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DIMENSIONING OF LINEAR DRAINAGE SYSTEMS

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Abstract: On the basis of investigations carried out by the authors, connected with the verification of analytical methods for estimating linear drainage systems capacity ability, a procedure of dimensioning the individual elements of that system is given, including a grate, drainage flume, trash box and conduit carrying away water from system. The producers of some available drainage systems usually define conditions for their choice, but they are not always compatible with real conditions of their working. This concerns especially a hydraulic work of the separate elements mentioned above. The authors, based on their experience in the dimensioning of surface drainage systems, carried out a trial to systematize the work conditions of the devices of such a type and also computational procedure for determining the possibility of collecting a given discharge from precipitation waters, considering every component of system separately and also in their general configuration.

1. INTRODUCTION

Linear drainage systems are included in surface drainage systems, collecting precipitation waters from the most often paved parking places, yards of logistic centres, entries into road tunnels, pedestrian subways or locally from the entries into garages [1], [3]–[5]. These systems considerably improve a beauty of drained areas; however, to obtain this effect the components of system should be made in such a way that does not change an existing or adopted elevation configuration of drained surface [4]. On the other hand, a functional basis for all types of drainage systems is to give to drained areas both the longitudinal slopes and crosswise slopes. Hence, it is difficult to reconcile these two questions without functional loss of system, which is understood as capacity ability. A linear drainage system has the essential added advantage of uniformly collecting water from drained area. However, it suffers from one drawback, i.e. the necessity of frequent carrying away waters and draining them to a recipient, for example, to a storm-water drainage or more and more often used the retention–seepage systems.

2. SYSTEMS OF LINEAR DRAINAGE

The system of linear drainage consists of a few basic elements, i.e.: drainage flume, grate closing a flume from above and trash box with conduit which connects a trash box to water recipient in a certain area [4], [5]. The above elements of linear drainage system fulfil some essential functions, allowing an effective collection of the whole of rainfall waters from the drained surface. The efficiency of surface drained systems depends on their capacity ability determined properly; in the case of linear drainage systems – additionally on the correctness of assumed computational schemes, provided that an exact adaptation to the existing conditions is made. A forced water movement becomes also an important problem and, simultaneously, the possibilities of carrying out fine pollutants that can occur in rainfall waters. Because such systems usually work under free flow conditions, a longitudinal slope of a bottom of drainage flume becomes also important [3] (figure 1).

