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Countermeasure Scour Equation Apply to Culverts Outlets.

Abstract– Understanding scour geometry is fundamental for the design and implementation of effective erosion and scour countermeasures, as it directly influences the structural integrity and service life of hydraulic infrastructure subjected to high-velocity flows in natural channels. This study evaluates a representative set of natural channels encompassing a broad range of hydraulic conditions, with Froude numbers spanning supercritical, critical, and subcritical flow regimes. The analyzed sites include typical hydraulic structures such as culverts, wing walls, and bridges.

Based on the hydraulic and geometric data obtained, an empirical equation was developed to estimate scour depth, width, and length for rivers exhibiting morphological and hydraulic characteristics representative of those found in Puerto Rico. The proposed equation was derived using numerical modeling tools within HEC-RAS, in conjunction with established methodologies such as HEC-14, which is widely applied for scour estimation at culverts

I. Introduction

Scour is a critical phenomenon that must be addressed in culvert design, as it can lead to structural failure and ground instability, particularly in regions subject to intense rainfall events and concentrated flows. High flow velocities at culvert inlets and outlets increase the potential for erosion due to flow acceleration and geometric confinement. Consequently, the analysis of scour hole characteristics at both the inlet and outlet of culverts is essential for the proper design of erosion protection measures.

The primary objective of this study is to estimate scour hole depth and to evaluate mitigation strategies through the implementation of energy dissipation devices. Scour depth predictions are influenced by soil type, which in this study is categorized as noncohesive soils (sand and gravel) and cohesive soils (clay and silt). Numerous empirical methodologies have been developed to predict scour, among which HEC-14 is widely recognized for its practical applicability and validation across diverse hydraulic conditions.

Scour hole geometry is governed by hydraulic parameters such as flow velocity, discharge, and channel slope, as well as by geotechnical properties of the bed material. However, the empirical assumptions underlying existing equations may not adequately represent all geotechnical and hydraulic environments. This limitation highlights the need for comparative model evaluation and supports the development of a modified empirical equation tailored to site-specific conditions.

II. Theoretical Information

1. Culvert: Subterranean structure that allows the channelling and passage of rainwater or small rivers below any surface.
2. Box Culvert: Type of culvert with a rectangular cross-section, typically made of reinforced concrete.
3. Head Walls: Structures positioned at the entrance and exit points of a box culvert.
4. Wing Walls: Vertical concrete slabs extend at an angle from the culvert opening and exit. They guide the water into the culvert and help reduce soil erosion around the ends of the culvert.
5. Inlet: Culvert entrance where scour also occurs.
6. Outlet: Final part of the culvert where it becomes open channel.
7. Scour: Erosion caused by a fluid.
8. Erosion: Wear of the earth's crust.
9. Non-cohesive Soil: Type of soil that do not adhere to each other. (Sand and Gravel)
10. Cohesive Soil: Type of soil that stick to each other. (Clay and silts)
11. Granulometry: Measurement and analysis of particle size distribution within a granular material.
12. Energy Dissipator: Devices or structures designed to reduce the energy of a flow, to protect structures and prevent damage.
13. HEC – 14: Hydraulic Engineering Circular No. 14, Hydraulic Design of Energy Dissipators for Culverts and Channels.
14. HEC – RAS: Hydrologic Engineering Center's River Analysis System.

III. HEC-14

HEC-14 is a design guidance document developed by the U.S. Federal Highway Administration (FHWA) to estimate and control scour at culvert inlets and outlets. It does not work as a numerical model by itself; instead, it provides empirical equations, charts, and design procedures that are commonly implemented within tools such as HEC-RAS or applied through manual calculations.

HEC-14 is a widely used hydraulic guided document that addresses local scour generated by high-velocity flows at culvert inlets and outlets. Its primary purpose is to provide engineers with practical tools to evaluate erosion risks associated with accelerated flow conditions and concentrated jets that commonly occur at these structures.

The methodology presented in HEC-14 enables the estimation of maximum scour depth and the characterization of scour hole geometry, including its depth, width, and longitudinal extent. By quantifying these parameters, engineers can better understand how erosive forces interact with the channel bed and surrounding soils under various hydraulic conditions.

