Development of transition mat scour protection design methodology and comparison to the state-of-the-practice

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Abstract. Culverts are designed to convey flow through or around obstructions such as roadway crossings, embankments, and riverine infrastructure. Flow exiting a culvert experiences an abrupt flow expansion generally resulting in flow regime changes and substantial energy dissipation. Such flow conditions can lead to bed scour, bank erosion, and local channel instability. Recent advancements in erosion control technology have resulted in the development of a class of products, termed transition mats (TM), designed to provide scour protection immediately downstream of culvert outlets. Colorado State University's Hydraulics Laboratory has conducted extensive testing of a transition mat under laboratory conditions to quantify system performance and develop a design methodology appropriate for implementing transition mats as scour protection. Prototype testing for both vegetated and unvegetated conditions has been coupled with Froude scale model data resulting in the development of an empirical method for determining an appropriate extent of culvert outfall protection and hydrodynamic design thresholds.

Hydraulic conditions associated with flow in and around culverts have been well documented and the Federal Highway Administration has developed numerous tools designed to quantify flow conditions and implement scour mitigation designs. The purpose of this paper will be to quantify site hydraulics for three unique field conditions and then compare scour mitigation designs utilizing transition mats to accepted riprap design methodologies.

1. Introduction

A new erosion protection technology, transition mats and corresponding anchoring systems, has been introduced, researched, and employed during the past decade. Transition mats were originally designed to protect areas downstream of culverts from scour until the erosive energy is dissipated. Transition mats are a biotechnical solution and mechanically protect erodible beds while integrating vegetation. Transition mats are used in conjunction with a soil cover such as sod or turf reinforcement mats.

Early research conducted by at Colorado State University on a distinct TM system indicated effective erosion protection capabilities in high-flow outfalls (Robeson *et al.* 2007); however, shear stresses experienced on the system during outfall testing were not quantified due to the rapidly varied flow conditions associated with culvert outfalls. A photograph of the initial full-scale culvert outfall testing conducted by CSU is presented in Figure 1.

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Figure 1. Full-scale culvert outfall testing at CSU

Subsequently, CSU began evaluating the TM system in a flume facility to obtain shear stress and flow velocity performance data using a test procedure similar to the ASTM D6460 testing standard. Cox and Carpenter (2008) documented performance results from the channelized testing for the TM. Initial performance of the TM installed over sod without root reinforcement exceeded the slope and discharge capacities of the indoor facility, indicating that further testing was needed to clearly define the performance parameters and system limitations.

In early 2007, CSU conducted additional indoor flume tests with the TM system over a hybrid turf reinforcement mat (TRM) utilizing a geotextile backing. The performance of the transition mat with TRM system exceeded the discharge and slope capacity of the indoor flume, providing additional information regarding system capabilities. During the initial testing, the anchoring system was identified as a critical component within the system which functioned to maintain contact between the TM and the subsurface.

Colorado State University was contracted to follow-up the flume research using a 2:1 H:V steep slope outdoor flume in the summer of 2007. Hydraulic testing was conducted on a newly installed TM system with sod which had not been allowed to establish vegetative roots into the subgrade, effectively replicating initial installation conditions. The objective was to conduct additional performance testing to determine system performance thresholds.

In 2009, CSU conducted further performance testing of the TM reinforced with established vegetation. Testing was conducted in the same flume utilized in the summer 2007 channelized testing. Results of the fully vegetated testing series indicated that the TM system was effective erosion protection in high-energy, steep slope applications by exceeding the discharge capabilities of the testing facility.

Finally, in 2009 and 2010, physical model studies were conducted to develop empirical methods for determining appropriate TM coverage extents and associated kinematic parameters for culvert outfalls. This document reports and discusses the developed empirical methods, and compares these methods with the current state-of-the-practice in culvert outfall protection, Thompson and Kilgore (2006). The methods provided by Thompson and Kilgore were simplified from previous research, and allow design of scour protection based on readily known parameters from typical culvert design. It is the intent of this paper to compare TM designs with the design methods provided by Thompson and Kilgore for riprap basins and aprons, and demonstrate the potential of TM for use in culvert outfall protection.

