HYDROLOGIC-HYDRAULIC DIMENSIONING OF ROAD DRAINAGE SYSTEMS

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Апстракт
Traffic safety depends on many factors, but primarily on the quality of the designed and constructed roads, as well as their maintenance during the period of exploatation. In the phase of road design and, certainly, in the period of exploatation, one of the key elements of traffic safety is well designed and constructed roads in accordance with the applicable norms for road design. One of the stages of road design that has a major impact on the quality of roads and the degree of traffic safety is drainage.
Drainage includes several segments: (1) quick and smooth drainage of the pavement surface from atmospheric precipitation in order to ensure traffic on dry roads, (2) drainage of surface waters from the surrounding basin areas that gravitate towards the carriageway in order to prevent flooding and/or damage to the roads under the influence of surface waters; and (3) drainage of underground waters from the road foundation zone in order to prevent unwanted damage to the carriageway under the influence of underground waters. These drainage systems, their proper design and dimensioning according to hydrological-hydraulic calculations as well as their maintenance in the exploitation stage are the subject of this paper.

Key words
hydrological-hydraulic dimensioning, drainage, safety, roads.

1. INTRODUCTION

An extremely important segment of modern life and development of each country is the infrastructure connectivity, which among other things, implies construction of modern and safe highways at a number of levels - local, regional, national, highway. No less important is the segment of maintenance and upgrading of existing traffic structures.

With climate change becoming more pronounced, we are witnessing more frequent extreme events in the form of intense rainfall and extremely dry periods. These phenomena result in frequent floods causing damage to settlements and beyond. As a result, there are frequent problems and damages in all sectors of modern living.

The problems that arise in the case of traffic lines range from minor ones that endanger the safety of traffic due to precipitation that leads to wet roads aggravating the traffic conditions to extreme ones caused by occurrence of floods inflicting catastrophic material damage to the carriageways, endangering the safety of road users and culminating in loss of human lives.

In recent years, we have witnessed catastrophic floods in Macedonia which unfortunately caused greater material damage and a greater number of human casualties. There are many cases that can be mentioned, but presented here are just a few examples.

On August 3, 2015, a catastrophic flood hit the north western region of Macedonia - Polog, killing six people and causing damage to the municipal infrastructure and houses in the town of Tetovo and the villages in the surrounding mountainous areas. The total damage due to these floods was estimated at 21.5 million euros [1], Figure 1.

In June 2019, the traffic in the urban area of Gostivar was interrupted by the flood caused by intensive rainfall, Figure 2.

The flood that occurred at the Skopje bypass during the night of 6 and 7 August 2016 caused material damage to the road infrastructure, surrounding villages and agricultural land estimated at around 30m euros and 23 human casualties. [2], Figure 3.

Fig.1: Disruption of traffic to Jagunovce village due to the flood in Polog, 2015

Fig. 2:Traffic disruption in Gostivar, June 2019

Fig. 3:Flooding of the Skopje bypass, 2016

In these examples of floods that caused major material damage, in addition to natural factors that were crucial for the occurrence of the floods, it can be concluded that drainage systems were of low and insufficient capacity, completely inadequately designed or completely non-existent.
All this shows that drainage of roads is an extremely important segment of road design.

2. NEED FOR DRAINAGE SYSTEM AND ITS IMPORTANCE

The continuous presence of water on road surfaces and subsurfaces weakens the carriageways, resulting in damages in the form of asphalt deformations, folding, cracks and holes. The presence of water in the subsurface layer reduces the bearing and load capacity of the carriageways. The lack of a drainage system or an inadequate drainage system is the main cause of damage to road surfaces. Hence, an efficient water drainage by means of an adequate drainage system is an imperative.
The importance of road drainage systems was well known by the ancient road builders such as the Romans and the Aryans, while the pioneers of the modern era such as MacAdam, Telford and Tresaguet considered a good drainage system to be a prerequisite for successfully designed roads and an element affecting the length of their serviceability period.