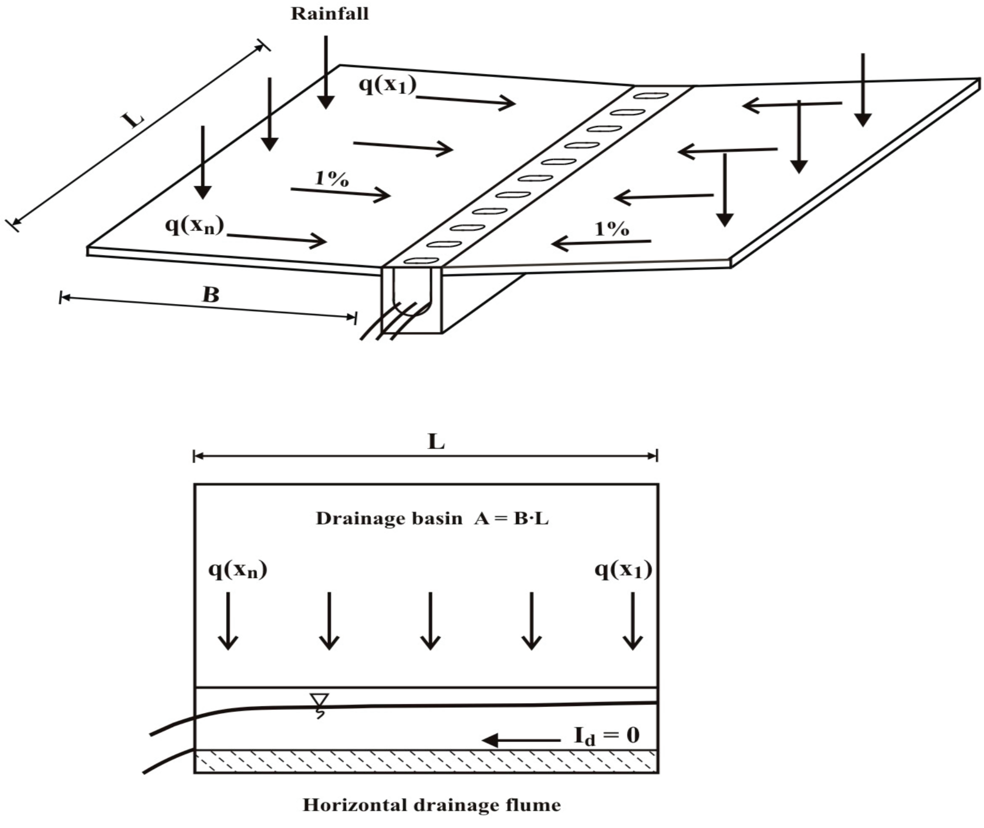

Fig. 1. Scheme of system of linear drainage

The task of the drainage flume of linear drainage system is to collect a whole outflow of rainfall from a drainage basin (figure 1), hence its dimensions and also a longitudinal slope of bottom line (figure 2) should guarantee appropriate capacity ability, which is important as regards removal of fine pollutants from flume cross-section. The dimensions of drainage flume should also force the water movement with assumed velocity, thus with the assumed capacity ability.

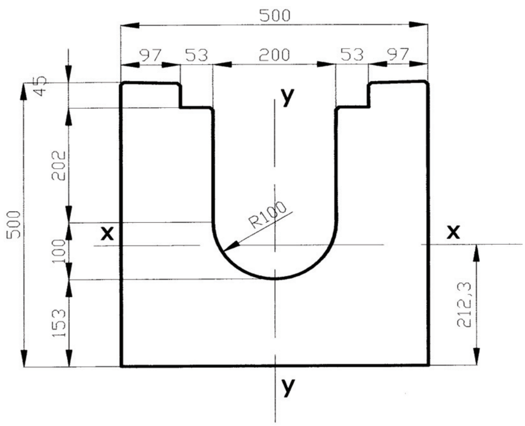

Fig. 2. Cross-section and dimensions of drainage flume

The grate closing a drainage flume from above is an entry for rainfall waters into a flume and simultaneously it effectively retains bigger impurities washed out from the drainage area. The impurities retained in this way do not influence the grate capacity ability. Therefore the cross-section of one grate gap plays an important role in respect of the gap length and width as well as the number of gaps per one running meter of drainage flume length. A general view of grate closing a drainage flume is shown in figure 3.

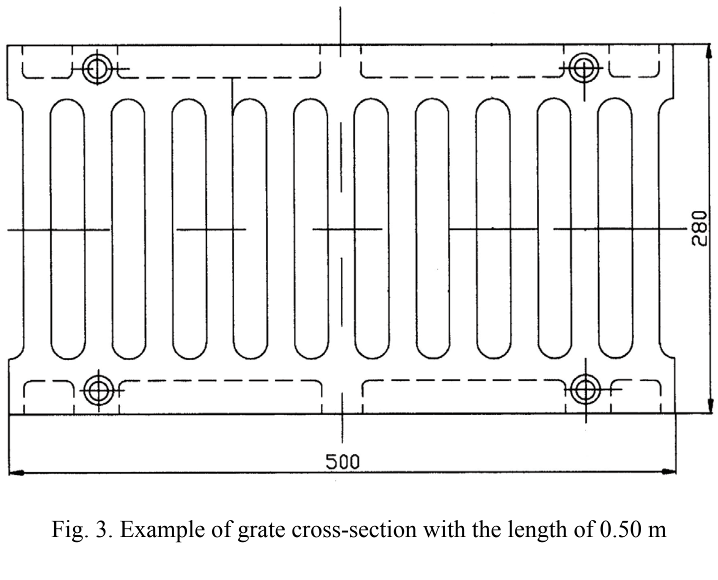

Fig. 3. Example of grate cross-section with the length of 0.50 m

The trash box (figure 4), mounted usually halfway across the drainage flume section, collects water from flume and carries it away to the nearest recipient by conduit with a properly chosen diameter and an appropriate longitudinal slope of bottom line. Therefore, in trash box computations it is important not only to select a hole diameter but also to determine its height in relation to water level at the outlet of drainage flume. Taking account of the above, the dimensions of trash box are chosen in such a way that outlet is placed at the depth making the water damming possible. The water is dammed up above the outlet to the height that would produce velocity which makes an effective water removal from the system possible.