In addition, HEC-14 supports the design and sizing of erosion protection measures, such as riprap aprons, stilling basins, and energy dissipators. These countermeasures are essential for reducing flow velocity, dissipating excess energy, and preventing structural instability or downstream channel degradation.

IV. Types of Scours Addressed by HEC-14

HEC-14 is specifically focused on the evaluation of local scour associated with culvert hydraulics and does not address long-term channel degradation or watershed-scale geomorphic adjustments. The guidance targets scour processes that develop in the immediate vicinity of culvert structures, where flow acceleration and turbulence are dominant.

The primary scour conditions considered include outlet scour generated by high-velocity jets as flow exits the culvert barrel, which can result in deep and localized scour holes downstream. In addition, HEC-14 addresses inlet scour caused by flow contraction and acceleration at the culvert entrance, particularly under submerged or partially submerged conditions. Scour occurring downstream of structural elements such as headwalls, wing walls, and aprons is also considered, recognizing the role of flow separation and energy dissipation transitions in these areas.

The methodology assumes that scour development is driven primarily by hydraulic forces, including velocity, turbulence, and jet impingement, rather than by long-term geomorphic processes such as channel migration or bed degradation.

The application of HEC-14 requires a set of hydraulic, geometric, and material parameters that collectively define the flow conditions and physical characteristics governing local scour at culvert inlets and outlets. These inputs are essential for estimating scour depth, scour hole geometry, and the appropriate extent of erosion protection measures.

Hydraulic input parameters include the design discharge, typically associated with a selected return period, and the corresponding flow depth and velocity at the culvert inlet and outlet. Tailwater depth downstream of the culvert is also required, as it strongly influences jet behavior, energy dissipation, and the resulting scour depth. Flow regime information, such as whether the culvert operates under inlet or outlet control, is necessary to correctly apply the HEC-14 equations.

Geometric parameters describe the culvert and channel configuration. These include culvert shape (circular, box, or pipe-arch), barrel dimensions, length, slope, and outlet configuration. The presence and geometry of structural elements such as headwalls, wing walls, aprons, or flared end sections must also be defined, as these features affect flow contraction, expansion, and turbulence patterns.

Material properties of the channel bed and banks are another critical set of inputs. HEC-14 requires information on bed material size, typically represented by a characteristic particle diameter (e.g., D_{50}), as well as soil or rock type. These properties control the resistance of the bed to erosion and directly influence the predicted scour depth and the sizing of riprap or other countermeasures.

V. Flow Regime

The flow regime describes the hydraulic behavior of water as it moves through a channel or hydraulic structure, and it is primarily governed by the relationship between flow velocity, flow depth, and gravitational forces. Classification of the flow regime is essential in hydraulic analysis because it influences energy distribution, flow stability, and the potential for erosion and scour.

Flow regimes are commonly classified as subcritical, critical, or supercritical.

Subcritical flow is characterized by relatively low velocities and greater flow depths, with gravitational forces dominating the flow behavior. Under these conditions, disturbances can propagate upstream, and the flow is generally stable. Subcritical conditions are typical of mild-slope channels and downstream areas with significant tailwater influence.

Critical flow represents a transitional state between subcritical and supercritical conditions. At this regime, the flow is highly sensitive to changes in depth or velocity, and it often occurs at hydraulic control sections such as culvert inlets, weirs, or channel contractions. Because of its unstable nature, critical flow plays a key role in controlling upstream and downstream hydraulic conditions.

Supercritical flow is defined by high velocities and shallow flow depths, where inertial forces dominate over gravitational forces. This regime is commonly associated with steep channel slopes and culvert outlets. Supercritical flow is hydraulically unstable and is often responsible for the formation of hydraulic jumps and localized scour due to the high energy of the flow [1].

The flow regime is quantitatively identified using the Froude number, which is expressed as:

$$\boldsymbol{Fr} = \frac{\boldsymbol{V}}{\sqrt{\boldsymbol{gD}}}$$

where $\boldsymbol{V}$ is the mean flow velocity, $\boldsymbol{g}$ is the acceleration due to gravity, and $\boldsymbol{D}$ is the hydraulic depth. A Froude number less than one indicates subcritical flow, a value equal to one represents critical flow, and values greater than one correspond to supercritical flow.