2. Test Program

Following the initial TM performance testing conducted between 2005 and 2009, a scaled physical model study was developed and executed by CSU to predict the hydraulic conditions downstream of culvert outfalls and provide data to develop a methodology to design TM coverage extents. A 1:4 Froude scale model was utilized for the study and a total of 60 tests were conducted. Two system Manning's roughness values were modeled, one representing an unvegetated TM system composed of the TM system and a high-performance turf reinforcement mat (HPTRM) and the second representing a TM and sod system. Of the 60 total tests, 35 were conducted on the scaled TM and HPTRM system and 25 were conducted on the scaled TM and sod system. A photograph of a prototype-scale TM is presented in Figure 2 and Figure 3 presents a photograph of the culvert outfall model with the installed 1:4 scale TM simulating the unvegetated condition with a HPTRM. Figure 4 presents a photograph of the culvert outfall model complete with the installed 1:4 scale TM simulating the vegetated condition.

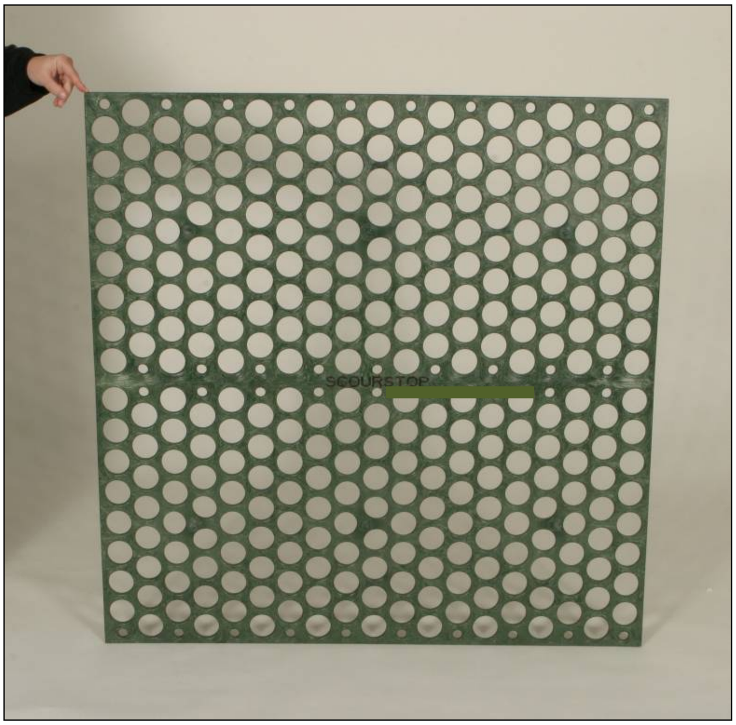


Figure 2. Photograph of the TM

Figure 3. Photograph of 1:4 physical model with simulated unvegetated TM with HPTRM