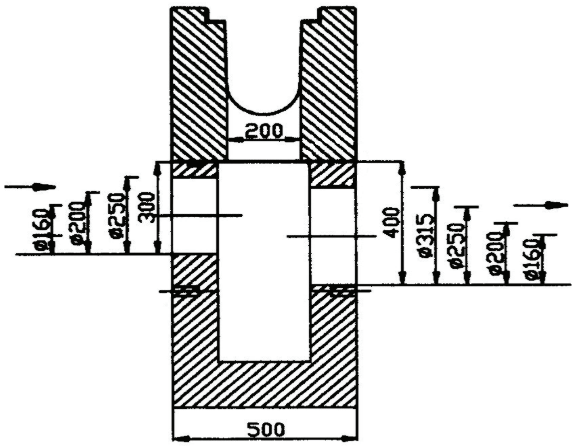

Fig. 4. An example of cross-section of trash box

In the case of linear drainage systems application, a rainfall water is usually collected by the nearest conduit of storm water drainage, and in the case of its lack – by even more frequently used retention–seepage systems that under convenient soil–water conditions allow the part of rainfall to be collected by the subsoil of the drained area [4], [5].

3. ANALYTICAL CALCULATIONS

3.1. HYDROLOGICAL COMPUTATIONS

The precipitations used for the computations necessary for designing linear systems for dewatering hard surfaces of car-parks, entries into road tunnels or pedestrian subways have a continuous character. These precipitations are brought by low stratus clouds. They are characterized by a comparatively long time and a small rain intensity. For the calculations of outflow from small catchments, the problem is simplified in such a way that time of rain duration is not calculated, we only assume the shortest admissible one equal to $t_d = 10 \div 15$ min [1].

The checking calculations are carried out to determine the quantity of a surface runoff of rainfall water flowing directly to linear drainage system connected to the nearest storm water drainage. Next, the capacity ability of this system, for an assumed altitude of its location, and the possibility of water reception by the system of storm water drainage were determined. Input assumptions for calculations were as follows:

- the area of drainage basins,
- the direction of surface runoff of rainfall waters,
- the location of the elements of linear drainage system, showing a main direction of runoff and rainfall water draining,
- appointing the recipient of the waters collected by the linear drainage system.

A computational precipitation is the rain, whose time of duration is equal to the time of runoff of single rain drop from the point which is furthest from a computational cross-section. Hence, a computational cross-section is a section of the outlet of linear drainage system to the recipient, i.e. a chamber of storm water drainage. The time of rain duration can change in a quite wide range; however it should not exceed the minimum time $t_d = 10 \div 15$ min. Hence, usually for small drained areas, the time of duration equal 10 min is assumed [1], [3]. A similar way is adopted for the computational example analyzed. Rain intensity should be calculated as follows:

$$q = \frac{A_q}{t_d^{2/3}}, \tag{1}$$

where:

q – the rain intensity, dm^3 s^{-1} ha,

A_q – the parameter which is the function of the occurrence frequency C and normal precipitation P_n (annual average based on many years),

t_d – the time of rain duration, min.

The outflow from linear drainage system is calculated from the following formula [1], [3]:

$$Q_o = F \times q \times \psi \times \varphi, \tag{2}$$

where:

Q_o – the outflow from drainage basin, dm^3 s^{-1},

F – the drainage basin area, ha,

q – the rain intensity, dm^3 s^{-1} ha,

ψ – the runoff coefficient,

φ – the coefficient of outflow time-lag.

In the further part of the paper, examples of calculations are shown, which were carried out for exactly determined catchment area as well as the kind of drained surface, according to the assumed water removal in the direction of the nearest storm water drainage system, or in the case of favourable soil–water conditions into retention–seepage system.

