Simulation of Hydraulic Characteristics for Pipelines Consisting of Different Materials and Diameters

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Abstract. This paper deals with aspects affecting problems of coming up with a unified method for assessing the hydraulic compatibility of recovered and non-recovered sections of existing pipeline networks subjected to various methods of trenchless repairs. These issues are closely related to the problem of preserving the transporting ability of the wastewater fluid in a non-pressure pipeline during its trenchless renovation with polymer pipes. Theoretical approaches are given to determine the hydraulic parameters in the pipeline system, taking into account the renovation site and sites adjacent to a segment in question located up and down waste liquid fluid. It is shown that the priority measure to maintain the required degree of self-purification of the recovered pipeline section, as well as adjacent areas, is the magnitude of the water flow rate, which allows to provide required transporting capacity of the pipeline system. A formula to determine the length of the velocity destabilization zone is proposed, and the results of calculations using the automated program developed by the authors are put on display where algorithm includes dependencies determining hydraulic pipeline materials friction coefficients on different parameters as well as diameters, pipeline expanses and their slopes. The essence of the calculations, the sequence of input of the initial information using an automated complex, the type of output table information is described. Comparison of the counting results under different design conditions has been carried out. As conclusions, practical recommendations are presented in the way of managerial decisions for the potential achievement of hydraulic balance in a pipeline system and the creation of conditions under which the destabilization zone at the site after repairs is minimized and the number of preventive cleanings of the pipeline network is also reduced to a minimum.

1. Introduction

At present, the methods of threading new pipes or hoses (stockings) mostly made from polymeric materials through non-pressure and pressure pipeline networks find greatest applications in trenchless reconstruction and modernization of such types of networks [1, 2]. In the construction markets, new composite materials appear that can meet strict requirements imposed first of all on the strength characteristics of restored engineering networks [3]. Wide use of trenchless technologies for renovation and construction of pipeline communications has many positive aspects, which are based primarily on achieving economic and environmental effects, as well as the efficiency of construction and installation works [4]. However, in case of trenchless repair, difficulties may arise related to the compatibility of the hydraulic characteristics of old and new sections of pipelines [5]. As practice shows, urban pipe networks after a considerable period of operation and repeated repairs constitute a system that actually
consists of “patches”, which are understood as separate sections of the pipeline network made of various materials. When designing repairs with trenchless methods of pulling new pipes into the old pipeline, it is necessary to do one’s best to achieve the conditions of hydraulic compatibility of these sections, i.e. maximally ensuring effective joint operation of old and reconstructed areas, creating conditions for the smooth passage of fluid [6].

When focusing on the use of trenchless technologies for the construction and reconstruction of pipeline transport using appropriate repairing materials (protective coatings), it is necessary to check restored and existing sections of pressure and gravity pipelines for hydraulic compatibility. The term “hydraulic compatibility” for ring water supply networks should be meant as project requirements to ensure and maintain, during the operation of pipelines, pressure losses in closed circuits, regardless of the repair material and diameter of used pipes. For non-pressure pipelines, “hydraulic compatibility” is interpreted as providing and maintaining certain values of flow rates of waste fluid from site to site in the direction of flow. Speaking about the hydraulic compatibility of non-pressure drainage networks, it is meant that regardless of the repairing material used (a separate pipe or protective coating on the section under repairs), the flow rate of the waste fluid throughout the whole pipeline should not decrease. It should remain steady or grow from site to site. Only if these conditions are met, it is possible to ensure the normal operation and operation of non-pressure networks, reducing the risk of local flooding that can occur if the flow rate is incorrect which can result in settlement of suspended substances (sand). These circumstances lead the system to a “hydraulic imbalance” (an antonym of hydraulic compatibility), which results in frequent cleaning of pipeline networks [7, 8].