When evaluating scour, identifying the prevailing flow regime is a fundamental step in the analysis.

In HEC-14, the identification of the flow regime is particularly important because local scour at culvert inlets and outlets is predominantly associated with supercritical, high-velocity flows. Accurate determination of the flow regime supports reliable scour predictions and informs the design of effective energy dissipation and erosion control measures.

When evaluating scour, identifying the prevailing flow regime is a fundamental step in the analysis.

VI. Compute Outlet Velocity and Depth

In the HEC-14 methodology, the computation of outlet velocity and flow depth is essential because these parameters directly control the formation and strength of the flow jet exiting the culvert, which is the primary mechanism responsible for local scour.
Outlet velocity represents the kinetic energy of the flow as it leaves the culvert. Higher velocities produce more energetic jets with greater erosive capacity, increasing the potential scour depth and extending downstream.
Since HEC-14 scour equations are strongly velocity-dependent, accurate estimation of outlet velocity is critical for reliable scour predictions.
Flow depth at the outlet, together with tailwater depth, governs jet expansion and submergence. Shallow flow depths and low tailwater conditions allow the jet to impinge directly on the channel bed, intensifying erosion.
Conversely, greater depths promote energy dissipation and reduce scour severity. These depth relationships are fundamental inputs in defining scour hole geometry, including depth, width, and length [2].

Therefore, computing outlet velocity and depth is important in HEC-14 because they define the hydraulic regime, control the interaction between the flow jet and the channel bed, and provide the basis for designing effective erosion protection measures such as riprap aprons and energy dissipators.

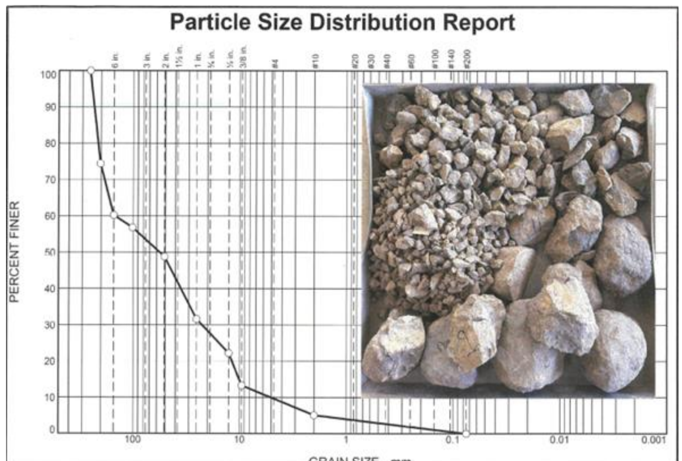
VII. Soil Types

Most of the HEC-14 equations were developed for cohesionless soils, because these soils are easily eroded by high-velocity flows. Cohesionless soils like sand and gravel. Empirical relationships for scour depth, width, and length are most accurate for uniform or graded sands and gravels. Riprap sizing and scour hole geometry formulas are directly based on these soil types [3].

For cohesive soils like clays and silts, HEC-14 can be used for cohesive soils, but the scour depth predictions are more uncertain. Cohesive soils resist erosion due to cohesion, so scouring is generally less severe than in cohesionless beds under the same flow conditions.
HEC-14 provides adjustment factors or suggests field judgment and additional safety factors when cohesive soils are present [4].

Finally, Rock or very Dense soils, for this type of soil HEC-14 may not be appropriate, as the empirical relationships are based on erodible beds. Designers usually rely on stability analysis or different guidelines for non-erodible channels.