3.2. ESTIMATION OF HYDRAULIC EFFICIENCY OF LINEAR DRAINAGE SYSTEM

The systems of linear drainage have to fulfil a number of tasks, because only then is a certain system hydraulically efficient [1], [3]–[5]. These tasks are as follows:

- collecting all precipitation waters, flowing crosswise in relation to drainage flume with outlet to recipient,
- obtaining the highest possible hydraulic efficiency under certain conditions, as a result of the size of flow cross-section, its smoothness and longitudinal slope,
- developing the ability to create and maintain a self-purification velocity, which guarantees the removal of fine impurities washed out by precipitation waters from drained area and carried in the direction of drainage system,
- achieving the maximum possible hydraulic efficiency of a grate closing a drainage flume, which guarantees collection of entire flowing precipitation waters and fine impurities washed out from drained area without their retention on grate surface.

The aim of the hydraulic computations carried out (see the calculation example) was to determine the capacity ability of individual elements of linear drainage system, under precisely determined conditions of their building-in. These conditions are as follows: determining the grate inlet ability, capacity ability of drainage flume, inlet ability of trash box and capacity ability of conduit collecting precipitation waters from system. For this purpose, the hydraulics equations were applied, chosen depending on the working conditions of a certain device.

3.3. ANALYSIS OF GRATE INLET ABILITY

The analysis of grate inlet ability was carried out using the formula (3) given in [9] and based on a fixed precipitation water level that fills a space over the inlet edge of a grate:

$$Q_s = \alpha \times A \times \varphi \sqrt{2\, g\, h}\,, \tag{3}$$

where:

Q_s – the absorbability of single grate mesh over a flume, $m^3\ s^{-1}$,
α – the coefficient of side contraction,
A – the area of single grate mesh, m^2,
φ – the velocity coefficient,
h – the thickness of water layer over grate mesh, m.

The thickness of a water layer over the inlet edge of a grate affects most significantly the inlet ability of a grate, giving a resultant velocity of water outflow and in connection with the parameters of grate meshes – an expected capacity ability. Unfortunately, in the regions drained by linear drainage systems, the conditions of building-in drainage flume do not allow too great a depth *h*, hence it varies between 0.01 and 0.03 m.

3.4. CAPACITY ABILITY OF DRAINAGE FLUME

The analysis of the capacity ability of drainage flume was carried out for two cases of its building-in on the section that needs to be drained. The first case represents the flume with longitudinal slope of bottom, being independent of a suitable slope of whole flume or a required slope of flume inside. The second one is presented below as the computational situation for a bottom flume slope equal zero.

The analysis of the capacity ability of drainage flume in both cases is carried out applying a differential equation describing a lay-out of water level lines along a drainage flume, then a slope of water level line will impact water movement in a drainage flume. A differential equation could be derived in a way given below [2], [6], [8].

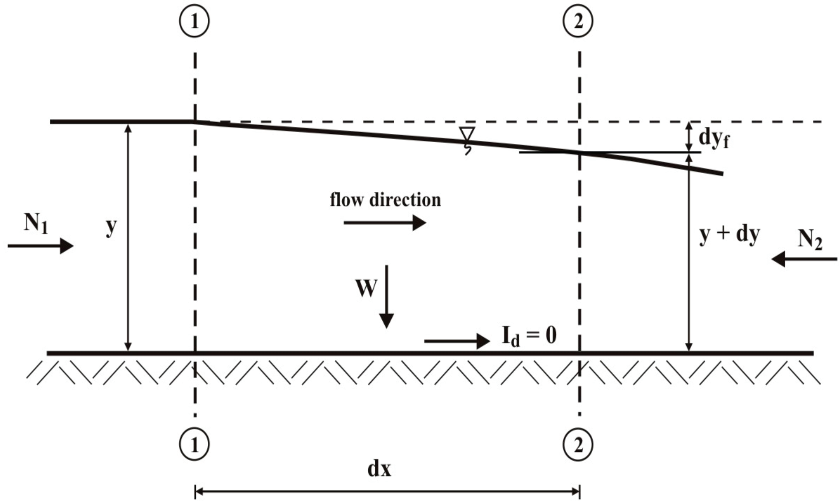

Fig. 5. Procedure scheme

Conditions of flowing precipitation waters to drainage flume cross-section lead to a specific motion in this flume. In professional literature, they are described as spatially variable [2], [6], [8]. This motion occurs when we deal with a lateral inflow q_L to the conduit, and a particular feature of that motion is a gradual rise of discharge in conduit, consistent with the flow direction. It should be emphasized that such a motion occurs in conduit independently of whether the slope of flume bottom is longitudinal or horizontal – as it often occurs for drainage flumes of linear drainage systems. The best solution for the problem described is the application of the principle of conservation of momentum based on the procedure scheme presented in figure 5 for the horizontal flume bottom.