There are generally three main goals of road drainage:
a) Rapid removal of surface water to ensure traffic safety;
b) Providing an efficient sub-surface drainage to increase the duration of the road; and,
c) Appropriate treatment of the water from the carriageway before it is discharged to the nearest recipient in order to minimize its negative impact on the environment. [3]

3. TYPES OF DRAINAGE SYSTEMS

Road drainage can be divided into several segments:
(1) Pavement drainage - achieved by appropriate longitudinal and transverse pavement slopes and facilities for receiving this water (for roads in settlements - appropriate storm sewers that will seamlessly accept this water and transport it safely to the nearest recipient, while for all other roads - an appropriate system of gutters, slope canals and culverts),
(2) drainage of surface waters from the surrounding watersheds that gravitate to the pavement - achieved by safe intake of atmospheric waters gravitating to the carriageways, preventing thus damage to pavements and road foundations, and regulation of existing watercurses (streams, rivers etc.) overpassed by roads (system of ducts, open canals, culverts, bridges), and
(3) groundwater drainage - achieved by dimensioning appropriate drainage systems to intake the groundwater from the road foundation.

4. DESIGN OF DRAINAGE SYSTEMS

Проектирањето на системите за одводнување се состојат од два дела: Хидролошка анализа и Хидрауличка анализа The design of drainage systems consists of two parts: hydrological analysis and hydraulic analysis.

4.1 HYDROLOGICAL ANALYSIS

Hydrological analysis consists of determining the referent quantities of drainage water to be used as the basis for hydraulic dimensioning. The same can be done on the basis of measured precipitation data and/or measured discharge data, if a constant water flow is analyzed.
The quantities of waters drained from the road surface for catchment areas of less than 10 km2 are calculated according to the known Rational Formula [4]:

$$Q_p=0,278 \cdot C \cdot i \cdot A \quad [1]$$

where: (Q) [m3 / s] is the discharge, (C) is the nodimensional discharge coefficient depending on the watershed characteristics, (i) [mm] is the intensity of total precipitation, (A) [km2] is the watershed area.

The discharge coefficient (C) has the value of 0.05 for flat sand substrates with a slope of up to 2% and up to 0.95 for asphalt surfaces. This coefficient has a variable value and depends on the percentage of presence of asphalt, urban areas, residential areas, green areas, etc. in the catchment area as well as the type of substrate/soil and the slope of the catchment area.

If the watershed consists of a combination of different types of surfaces, soils and slopes, the discharge coefficient is determined for each surface taken separately, while the total coefficient for the whole watershed is determined by the following formula:

$$C = \frac{\sum C_i \cdot A_i}{A} \quad [2]$$

where:(Ai) are areas with appropriate coefficient (Ci), (A) is the total area of the basin.

For the intensity of precipitation, it is recommended to use values of rain that falls uniformly, in time and space, over the entire basin area, with a duration equal to the basin concentration time.The basin concentration time (Tc) is herein defined as the time it takes for the surface runoff to cross the road from the hydraulically most distant point in the basin to the profile considered. This concentration time represents the sum of the surface runoff time (Tc *) and the flow time in the river bed and the tributaries (Tc **), if any. Time (Tc *) depends on the slope of the watershed, its surface roughness, infiltration characteristics, surface depressions, rainfall intensity and other factors and it is usually defined by use of some empirical expressions as is the equation of Kirpich:

$$T_c^* = 0,0195 \cdot L^{0,77} S^{-0,382} \quad [3]$$

where time (Tc *) is in (min), (S) is the slope of the catchment area in (m / m), a (L) is the longest line of the surface runoff in (m).

For catchment areas larger than 10 km2, the synthetic hydrogram method (SCS method) is applied.

For dimensioning of structures on permanent watercourses (bridges), the competent waters for dimensioning are recommended to be defined by use of statistical methods for definition of flood waters with different return periods based on measured flow data [4].

According to IRC: SP: 42-1994: (Guidelines on Road Drainage) and IRC: SP: 50-1999: (Guidelines on Urban Drainage) the dimensioning of structures within surface water drainage systems (gutters, channels, slope canals and alike) is done for a referent rainfall with a return period of 1 to 2 years.

According to the DPWH Design Guideline (Page 697), for dimensioning of bridges, the recommended return period of referent waters is 50 years. For box culvers and pipe culverts, it is recommended to be 25 years and 10 years, respectively. For channels, gutters and slope canals, the return period is recommended to be 1 to 2 years.