Thus, to assess the situation in the water supply and drainage networks, it is necessary to be aware of the hydraulic characteristics of old and new repairing materials (cement-sand coatings, polymer protective coatings, new types of polymer pipes, etc.). This is especially relevant today, when there is a widespread application of new building materials to pipelines repairs, while there is no universal approach to determine the hydraulic performance of various types of coating, as well as common methods for assessing the hydraulic compatibility of restored and unrestored sections of existing pipeline networks. In some situations, the design practice is carried out, due to the lack of objective data over the hydraulic characteristics of protective materials, to be guided by methods of hydraulic calculations, strength and hydraulic indicators, that are represented by pipe manufacturers, which cannot be an objective argument in favor of the material used. With this regard, the role of independent expertise is increasing, allowing to unify the requirements and approaches to the definition of special indicators of materials and their adaptation to the material of existing pipeline.

Considering in detail the aspects of the transporting ability of waste liquid fluid, researchers are interested in identifying both absolute velocity values and analyzing the unevenness of admixtures transportation speeds on the surface, in the depth of the fluid and on the pipe section when moving sediment. Research results show that the more undissolved impurities are in water and the larger they are; the greater the resistance to movement will be experienced by the fluid [9]. As a result of the resistance encountered by the flow, solid particles move from layer to layer towards the tray. In trays with insufficient speed caused by the increasing mass of suspended particles, bottom sediments may form, hardening over time [10]. It should be noted that the empirical formulas to determine non-sedimentary velocity obtained by researchers in different years are mainly characteristic of sand transportation conditions [11].

2. Materials and methods. Theoretical substantiation of a hydraulic imbalance after repairs on the pipelines
As a material object a pipeline comprised of three sections is considered, the middle of which sections is made of polyethylene as a result of trenchless reconstruction work. The problem-solving method is based on the automated processing of various design options (simulations) unveiling their optimal variants.
A number of researchers have found that in the course of carrying out repairs on any part of the pipeline network by applying internal protective coatings with a smooth surface, the phenomenon of speed imbalance in subsequent sections is not excluded [12]. Getting from a repaired (new) section, which has, as a rule, less surface roughness to an old (unrestored) one with greater roughness, water begins to lose speed due to a different roughness and diameter, i.e. flow becomes equally slow at a certain distance along the length of the section. This site can be referred to as “speed destabilization zone”. Within this zone, as a result of a kind of braking, backwater can be observed and sediment can appear with the formation of sediment ridges. Over a period of time, sediment can go into a stage of dense, even difficult to wash off deposits. This is where the network imbalance is put on display [13]. If the designers do not provide appropriate countermeasures for a potential hydraulic imbalance, then the responsibility of organizations involved in the operation of the drainage network will sharply increase. In this case, the tasks set to the operation services will include the elimination of possible consequences, expressed in additional (preventive) cleanings of sections of the pipeline network. First of all, it will concern area following the restored one by removing in time dense permanent deposits accumulated in their bottom part.

Based on hands-on experience and theoretical developments to create a hydraulic model of a pipeline network, a formula is proposed to determine the length of destabilization zone of speeds $S$, m (1):

$$S = \frac{(V_0^2 - V_k^2)}{[\lambda \cdot \frac{V_0^2}{4R} - 2g \cdot i]}, \quad (1)$$

where $V_0, V_k$ are the speeds in cross sections in a new (restored) section and an old (unrestored) section, respectively, in the direction of the flow; $m / s$; $\lambda$ is a coefficient of hydraulic friction of the material of the unrestored area; $R$ is the hydraulic radius measured in meters; $i$ is the slope of the pipeline; $g$ is an acceleration of gravity, $m/s^2$;

The use of formula (1), which describes the dependence of the destabilization zone on the coefficients of hydraulic friction of pipelines, their slopes, hydraulic radius and flow rates, allowed to develop an algorithm and an automated program “Hydraulic compatibility” [14].