A section of drainage flume is taken into account with the length dx between two cross-sections, the upstream one (1) and the downstream one (2). It is assumed that a flow velocity at upstream cross-section is equal to v and the discharge equals Q. In the downstream cross-section the velocity and discharge are equal, respectively, to $v + dv$ and $Q + dQ$, where dQ means an increase of discharge along the computational distance dx.

Because the slope of a drainage flume is equal to zero, that is why there is no impact of water weight component in the section dx being consistent with a flow direction. Simultaneously, between the upstream and downstream cross-sections, a loss occurs which results from the roughness of the material of drainage flume. In a general notation, that loss can be written in the following way:

$$h_f = S_f \, dx \,, \tag{4}$$

where S_f – the energy line decline, determined on a length dx, for instance, from modified Manning's formula [2], [6], [7], [9].

Friction force along the walls of drainage flume on a section length dx can be described as:

$$\gamma \, (A + 1/2 \; A) S_f \, dx \cong \gamma A S_f \, dx \,, \tag{5}$$

where:

A – upstream cross-sectional area of flow,
γ – water specific gravity,
S_f – energy line decline on a section length dx.

The hydrostatic forces N_1 and N_2 act at the upstream cross-section and at the downstream cross-section, respectively. The force N_1 can be calculated as follows:

$$N_1 = \gamma \bar{z} A \,, \tag{6}$$

where $\bar{z}$ is the position of the centre of gravity of the area A in relation to water level line in drainage flume.

The hydrostatic force N_2 acting at the downstream cross-section can be defined by:

$$N_2 = \gamma \, (\bar{z} + dy) \, A + \frac{\gamma}{2} dA \, dy = \gamma \, (\bar{z} + dy) \, A \,. \tag{7}$$

Hence, a resultant force acting on a water volume between the upstream and downstream cross-sections is equal to:

$$N_1 - N_2 = \gamma A d y \,. \tag{8}$$

Between the upstream and downstream cross-sections there is the change of momentum which can be written in the form [2], [6]:

$$[\rho\,(Q + dQ)\,(v + dv) - \rho Q v] = \rho\,[Q d v + (v + d v) dQ] \,. \tag{9}$$

In accordance with the principle of momentum conservation [2], [6], [8], [9], the momentum should be equal to the sum of external forces acting on a water volume contained between two cross-sections, i.e., a pressure and the resultant hydrostatic force and friction forces, hence:

$$\rho[Q\,dv + (v + dv)\,dQ] = -\gamma A d y - \gamma A S_f\, d x \,. \tag{10}$$

Substituting the differentials by the finite differences, equation (10) can be given by:

$$\frac{\gamma}{g}[Q\Delta v + (v + \Delta v)\Delta Q] = -\gamma \int_0^{\Delta y} A d y - \gamma S_f \int_0^{\Delta x} A d x = \gamma \overline{A}\Delta y + \gamma S_f \overline{A}\Delta x \,. \tag{11}$$

Because the flow rate in a drainage flume changes (increases) with its length, a mean area of flume cross-section can be defined:

$$\overline{A} = \frac{Q_1 + Q_2}{v_1 + v_2} \,. \tag{12}$$

Assuming simultaneously that $Q = Q_1$ and $v + \Delta v = v_2$, after some transformations equation (11) can be written in the form [2], [6], [8]:

$$\Delta y = -\frac{Q_1\,(v_1 + v_2)}{g\,(Q_1 + Q_2)}\left\{\Delta v + \frac{v_2}{Q_1}\,\Delta Q\right\} - S_f\,\Delta x \,. \tag{13}$$

The first term of equation (13) shows the change in a filling of a drainage flume cross-section, the second one – an energy loss as a result of friction force action. This equation was solved numerically in the example at the end of this paper.

