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BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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A. M. ONYSHCHENKO[1*], B. M. OSTROVERKH[2], Y. S. DUKHNENKO[3]

[1*]Department of Bridges, Tunnels and Hydraulic structures, National Transport University,
Mykhaila Omelianovycha-Pavlenka St., 1, Ukraine, Kyiv, 01010, tel. +38(068) 777 18 99,
e-mail onyshchenko.a.m.ntu@gmail.com, ORCID 0000-0002-1040-4530
[2]Department of Wave and Channel Flow Hydrodynamics, Institute of Hydromechanics, NAS of Ukraine,
M. Kapnist street, 8/4, Ukraine, Kyiv, 02000, tel. + 38(044) 371-65-57,
e-mail borys.ostro@gmail.com, ORCID 0000-0002-3373-5535
[3]Department of Bridges, Tunnels and Hydraulic structures, National Transport University,
Mykhaila Omelianovycha-Pavlenka St., 1, Ukraine, Kyiv, 01010, tel. +38(063) 835 22 05,
e-mail yana.duhnenko@gmail.com, ORCID 0009-0007-8742-7718

METHOD FOR EVALUATING HYDRAULIC AND EROSION PROTECTION OF CULVERTS

Purpose. The primary goal of this research is the scientific substantiation and development of a comprehensive method for assessing the hydraulic state and erosion protection of culverts in road construction. The work aims to create a holistic approach that accounts for the complex interaction between different types of flow control – at the inlet and the outlet of the structure – depending on hydrological conditions and the geometric parameters of the site. **Methodology.** The methodological framework of the study is based on the fundamental principles of open-channel hydraulics, particularly the analysis of the Bernoulli energy equation and the Manning empirical equation to establish relationships between water discharge and channel morphometric characteristics. In the course of the work, methods of successive approximations (iterative procedures) were applied for the precise calculation of normal and critical depths in circular and rectangular culverts, allowing for the correct classification of the flow regime. The assessment of erosion processes is based on modern empirical models that correlate the kinetic energy of the flow (expressed via the Froude number) and the relative tailwater level with the necessary parameters of the protective apron. **Findings**. As a result of the study, the physical conditions and criteria for the occurrence of inlet and outlet flow control regimes were systematized, enabling the formation of an adaptive mathematical framework for calculating the discharge capacity of structures under various filling scenarios. It was demonstrated that traditional design methods often underestimate the velocity regime at the outlet, leading to the occurrence of supercritical flows that necessitate the mandatory installation of energy-dissipating protective aprons. Based on the calculations performed, a refined set of formulas for calculating the required length (L_a) of the riprap is presented. Furthermore, a classification of stone material sizes was developed depending on the pipe diameter and hydraulic head, which allows for the optimization of material costs while ensuring the reliability of the structure. **Originality.** The scientific novelty of the obtained results lies in the improvement of the theoretical approach to assessing the hydraulic efficiency of culverts by integrating dimensionless inlet control functions with the dynamic indicators of the downstream reach. For the first time, a methodology has been proposed that simultaneously accounts for the variability of tailwater levels when calculating erosion stability parameters, thereby avoiding design errors in protective structures under variable backwater conditions. The use of approximate explicit formulas for the rapid determination of critical flow parameters was substantiated, significantly simplifying the hydraulic analysis procedure for complex transitional regimes without losing the accuracy required for engineering calculations. **Practical value.** The developed methodology allows design engineers, at the documentation development stage, to accurately predict the risks of overtopping and minimize the likelihood of emergency situations. The data obtained regarding the rational selection of rock riprap classes for pipes with diameters up to 1.5 m allows for the standardization of engineering protection solutions, reduced operational maintenance costs for drainage structures, and an extended maintenance-free service life.

Keywords: culverts; hydraulic calculation; inlet control; outlet control; normal depth; critical depth; outlet velocity; erosion protection; rock riprap

Introduction

The flow velocity through culverts is determined primarily by the headwater depth, i.e., the water level at the entrance to the structure. However, this indicator is also influenced by the elevation levels of the tailwater and the physical parameters of the pipe itself, in particular its shape, cross-sectional area, length, longitudinal slope, wall roughness, and the geometry of the inlet.

