A COMPARATIVE ANALYSIS OF ALTERNATIVE METHODS OF HYDRAULIC CALCULATIONS OF PLASTIC SEWER PIPELINES

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The design of external sewer network pipelines cannot be assessed without a sound understanding of the hydraulic calculation for the pipeline network. The purpose of the calculation is to determine the inner diameter of the pipelines that will provide a required flow capacity, and guarantee the required hydraulic parameters for wastewater flow, at both pressure and non-pressure operating modes.

The Russian method for the design of gravity pipelines uses Lukinyh tables to help determine pipe sizes to provide optimal hydraulic characteristics. These tables are calculated using the formula of Academic N.N. Pavlovskiy for Chézy coefficient determination suggested in 1925 [3]:

$$C = \frac{1}{n} R^{y}$$

where

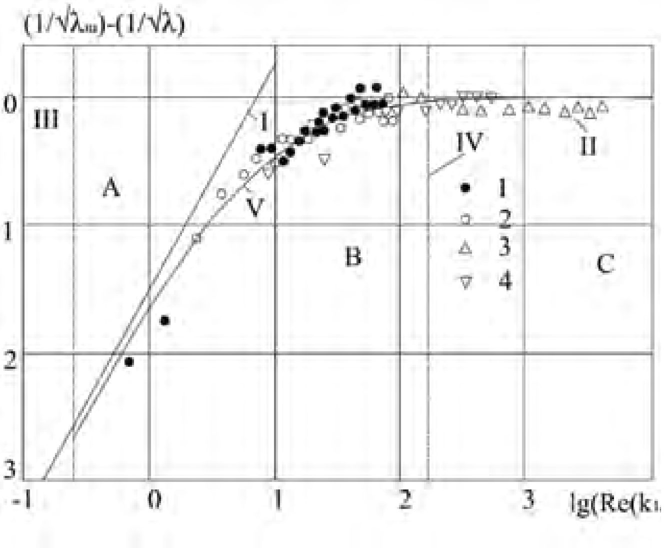
$$y = 2{,}5\sqrt{n} - 0{,}13 - 0{,}75\sqrt{R}\left(\sqrt{n} - 0{,}1\right),$$

where

R – hydraulic radius, m;

n – dimensionless roughness coefficient characterising the inner surface of the pipeline wall, specific only to the Pavlovskiy formula.

It is a precise and effective formula, supported by the practice of domestic hydrotechnical construction. It should be noted that this formula is true for the area of quite rough friction, or otherwise, in quadratic realm of hydraulic resistances [2]. Research data obtained as a result of hydraulic experiments in the laboratory of the Moscow Institute of Civil Construction Engineers (presently NIU MGSU), show that the main area of service pipeline operation is the mixed friction zone, where head loss value (and other hydraulic indicators) depends on both roughness of the inner surface of the pipe wall and the water viscosity [1]. Based on the results of Murin, Friman (pic. 1) and NII VODGEO, we can assume that implication of relationships describing head loss without water viscosity consideration is true in case of calculations for old and cast iron pipelines (i.e. pipes with high inner wall roughness value) [1]. The operational conditions of new steel, brass, glass pipes (i.e. pipes with extremely low roughness) refer to the mix friction zone [1].



Pic. 1. Experimental data and analytically obtained dependence of hydraulic friction coefficient from the Reynolds number.

A – area of hydraulically smooth pipes, B – mixed friction area, C – area of rough friction; I – the line of hydraulically smooth pipes, II – the line of rough pipes, III – the border of hydraulically smooth pipes area, IV – the borders of rough pipes area, V – analytically obtained dependency.

Points description: 1 – Murin's experiments on new steel pipes, d = 74 mm, 2 – same at d = 105.1 mm, 3 – Friman's experiments on old steel pipes d = 100 mm, 4 – same at d = 50 mm.

The design of sewer and water networks made of pipes with knowingly rough surfaces is carried out using formulas not considering head loss as a result of liquid viscosity. Therefore, the use of Lukihyh tables can be considered as correct for cast iron, concrete and asbestos cement pipes. However, the simple implementation of this calculation method for pipes made of plastic materials is not allowed given the extremely low roughness of the inner pipe surface, which remains consistently smooth during operation. Pipes made of plastic materials will operate in mixed friction zones. This is confirmed by the results of the experiments described above, as well as from the perspective of analytical dependencies used for polymer pipelines.

Then, Reynolds number, that corresponds the quadratic realm with hydraulic resistances of liquid turbulent flow, can be determined using the following formula [1]:

$$Re_{\text{кв}} = \frac{500 \cdot 4R}{K_{\text{э}}}$$

where actual Reynolds number:

$$Re_{\text{ф}} = \frac{V \cdot 4R}{\nu}$$

where:

$K_{\text{э}}$ – equivalent roughness coefficient; we use 0,0136 mm (this value is obtained based on the series of experiments on the PE100 pipeline, outer diameter 110 mm on the special hydraulic stand in the lab of Vodosnabzhenie, NIU MGSU [4]);

V – average water flow velocity, m/s;

R – hydraulic radius, m;

ν – kinematic water viscosity coefficient , m^2/s.