Equation (13) for the case with a longitudinal slope of flume bottom equal to S_0 changes inconsiderably its form to [2], [6], [8]:

$$\Delta y = -\frac{Q_1\,(v_1 + v_2)}{g\,(Q_1 + Q_2)}\left\{\Delta v + \frac{v_2}{Q_1}\,\Delta Q\right\} - (S_o - S_f)\,\Delta x \,. \tag{14}$$

3.5. EVALUATION OF EFFICIENCY OF PRECIPITATION WATER RECEPTION SYSTEM

The efficiency of precipitation water reception system is assessed based on determining the possibility of collecting precipitation waters, flowing to the final segment of drainage system, i.e. trash box. Trash box is placed somewhat below a bottom line of drainage flume with a hole of the diameter required. The possibility of collecting precipitation waters is of a fundamental importance for the efficiency of entire surface drainage system of traffic structures, understood as a system that offers the possibility of collecting the whole of precipitation waters flowing from drainage area and allows their fast removal from the system.

The capacity ability of a hole cross-section on the side-wall of trash box (figure 4) can be determined applying the formula which requires a precise determination of the water height *H* at inlet, being measured with respect to the axis of outflow conduit [9] (figure 6).

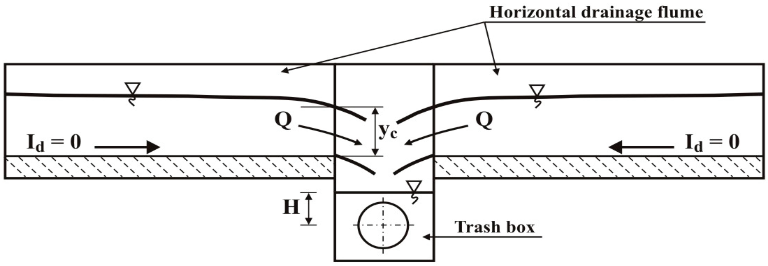

Fig. 6. Scheme for trash box calculation

Hence, the capacity ability of trash box is given by:

$$Q_z = \alpha \times A \times \varphi \sqrt{2\,g\,H}\,, \tag{15}$$

where:

Q_z – the capacity ability of a hole on the side-wall of trash box, $m^3\ s^{-1}$,
α – the coefficient of side contraction,
A – the area of a hole on side-wall, m^2,
φ – the velocity coefficient,
H – the thickness of water layer above an axis of outlet, necessary to create an entry velocity, m.

3.6. ANALYSIS OF WATER COLLECTION BY OUTFLOW CONDUIT TO SEWAGE SYSTEM

Calculations, checking the possibility of collecting precipitation water by outflow conduit, are carried out on the basis of nomogram designed for conduits with a circular cross-section and the walls with the assumed strict roughness. Such nomograms are designed according to the recommended in professional literature the Darcy–Weisbach and Colebrook–White formulas. Conditions of free surface work of this conduit are assumed, hence also a required longitudinal slope of conduit bottom [9].

3.7. COMPUTATIONAL EXAMPLE

The calculations of the capacity ability are carried out for a linear drainage system, collecting waters from rain and snowmelt from both sides of drainage area whose length L is 100 m, and width B is 40 m (figure 1). The drainage area is a hard surface covered with concrete plates whose slope towards draining devices equals 1.0%. To drain a given area, a drainage flume (figure 2) is used, with a bottom slope $I_d = 0$, with a trash box of size as in figure 4 installed in the middle of its length. A drainage flume is closed by a grate with the dimensions as in figure 3 and the following size of mesh: the width $b = 0.025$ m and the length $l = 0.20$ m.

Step 1. We determine the discharge Q_0 from the drainge basin, whose area is divided into two parts assigned to the length of drainage flume, hence $F = 50 \times 40 = 2000$ m^2 = 0.20 ha, adopting the runoff coefficient for impervious surface $\psi = 0.85$. For the calculations equations (2) and (1) are applied. Because for the areas (parking places, yards of logistic centres) drained by linear drainage systems the frequency occurrence C is usually one year, and for the regions with an average sum of precipitation $P_n < 800$ mm, we assume $A_q = 470$, hence:

$$q = \frac{470}{10^{2/3}} = 101.26 \text{ dm}^3 \text{ s}^{-1} \text{ ha},$$

$$Q_0 = F \times q \times \psi \times \varphi = 0.20 \cdot 101.26 \cdot 0.85 \cdot 1.0 = 17.21 \text{ dm}^3 \text{ s}^{-1}.$$

Because drainage basin is double-sided, water flows to drainage flume from both sides, hence a computational discharge along the flume length of 50 m equals 34.42 dm^3 s^{-1} (0.03442 m^3 s^{-1}).