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Insufficient capacity of the culverts creates significant risks: excessive accumulation of water in the headwater can lead to overflow across the road embankment, which threatens the destruction of the structure and damage to adjacent buildings.

Hydraulic analysis of the operation of such structures is based on the distribution of flow conditions into two main types:

- inlet control: occurs when the capacity of the inlet is less than the capacity of the pipe barrel; in this case, the inlet operates as an orifice or a weir;
- outlet control: is observed when the flow is limited by the water level in the tailwater and the hydraulic resistance of the barrel itself.

Traditional design often leads to the fact that the flow area inside the pipe is significantly reduced, because of which the water velocity at the outlet substantially increases. This causes intensive erosion and scour of the channel directly behind the structure. To prevent damage, it is necessary to provide for protective measures, the most common of which is the installation of stone riprap (armor) on the riverbed.

The effectiveness of such protection depends on the correct calculation of its parameters - the size of the stone, the length and width of the apron, which is directly related to the hydraulic characteristics of the flow.

Purpose

The primary goal of this research is the scientific substantiation and development of a comprehensive method for assessing the hydraulic state and erosion protection of culverts in road construction. The work aims to create a holistic approach that accounts for the complex interaction between different types of flow control – at the inlet and the outlet of the structure – depending on hydrological conditions and the geometric parameters of the site. A crucial component of this objective is the development of an algorithm for accurately determining the geometric and structural parameters of protective measures, specifically riprap. This is essential for preventing uncontrolled channel scour in the downstream reach and ensuring the overall stability of the road embankment during flood events.

Methodology

The capacity of culverts depends not only on the water depth at the inlet, but also on a complex of factors including the water level at the outlet and the physical parameters of the object (shape, cross-section, length, slope, and roughness). Incorrect calculation of these indicators threatens a critical rise in the headwater level, which risks washing out the roadbed and flooding territories. Hydraulic analysis of such systems is usually based on the differentiation of flow conditions, dividing them into cases where the flow is limited by the inlet (inlet control) or by the characteristics of the barrel itself and the tailwater (outlet control).

Inlet control (Figure 1) occurs when the capacity of the culvert inlet is less than the capacity of the culvert barrel. In this case, the headwater depth is calculated by treating the inlet as an orifice or a weir.

Outlet control (Figure 2) occurs when the downstream water level and the capacity of the culvert barrel restrict the flow.