The whole complex of hydraulic calculations made by the automated program of the Shezi’s $C$ coefficient is performed using three alternative formulas describing the flow regimes of the non-pressure fluid through drainage pipes made of various materials:

- Pavlovskiy’s: $C = \frac{1}{n}R^{0.5} + 0.13 - 0.75 \cdot R^{0.5} \cdot (n^{0.5} - 0.1)$
- Alshoul’s: $C = 20 \cdot \lg \left[ \frac{R}{(\varepsilon + 0.004 \cdot (R \cdot i)^{0.5})} \right]$
- Manning’s: $C = 1/n \cdot R^{0.6}$

where $\varepsilon$ is the reduced linear roughness, mm, $n$ is the roughness coefficient.

The indicators used in the formulas (coefficients, criteria) are adapted to real pipeline materials and correspond to the recommendations of A. Dobromyslov on the hydraulic calculation of plastic pipes and reference data on the magnitude of the roughness of pipes of various materials [15].

The program provides the researcher with a wide range of possibilities, in particular, the designer is provided with one to analyze the situation on the network as a result of considering alternative solutions to replace (renovate) one of the pipeline sections and track the changes in hydraulic characteristics such as change of diameters, costs, slopes, etc. The ultimate goal of this study is to find an optimal design option, i.e. to determine conditions when the zone of destabilization of speeds $S$ becomes smallest or completely absent. In practice, this will mean a decrease in the number of flooding in certain sections of the pipeline, eliminating backwaters due to the formation of compacted sludge on the pipe tray.

The positive side of occurring phenomena modeling that captures the dynamics of changes in hydraulic and geometrical indicators is that a specialist can make a comprehensive assessment of the situation and choose the most appropriate option in order to design repairs and restoration and other works in the studied area [16-18].
3. Object of research
As mentioned above, research object was a segment of the pipeline system, including three sections, the middle of which was renovated by pulling into it and fixing a thin-walled polymer pipe narrowing the inner diameter. The process of modelling the situation with searching an acceptable option (minimum speed imbalance zone) was to obtain design information for the entire complex of hydraulic and geometrical fluid characteristics by means of sorting over a certain range of water spending and possible changes of other parameters. Thus, as a result of operation of the automated complex, the managerial tasks of optimizing repairs and rehabilitation works in terms of following up hydraulic characteristics of a fragment of the pipeline system consisting of three sections were fully shown

Figure 1 shows in a simplified form the object of research, where the first and third sections are ceramic pipes, and the second one is a polyethylene pipe of smaller diameter, and figure 2 presents dialog boxes of an automated program with input information buttons and its output in tabular form. Specific data on the hydraulic and geometric characteristics of the object of modeling for individual sections are presented in table 1 (p. 4).

![Figure 1. Fragment of a pipeline system with a speed destabilization zone S](image)

1, 2, 3 - respectively ceramic, polyethylene and ceramic sections of the pipeline.

![Figure 2. Automated Program Dialog Box](image)

Program user work consists of the sequential execution of the following operations:
- data input and determining the length of the velocity destabilization zone in the last (third) section;
- analysis of forecast data on options with the adjustment of the initial parameters to ensure the conditions of hydraulic compatibility of old and new sections of the pipeline and a description of alternative measures to eliminate hydraulic imbalance phenomena (if available);
- justification of the most preferred option of repair and restoration works from ones proposed for consideration.

The program allows to print out both intermediate and final tables with information on hydraulic calculations of the drainage network and detection of the presence (absence) of hydraulic compatibility in adjacent sections of the drainage network (one under repairs and the next one).