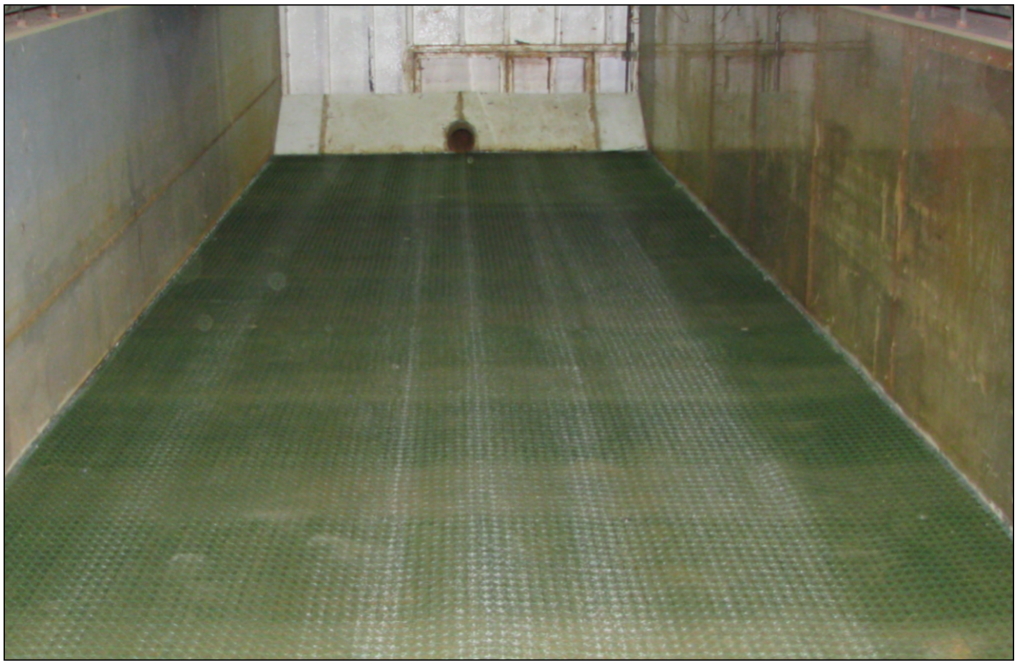


Figure 4. Photograph of 1:4 physical model with simulated vegetated TM

To provide data for the development of an empirical methodology appropriate for a wide range of field conditions, seven unique downstream channel width to culvert diameter (*w/D*) ratios were tested. The headwall of the model facility was constructed to allow channel widths and culvert diameters to be readily modulated. Each culvert was installed at a 0.020 slope. At the outfall, flow transitioned to the model apron, which was constructed at a 0.015 slope. A model apron length of 30 ft was selected based on predetermined culvert pipe sizes and discharges.

Perforated plate steel was located and determined to provide exact geometric similitude to the prototype unvegetated TM system with HPTRM. A Manning's roughness value of 0.025 was determined for the prototype unvegetated TM system based on performance testing documented by Turner *et al.* (2007). The Manning's roughness value was verified for the plate steel prior to testing and determined to be 0.020, which at a 1:4 Froude scale is equivalent to a 0.025 prototype Manning's roughness value.

An industrial high-performance turf reinforcement mat was used to simulate the vegetated TM at the 1:4 Froude scale. For the prototype vegetated TM system, the Manning's roughness was assumed to have a value of 0.035. The HPTRM was determined to have a Manning's roughness of 0.028, which at a 1:4 Froude scale is equivalent to a 0.035 prototype Manning's roughness value.

Five steady-state discharges were conveyed through the model for each *w/D* ratio on each TM system. During testing, spatial extents of the hydraulic jump downstream of the culvert brink were quantified. Additionally, measurements of centerline flow velocity and depth were recorded at 6-in intervals from the brink to the end of the modeled apron. Model discharges ranged from 0.5 to 11.1 ft^3 s^{-1} (16 to 355 ft^3 s^{-1} at prototype scale), model channel widths ranged between 4 and 8 ft (16 to 32 ft at prototype scale), model culvert diameters ranged between 0.5 and 1.4 ft (2.0 to 5.7 ft at prototype scale), and model brink velocities between 6.2 and 13.2 ft s^{-1} (11 and 26 ft s^{-1} at prototype scale). Figure 5 presents a representative photograph of testing in progress.

Figure 5. Testing in progress

3. Regression Analysis

Following the completion of testing and data compilation, regression analyses were undertaken to develop empirical relationships for several parameters determined to be important design considerations. In total, five regression equations were developed for the following dependent variables: maximum velocity recorded on the TM apron in ft s^{-1} (V_{max}), average velocity downstream of the hydraulic jump in ft s^{-1} (V_2), average flow depth downstream of the hydraulic jump in ft (y_2), length from the culvert brink to the location of the maximum velocity in ft (L_{Vmax}), and minimum required length of TM protection in ft (L_{TM}). All relationships for the dependent variables were regressed from a total of four independent variables: total discharge in ft^3 s^{-1} (Q), velocity at the culvert brink in ft s^{-1} (V), downstream channel width in ft (w), and culvert diameter in ft (D). A profile-view schematic presenting the dependent design variables is provided in Figure 6.

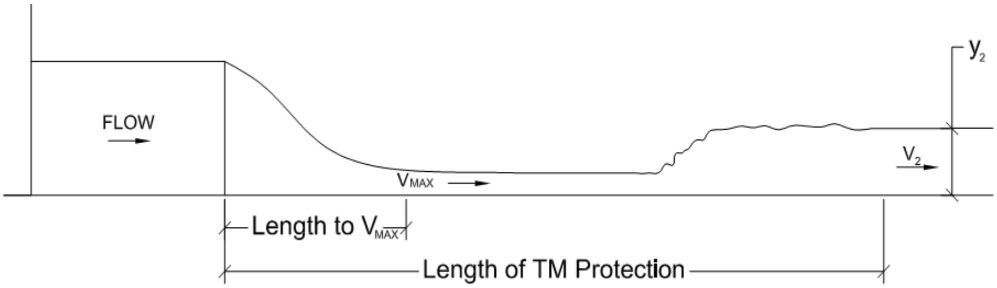


Figure 6. Profile-view schematic of design variables

All regressions were of a power function format. Power equations were selected due to the ease of manipulation and the simplicity in using the least-squares quality indicator method in regression. All regression equations took the form of Equation 1:

