercritical depth in pipe (ft.)

The length, width, and depth of rock are then calculated using the values provided in Table 1. Apron dimensions can then be determined using guidance similar to that provided by FHWA Federal Lands Highway Division. However, the reference is to an out-of-date publication.

Table 1 – Apron Dimensions Based on Rock Size

D_{50} (in)	Apron Length	Apron Depth
5	4D	$3.5D_{50}$
6	4D	$3.3D_{50}$
10	5D	$2.4D_{50}$
14	6D	$2.2D_{50}$
20	7D	$2.0D_{50}$
22	8D	$2.0D_{50}$

To understand the source of the guidance provided in Table 1, the authors contacted Mr. Eric Brown of the FHWA. In an email communication, Mr. Brown provided the following communication from Mr. Roger Kilgore who is one of the authors of HEC-14 (Brown, 2020):

> *In discussing Table 10.1 (in HEC 14) the text describes it as example guidance and leaves open the door for other rational approaches.*
>
> *I looked back in my notes on this section. We had evaluated several approaches including one from UD&FCD and Fletcher and Grace (1972). What we found is that several methods seemed overly conservative compared with the CFLHD guidance (Table 10.1) that had been in use for several years in a wide variety of situations. Given that, we thought it was appropriate to show it as a good example.*
>
> *It stands to reason that flow velocity and depth along with the presence of backwater will influence the length of protection needed. Pipe diameter is a simple proxy for discharge, velocity, and depth.*

HEC-14 also discusses the need for inspection of rock channel protection, "Over their service life, riprap aprons experience a wide variety of flow and tailwater conditions. In addition, the relations summarized in Table 1 do not fully account for the many variables in culvert design. To ensure continued satisfactory operation, maintenance personnel should inspect them after major flood events. If repeated severe damage occurs, the location may be a candidate for extending the apron or another type of energy dissipator.”

2.5 Specific State DOT Requirements

Several State DOT’s utilize HEC-14 for the design of culvert outlet energy dissipation measures with exceptions. Table 2 lists these states and documents the limitations.

Table 2 – State DOTs’ with Threshold Limitations on the use of HEC-14

State DOT	Limitation
Arizona	See Table 3
Indiana	HEC-14 when outlet velocity exceeds 13 fps
Kentucky	See Table 4
Minnesota	HEC-14 for pipe diameters > 48”
Nevada	HEC-14 Riprap Apron for outlet velocity < 12 fps. HEC-14 Structural dissipation for outlet velocity > 12 fps.
North Dakota	HEC-14 with maximum rock size of 3 ft.
South Dakota	HEC-14 for pipe culvert rock size. UCFCD for box culvert rock size In-house relationships for apron depth (see 2.5.1 and Table 5)

Table 3 – Arizona Dissipation Selection Criteria

Approach Flow	Downstream Flow	Dissipator	Debris Restrictions[1] Floating	Debris Restrictions[1] Boulders	Tailwater Required
Subcritical	Subcritical	Straight Drop	M	L	Yes
Supercritical, Fr=1 to 4	Supercritical	Weir Block	M	L	No
Fr=1 to 4	Subcritical	Abrupt Rise	M	L	Yes
Fr=1.7 to 17	Subcritical	SAF stilling basin	M	L	Yes
Fr=2.5 to 4.5	Subcritical	USBR Type VI	M	L	No

NOTE 1: Debris Restrictions: M-Medium, L-Large

Table 4 – Kentucky Energy Dissipater Guidelines

ENERGY DISSIPATER GUIDELINES				
DISSIPATER TYPE	DESCRIPTION	DESIGNATION	FROUDE NUMBER	COMMENT
Internal	Increased Resistance	–	–	–
	Tumbling Flow	–	> 1.0	–
External	Outlet Protection	Culvert with Headwall	≤ 1.5	Place 25' - 30' Riprap
			> 1.5 (Pipe D < 48")	Place 25' - 30' Riprap*
			> 1.5 (Pipe D > 48")	Design Riprap Transition*
		Protruding Culvert	≤ 1.5	Place 25' - 30' Riprap
			> 1.5 (Pipe D < 48")	Place 25' - 30' Riprap*
			1.5 – 3.0	Design Riprap-Lined Basin*
			> 3.0	Design SAF Dissipater
	Drop Structure	Straight	< 1.0	–
		Box Inlet	< 1.0	–
	@ Streambed Impact Basin	CSU Basin	< 3.0	–
		Contra Costa Basin	< 3.0	–
		Hook Basin	1.8 – 3.0	–
		USBR – 6	–	–
	Stilling Basin	S A F Basin	1.7 – 17	–
		USBR – 4	2.5 – 4.5	–
		USBR – 2	4.0 – 14	–
		USBR – 3	4.5 – 17	–

2.5.1 South Dakota DOT

South Dakota DOT uses HEC-14 for determining the required size of rock channel protection for pipe culverts. However, for box culverts, the equation utilized is that presented by the Urban Drainage and Flood Control District in Denver, Colorado (Urban Drainage and Flood Control District, 2017) and is of a slightly different form from the HEC-14 equation.

$$D_{50} = 0.014D\left(\frac{Q}{BD^{1.5}}\right)\left(\frac{D}{TW}\right) \quad (9)$$

where:

B = box span (ft.)

D = box rise (ft.)

Once the size of the rock channel protection has been calculated, South Dakota then uses HEC-14 modified for SD rock classes to determine apron depth and an in-house relationship for determining the apron length which is a function of the pipe outlet velocity (Table 5).

Table 5 – South Dakota Apron Length Relationship

V_o* (fps)	Apron Length (ft)
≤ 11	12
12	14
13	16
14	18
15	20
16	22
17	24
18	26

* V_o = *culvert outlet velocity for review frequency.*

Several other states indicate that the design of energy dissipation at a pipe outlet is in accordance with in-house procedures or HEC-14 with no preference given to either method. These states include Kansas, Maryland, Missouri, Montana, and Washington. Each in-house method is described in the following sections.