4. Results and discussions (interpretation of results)
Baseline data and simulation results with numerical values of hydraulic and geometrical parameters and their analysis for the variant of trenchless repair of a pipeline section by pulling a polymer pipe are presented below. Specific baseline information is presented in table 1.

| Pipeline Feature                | Section 1 (the old one) | Section 2 (under repairs) | Section 3 (the old one) |
|--------------------------------|-------------------------|---------------------------|-------------------------|
| Material:                      | ceramics                | polyethylene              | ceramics                |
| Internal diameters, mm:        | 300                     | 290                       | 300                     |
| Slopes:                        | 0.0035                  | 0.0035                    | 0.0035                  |
| Costs, 1/s (fixed in cycle):   | 22.4; 26.9; 31.5; 36.1; 40.7; 45.0; 50.0 | 22.4; 26.9; 31.5; 36.1; 40.7; 45.0; 50.0 | 22.4; 26.9; 31.5; 36.1; 40.7; 45.0; 50.0 |
| Coefficients:                  |                         |                           |                         |
| - reduced roughness:           | 0.2                     | 0.02                      | 0.2                     |
| - roughness:                   | 0.0134                  | 0.0095                    | 0.0134                  |
| - degrees of convergence of speeds: | 0.01                      | 0.01                      | 0.01                     |
| - equivalent roughness:        |                         | 0.011                     |                         |
| Empirical parameter:           | -                       | 0.258                     | -                       |

The final task of the simulation was to identify the dynamics of changes in the destabilization zone of $S$ velocities at various flow rates, fixed fillings and slopes close to the basic one by using basic mathematical dependencies on the definition of the Shezi’s $C$ coefficient (N. Manning’s, A. Altshul’s and N. Pavlovsky’s formula), etc.

Selected results of the automated calculation for the second and third sections are presented in a printout (table 2).
**Table 2.** Final results of destabilization area length calculation

| Formula to determine Shezi’s coefficient | Section 2 (polyethylene pipe) | Section 3 (ceramic pipe) |
|------------------------------------------|--------------------------------|--------------------------|
|                                          | Slope Consumption, l/s  | Speed, m/s            | Slope Consumption, l/s  | Speed, m/s | Destabilization area length, S, m |
| Pavlovsky’s                              | 0.0035                | 22.4                   | 1.049 | 0.0035                | 22.4 | 0.755 | 8.18 |
| Manning’s                                | 0.0035                | 22.4                   | 0.944 | 0.0035                | 22.4 | 0.743 | 8.25 |
| Altshul’s                                | 0.0035                | 22.4                   | 0.963 | 0.0035                | 22.4 | 0.773 | 8.91 |
| Pavlovsky’s                              | 0.0035                | 36.1                   | 1.184 | 0.0035                | 36.1 | 0.849 | 10.67 |
| Manning’s                                | 0.0035                | 36.1                   | 1.07  | 0.0035                | 36.1 | 0.836 | 10.37 |
| Altshul’s                                | 0.0035                | 36.1                   | 1.089 | 0.0035                | 36.1 | 0.872 | 11.35 |
| Pavlovsky’s                              | 0.0035                | 45.0                   | 1.246 | 0.0035                | 45.0 | 0.889 | 11.98 |
| Manning’s                                | 0.0035                | 45.0                   | 1.126 | 0.0035                | 45.0 | 0.874 | 10.82 |
| Altshul’s                                | 0.0035                | 45.0                   | 1.146 | 0.0035                | 45.0 | 0.914 | 11.72 |
| Pavlovsky’s                              | 0.0035                | 50.0                   | 1.276 | 0.0035                | 50.0 | 0.904 | 12.10 |
| Manning’s                                | 0.0035                | 50.0                   | 1.155 | 0.0035                | 50.0 | 0.889 | 11.77 |
| Altshul’s                                | 0.0035                | 50.0                   | 1.173 | 0.0035                | 50.0 | 0.931 | 12.87 |

Analysis of the data listed in the table 2 shows the following:
- there is a persistent tendency to increase the length of speed destabilization zones, for example, using the Pavlovsky’s formula, ranging from 8.18 to 12.10 m/s;
- the results of the calculation of the lengths of the destabilization zone using the three formulas to determine the Chezi C coefficient are comparable: the difference does not exceed 3%, which indicates the possibility of a potential interchange of formulas in engineering calculations;

Thus, the obtained results are evidence of useful application in design when deciding on parameters of the restored pipeline system. If we transfer obtained results to the objects of trenchless renovation, where the diameter in section 2 will be obviously less than other neighboring ones, then the destabilization zone will be virtually inevitable. The practice of operating pipeline networks and modeling of their work show that reducing wastewater spending leads to a decrease in the length of the destabilization zone. However, it is difficult to foresee a theoretically unambiguous result by the size of the destabilization zone without using a software package (with a wide range of changes in all hydraulic parameters).