$$f = Cw^a x^b y^c \dots m^n \qquad \text{Equation 1}$$

where:

f = dependent design variable;
C = equation coefficient;
a, b, c, n = regression exponents; and
w, x, y, m = independent variables from testing.

Statistical significance of all independent variables was determined from the p-level, which provides evidence of correlation between independent and dependent variables. All independent variables used in the regressions had a p-value of less than 0.05, standard for a threshold of significance. Envelope equations were also developed by adjusting the intercept of the regression equation by the most conservative residual error, and by truncating all coefficients and exponents. Although regression equations were developed for unvegetated condition in addition to vegetated conditions, the empirical regressions for vegetated conditions are provided as the appropriate equations for the comparative purposes in this case. Table 4 presents the vegetated regression equations that were developed from measured data.

Table 4. Regression equations for vegetated TM

Variable	Regression Equation
V_{max}	$V_{max} = C_1 V^{a_1}$
V_2	$V_2 = C_2 V^{a_2} \left(\frac{W}{D}\right)^{b_1}$
y_2	$y_2 = C_3 V^{a_3} W^{c_1} D^{d_1}$
L_{Vmax}	$L_{Vmax} = C_4 Q^{e_1} V^{a_4} D^{d_2}$
L_{TM}	$L_{protection} = C_5 Q^{e_2} V^{a_5} D^{d_3}$

V_{max} = maximum velocity experienced on the TM apron (ft s^{-1})
V_2 = average velocity downstream of the hydraulic jump (ft s^{-1})
y_2 = average flow depth downstream of the hydraulic jump (ft)
L_{Vmax} = length from the culvert brink to the maximum velocity experienced on the TM apron (ft)
L_{TM} = minimum necessary length of TM apron (ft)

4. Comparison to Current State-of-the-Practice

To quantify the relative performance of the TM to accepted methods for culvert outfall protection, a comparative analysis was undertaken between the results of the empirical methods for the length of TM protection in vegetated conditions and selected methods for riprap basin and apron design. Design methods presented by Thompson and Kilgore (2006) represent the current state-of-the-practice in culvert outfall protection for supercritical culvert exit conditions with Froude numbers of less than 3 and were utilized for the comparison of outfall protection designs. For comparison of culvert outfall protection measures, three representative conditions were selected. Table 5 provides the example conditions that were selected which represent low, medium, and high exit velocities for culverts flowing partially full.

Table 5. Sample data for protection comparison

Condition	ExitCondition (full/partial)	Culvert Diameter ft	Discharge $ft^3\ s^{-1}$	Culvert Exit Velocity ft s^{-1}	Brink Depth ft
1	partial	3.0	50	15	1.4
2	partial	3.0	20	10	1.0
3	partial	3.0	10	7	0.8

Riprap basin design, as described by Thompson and Kilgore (2006), uses a pre-formed scour hole lined with riprap that is at least two times the median stone size in thickness, and includes a downstream riprap apron that assists in transitioning flow from the basin to the downstream channel. Figure 7 presents a schematic of the riprap basin described by Thompson and Kilgore (2006). The purpose of the riprap basin is to dissipate energy associated with high-energy outfalls when there is significant risk of downstream channel degradation. Based on the scour hole geometry that would occur in an unprotected culvert outfall, the floor of the basin pool is constructed at an elevation that approximates the maximum depth of scour. The length of the dissipation pool is roughly ten times the pool depth, and the length of the pool and apron together is typically fifteen times the pool depth. The basin design methodology differentiates between minimum and maximum tailwater, and the design is adjusted accordingly for the different scour regimes that occur with each condition.