Figure 1 shows a representative soil sample



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
46.5	25.8	18.1	4.5	2.4	2.7	0.0	0.0

Figure 1. Representative soil sample

VIII. Equations

The general empirical expression used in HEC-14 for cohesionless soil scour geometry is:

$$\left[\frac{hs}{R_c},\frac{Ws}{R_c},\frac{Ls}{R_c},\frac{Vs}{{R_c}^3}\right]=C_sC_h\left(\frac{\alpha}{\sigma^{1/3}}\right)\left(\frac{Q}{\sqrt{g}R_c^{2.5}}\right)^{\beta}\left(\frac{t}{316}\right)^{\theta}$$

Where;

h_s= maximum scour depth (m or ft)
W_s= scour width (m or ft)
L_s= scour length (m or ft)
V_s= scour volume (m³ or ft³)

Q= design discharge (m^3/s or ft^3/s)
g= acceleration of gravity (9.81 m/s^2 or 32.2 ft/s^2)
R_c= hydraulic radius at the culvert outlet (flow area/wetted perimeter at full flow)
t= duration of flow in minutes
$\sigma = (D_{84}/D_{16})^{0.5}$ = material standard deviation (dimensionless)
α, β, θ= empirical coefficients for each scour dimension
C_s= slope correction coefficient, A steeper slope is greater scour potential and larger C_s.
C_h= drop-height adjustment coefficient, is the drop height adjustment coefficient, used to account for the effect of a vertical drop between the culvert outlet and the downstream channel bed on scour development.

All these coefficients and adjustment factors are tabulated in HEC-14 for different situations.
Flow intensity ($Q/gR_c^{2.5}$)
Flow duration (t)
Hydraulic size scale (R_c)
Soil gradation (σ)
Site factors (slope and drop height corrections)

Table 1, presents typical coefficients (for cohesionless soils)

Table 1. Typical Coefficients

Scour Dimension	α	β	θ
Depth (h_s)	2.27	0.39	0.06
Width (W_s)	6.94	0.53	0.08
Length (L_s)	17.10	0.47	0.10
Volume (V_s)	127.08	1.24	0.18

The equation is valid for culvert outlet scour, cohesionless soils only like sand and gravel, and when the sediments are uniform. This is not valid for clay or cohesive beds, bedrock channels and strongly armored beds [5].

Using this equation the scour increase with Higher discharge Q, longer duration t, smaller culvert size Rc, poorly graded material (low σ), sediment gradation reduces scour as material becomes better graded.

The time of scourt (t) is estimated based on peak flow duration. It is recommended to use a time of 30 minutes if the discharge time is unknown since tests indicate that 2/3 to 3/4 of the maximum scour depth occurs in the first 30 minutes of the flow duration. [6]

D_{84} and D_{16} are important because they quantify sediment gradation, which directly controls how much scour can develop at a culvert outlet in cohesionless soils.

IX. Application of Culvert Scour Analysis

The proposed equations were applied to a three-cell box culvert on the Toa Vaca River. The culvert consists of three rectangular barrels, each with a width between 3.60 and 3.78 m and a uniform height of 2.98 m. Figure 2 presents the schematic of the culvert. For the width, the values were averaged to convert the culvert into a single opening. Its measurements are length of the culvert 12.10 ft and width of the culvert 9.78 ft respectively.