In table 3, as a comparison, the results of the automated calculation are presented when the pipeline slope changes from 0.0035 to 0.005.
Table 3. The final results of the calculation of the destabilization zone S length with an increased slope

| Formula to determine Shezi’s coefficient | Section 2 (restored from polyethylene pipes) | Section 3 (non-restored from ceramic pipes) |
|------------------------------------------|---------------------------------------------|---------------------------------------------|
|                                          | Slope | Consump., l/s | Speed, m/s | Slope | Consump., l/s | Speed, m/s | Destabilization area length, S,m |
| Pavlovsky’s                             | 0.005 | 22.4          | 1.198      | 0.005 | 22.4          | 0.861      | 7.58 |
| Manning’s                               | 0.005 | 22.4          | 1.075      | 0.005 | 22.4          | 0.847      | 7.32 |
| Altshul’s                               | 0.005 | 22.4          | 1.103      | 0.005 | 22.4          | 0.881      | 7.81 |
| Pavlovsky’s                             | 0.005 | 36.1          | 1.354      | 0.005 | 36.1          | 0.974      | 9.58 |
| Manning’s                               | 0.005 | 36.1          | 1.223      | 0.005 | 36.1          | 0.959      | 9.27 |
| Altshul’s                               | 0.005 | 36.1          | 1.251      | 0.005 | 36.1          | 0.999      | 10.06 |
| Pavlovsky’s                             | 0.005 | 45.0          | 1.429      | 0.005 | 45.0          | 1.025      | 10.71 |
| Manning’s                               | 0.005 | 45.0          | 1.292      | 0.005 | 45.0          | 1.008      | 10.73 |
| Altshul’s                               | 0.005 | 45.0          | 1.321      | 0.005 | 45.0          | 1.053      | 11.32 |
| Pavlovsky’s                             | 0.005 | 50.0          | 1.465      | 0.005 | 50.0          | 1.048      | 10.99 |
| Manning’s                               | 0.005 | 50.0          | 1.326      | 0.005 | 50.0          | 1.032      | 10.59 |
| Altshul’s                               | 0.005 | 50.0          | 1.354      | 0.005 | 50.0          | 1.078      | 11.52 |

Analysis of the calculated data in tables 2 and 3 shows the following: the established patterns are almost identical, with the exception of absolute lengths values of the destabilization zones. The length of the destabilization zone decreases with increasing slope by an approximate value of 10-12% in each of the cases under consideration, regardless of the formulas used to calculate the Shezy’s coefficient C.

In table 4, as a comparison, the result of the automated calculation is shown when the diameter of the pipeline changes on the section 2 from 290 to 280 mm.

Table 4. The final results of the calculation of the destabilization zone S length with an increased slope

| Formula to determine Shezi’s coefficient | Section 2 (restored from polyethylene pipes) | Section 3 (non-restored from ceramic pipes) |
|------------------------------------------|---------------------------------------------|---------------------------------------------|
|                                          | Slope | Consump., l/s | Speed, m/s | Slope | Consump., l/s | Speed, m/s | Destabilization area length, S,m |
| Pavlovsky’s                             | 0.0035 | 22.4          | 1.052      | 0.0035 | 22.4          | 0.755      | 8.18 |
| Manning’s                               | 0.0035 | 22.4          | 0.947      | 0.0035 | 22.4          | 0.743      | 8.25 |
| Altshul’s                               | 0.0035 | 22.4          | 0.965      | 0.0035 | 22.4          | 0.773      | 8.91 |
| Pavlovsky’s                             | 0.0035 | 36.1          | 1.184      | 0.0035 | 36.1          | 0.849      | 10.67 |
| Manning’s                               | 0.0035 | 36.1          | 1.069      | 0.0035 | 36.1          | 0.836      | 10.37 |
| Altshul’s                               | 0.0035 | 36.1          | 1.089      | 0.0035 | 36.1          | 0.872      | 11.35 |
| Pavlovsky’s                             | 0.0035 | 45.0          | 1.246      | 0.0035 | 45.0          | 0.019      | 12.59 |
Table 5. The final results of the calculation of the destabilization zone S length with an increased slope - continued