2.5.2 Kansas DOT

Kansas DOT allows for the natural formation of a scour hole at the pipe outlet. This scour hole acts as a natural dissipation device. If the scour hole is expected to be detrimental to the culvert or roadway, then countermeasures such as RCP or concrete aprons are recommended. For cases of severe erosion, the use of HEC-14 is recommended.

2.5.3 Maryland SHA

Maryland State Highway Administration (MSHA) uses nomographs originally developed by the United States Department of Agriculture Soil Conservation Service for Froude Numbers less than 2.5. The nomographs are presented herein as Figure 3 and Figure 4. The nomographs were originally published by the US Soil Conservation Service. HEC-14 is utilized for Froude Numbers above 2.5.

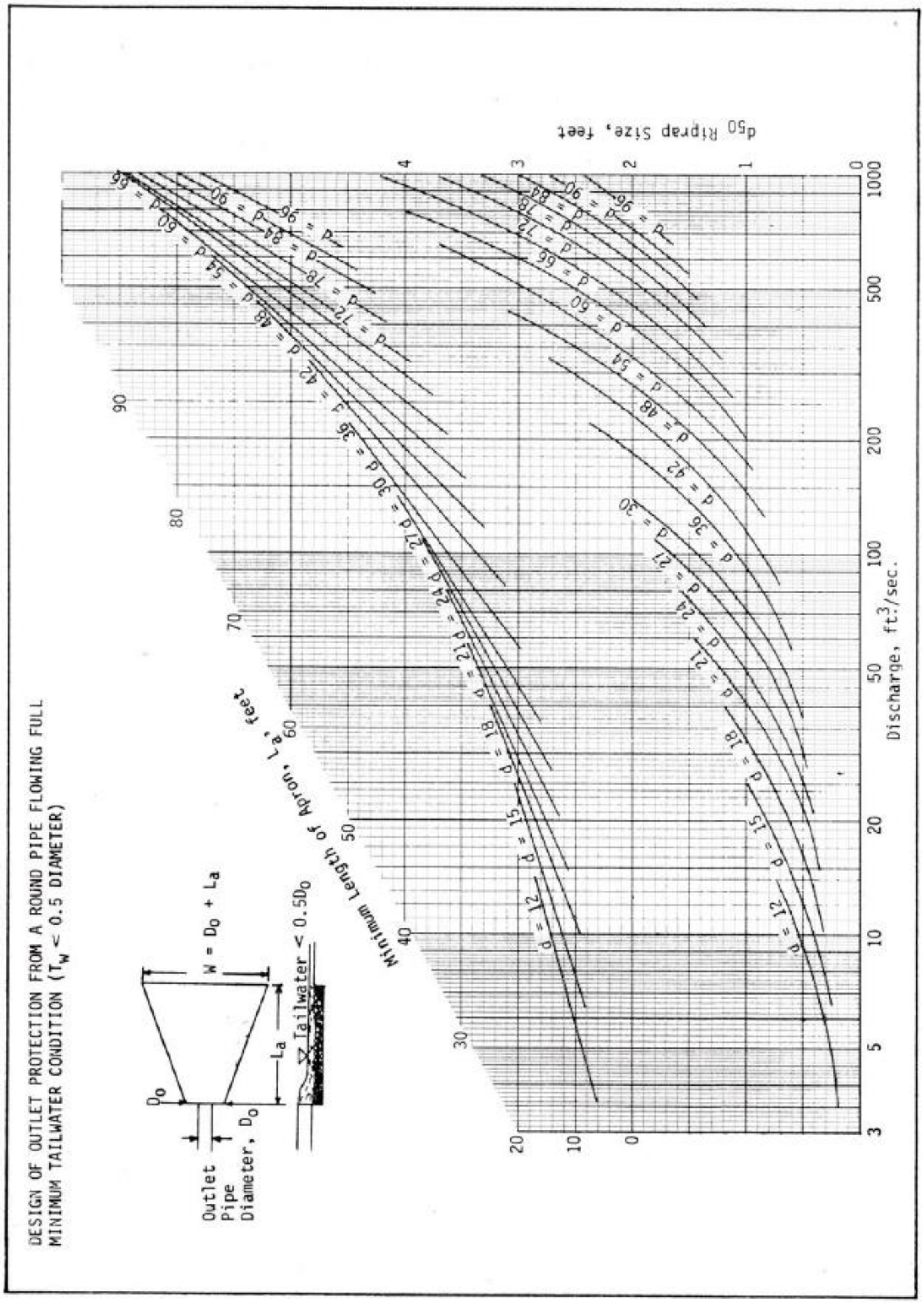


Figure 3 – MDSHA Outlet Protection for a Round Pipe Flowing Full with Minimum Tailwater (originally from USDA-SCS)