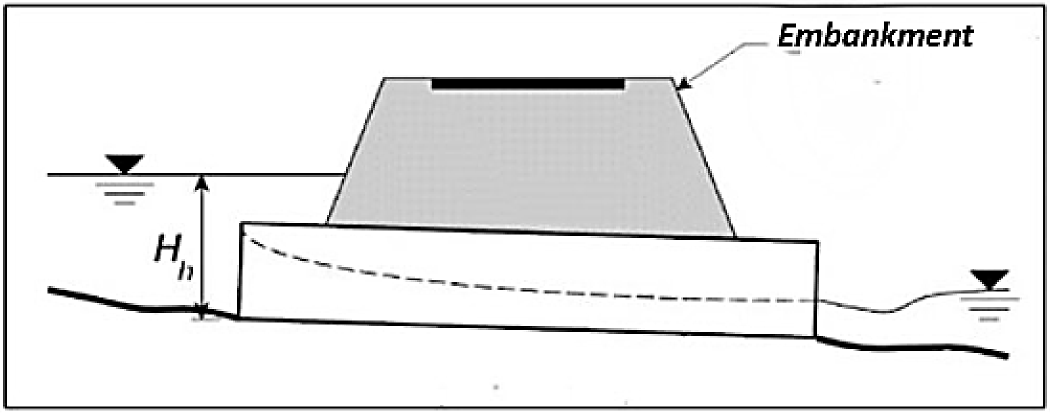

Figure 1. Flow controlled by inlet characteristics

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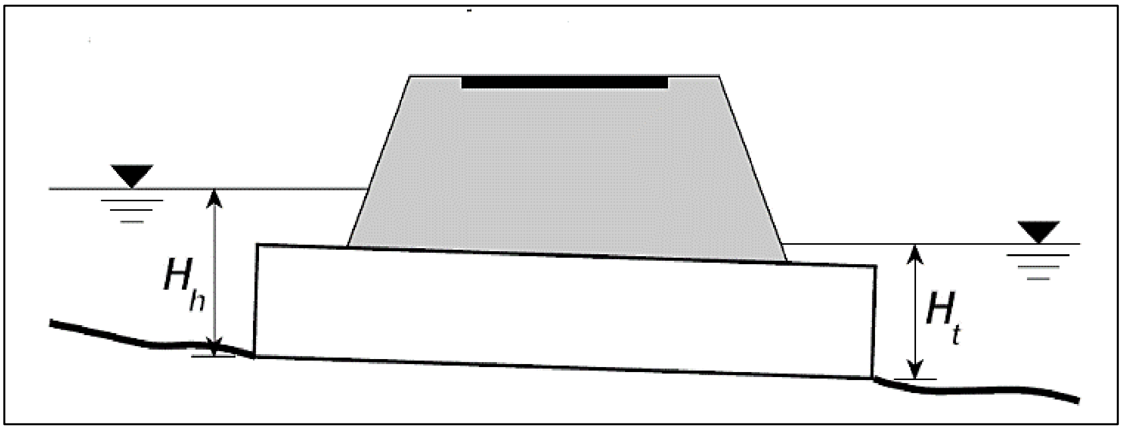

Figure 2. Flow regulated by the barrel capacity and the downstream water level

Flow in a culvert is classified as being regulated primarily by the characteristics of the inlet or the outlet of the culvert. The capacity is calculated for the two types of control.

Under inlet control, culverts have a shallow, high-velocity supercritical flow immediately downstream of their inlets. Culverts will never be completely full throughout their entire length, whether their inlets are submerged or unsubmerged. The flow rate under these conditions depends primarily on the headwater depth and the inlet characteristics. The headwater depth ratios for unsubmerged and submerged inlets are calculated as follows (FHWA-RD-03-053, 2003):

$$\frac{H_w}{D_c} = K'\left(\frac{Q}{A_c\sqrt{gD_c}}\right)^M \text{ unsubmerged, (1)}$$

$$\frac{H_w}{D_c} = c'\frac{Q^2}{A_c^2 gD_c} + Y + mS_0 \text{ submerged, (2)}$$

where H_w is the headwater depth; D_c is the interior height of the liquid column in the culvert; Q is the flow rate in the barrel; A_c is the full cross-sectional area of the culvert; g is the gravitational acceleration; S_0 is the culvert slope; K', M, c', Y are constants based on the culvert material, cross-sectional shape, m = 0.7 for mitered inlets and m = -0.5 for all other inlets (Normann, Houghtalen, & Johnston, 1985).

Under outlet control, culverts are either full throughout their entire length or are in a subcritical state without being completely full. The outlet flow is calculated based on a direct energy balance between the upstream and downstream ends of the culvert as follows:

$$\frac{H_w}{D_c} = \frac{H_0}{D_c} + \frac{Q^2}{2gA_c^2 D_c}\left(1 + K_e + \frac{2gn_c^2 L_c}{R_c^{4/3}}\right) - S_0\frac{L_c}{D_c}, \quad (3)$$

where $H_0 = \max(\mathrm{T}_w, (d_c + D_c)/2$, T_w – tailwater depth, d_c – critical depth at the outlet, K_e – inlet energy loss coefficient for various inlet configurations, n_c – Manning's roughness coefficient, $R_c = A_c / P_c$ – hydraulic radius of the culvert, P_c – wetted perimeter, L_c – length of the culvert.

The energy balance assumes that the channel velocities both upstream and downstream of the culvert are small compared to the velocity within the barrel. Based on formulas (1)-(3) for both types of control, the culvert flow rates are determined as follows (FHWA-RD-03-053, 2003):

$$Q_c = NC_c A_c\sqrt{2gH_c}, \quad (4)$$

where N is the number of identical culverts, C_c is the discharge coefficient, which depends on the flow control (inlet or outlet) and the culvert characteristics, H_c is the head, and A_c is the cross-sectional area of the culvert barrel.