Step 2. We determine the inlet ability of grate; a discharge of single grate mesh of the area $A = b \times l = 0.025 \times 0.20 = 0.005$ m^2 is taken into account. It is assumed that the height h of water-level over a grate is equal to 0.01 m, the velocity coefficient $\varphi = 0.75$ and the side-contraction coefficient $\alpha = 0.85$. Equation (3) is applied, hence:

$$Q_s = \alpha \times A \times \varphi \sqrt{2\, g\, h} = 0.85 \cdot 0.005 \cdot 0.75 \sqrt{2 \cdot 9.81 \cdot 0.01} = 0.00141 \text{ m}^3 \text{ s}^{-1}.$$

Because for one running metre of drainage flume length a grate has twenty gaps, a discharge of 1-m grate length equals:

$$0.00141 \cdot 20 = 0.0282 \text{ m}^3 \text{ s}^{-1}.$$

There is the possibility of some mesh choking [3], so the factor of safety equal to 2 is taken for calculations and a final grate discharge is given by:

$$0.0282 : 2 = 0.0141 \text{ m}^3 \text{ s}^{-1}.$$

Step 3. We calculate the capacity ability of drainage flume along the length $L/2$ = 50 m, using equation (15), in order to obtain a computer model designed by the authors. It was assumed simultaneously that along 1 running metre of drainage flume a discharge is equal $\Delta Q = 0.688$ dm^3 s^{-1}. In the calculations, the direction of procedure is important. For a supercritical flow in a flume this procedure should progress upstream; for a subcritical flow in a flume the calculation procedure should be reverse [6], [8], [9]. For drainage flume with longitudinal slope of bottom equal zero the calculation procedure should progress upstream.

In every case however, an initial depth is important for the properly carried out calculations. For a given example under supercritical flow conditions, it is the depth that results from free fall of water in a joint cross-section of flume with trash box (figure 6). In that cross-section, and for the computational assumptions made it is a critical depth y_c, which can be calculated from critical flow condition [6], [9]:

$$\frac{A^3}{B} = \frac{\alpha Q^2}{g}, \tag{16}$$

where:

A – the cross-sectional area of flow, m^2,
B – the width measured at a height of water level, m,
α – the Saint-Venant coefficient,
Q – the computational discharge, m^3 s^{-1},
g – the acceleration of gravity, m s^{-2}.

For drainage flume parameters shown in figure 2, when the discharge Q_0 = 0.03442 m^3 s^{-1} reaches the outlet cross-section, the critical depth y_c determined from equation (16) equals 0.173 m.

Table

Hydraulic characteristics of drainage flume with bottom longitudinal slope $I_d = 0$

Flume length Δx (m)	Depth y (m)	Cross-sectional area of flow A (m^2)	Sum of discharge $q(x)$ (m^3 s^{-1})	Flow velocity v (m s^{-1})	Energy line slope S_f	Δy (m)
1	2	3	4	5	6	7
0	0.173	0.0303	0.0344	1.136	0.006982	0.02914
5	0.240	0.0437	0.0310	0.709	0.002347	0.00574
10	0.264	0.0485	0.0275	0.568	0.001453	0.00339
15	0.279	0.0515	0.0241	0.468	0.000968	0.00235
20	0.289	0.0535	0.0207	0.386	0.000651	0.00172
25	0.296	0.0549	0.0172	0.313	0.000426	0.00123
30	0.301	0.0559	0.0138	0.246	0.000262	0.00087
35	0.306	0.0569	0.0103	0.181	0.000141	0.00057
40	0.311	0.0579	0.0069	0.119	0.000060	0.00033
45	0.316	0.0589	0.0034	0.058	0.000015	0.00014
50	0.321	0.0599	0.0000	0.000	0.000000	0.00001

The results of calculations for discharge passage through drainage flume are given in the table and shown in figure 7.