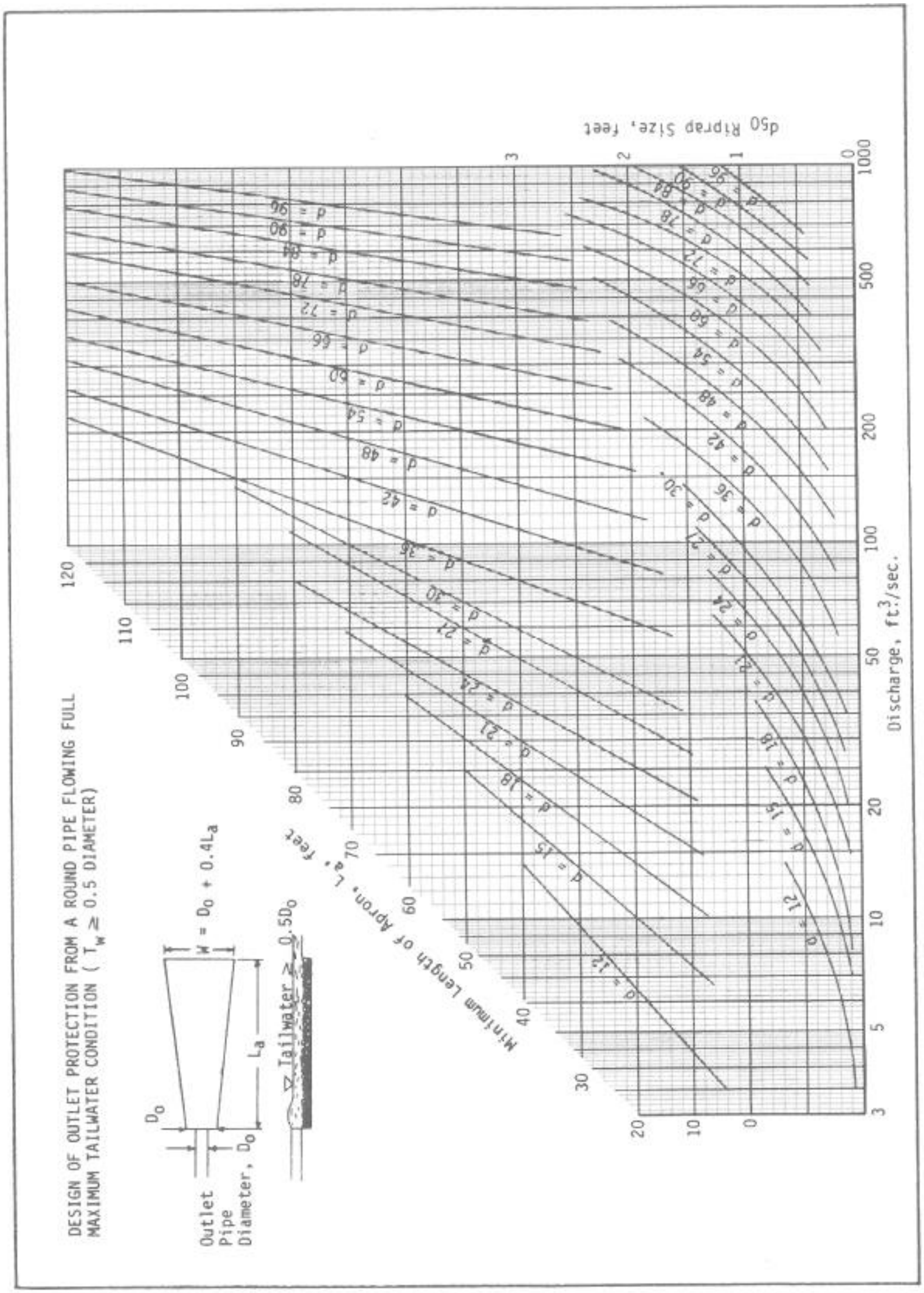


Figure 4 – MDSHA Outlet Protection for a Round Pipe Flowing Full with Maximum Tailwater (originally from USDA-SCS)

2.5.4 *Missouri DOT*

Missouri DOT utilizes a design chart for determining the required rock size. This is provided as Figure 5. A standard detail sheet, Figure 6, provides a table which specifies the required depth, length, and width of the RCP apron. The dimensions of the apron are based solely on the diameter of the pipe.