For inlet flow control:

$$H_c = z_w^h - z_{inv}, \quad (5)$$

$$C_c = C_{c1} = \sqrt{\frac{1 - \frac{D_c}{H_c}(Y + mS_0)}{2c'}}, \ H_c \ge D_c \quad (6)$$

$$C_c = C_{c2} = \frac{1}{\sqrt{2}K'^{\frac{1}{M}}}\left(\frac{H_c}{D_c}\right)^{\frac{1}{M}-\frac{1}{2}}, \ H_c < D_c. \quad (7)$$

In the transition zone near the point $H_c = D_c$, the discharge coefficient is calculated using the formula:

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$$C_c = \min(C_{c1}, C_{c2}) . \qquad (8)$$

For outlet flow control:

$$H_c = z_w^h - z_{inv} + S_0 L_c - z_w^t , \qquad (9)$$

$$C_c = \frac{1}{\sqrt{1 + K_e + \frac{2 g n_c^2 L_c}{R_c^{4/3}}}} , \qquad (10)$$

where z_w^h – the water surface elevation upstream (i.e., the headwater elevation), z_w^h – the water surface elevation at the downstream end of the culvert, z_{inv} – inlet invert elevation of the culvert.

The graphical representation of formula (4) is called a performance curve. A performance curve is a plot of the dependence of the head or headwater elevation on the flow rate. Representing culvert operation graphically is useful for evaluating the hydraulic capacity of a culvert across various heads. Among other applications, the performance curve illustrates the benefits of inlet improvements.

When constructing a performance curve, it is necessary to plot both the inlet control and outlet control curves. This is essential because the dominant control at a given head is difficult to predict. Furthermore, the control may shift from inlet to outlet, or vice versa, within a range of flow rates.

The hydraulic parameters of a culvert include normal depth, critical depth, and outlet velocity. Culverts typically result in outlet velocities that are higher than natural flow velocities; therefore, the outlet velocity should be calculated to determine the necessity for downstream erosion protection.

Normal depth y_n is the constant water depth in a culvert where gravitational forces equal frictional resistance, resulting in uniform, steady flow (Figure 3). This parameter is vital for the hydraulic design and analysis of culverts (Онищенко, Ковальчук, Гаркуша, et al., 2023).

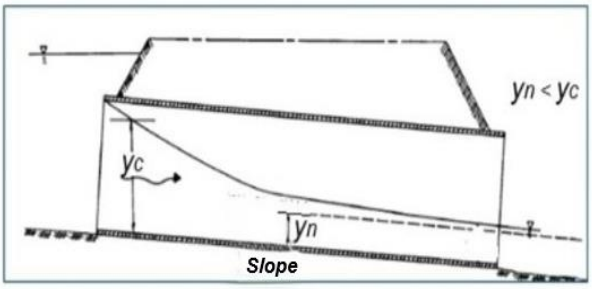

Figure 3. Normal and critical depth on steep slopes

Assuming a constant slope, cross-section, and roughness, the normal depth is calculated using the Manning equation:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} , \qquad (11)$$

where Q is the discharge, A is the cross-sectional area of the flow, R is the hydraulic radius, n is the Manning's roughness coefficient, and S is the longitudinal slope. The parameters Q and S are constants, while A and R depend on the normal depth y_n.

Normal depth is used to determine culvert sizes for passing peak runoff without exceeding the pipe diameter (full flow), and to determine the outlet velocity for culverts operating under inlet control. Normal depth is not defined for horizontal or adverse slopes. For design purposes, if the normal depth is less than the critical depth, the slope is considered steep (supercritical), and the flow reaches critical depth near the inlet.

The critical depth of a culvert, y_c is the flow depth that marks the transition between subcritical (slow) and supercritical (fast) flow. It is a crucial parameter in culvert hydraulics, determining the water surface profile under inlet control and acting as the lower bound for the water depth at the outlet under certain conditions. The critical depth satisfies the equation:

$$\frac{Q^2 T}{g A^3} = 1 \Leftrightarrow Fr^2 = 1 , \qquad (12)$$

where Q is the discharge, A is the cross-sectional area of the flow, T is the top width of the free surface, and $Fr = \frac{V}{\sqrt{gy}}$ is the Froude number. The parameters Q and T are constants, while A, T depend on the critical depth y_c.