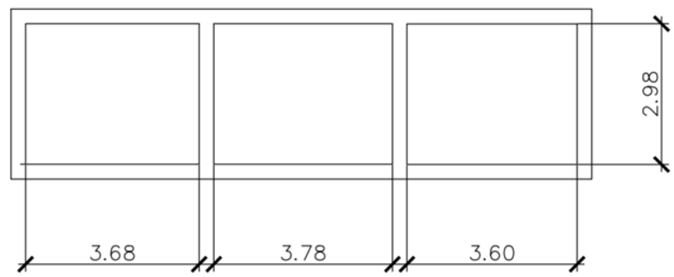


Figure 2. Schematic box Culvert downstream cross section

A particle distribution test was conducted, where the particle size distribution (PSD) analysis indicates that the sampled material corresponds to a coarse-grained riverbed deposit dominated by gravel, cobbles, and small boulders, with a negligible presence of fine particles [7]. Approximately 46.5% of the material consists of particles larger than 3 in, while gravel-sized fractions represent 48.4% of the total sample, including 25.8% coarse gravel and 18.1% fine gravel. Sand-sized particles account for only 4.5%, and no silt or clay fractions were identified.
The characteristic particle diameters obtained from the gradation curve further confirm the coarse nature of the material. The median particle size is $D_{50} \approx 56$ mm, while $D_{84} \approx 223$ mm and $D_{90} \approx 233$ mm, indicating a significant proportion of large particles capable of providing bed armoring. The effective grain size is $D_{10} \approx 5.1$ mm, reflecting a wide spread in particle sizes.
The calculated gradation coefficients yield a coefficient of uniformity $C_u \approx 10.6$and a coefficient of curvature $C_c \approx 0.67$, characteristic of a broadly graded natural aggregate. Based on the Unified Soil Classification System (USCS), the material is classified as GP (poorly graded gravel), and according to AASHTO criteria, it falls under A-1-a. The material is non-plastic, as confirmed by the absence of Atterberg limits [8].

River Data: For the 100-year return period, the total river discharge is 6,653.7 cfs. Given that the culvert consists of three cells, the discharge was assumed to be uniformly distributed, yielding 2,217.9 cfs per cell. The culvert slope is

0.001517, and the corresponding mean flow velocity is 11.94 ft/s.

Design discharges were evaluated for multiple return periods to characterize the hydraulic response of the river system [9]. The estimated peak flows increase with return period, ranging from 1,634.2 cfs for the 2-year event to 3,260.0 cfs for the 10-year event, 4,437.1 cfs for the 25-year event, and 5,495.5 cfs for the 50-year event. The 100-year return period produces the maximum discharge of 6,653.7 cfs, which governs the design and scour assessment for the culvert structure.

X. Hydraulic Analysis

A hydraulic analysis was performed to determine the key hydraulic parameters of the Toa Vaca River for evaluating channel behavior, streambed conditions, and potential erosion. The results of this analysis were used to develop recommendations for the protection of the culverts and wingwalls. The analysis was conducted using the HEC-RAS mathematical model developed by the U.S. Army Corps of Engineers, assuming steady, uniform, one-dimensional flow conditions.

The existing crossing consists of three reinforced concrete box culverts with dimensions of 3.68 × 2.98 m, 3.78 × 2.98 m, and 3.60 × 2.98 m. The existing-condition hydraulic model represents the watercourse in its current configuration. A total of five (5) cross sections were used to define the stormwater channel geometry. A Manning's roughness coefficient of n = 0.055 was adopted for undeveloped areas based on surface conditions observed during the site visit. Figure 3 presents the cross sections.

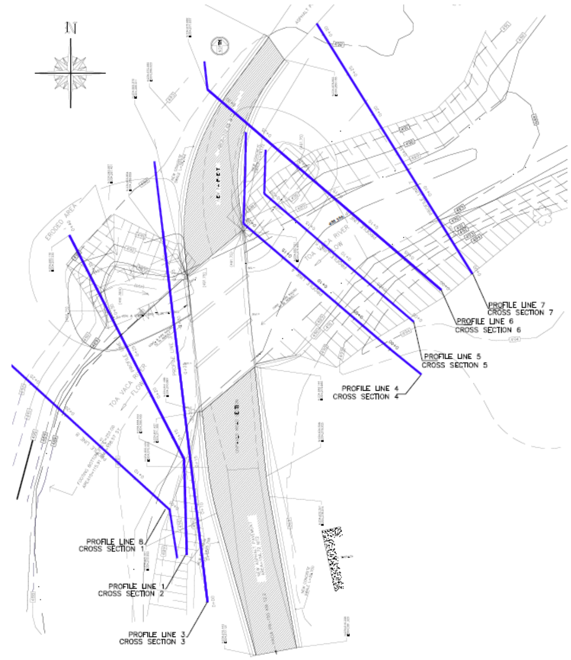


Figure 3. Schematic of cross sections

The hydraulic results at Cross Section 4, located immediately upstream of the culvert, indicate a progressive increase in flow depth, velocity, and energy slope with increasing return period. For the 2-year event, the mean channel velocity is 1.88 m/s with a Froude number of 0.44, indicating subcritical flow conditions. As discharge increases, velocities rise to 3.62 m/s for the 100-year event, accompanied by an increase in the energy grade slope to 0.011592 m/m. The corresponding Froude number (0.65) suggests flow approaching critical conditions, indicating an elevated potential for erosion near the culvert entrance. The flow area and top width also increase significantly with discharge, reflecting flow expansion upstream of the structure.