Considering the ratio of $Re_{\text{кв}}$ to $Re_{\text{ф}}$ and specifying such conditions of the pipeline operation where quadratic realm of hydraulic resistances will appear with significant probability.

Then we get:

$$\frac{Re_{\text{кв}}}{Re_{\text{ф}}} = \frac{500 \cdot \nu}{K_{\text{э}} \cdot V}$$

where:

V = 10 m/s – maximal velocity in storm water sewer made of plastic pipes (for domestic sewage systems V = 8 m/s) [6];

ν = 0,475 · 10^{-6} m^2/s – kinematic water viscosity at 60°C (as a maximum acceptable temperature for external pipe networks made of plastic pipes [7]). It should be noted that it is recommended for domestic sewage ν = 1,49 · 10^{-6} m^2/s [7].

Then we get:

$$\frac{Re_{\text{кв}}}{Re_{\text{ф}}} = \frac{500 \cdot \nu}{K_{\text{э}} \cdot V} = \frac{500 \cdot 0{,}475 \cdot 10^{-6}}{0{,}0000136 \cdot 10} = 1{,}75$$

Therefore: $\frac{Re_{\text{кв}}}{Re_{\text{ф}}} > 1$ or otherwise: $Re_{\text{кв}} > Re_{\text{ф}}$

The present inequality means that the actual operating mode of plastic pipelines (even in cases closest to the area of quite rough friction) will still be in the area of mixed friction. So we need to consider the influence of water viscosity on the hydraulic parameters of pipelines.

The German ATV-DVWK-A 110E standard (the source of extra information according to DIN EN 752, part 4, chapter 4, and, therefore part of the European standard) uses Kolbruk's formula [8] to determine the hydraulic resistance of a gravity disposal pipeline or channel:

$$\frac{1}{\sqrt{\lambda}} = -2 \cdot \lg\left[\frac{2{,}51}{Re \cdot \sqrt{\lambda}} + \frac{1}{3{,}71} \cdot \frac{k_{\text{э}}}{4R}\right]$$

where λ – hydraulic resistance coefficient of the gravity pipeline (channel) with hydraulic radius equaling R.

It is also noted that only this equation has a practical significance for calculation for pipelines and water disposal channels [8].

The flow capacity of the gravity channel is determined using the following formula [8]:

$$Q = A \cdot \left\{ -2 \cdot \lg\left[\frac{2{,}51 \cdot \nu}{4R \cdot \sqrt{2g \cdot 4R \cdot J_E}} + \frac{k_{\text{э}}}{14{,}84 \cdot R}\right] \cdot \sqrt{2g \cdot d \cdot J_E} \right\}$$

where:

A – flow section of disposal water, m^2;

J_E – energy gradient, determined as relation of head loss (energy) h_f, m, on the friction in the pipeline to its length l, m [8]:

$$J_E = \frac{h_f}{l}$$

Kolbruk's formula is considered reliable and based on experimental data, including water viscosity and possibilities of pipelines operation in mixed friction.

However, in A.D. Altshul's works (based on the experimental data of Powel, Warwick and other scientists), it notes that the resistance of gravity pipes and canals in most cases, is completely different from the resistance of round pressure pipes with the same Reynolds number and roughness of the inner pipe wall. Consequently, Altshul insists it is not possible to use the formulae normally recommended for round pressure pipes, for calculations of movement in gravity pipelines and canals [1]. Also, in support of inaccuracy of the calculations for gravity pipes and canals using formulae for pressure pipes, Altshul brings comparison of dependancies to determine Chézy coefficient, derived:

– from recalculations using Kolbruk's formula [1]:

$$C = 17{,}72 \cdot \lg \frac{R}{\varepsilon_1 + \frac{0{,}223 \cdot \nu}{\sqrt{gRi}}}$$

– using generalised formula for hydraulic calculations for open canals and non-pressure pipes, which would consider the influence of inner pipe wall (canal) roughness and liquid viscosity as well as turbulent flow in the pipe (canal) as a whole unit (without segregation for turbulent core and laminar sub-layer) [1]:

$$C = 20 \cdot \lg \frac{R}{\varepsilon + \frac{0{,}385 \cdot \nu}{\sqrt{gRi}}}$$

where ε and ε_1 – specific linear roughness, m. Where ε is linked with average height of roughness peaks k, and ε_1 is linked with the coefficient equal equigranular roughness $k_{\text{э}}$.

Altshul notes that both formulae have similar structures, but the formula derived from the recalculation of the formula for pressure pipes (Kolbruk's formula) has other values of constants which will lead to inaccuracies in calculations [1].

Therefore, it could be concluded that calculation according to the ATV-DVWK-A 110E standard for drainage water pipelines and canals will have insufficient accuracy due to its primary orientation of the formulae for pressure water flow in round pipes.