According to JUS U.C4.020-1982, the choice of a return period depends on the location and type of road as well as local conditions (risk, magnitude and frequency of floods and their consequences). For highways, this return period is recommended to be 10 years, while a 5 year return period is recommended for regional, national and local roads. To dimension culvers and bridges as an integral part of the road drainage system, it is recommended that this return period is 100 years for all road categories.

4.2 HYDRAULIC ANALYSIS

For dimensioning side gutters, slope canals and channels that accept surface waters from the pavement and the catchment area that gravitates toward the pavement, the Q-AV continuity equation is used for open channels under stationary flow conditions. The velocity of the water flow in the channel is determined by the known Chezzy equation::

$$V = \frac{1}{n} R^{1/6} \sqrt{R I_f} \quad \text{(m/s)} \ [4]$$

where: (n) is the coefficient of roughness, which depends on the material of which the channel, the slope canal or the gutter is made, its most common values being 0.012 to 0.02, (R = A / O) is the hydraulic radius calculated as the ratio between the flow surface

-A (m2) and the wet perimeter of the channel O (m), and (Sf) is the slope of the energy line which, in conditions of a stationary steady flow, equals the slope of the channel bottom (Sf=So).The water velocity ranges from 0.3 to 6 (m / s).

The flow in this drainage system should be subcritical, i.e., a calm flow. This is confirmed by checking the Freud number, critical depth, or critical flow slope in open channels (Fr <1, yk <yo, Sk> So). If this condition is not met, the slope of the bottom or the material from which the channel is made is corrected by selecting the coefficient of roughness.

Drainage water from these channels is discharged to the nearest recipient through an open channel system or discharged to the nearest culvert to allow water to flow from the other side of the road foundation. Prior to its release, appropriate measures should be taken in accordance with the recommendations for the protection of the environment in order to reduce the negative impact of this water on the flora and fauna.

A hydraulic analysis of the flow in the culvert zone (at the inlet, in and after the culvert), as well as in the zone of the bridge structures is performed in order to evaluate the effect of the facilities upon the free water surface in conditions of stationary uneven flow, i.e., whether they have the capacity to accept these waters and safely remove them without any adverse consequences.

Fig. 4.1: Pipe culverts

Fig. 4.2: Box culverts

Structures in the river bed (bridges, culverts, etc.) that deform the free water surface causing upstream elevation are recommended to be modeled in the hydraulic analysis by any of the known software, for example, HEC-RAS, River Analysis System, Steady Flow Water Surface Profilee, using the unidimensional concept. The basic energy equation used to determine the free water line is:

$$y_2 + z_2 + \frac{\alpha_2 V_2^2}{2g} = y_1 + z_1 + \frac{\alpha_1 V_1^2}{2g} + h_E \qquad [5]$$

where: (y1) and (y2) are the depths of two consecutive cross-sections, (z1) and (z2) are the elevation positions of the bottom of the cross-sections, (Σ1) and (Σ2) are the kinetic energy coefficients due to the uneven velocity distribution, (V1) and (V2) are mean velocities at the cross-sections, g = 9.81 ms-2 is the gravity acceleration and hE is the energy loss determined by the equation:

$$h_E = \overline{S_f}\, L + K \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \qquad [6]$$

where:( ) is the hydraulic gradient (median slope of energy), (L) is the distance between the cross- sections 1 and 2, and (K) is the coefficient of local loss. Indication (1) refers to the downstream section and (2) refers to the upstream section. The calculation is performed upside down. For a given flow Q = const., the initial intersection (1) is determined by all parameters: depth, velocity and hydraulic gradient, and the flow parameters in cross section (2) are calculated. For the modeled section, the initial cross-section is the profile located at the farthest point downstream the section where the boundary condition is defined by the slope (Sf = So) or the normal flow depth.

The following eguation is used to determine the losses in the culverts:

$$h_E = h_f + h_{vl} + h_{izl} \qquad [7]$$

where: (hf = L) is the loss of energy due to friction,

$$(h_{vl} = K_{vl}\left|\frac{\alpha_2 V_2^2}{2g}\right|)$$

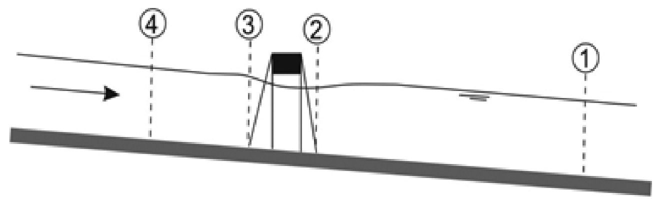
is the energy loss due to the inlet structure of the culvert, and (Kvl) is the loss coefficient of the inlet structure depending on the shape of the inlet structure, its values being within the limits of 0.2 to 0.7,

$$(h_{izl} = K_{izl}\left|\frac{\alpha_1 V_1^2}{2g}\right|)$$

is the loss of energy due to the outlet structure of the culvert, (Kizl) is the loss coefficient of the outlet of the culvert depending on the shape of the outlet structure, its values being in the range of 0.3 to 1.0.