At Cross Section 3, located downstream of the culvert, flow conditions remain predominantly subcritical across all return periods, with Froude numbers ranging from 0.34 to 0.37. Channel velocities are comparatively lower than those observed upstream, increasing from 1.37 m/s for the 2-year event to 2.06 m/s for the 100-year event. The energy grade slope remains relatively mild, decreasing slightly with increasing discharge, which is indicative of flow recovery and energy dissipation downstream of the culvert. The increase in flow area and top width downstream reflects flow expansion and reduced confinement, contributing to lower velocities relative to the upstream section.

Overall, the contrast between Cross Sections 4 and 3 highlights the hydraulic acceleration upstream of the culvert and energy dissipation downstream, conditions that are consistent with the observed erosion patterns and support the need for localized scour and erosion protection measures near the culvert entrance and outlet.

XI. RESULTS

Table 2. Parameters.

Length of the culvert (ft)	12.1063
Width of the culvert (ft)	9.776903
Slope %	0.001517
Drop Heigh (ft)	0.6562
Diameter (ft)	15.56
Hd	0.04
D90 (ft)	0.763747
D84 (ft)	0.73097
D50 (ft)	0.184941
D16 (ft)	0.03314
Standard Deviation	4.7
Discharge (ft^3/seg)	2217.883
Gravity (ft/seg^2)	32.2
Area (ft^2)	118.36
Weeping Perimeter (ft)	31.6601
Hydraulic Radio (ft)	3.74
Time (min)	30
Velocity (ft/s)	10.96
Vc (ft/s)	18.8202

HEC – 14 equation result:

$$h_s = C_s C_h \left(\frac{\alpha}{\sigma^{1/3}}\right)\left(\frac{Q}{\sqrt{g R_c^{2.5}}}\right)^{\beta}\left(\frac{t}{316}\right)^{\theta}(R_c)$$

$$h_s = 1 * 1\left(\frac{2.27}{4.7^{\frac{1}{3}}}\right)\left(\frac{2217.88}{\sqrt{32.2}(3.74^{2.5})}\right)^{0.39}\left(\frac{30}{316}\right)^{0.06}(3.74) = 12.47 ft$$

Federal Highway Administration equation result:

$$d_s = 0.47\left(\frac{q}{\sqrt{g * d_{50}}}\right)^{0.54} H^{0.18}$$

Where d_s represent maximum scour depth (ft or m), while q represent the discharge flow per unit width (ft^2/s or m^2/s), g denotes gravitational acceleration, d_{50} is the median sediment particle size (ft or m) and H corresponds to the culvert height or barrel diameter (ft or m).

$$d_s = 0.47\left(\frac{\frac{2217.88}{9.7769}}{\sqrt{32.3 * 0.184941}}\right)^{0.54}(9.7769^{0.18}) = 8.19 ft$$

Colorado State University equation result:

$$d_s = 2.0\left(\frac{V}{\sqrt{g * d_{50}}}\right)^{0.67} H^{0.22}$$

Where d_s represent maximum scour depth (ft or m), while V represent the velocity (ft/s or m/s), g denotes gravitational acceleration, d_{50} is the median sediment particle size and H corresponds to the culvert height or barrel diameter (ft or m).

$$d_s = 2.0\left(\frac{10.96}{\sqrt{32.2 * 0.184941}}\right)^{0.67}(9.7769^{0.18}) = 9.04 ft$$

United States Army Corps of Engineers equation result:

$$d_s = K\left(\frac{Q}{A}\right)^{0.54} H^{0.5}$$

Where d_s represent maximum scour depth (ft or m), while K represent an empirical constant (typically taken as 1.0 or adjusted for local conditions), Q denotes flow rate (cfs or m^3/s), A is the culvert cross-sectional area (ft^2 or m^2) and H corresponds to height or diameter of the culvert (ft or m).