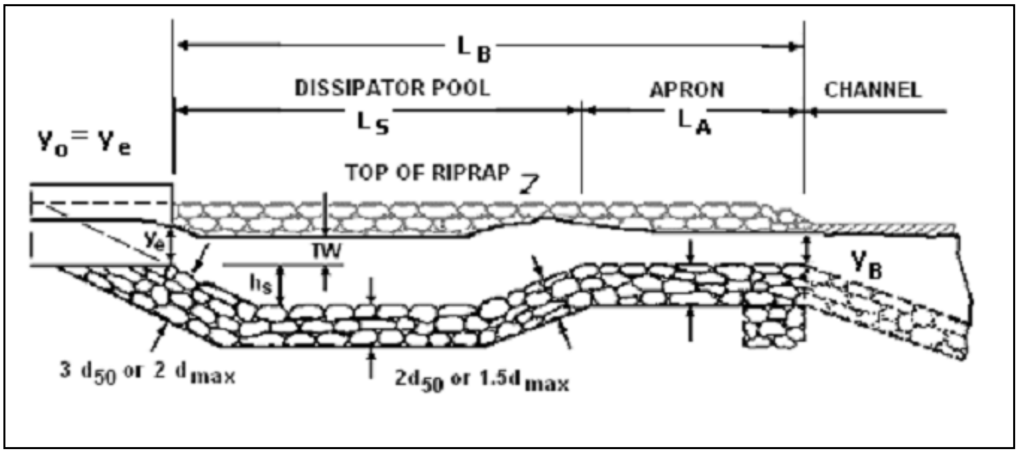
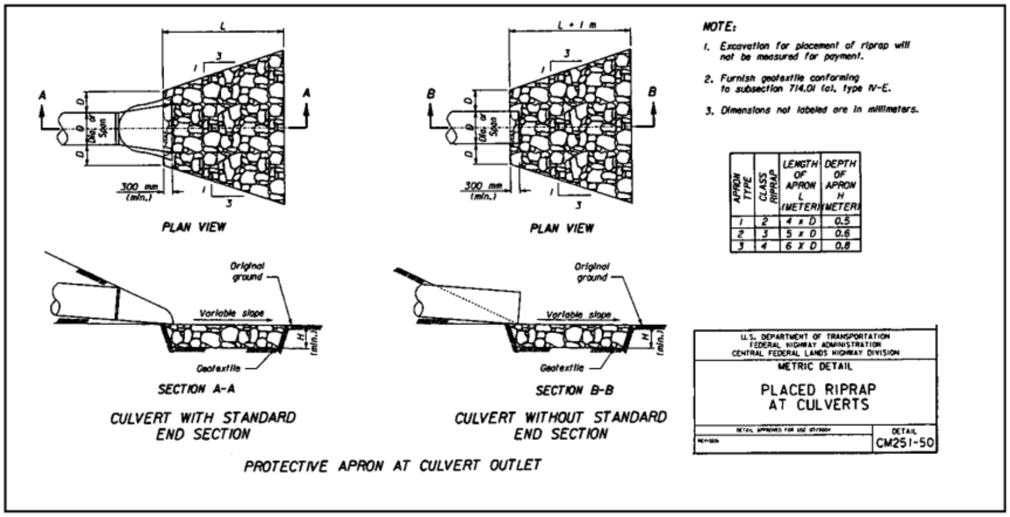


Figure 7. Schematic of riprap basin (from Thompson and Kilgore, 2006)

Thompson and Kilgore (2006) also standardized riprap classes and the appropriate dimensions of independent riprap aprons. The riprap aprons described by Thompson and Kilgore (2006) are widely used for outfall protection in culverts smaller than 5 ft in diameter and are constructed at a zero-grade. The riprap aprons do not dissipate significant energy, but rather serve to 'spread' the flow as it exits the culvert. Figure 8 presents a schematic of the riprap apron described by Thompson and Kilgore (2006). According to Thompson and Kilgore (2006), inadequacy in the design of a riprap apron can result in channel degradation, and thus accurate design of riprap size and apron dimensions are important.



NOTE:

1. Excavation for placement of riprap will not be measured for payment.
2. Furnish geotextile conforming to subsection 714.01 (a), type IV-E.
3. Dimensions not labeled are in millimeters.