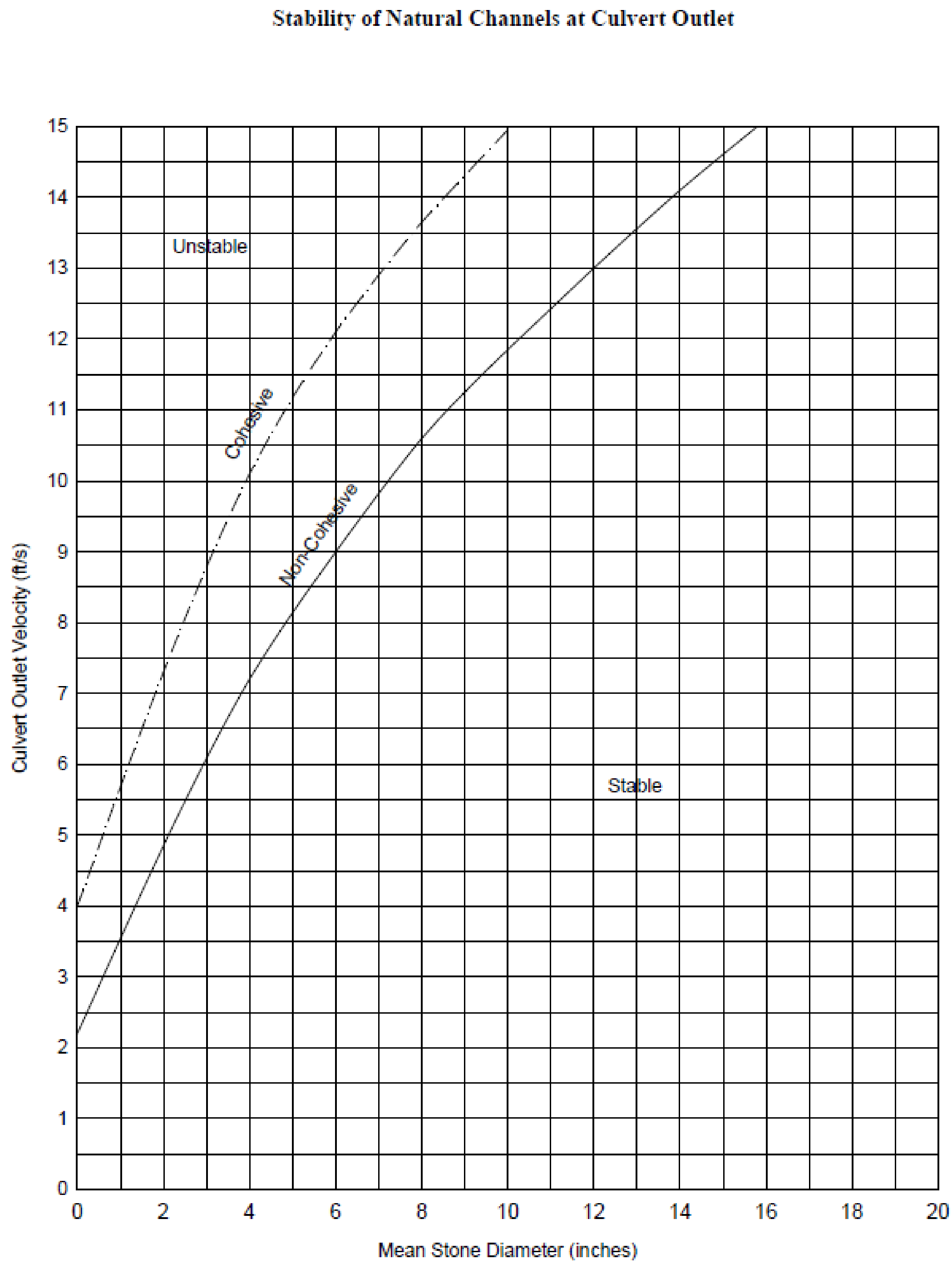


Figure 5 – MODOT Chart for Sizing Rock Channel Protection

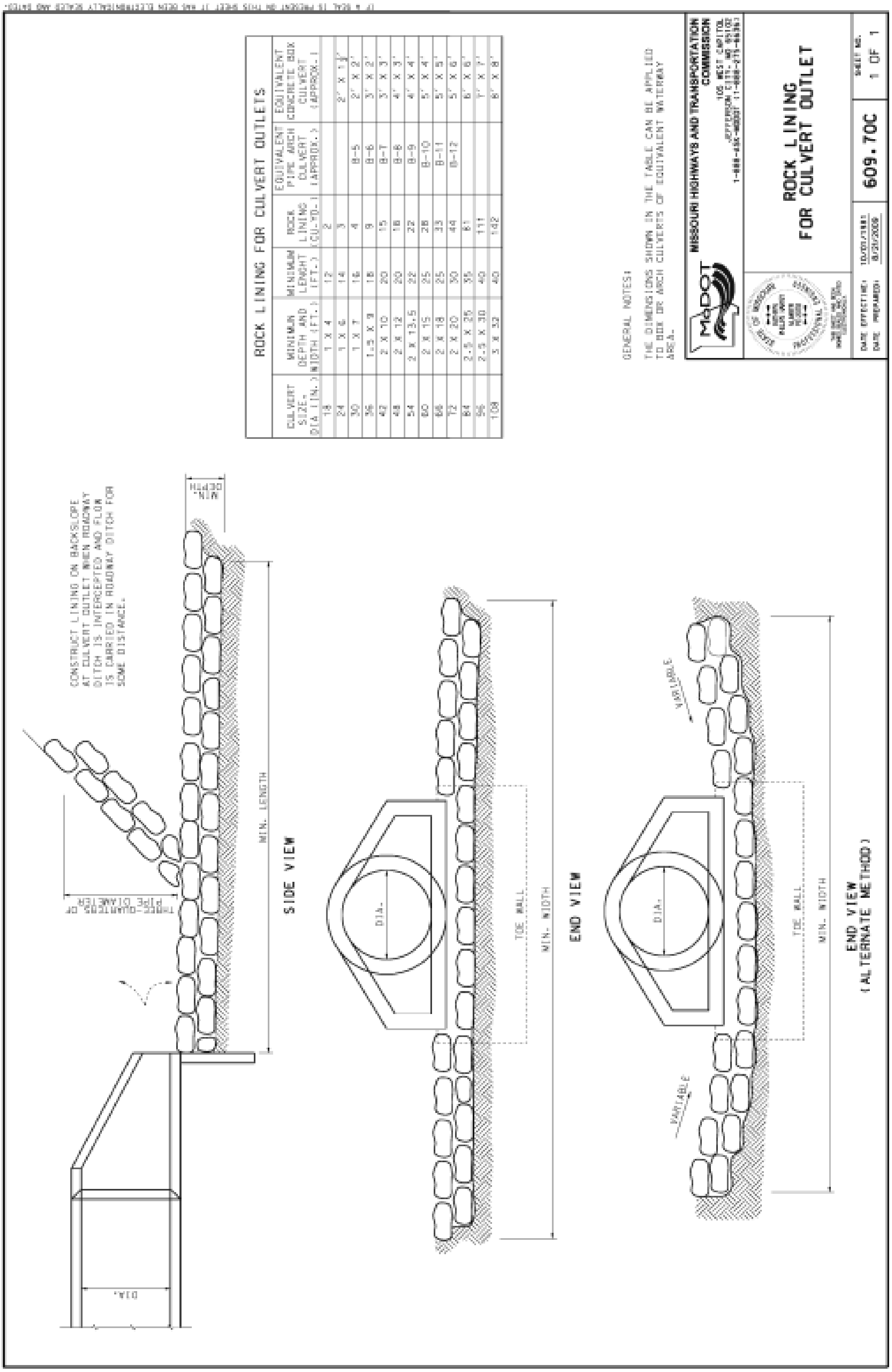


Figure 6 – MODOT Standard Detail for RCP including Apron Dimensions

2.5.5 Montana DOT

Montana DOT utilizes the equations set forth in an out-of-date FHWA publication (Schilling, 1975). However, the procedure is given as a guide, and the manual indicates that engineering judgement along with field observations of the actual scour hole, should be used in determining the required size of RCP. The equations utilized for rock size and length of protection are:

$$D_{50} = 0.02D\left(\frac{Q}{D^{2.5}}\right)^{1.333}\left(\frac{D^2}{TW}\right) \tag{10}$$