$$d_s = 1.0\left(\frac{2217.88}{118.36}\right)^{0.5}(9.7769^{0.5}) = 13.54 ft$$

The California Department of Transportation (Caltrans) equation result:

$$Y_s = K_s\left(\frac{q}{V_0}\right)^{0.57} D_{50}{}^{-0.21}$$

Where Y_s represent scour depth below tailwater (ft or m), while K_s represent correction factor for tailwater condition, q denotes discharge at the culvert outlet (cfs or m^3/s), V_o is the velocity at the outlet (ft/s or m/s) and d_{50} corresponds to median sediment particle size (ft or m).

$$Y_s = 0.5 * \left(\frac{2217.88}{10.96}\right)^{0.57}(0.184941^{-0.21}) = 14.70 ft$$

XII. DEVELOPMENT OF NEW EQUATION

A new predictive equation was developed based on measured data from real-world river systems and observed scour conditions. The formulation integrates several parameters representative of the current geomorphological conditions of rivers in Puerto Rico. The equation was evaluated using multiple case studies and was found to be the most applicable among the tested formulations for contemporary river environments.

A new empirical equation will be created based on the previous equations, including HEC - 14 and the others, using the parameters they have in common.

$$y_s = C\left(\frac{Q}{b * Vc}\right)^{\alpha}\left(\frac{a}{y1}\right)^{\beta}\left(\frac{V}{\sqrt{g * y1}}\right)^{\theta}\left(\frac{1}{d_{50}}\right)^{\delta}$$

Where y_s represents the scour depth at the culvert outlet (ft or m), Q is the discharge (cfs or m³/s), and b denotes the culvert width or the effective width of the approaching flow (ft or m). The parameter V_c corresponds to the critical velocity for sediment motion (ft/s or m/s), while α represents the culvert width or equivalent hydraulic diameter. The variable y_1 is the approach flow depth, and V is the approach flow velocity (ft/s or m/s). The constant g denotes gravitational acceleration, and d_{50} is the median sediment particle size. Finally, C, α, β, γ, and δ are empirical coefficients that must be determined through calibration.
Range of parameter could be α between 0.3 and 0.5, β= 0.5, γ=0.4 and δ between 0.5 and 1.0.

$$y_s = 0.01\left(\frac{2217.88}{9.7769 * 18.820}\right)^{0.5}\left(\frac{9.7769}{11}\right)^{0.5}\left(\frac{10.96}{\sqrt{32.2 * 11}}\right)^{0.4}\left(\frac{1}{0.184941}\right)^{0.5} = 12.14\,ft$$