APRON TYPE	CLASS RIPRAP	LENGTH OF APRON L (METER)	DEPTH OF APRON H (METER)
1	2	4 x D	0.5
2	3	5 x D	0.6
3	4	6 X D	0.8

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
CENTRAL FEDERAL LANDS HIGHWAY DIVISION
METRIC DETAIL
PLACED RIPRAP
AT CULVERTS
DETAIL APPROVED FOR USE 07/2004
REVISION
DETAIL
CM251-50

Figure 8. Schematic of riprap apron (from Thompson and Kilgore, 2006)

A comparative analysis was undertaken between the Thompson and Kilgore (2006) riprap basin and riprap apron, and the vegetated TM apron empirical design method for the data presented in Table 5. It should be noted that for this study, comparisons focused on the spatial extents of the protection schemes, and not on flow properties on the receiving channel. The results of the comparison analysis for the partially-full culverts are presented in Table 6, Table 7, and Table 8 for the three designs, respectively. A chart comparing the necessary protection lengths is presented in Figure 9 for the partially full conditions.

Table 6. Dimensions for riprap basin

Condition	Basin Length	Pool Length	Apron Length	Pool Depth
	ft	ft	ft	ft
1	23.8	15.9	8.0	1.6
2	14.2	9.5	4.7	0.9
3	12.0	9.0	3.0	0.6

Table 7. Dimensions for riprap apron

Condition	Apron Length	Apron Width	Apron Depth
	ft	ft	ft
1	15.5	19.3	2.8
2	10.0	15.6	1.3
3	7.5	14.0	0.8

Table 8. Dimensions for vegetated TM apron

Condition	Length of Protection	Length to the Maximum Velocity
	ft	ft
1	15.1	9.9
2	10.2	6.7
3	8.0	5.4

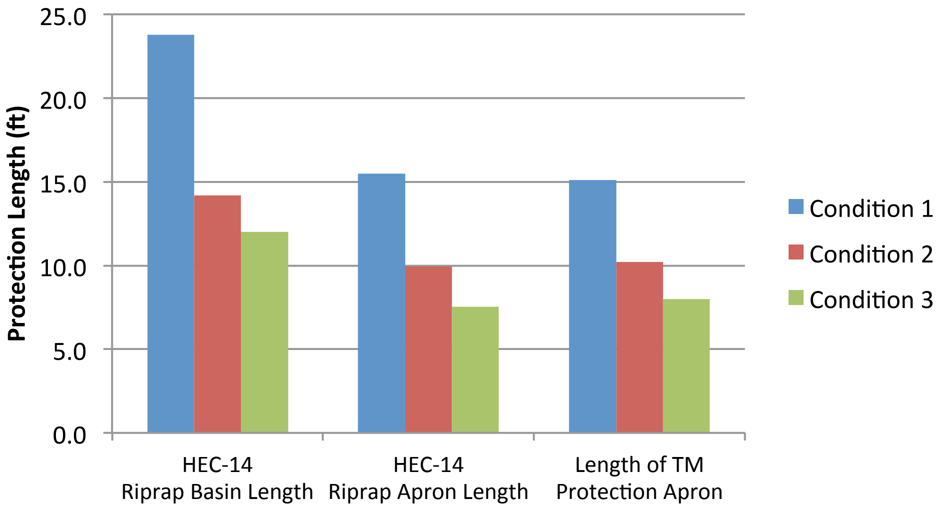


Figure 9. Results from comparative analysis for partially full culverts

5. Discussion

Results of the comparative analysis, as shown in Figure 9, demonstrate that TM aprons may be used in areas where a vegetated solution is preferred. For the investigated conditions, the average length of protection for the TM apron was 33% shorter and 1% longer than the required lengths for the Thompson and Kilgore (2006) basin and apron designs, respectively. Specifically, Figure 11 illustrates that the required length for a TM apron is generally greater than the required length of a riprap apron, but less than the required length of a riprap basin.

The TM culvert and stormwater outlet protection design methodologies presented in this document were designed to be used in conjunction with previous recorded performance results from full-scale testing conducted by CSU. Based on the prototype discharge range of 16 to 355 $ft^3\ s^{-1}$ and *w/D* ratios between 2.8 and 16, the TM design methods are applicable to a wide range of culvert outfall conditions. Considering system performance results from testing programs at CSU, as well as consideration of installation, material, and maintenance costs, the TM apron may be a viable biotechnical solution for scour protection.

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