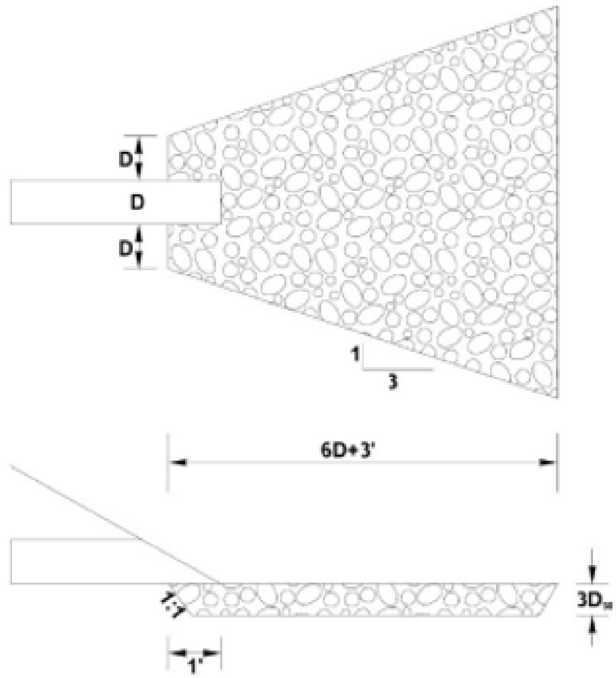
$$C = \left[1.7D\left(\frac{Q}{D^{2.5}}\right)\right] + 8 \tag{11}$$

where:

C = Apron Length (ft.)

2.5.6 Washington DOT

Washington DOT utilizes a design chart for determining the required rock size which is based solely on pipe outlet velocity. This is provided as Figure 7. Similar to MODOT the horizontal dimensions of the apron are based solely on the diameter of the pipe. However, the depth of RCP is $3D_{50}$.



Note: Evaluate need to extend splash pad made to suit site conditions.

Outlet Velocity (feet/second)	Material
5–7	Quarry Spalls
7–10	Rock for Erosion and Scour Protection Class A
10–15	Rock for Erosion and Scour Protection Class B
>15	Rock for Erosion and Scour Protection Class C

Figure 7 – WashDOT Rock Channel Protection Apron Details and Rock Sizing

There are four state DOT's which utilize procedures wholly independent from HEC-14. These include Arkansas, North Carolina, New Jersey, and Wyoming. Specific requirements are provided in the following sections.

2.5.7 Arkansas DOT

ARDOT requires rock channel protection immediately downstream of a culvert outlet for a distance not less than 20 ft, or to the right-of-way, whichever is less. ARDOT also has a nomograph, based on the Manning's Equation, for determining the necessary size of RCP for given channel parameters. Manning's Equation is modified such than Manning's Number, *n*, is a function of the RCP D_{50}, with:

$$n = 0.0395\, D_{50}{}^{1/6} \tag{12}$$

2.5.8 New Jersey DOT

NJDOT utilizes a series of equations for the design of RCP size and apron length. The section lists the work of Fletcher, et. al. (Fletcher, et al., 1972) as a reference document. The provided equation for RCP size is:

$$D_{50} = \frac{0.02}{TW}\left(\frac{Q}{D_o}\right)^{4/3} \tag{13}$$

and the equations for RCP length of need are:

$$L_a = \frac{1.8\frac{Q}{W_o}}{D_o{}^{1/2}} + 7D_o \qquad if\ TW < \frac{1}{2}D_o \tag{14}$$

$$L_a = \frac{3\frac{Q}{W_o}}{D_o{}^{1/2}} \qquad if\ TW > \frac{1}{2}D_o \tag{15}$$

where:

L_a = RCP length of need (ft.)
D_o = Inside vertical dimension of pipe
W_o = Inside horizontal dimension of pipe

2.5.9 North Carolina DOT

North Carolina provides a series of nomographs for assessing the stability of different standard rock classes considering the velocity, discharge, depth of flow and stream slope. A typical example nomograph is provided as Figure 8. However, NCDOT does not provide guidance on how to determine the RCP length of need.

2.5.10 Wyoming DOT

WYDOT is the only DOT which utilizes a shear stress based approach. WYDOT uses an in-house computer program Culvert Design System to determine the outlet shear stress and scour hole, as well as the RCP size and length of need. For small culverts, the software results are then used in a flow chart to determine appropriate erosion protection, see Figure 9.

An equation is also presented for determining the RCP length of need. The equation used is:

$$L_a = \left(D \frac{Q}{D^{2.5}}\right) + 8 \tag{16}$$

The designer is then advised to use engineering judgement based on the site conditions and calculation results to determine which of the three calculated length (CDS scour, CDS RCP length of need, calculated RCP length of need) as being most suitable for the site.