Under outlet control, the cross-sectional area of the flow is determined by either the tailwater depth or the critical depth. Critical depth is used when the tailwater depth is less than the critical depth. The tailwater depth is used when it is greater than the critical depth but below the top of the barrel. The full area of the barrel is used when the tailwater level exceeds the top of the barrel (Онищенко, Гаркуша, & Клименко, 2022a; 2022b).

When the tailwater depth is low, the flow in a culvert on mild or horizontal slopes reaches critical depth near the outlet (Figure 4).

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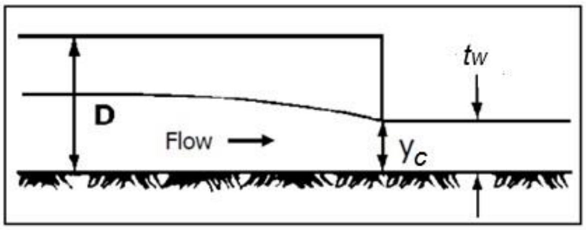

Figure 4. Critical depth at the outlet on mild slopes

Normal depth is used for comparison with critical depth to determine flow behavior. If the normal depth is greater than the critical depth and the water level in the tailwater is low, the culvert can act as a free-flowing channel.

To determine the normal depth, formulas for the cross-sectional area and hydraulic radius can be added to equation (11) to obtain a system of equations, from which the normal flow depth, cross-sectional area, and outlet velocity can be obtained by the method of successive approximations. For example, for a circular pipe (Figure 5), the cross-sectional area and hydraulic radius are equal to.

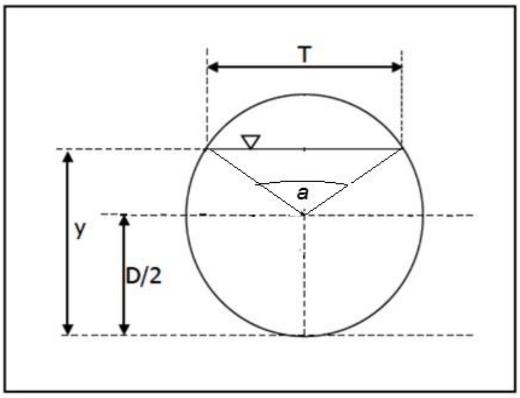

Figure 5. Cross-sectional area of a circular culvert

$$A = \frac{\pi D^2}{4} - \frac{D^2}{8}(\alpha - \sin(\alpha)), \tag{13}$$

$$\alpha = 2\arccos(2y_n/\mathrm{D} - 1),$$

$$R = A/P, \tag{14}$$

$$P = \frac{D}{2}(2\pi - \alpha),$$

where y_n is the normal depth, D is the diameter, and P is the wetted perimeter.

To determine the critical depth, formulas for the cross-sectional area and the free surface width can be added to equation (12) to obtain a system of equations, from which the critical flow depth, cross-sectional area, and outlet velocity can be determined by the method of successive approximations. For example, for a circular pipe (Figure 5), the cross-sectional area and the free surface width are equal to

$$A = \frac{\pi D^2}{4} - \frac{D^2}{8}(\alpha - \sin(\alpha)), \tag{15}$$

$$T = D\sin(\alpha/2). \tag{16}$$

For a rectangular (box) culvert, the critical depth is calculated using the formula

$$y_c = \sqrt[3]{\frac{(Q/B)^2}{g}}, \tag{17}$$

where B is the width of the culvert, and g is the gravitational acceleration.

Approximate formulas for critical and normal depth exist for both circular and rectangular cross-sections (Vatankhaha, & Easa, 2010; Liu, Wang, Leng, & Zhao, 2012).

For a circular cross-section, the critical depth is calculated using the approximate formula

$$y_c = D(13.6\varepsilon_c^{-2.1135} - 13\varepsilon_c^{-2.1} + 1)^{-0.1156}, \tag{18}$$

where $\varepsilon_c = \dfrac{Q^2}{gD^5\sqrt{1-S^2}}$.