| Formula to determine Shezi’s coefficient | Section 2 (restored from polyethylene pipes) | Section 3 (non-restored from ceramic pipes) |
|------------------------------------------|----------------------------------------------|-------------------------------------------|
|                                          | Slope | Consumption, l/s | Speed, m/s | Slope | Consumption, l/s | Speed, m/s | Destabilization area length S, m |
| Manning’s                                | 0.0035 | 45.0             | 1.125      | 0.0035 | 45.0             | 0.897      | 11.40                          |
| Alshul’s                                 | 0.0035 | 45.0             | 1.144      | 0.0035 | 45.0             | 0.914      | 11.72                          |
| Pavlovsky’s                              | 0.0035 | 50.0             | 1.273      | 0.0035 | 50.0             | 0.936      | 12.66                          |
| Manning’s                                | 0.0035 | 50.0             | 1.149      | 0.0035 | 50.0             | 0.912      | 11.81                          |
| Alshul’s                                 | 0.0035 | 50.0             | 1.162      | 0.0035 | 50.0             | 0.931      | 12.88                          |

The calculated data from table 4 indicates that when replacing the old pipeline section by a new one made from a polymer material, regardless of its slope or diameter (see table 2 and 3), there will always be a rate destabilization zone of higher or lower lengths. A characteristic feature is that the reduction in diameter on the section 2 to 280 mm compared with a diameter of 290 mm (see table 2) has practically no effect on the size of the destabilization zone (at flow rates up to 36.1 l/s), and at high spending (up to 50 l/s) the destabilization zone is increased by less than 0.5% (using the Pavlovsky’s and Manning’s formulas).

The above results allow us to make appropriate conclusions. If the lengths of destabilization zones are insignificant, for example, about 1-1.5 m, i.e. are commensurate with the length of the open tray of the manhole, or are large enough when they exceed the length of the subsequent section of the pipeline, it is obvious that no measures are needed to correct the negative situation. In an alternative situation where the destabilization zone does not exceed the length of the subsequent section of the pipeline, i.e. comparable with it, the phenomena of flooding in places where the flow velocity will be equally slow will not be excluded. One of the ways out of such a situation may be carrying out restoration work on a longer network interval (several sections) to the nearest drop well or even to the point of connection with a pipeline having such diameter and slope that ensure the conditions of hydraulic compatibility when dealing with a foreseen flow. In any case, automated programs having wide possibilities for modeling various indicators could act as an adviser to the designer [19, 20].

5. Conclusions
1. Practical results to identify faults of the transporting capacity of the drainage network are analyzed, and theoretical calculations to determine speed destabilization zone in adjacent sections of the drainage network subjected to renovation using the trenchless method of pulling new plastic pipes into the old pipeline are also presented.
2. The principle of operation of an automated program for calculating hydraulic and geometrical parameters in adjacent sections of the pipeline to be renovated is described.
3. Using the results of the calculation obtained in an automated mode and their subsequent analysis, the intervals of possible destabilization zones of hydraulic parameters are determined by means of alternative mathematical dependencies to determine the Chezy’s coefficient.
4. The ranges of changes in a number of hydraulic and geometrical parameters (length of destabilization zones, flow velocity, etc.) are established, and options excluding hydraulic imbalance are proposed.

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