Dobromyslov's approach to determining the hydraulic parameters of gravity water drainage pipe differs from the above-mentioned methods. In his analysis of behaviour of steady set water flow in gravity drainage pipelines, Dobromyslov (based on the Pavlovskiy and Darcy-Weisbach formulae) obtains velocity distribution in a cross-section of non-pressure flow for all areas of turbulent water flow including areas of mixed friction

$$\left(\frac{V_{\text{н}}}{V_{\text{п}}}\right)^{b} = \left(\frac{R_{\text{н}}}{R_{\text{п}}}\right)^{1+a}$$

where:
$V_н$ and $V_п$ – water flow velocity at partial and complete filling of the pipeline;
$R_н$ and $R_п$ – hydraulic radius at partial and complete filling of the pipeline;
$\alpha = 0{,}3124\, K_э^{0{,}0516}$;
b – indicator of water flow condition (1 – laminar condition; from 1 to 2 – turbulent condition, area of mixed friction; >2 – turbulent condition, quadratic realm of resistance).
In case of full pipeline filling, based on extended analysis and experimental research, Dobromyslov suggests the following dependance for $b_п$ determination [2]:

$$b_{\text{п}} = 3 - \frac{\log Re_{\text{кв}}}{\log Re_{\text{ф}}}$$

It should be noted, that Dobromyslov in his approach suggests disregarding the variety of characteristics of the quality of the inner pipe wall (roughness coefficient), which for gravity pipelines have their own specific value and legend depending on the formula used. Further, he suggests taking a uniform coefficient of equigranular roughness $k_э$ with linear size (mm), which was regularly used in practice for hydraulic calculations for pressure pipes and comes with relevant and proven values for pipes made of different materials [2]. This coefficient obtained for pressure pipelines made of given material (e.g. PE 100) can be successfully used for hydraulic calculations of gravity pipelines made of the same material.

According to Dobromyslov, water flow velocity at full capacity, considering the possible operation of the pipeline in non-quadratic areas of resistance is determined based on the Darcy-Weisbach formula:

$$V^{b}{}_{\text{п}} = \frac{i \cdot 2g \cdot 4R_{\text{п}}}{\lambda_{\text{п}}}$$

and coefficient of hydraulic resistance $\lambda_п$ at full filling of the pipeline as

$$\lambda_{\text{п}} = 0{,}2\left(\frac{K_{\text{э}}}{4R_{\text{п}}}\right)^{\alpha}$$

Therefore, after obtaining water flow velocity in the full pipeline, as described by Dobromyslov's law of velocity distribution in the cross-section of non-pressure flow, water flow velocity in a gravity pipeline can be obtained at any filling (gravity pipeline flow capacity):

$$q_{н} = V_{н} \cdot \omega \,,$$

where ω – live cross-section of liquid flow at given filling of the pipeline, m^2

After calculating using the formulae based on the Dobromyslov method, the table of hydraulic characteristics for specific sizes of gravity pipeline built at a certain inclination can be calculated. Dobromyslov made up his tables for hydraulic calculations for non-pressure pipelines made of plastic materials, based on this method,

We do need to bear in mind that in his tables (for both gravity and pressure pipelines) Dobromyslov refers to the old classification of pipelines made of plastic materials. It is necessary to compare the inner diameter of the pipe in question with the inner pipe diameters in Dobromyslov's Hydraulic calculation tables, due to the modern trend for creating new pipe types made of plastic materials (e.g. plastic pipes with structured walls for external sewerage systems).

It should also be noted that pressure pipelines made of PE now have updated tables for hydraulic calculations based on the Dobromyslov method and written by O.Prodous, containing an SDR pipes classification. Unfortunately, there are no similar tables for gravity pipelines, although it would not be a problem for a skilled designer or engineer to create a simple programme for making a hydraulic table based on the Dobromyslov method for certain brands and types of gravity plastic pipelines.

Conclusions:

1. The most relevant and most frequently applied practices of hydraulic analysis of water disposal pipelines and hydraulic calculations of sewer pipes have been considered.
2. It has been proved experimentally and analytically that the tables for the Lukinyh hydraulic calculations for gravity pipelines, based on the Pavlovskiy formula for Chezy coefficient, cannot ensure exact data for hydraulic characteristics for non-pressure plastic pipelines due to the absence of the liquid viscosity influence on hydraulic parameters of pipeline operation in this formula.
3. It is proved that Kolbruk's formula for pressure pipelines (that makes the basis for hydraulic calculations in ATV-DVWK-A 110E Standard) insufficiently describes the hydraulic parameters of gravity pipelines and canals.
4. It is noted that Dobromyslov's method of hydraulic calculation for gravity pipelines (based on the velocity distribution in the cross-section) includes a well-studied and universal coefficient of equigranular roughness, which is able to precisely determine the hydraulic parameters of the non-pressure pipeline taking into consideration its operation in mixed friction areas.

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