Figures 4 and 5 present the cross-sectional views of the culverts

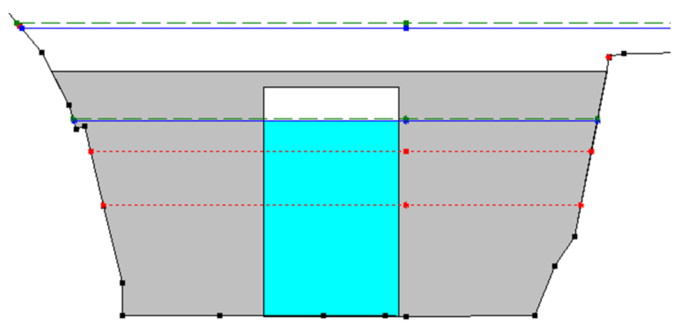


Figure 4. Culvert up stream cross section

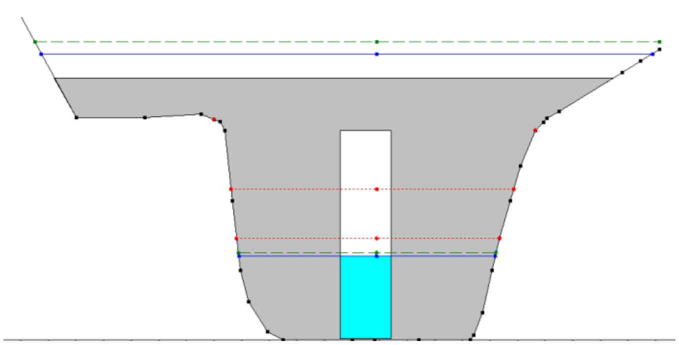


Figure 5. Culvert downstream cross section

XIII. Discussion

The results indicate that the scour depths predicted by the six evaluated equations are of similar magnitude. This consistency suggests that, despite differences in formulation, the governing parameters—such as discharge, flow velocity, sediment characteristics, and hydraulic conditions—are the primary factors influencing scour depth. Scour hole geometry is strongly dependent on soil type and site-specific conditions; therefore, the HEC-14 method incorporates empirical coefficients to account for spatial variability in sediment properties. Similar behavior is observed in the other equations through the use of correction factors and tailwater conditions, which vary according to the sediment characteristics considered in each formulation.
All evaluated equations share a common set of fundamental parameters, including discharge, velocity, gravitational acceleration, sediment particle size, and culvert geometry. These parameters are the dominant controls on scour development at culvert outlets. Accordingly, in the development of the proposed equation, empirical coefficients were allowed to vary as a function of soil conditions and tailwater effects, while the remaining hydraulic and geometric parameters were prescribed. Two additional parameters were incorporated into the proposed formulation: approach flow depth and critical velocity. The approach flow depth is defined as the difference between the upstream culvert invert elevation and the upstream water surface elevation. Critical velocity corresponds to the condition at which the Froude number equals unity, indicating critical flow.
Hydraulic modeling performed using HEC-RAS provided water surface elevations for the 100-year flood profile, allowing assessment of culvert performance under extreme flow conditions. This analysis offers insight into whether the existing culvert configuration is adequate or requires modification to accommodate the hydraulic demands of the watercourse. The results also illustrate flow contraction downstream of the culvert and flow expansion upstream, consistent with expected culvert hydraulics.

A comparative table was developed using approximately seven scour analyses conducted at different locations across the island. The comparison indicates that the difference between the equations presented in HEC-14 and the empirically developed equation is approximately 10%.
Although this difference may appear significant, it should be noted that the HEC-14 equation was developed for rivers and streams in the United States, taking into consideration the geomorphological and topographic characteristics typical of those environments. Consequently, variations are expected when applying the equation to local conditions with different hydraulic and geomorphic characteristics.
Table 3 presents the characteristic scour parameters, including depth, width, length, and volume, calculated using both the HEC-14 equation and the empirically developed equation.

Table 3. Results

	HEC-14	Empirical equation
Depth (ft)	20	18
Width (ft)	35	30
Length (ft)	55	53
Volume (ft^3)	38,500	28,620

XIV. Conclusion

Scour at culvert outlets represents a critical threat to the structural stability of hydraulic infrastructure, particularly under high-flow conditions and in cohesionless soils. This study evaluated and compared several empirical equations used to estimate scour hole geometry, emphasizing the influence of key hydraulic and sediment parameters, including discharge, flow velocity, channel slope, and particle size. Through a comparative assessment of the HEC-14 methodology and other established models (FHWA, Caltrans, USACE, and CSU), a common set of governing variables was identified, enabling the development of a new empirical equation calibrated to local conditions. Hydraulic simulations conducted using HEC-RAS complemented the analysis by characterizing flow behavior within the culvert for the 100-year design flood.

The results indicate that, despite differences in empirical coefficients among the evaluated equations, the predicted scour depths were generally comparable, underscoring the importance of model calibration based on site-specific hydraulic and soil conditions. The findings further demonstrate that accurate characterization of sediment properties and hydraulic conditions is essential for reliable scour prediction. With respect to scour mitigation at culvert outlets, a range of countermeasures may be employed. Common approaches include energy-dissipation structures such as stilling basins, sediment traps, and Type B or SAF dissipation basins. Additional stabilization measures include properly sized riprap linings, geotextiles, and vegetative reinforcement. In more severe conditions, structural solutions such as baffles, drop chutes, or retaining walls may be required, along with outlet designs that reduce flow energy. The selection of an appropriate mitigation strategy depends on soil characteristics, anticipated flow conditions, and site-specific geomorphic and geographic constraints.

XV. References

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