Approximate formulas for the normal depth of circular and rectangular cross-sections are as follows:

$$y_{nc} = D(15.088\beta_c^3 - 8.3569\beta_c^2 + 3.3748\beta_c + 0.1202), \tag{19}$$

where $\beta_c = \dfrac{nQ}{D^{8/3}S^{1/2}}$.

$$y_{nb} = D\beta_b^{3/5}(1 + 2\beta_b^{3/5} + 1.712\beta_b^{6/5})^{2/5}, \tag{20}$$

where $\beta_b = \dfrac{nQ}{B^{8/3}S^{1/2}}$.

The average flow velocity at the culvert outlet is determined by the flow rate and the cross-sectional area at the outlet.

$$V_{out} = Q/\mathrm{A}. \tag{21}$$

Findings

Traditional hydraulic design of culverts usually results in the flow area within the structure being significantly reduced compared to the initial cross-sectional area under design conditions; consequently, the outlet velocity can cause substantial flow erosion near the exit. Therefore, some form of protection is typically required at the outlets (and inlets).

According to (Fletcher, & Grace, 1972; Bohan, 1970; Thompson & Kilgore, 2006) the most common structures for protecting culvert openings, primarily for culverts with a diameter of 1.5 m or less, are rock riprap armoring. An example of a rock riprap layout is shown in Figure 6.

This scour protection measure consists of one or more layers of stone on a level surface, extending a certain distance downstream from the culvert outlet and designed to act as armor for the erodible riverbed.

They are constructed at zero grade over a distance that is often related to the outlet pipe diameter. These reinforcements do not dissipate significant energy, except through increased roughness over a short distance. However, they serve to spread the flow, helping transition to surface flow where no natural drainage path exists. Nevertheless, if they are too short or otherwise ineffective, they simply shift the location of potential erosion further downstream. The key design elements are the stone size, as well as the length, width, and depth of the embankment (Bohan, 1970).

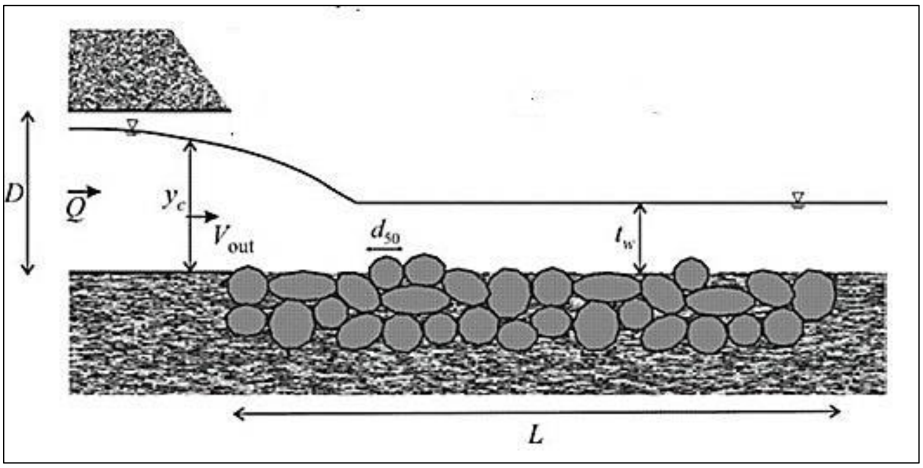

Figure 6. Diagram of a culvert and rock riprap

While these studies focus on the issue of stone size, the design of the apron must also account for geometry. More specifically, the extent to which any rough apron can dissipate the energy of the outlet flow has been investigated.

A key observation of this study is the distinctly different behavior of water depending on the tailwater level, namely: the minimum tailwater condition and the maximum tailwater condition, with this distinction being defined in terms of the ratio of the water level to the culvert diameter, t_w/D. Thus, the model equation is as follows (Bohan, 1970):

$$\frac{d_{50}}{D} = 0.25\frac{V_{out}}{\sqrt{gD}}, \ \frac{t_w}{D} \le \frac{1}{2}, \tag{22}$$

$$\frac{d_{50}}{D} = 0.25\frac{V_{out}}{\sqrt{gD}} - 0.15, \ \frac{t_w}{D} > \frac{1}{2}. \tag{23}$$

V_{outt} is the average flow velocity at the culvert outlet, and g is the gravitational acceleration.