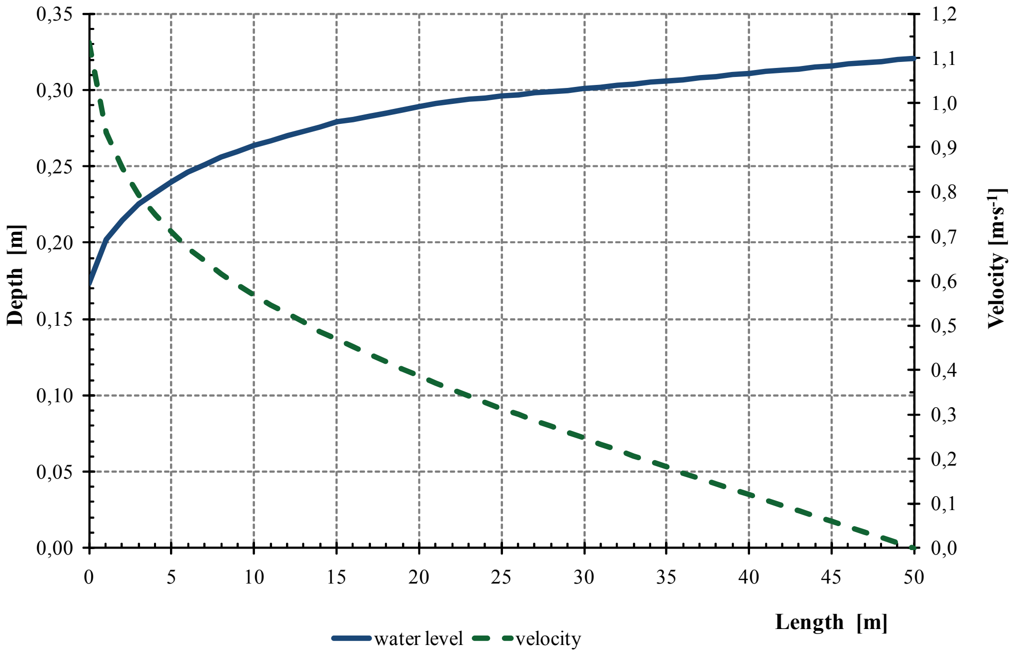

Fig. 7. Hydraulic characteristics of drainage flume with bottom longitudinal slope $I_d = 0$

Step 4. We assess the possibility of collecting precipitation waters from drainage flume by trash box. The aim of calculation is to determine hole diameter adjusted to a water height over its axis. We apply equation (15) in which H is replaced with a given height of water layer at trash box cross-section, measured in relation to outlet axis, hence assuming initially an outlet diameter $D = 0.30$ m, a discharge is equal to:

$$Q_z = \alpha \times A \times \varphi \sqrt{2\,g\,H} = 0.90 \cdot 0.0707 \cdot 0.85 \sqrt{2 \cdot 9.81 \cdot 0.20} = 0.1071\,\mathrm{m^3\,s^{-1}}.$$

Because an inflow to an outlet equals $2 \cdot Q_0 = 34.42 \cdot 2 = 68.84$ dm^3 s^{-1}, hence for an advisable water damming up over an axis of conduit with diameter DN 0.300 m there is the possibility of free carrying away computational waters from the system.

Step 5. We determine the cross-section and the longitudinal slope of conduit collecting the precipitation waters from trash box and draining them to the nearest well of storm water drainage. The ability to collect precipitation waters was determined assuming a conduit diameter DN 0.300 m and a longitudinal slope of conduit bottom $I_d = 2.6‰$; for such assumptions the discharge $Q_z = 0.06884$ m^3 s^{-1} (68.84 dm^3 s^{-1}).

4. SUMMARY

The producers of linear drainage systems rarely define their capacity ability which results in defective working, particularly concerning a grate and also a drainage flume. The authors define every component of the system from the point of view of hydraulic conditions of their operation. It has an important impact on their ability to collect waters from precipitation and snowmelt flowing from the drainage area, included in a drainage project. This is reflected in the beauty of the drained areas and in the safety of vehicles and pedestrians using these areas. In every computational case, it is necessary to confirm by calculations the possibility of collecting precipitation waters by system, in which the rules of its dimensioning given in the paper are helpful.

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