To determine the hydraulic losses from the bridges, four cross-sections are analyzed, Figure 5. Cross-section (1) is downstream the bridge and is selected so that the structure/bridge has no influence on the flow in the river bed. Cross-sections (2) and (3) are located directly downstream and directly upstream of the bridge structure, while cross-section (4) is upstream the bridge profile where the current lines are almost parallel and without local influence of the bridge structur.

Fig.5: Location of the bridge cross-sections



The following simulations are possible with hydraulic analysis of bridges for different flows:

a) Free flow through the bridge openings (small and medium flows);

b) Submersion of the upstream cross-section and free flow in the downstream section;

c) Submersion of both bridge cross-sections upstream and downstream (passing of flood waters);

d) Overflowing of the bridge (passing of flood waters).

For case a), the basic energy equation (5) is applied, while for the cases under b) equation (8), c) equation (9) and d) equation (10), the following equation is applied:

$$Q = C_Q A\sqrt{2g}\left[y_3 - \frac{z}{2} + \frac{\alpha_3 V_3^2}{2g}\right]^{1/2} \qquad [8]$$

where: (CQ) is the flow coefficient (CQ = 0.27 ÷ 0.5), (A) is the flow cross-sectional area of the bridge openings in the upstream section, (y3) is the depth in the upstream cross-section of the bridge (3), and (z) is the vertical distance from the bridge substructure to the bottom of the river bed in the upstream cross-section of the bridge.

$$Q = CA\sqrt{2gH} \qquad [9]$$

where: (C) is the flow coefficient for the submerged flow (C = 0.8), (A) is the cross-sectional area of the bridge, and (H) is the pressure of the submerged flow (the difference between the energy line in the upstream cross-section of the bridge and the water level in the downstream cross-section of the bridge).

$$Q = B\sqrt{2g}H^{3/2} \qquad [10]$$

where: (C) is the overflow coefficient for a wide threshold overflow (C = 0.35 ÷ 0.386), (B) is the overflow width or the effective length of the bridge affected by the overflow, (H) is the overflow height or overflow pressure (difference between the energy line in the upstream cross-section and the bridge superstructure, i.e., the overflow edge).

5. CONCLUSIONS

Drainage systems, their proper design and dimensioning according to hydrological-hydraulic calculations as well as their maintenance during the exploitation phase are a key element of traffic safety. Well-designed roads with all their accompanying infrastructure facilities are an imperative for modern living. Road drainage systems represent systems consisting of gutters, slope canals, channels, drains, culverts, bridges and alike. Their task is to drain the pavement surface from atmospheric waters, lower groundwater levels and capture surface atmospheric waters from the surrounding catchment area that gravitates towards the road foundation. For the system to work, each part of it must be proportioned hydrologically and hydraulically, done according to project documentation and maintained in the phase of operation.

Hydrological analyzes are carried out to define the quantities of water that should be accepted by the drainage system. The choice of the return period of occurrence of flood waters to be used for dimensioning depends on the location and the type of road as well as the local conditions (risk, magnitude and frequency of floods and their consequences).

With the hydraulic calculation, each structure is dimensioned according to the recommendations, in order to allow the system to intake the water from the asphalt surface in the shortest possible time and have sufficient capacity to accept atmospheric waters and groundwaters and conduct them safely to the nearest recipient while respecting the environment in which they are released. In order to have a system that will function smoothly during the exploitation phase, it must be dimensioned to allow undisturbed operation with minimum interventions, that is, it must represent a system in which hydraulic parameters will prevent erosion processes or depositing of eroded material that may reduce its capacity, jeopardize traffic safety and finally disturb the stability of the road foundation or inflict damages

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