The specification of the riprap length L_a distinguishes not only between the minimum and maximum tailwater levels but also considers the value of the outlet Froude number

$$Fr_{D,out} = \frac{V_{out}}{\sqrt{gD}}. \tag{24}$$

Thus, the equation for L_a can be expressed as

$$\frac{L_a}{D} = 8, \ Fr_{D,out} \le 1, \tag{25}$$

$$\frac{L_a}{D} = 8 + 17\log_{10} Fr_{D,out}, \ Fr_{D,out} > 1, \ \frac{t_w}{D} < \frac{1}{2}, \tag{26}$$

$$\frac{L_a}{D} = 8 + 55\log_{10} Fr_{D,out}, \ Fr_{D,out} > 1, \ \frac{t_w}{D} \ge \frac{1}{2}. \tag{27}$$

From equations (25-27), the required length L_a for maximum tailwater conditions (and $Fr_{D,out} > 1$) will be significantly greater than for the corresponding case of minimum tailwater conditions. Consequently, these equations can lead to rather long aprons, with L_a/D exceeding 20 in extreme cases for maximum tailwater conditions.

In contrast, the study "Hydraulic design of energy dissipators for culverts and channels" does not account for any dependence on tailwater conditions; instead, the riprap length varies depending in the stone size (Table 1), with a maximum length of $L_a = 8D$.

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Table 1

The riprap length varies depending in the stone size

Class	Stone size, d50 (m)	Apron length, L_a	Apron depth
1	0.125	4D	$3.5d_{50}$
2	0.150	4D	$3.3d_{50}$
3	0.250	5D	$2.4d_{50}$
4	0.350	6D	$2.2d^{50}$
5	0.500	7D	$2.0d_{50}$
6	0.550	8D	$2.0d_{50}$

Originality and practical value

Scientific novelty of the obtained results lies in the improvement of the theoretical approach to assessing the hydraulic efficiency of culverts by integrating dimensionless inlet control functions with the dynamic indicators of the tailwater. For the first time, a methodology is proposed that simultaneously takes into account the variability of water levels downstream of the structure when calculating erosion stability parameters, which allows for avoiding design errors of protection under variable backwater conditions. Additionally, the use of approximate explicit formulas for the rapid determination of critical flow parameters is substantiated, which significantly simplifies the hydraulic analysis procedure for complex transition regimes without loss of the accuracy required for engineering calculations.

Conclusions

In the course of the study, it was established that the efficiency and operational safety of culverts directly depend on the accurate determination of the structure's operating mode – inlet control or outlet control. Since these modes are determined by different physical factors (inlet geometry in the first case and hydraulic resistance of the barrel and tailwater level in the second), a comprehensive approach to their analysis is critically important for preventing emergency situations.

The analysis results indicate that the flow velocity at the pipe outlet almost always exceeds the natural flow velocity in the channel, which creates a high energetic potential for bed scour. It has been proven that traditional calculation methods without considering the variability of the tailwater depth can lead to an erroneous choice of protection parameters. The proposed methodology for calculating the parameters of the rock riprap allows for the adaptation of energy dissipator designs to specific hydrological conditions.

Particular attention is paid to the use of iterative methods and approximate formulas for calculating normal and critical depths in circular and rectangular cross-sections. This allows for a significant simplification of engineering calculations while maintaining high accuracy in predicting hydraulic characteristics.

In summary, it can be stated that the implementation of a systemic method for assessing the hydraulic state and erosion protection ensures the durability of road structures. The use of substantiated classes of rock riprap and the optimization of inlet headwall geometry allow not only for reducing the risk of water overtopping the embankment but also for significantly decreasing operational costs for restoring scoured sections of the channel in the tailwater.