SHEET 4

2 FT. BASE DITCH WITH RIPRAP LINING 2:1 SIDE SLOPES

base width (ft)	Multiply Q by:
3	0.7
4	0.6
5	0.5
6	0.4

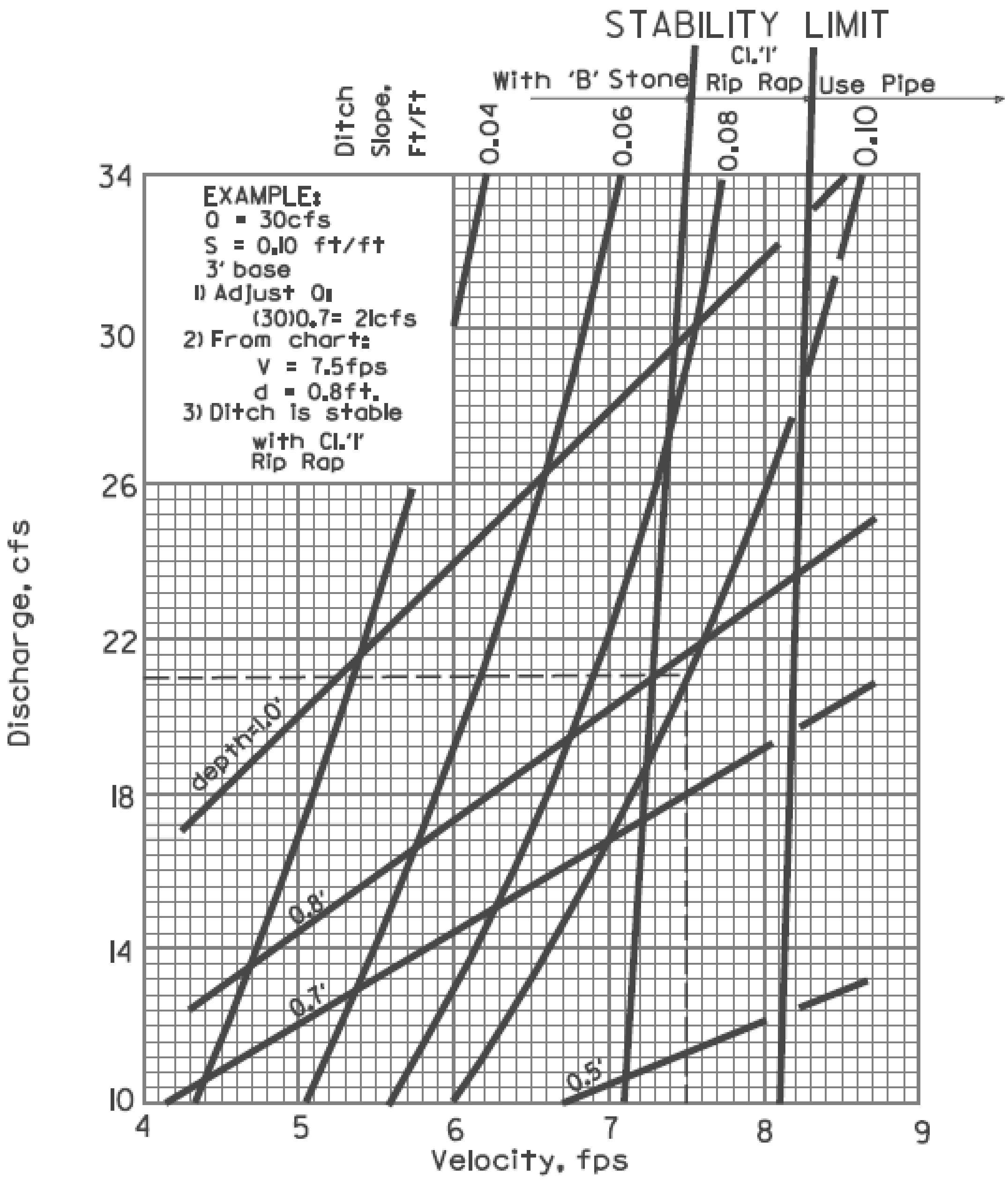


Figure 8 – NCDOT RCP Stability Nomograph

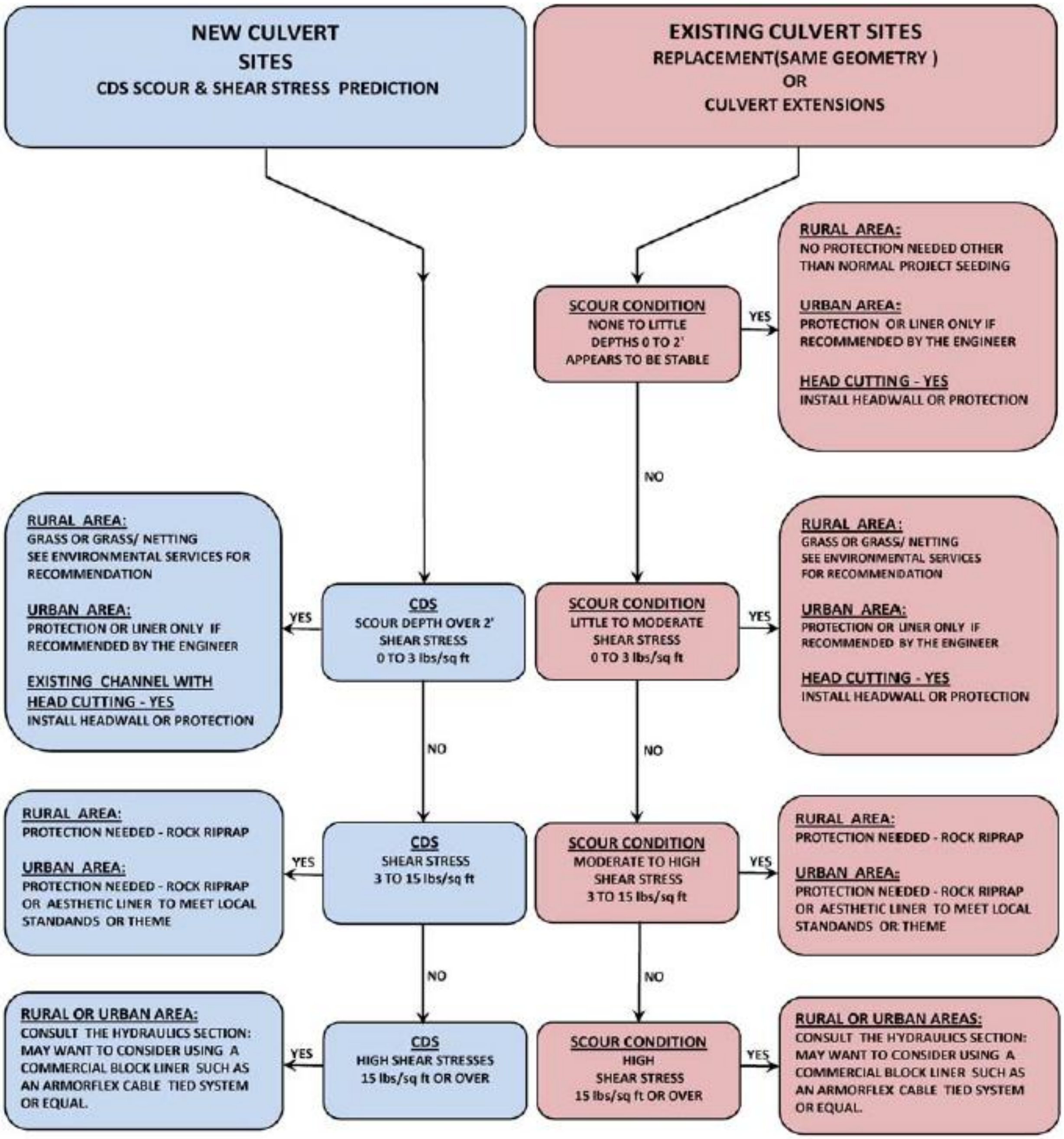


Figure 9 – WYDOT Erosion Control Flow Chart

3 ODOT Rock Channel Protection and Comparison with Other Methodologies

This chapter presents an investigation into the source of the ODOT methodology as well as a comparison of several of the methodologies presented in the Literature Review.

3.1 ODOT Methodology

It has been long assumed that the research report by Laushey (1966) was the basis for the ODOT Rock Channel Protection Figure, shown in Figure 1. This belief is also stated by Sarikelle and Simon in their 1980 study. However, an investigation of the Figure, as compared to the equations believed to be the source, leads to the following observations.

The ODOT Location and Design Manual, Figure 1107-1 (Figure 1) relationship between RCP length of need and velocity is a continuous function for each pipe diameter. In other words, for the curves to be continuous, the dependent variable, length of need, can only contain velocity and pipe diameter as independent variables. However, this is not the case for the Laushey equations, as the length calculation, Equation 4, also includes the size of rock as a dependent variable.

Since the change in rock size is step-wise, there must be a corresponding discontinuity in the curves when the size of rock changes. Otherwise, separate curves would need to be developed for each diameter and each rock size.

The authors also contacted Mr. John Hurd, former Assistant Hydraulic Engineer, for the ODOT. Mr. Hurd indicated that the figure predated his tenure, and he is unaware of its source (Hurd, 2020).

Finally, a spot comparison of required rock size was made between the values in the ODOT Figure and the results from Equation 5. The results are tabulated as follows:

Table 6 – Comparison of D_{50} Values Between ODOT Figure and Calculated Values

Velocity (ft/sec)	Diameter (ft.)	Calculated D_{50} (ft.)	ODOT Figure D_{50} (ft.)
14.8	2	1.3	1
11.8	3	1.4	1
18	3	1.9	1.5
8.2	4	1.4	1
15.3	4	2.1	1.5
5	5	1.1	1
14	5	2.2	1.5
13.2	6	2.4	1.5
12.6	7	2.6	1.5
12	8	2.8	1.5
18	6	3.0	2
16.3	7	3.1	2
15.7	8	3.3	2

The above information suggests that ODOT Figure 1107-1 tends to be unconservative, and that either the Laushey report is not the basis for ODOT Figure 1107-1, or there were simplifications or curve fitting procedures utilized to produce the figure since there is no evident correlation between the two.

3.2 Comparison between ODOT, HEC-14, and other DOT methodologies

Comparing the results from ODOT Figure 1107-1 can be a good way to assess the suitability of the methodology for design purposes. When comparing ODOT with SDDOT (Table 5), it is seen that the ODOT method tends to be more conservative for larger diameter pipes and less conservative for smaller diameter pipes; however, a direct comparison is difficult in that the SDDOT methodology is dependent upon outlet velocity only. MODOT and WashDOT use diameter only in determining the length of rock channel protection. The required lengths are given in Table 7. The MODOT, NJDOT and WashDOT methods are slightly more conservative than the ODOT method in terms of length of rock while the NJDOT method is considerably more conservative; however, MODOT utilizes significantly smaller rock sizes. WashDOT uses smaller rock sizes than ODOT for lesser velocities and slightly larger rock sizes for higher velocities. Rock sizes for both MODOT and WashDOT are provided in Table 8.

Table 7 – Length of Rock Channel Protection Need for Several State DOTs

Diameter (ft.)	**Velocity (ft/sec)**	**Length of RCP Need (ft.)**				
		MODOT (independent of velocity)	WashDOT (independent of velocity)	NJDOT	WYDOT	Ohio DOT
1	6	12	9	15	13	4.7
	12			24	17	5.3
	18			32	22	6
3	6	18	21	36	16	9
	12			50	24	11
	18			65	32	15
5	6	25	33	54	19	12
	12			73	29	16
	18			92	40	21
7	6	35	45	71	20	18
	12			94	33	21
	18			116	45	27
9	6	40	57	88	22	23
	12			114	36	27
	18			139	50	n/a

Table 8 – WashDOT and MODOT RCP Sizes

Velocity (ft./sec)	**Size of RCP (D_{50}) (ft.)**		
	MODOT Cohesive Soil	MODOT Non-Cohesive Soil	WashDOT
6	0.09	0.25	0.31
12	0.50	0.85	1.83
15	0.83	1.31	2.33

Finally, a comparison is made between the ODOT methodology and the HEC-14 methodology. Using Equation 7 and Table 1, a chart similar to ODOT Figure 1107-1 has been prepared. The results are provided as Figure 10. In comparing the results between ODOT and HEC-14 it is evident that the HEC-14 methodology is considerably more conservative when considering the rock channel protection length of need. However, when considering the rock size, the ODOT method tends to be more conservative for larger pipes at lower velocities, whereas the HEC-14 method tends to be more conservative for higher velocities.