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А. М. ОНИЩЕНКО[1*], Б. М. ОСТРОВЕРХ[2], Я. С. ДУХНЕНКО[3]

[1*]Кафедра мостів, тунелів та гідротехнічних споруд, Національний транспортний університет,
вул. Михайла Омеляновича-Павленка, 1, Київ, Україна, 01010, тел. +38(068) 777 18 99,
ел. пошта onyshchenko.a.m.ntu@gmail.com,ORCID 0000-0002-1040-4530
[2]Відділ гідродинаміки хвильових та руслових потоків, Інститут гідромеханіки НАН України,
вул. Марії Капніст, 8/4, Київ, 02000, Київ, Україна, тел. + 38(044) 371-64-03,
ел. пошта borys.ostro@gmail.com, ORCID 0000-0002-3373-5535
[3]Кафедра мостів, тунелів та гідротехнічних споруд, Національний транспортний університет,
вул. Михайла Омеляновича-Павленка, 1, Київ, Україна, 01010, тел. +38(063) 835 22 05,
ел. пошта yana.duhnenko@gmail.com, ORCID 0009-0007-8742-7718

МЕТОД ОЦІНЮВАННЯ ГІДРАВЛІЧНОГО ТА ЕРОЗІЙНОГО ЗАХИСТУ ВОДОПРОПУСКНИХ ТРУБ

Мета. Основною метою проведеного дослідження є наукове обґрунтування та розробка комплексного методу оцінювання гідравлічного стану та ерозійного захисту водопропускних труб у дорожньому будівництві. Робота спрямована на створення цілісного підходу, який би дозволяв враховувати складну взаємодію різних типів регулювання потоку – на вході та виході зі споруди – залежно від гідрологічних умов та геометричних параметрів об’єкта. **Методика.** Методологічна база дослідження ґрунтується на фундаментальних положеннях гідравліки відкритих потоків, зокрема на аналізі енергетичного рівняння Бернуллі та емпіричного рівняння Маннінга для встановлення залежностей між витратою води та морфометричними характеристиками русла. У ході роботи застосовано методи послідовних наближень (ітераційні процедури) для точного розрахунку нормальної та критичної глибин у трубах кругового та прямокутного перерізів, що дозволяє коректно класифікувати режим течії. Оцінювання ерозійних процесів базується на використанні сучасних емпіричних моделей, які пов’язують кінетичну енергію потоку (виражену через число Фруда) та відносний рівень води в нижньому б’єфі з необхідними параметрами захисного настилу. **Результати.** У результаті дослідження було систематизовано фізичні умови та критерії виникнення режимів регулювання потоку на вході та виході водопропускних труб, що дозволило сформувати адаптивний математичний апарат для розрахунку пропускної здатності споруд за різних сценаріїв наповнення. Було доведено, що традиційні методи проєктування часто недооцінюють швидкісний режим на виході, що призводить до виникнення надкритичних потоків, які потребують обов’язкового влаштування енергопоглинаючих захисних настилів. На основі проведених розрахунків представлено уточнений набір формул для обчислення необхідної довжини (L_a) кам’яного накиду. Крім того, розроблено класифікацію розмірів кам’яного матеріалу залежно від діаметра труби та гідравлічного напору, що дозволяє оптимізувати витрати матеріалів при забезпеченні надійності споруди. **Наукова новизна.** Наукова новизна отриманих результатів полягає в удосконаленні теоретичного підходу до оцінки гідравлічної ефективності водопропускних труб шляхом інтеграції безрозмірних функцій регулювання вхідного отвору з динамічними показниками нижнього б’єфа. Вперше запропоновано методику, яка одночасно враховує варіативність рівнів води за спорудою при розрахунку параметрів ерозійної стійкості, що дозволяє уникнути помилок при проектуванні захисту в умовах змінного підпору. Додатково обґрунтовано використання наближених експліцитних формул для швидкого визначення критичних параметрів потоку, що значно спрощує процедуру гідравлічного аналізу складних перехідних режимів без втрати точності, необхідної для інженерних розрахунків. **Практична значимість.** Розроблена методика дозволяє інженерам-проєктувальникам ще на стадії розробки документації точно прогнозувати ризики виникнення

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переливу води через дорожнє полотно та мінімізувати ймовірність аварійних ситуацій. Отримані дані щодо раціонального вибору класів кам’яного накиду для труб діаметром до 1,5 м дозволяють типово уніфікувати рішення з інженерного захисту територій, знизити експлуатаційні витрати на утримання водопропускних споруд та подовжити термін їхнього безремонтної служби.

Ключові слова: водопропускні труби; гідравлічний розрахунок; регулювання на вході; регулювання на виході; нормальна глибина; критична глибина; швидкість на виході; ерозійний захист; кам’яний накид

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