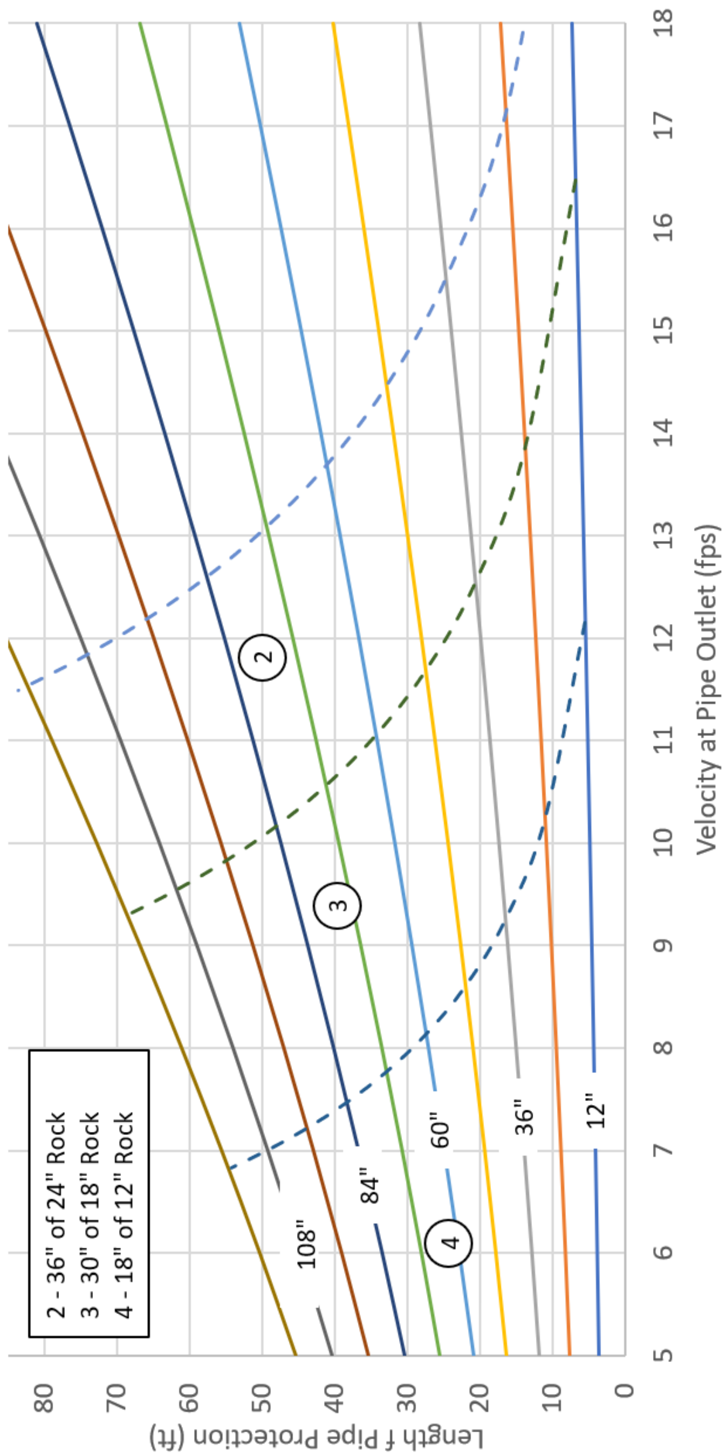


Figure 10 – Rock Channel Protection at Pipe Outlets using HEC-14 Methodology

4 Conclusions and Recommendations

The following conclusions and recommendations are made in consideration of the project goals, reiterated as:

- Evaluate the current RCP design methodology utilized by ODOT as compared to the current practice of other North American governmental agencies. This was a search of state DOT and provincial governmental agencies drainage design procedures and interviews with select DOT staff. It did not include a survey of State DOTs'.
- Critically assess ODOT methodologies for determining RCP for use as erosion control and velocity dissipation at culvert and storm sewer outlets.
- Propose improvement to the ODOT RCP design methodology considering the current state of the practice.

A majority of State DOTs', 35 of 42 with a published methodology, either use HEC-14 directly or use some modification of HEC-14. Five state DOTs' utilize a procedure unrelated to HEC-14.

In general, the ODOT RCP design methodology is neither conservative nor unconservative. Depending on the criteria selected, either size of RCP or length of RCP, ODOT's methodology is conservative when compared to some state DOTs' and unconservative when compared to some state DOTs'. However, of the state DOTs' with a documented Length of Need calculation methodology, more of these states require a greater RCP length of need as compared to ODOT.

Given the overall results of the finding documented herein, coupled with the results of the Sarikelle field work (Sarikelle, et al., 1980), it does not appear justified to revise or modify the current ODOT methodology. The methodology appears to be working satisfactorily, especially in light of the following maintenance guidance in HEC-14. Specifically, HEC-14 states, "Over their service life, riprap aprons experience a wide variety of flow and tailwater conditions. In addition, the relations summarized in [Table 1] do not fully account for the many variables in culvert design. To ensure continued satisfactory operation, maintenance personnel should inspect them after major flood events. If repeated severe damage occurs, the location may be a candidate for extending the apron or another type of energy dissipator."

Given that a clear link between the Laushey report and ODOT Figure 1107-1 could not be found, along with the age of the report, it may be a useful endeavor to initiate research to:

1. Verify the suitability of the Laushey equation for determining RCP size.
2. Develop an apron dimensions table similar to the HEC-14 table, included herein as Table 1.

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