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ANALYSIS OF THE CONSTRUCTION OF NODES OF A WATER PIPELINE NETWORK AND MODELING OF PLANNED OVERALL DIMENSIONS OF ITS WORKING CHAMBERS

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ABSTRACT

While designing water supply networks, an important task consists in establishing the place necessary for an installation of water supply wells along with water supply units located in them, in aim to determine the number of structural elements in the composition of individual pipelines of this water supply network. It has been proposed to apply a methodology for predictive calculation of a number of structural elements of the water supply pipeline system by indirect signs. An improvement of this technique was carried out by systematising the structural elements into simple and complex ones, with the determination of an indicator of the structural device for each of them. In order to analyse the role of each structural element of the same type, belonging to an assembly consisting of a linear part of a pipeline and nodes, a concept of coefficient of constructiveness was introduced. Analytical and graphical dependencies for predicting the value of the coefficient of constructiveness have been obtained. For typical (simple) nodes, the minimum value of the coefficient of constructiveness is 1.3 and maximum value is 2.54. The largest value of the coefficient of constructiveness for a conventional (complex) node is 1.45, the minimum value is 1.13. Recommendations have been given for assessment of the complexity of the installation of water supply units in practice in the design of new and reconstruction of existing water supply networks. For the above water supply units, working chambers of a round shape are recommended, which makes it possible in practice to reduce the overall planned dimensions of a water well in comparison with a rectangular shape of the same chamber.

Key words: water supply network, fitting, water supply unit, coefficient of constructiveness

INTRODUCTION

The water supply network is a pipeline system, the main task of which is the continuous and reliable transportation of water as well as maintaining sufficient pressure to provide all categories of consumers with quality water at a minimum cost of funds for its construction and operation. The reliability and efficiency of water supply systems, which include the water supply networks, can be realisation increased by using an optimal number of structural elements (nodes on the network and linear part) (State Enterprise Ukrainian Scientific Research and Training Center for Standardization, Certification and Quality Problems [SE UkrNDNC], 2005, 2009, 2010, 2013).

Determination of the number of constituent structural elements of a network is a laborious task, especially for existing networks and water pipelines. It is characteristic for a pipeline system that most of its linear component is located below the earth's surface, directly in the ground, and therefore there is no accurate information about its structural arrangement. Only water

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supply units located in the chambers of water wells are freely available for timely inspection and repair (Khoruzhiy et al., 1992; SE UkrNDNC, 2005, 2013).

Analysis of existing methods for establishing the optimal level of structural complexity of both individual sections of the water supply network and the entire network as a whole in aim to ensure a sufficient level of its reliability and efficiency shows that they should be improved (Khoruzhiy et al., 1992; Khoruzhiy, Tkachuk & Kosinov, 1993; SE UkrNDNC, 2009, 2013; Kosinov, 2016).

According to some authors (Matyash, 2015; Kosinov, Trach, Lavryentyeva, 2018; Tkachuk & Shevchuk, 2019) modern water supply systems in general and their distribution systems are characterized by structural complexity, dynamic state and imperfect work. However, issues of a comprehensive assessment of reliability of water supply structures, which is influenced by its design and functional indicators, remain unresolved. The water supply system is considered globally and the influence of individual structural elements and structural elements of the same type on the system as a whole has not been analysed. The presented results of investigations on operational reliability indicators are insufficiently related to indicators of structural reliability of water supply units. The given methodology for calculating the reliability characteristics does not take into account the structural composition of each water supply unit.

Calculations of the number of structural elements in the composition of the water supply unit are usually made by direct calculations (if the structural scheme of a water supply unit is known) (SE UkrNDNC, 2005, 2009, 2010, 2013). The use of direct counting shows that this process is more cumbersome, and in some cases (in the absence of accurate information about the design of the water supply unit) is simply impossible to implement (Matyash, 2015; Novodom & Matyash, 2015; Matyash & Usenko, 2016).

The process of analysis of reliability of a water supply network is divided to two types (Boryczko, Janusz & Tchórzewska-Cieślak, 2014; Rajeev, Kodikara, Robert, Zeman & Rajani, 2014; Novodom & Matyash, 2015): criteria for evaluating nodes and pipes. If the water pressure in a node is lower than the design pressure or exceeds the maximum possible value, then this node is considered as a failure node for the system. If the water pressure in the node is higher than the calculated pressure and lower than the water pressure in the node, what can satisfy water consumption for technical needs, then this node is considered influencing for the system of nodes and the network as a whole. The purpose of such division of nodes into failure nodes and influencing nodes according to the water pressure level in them enables an analysis of the sensitivity of nodes in case of their possible cascade failure and failure of key nodes (Boryczko, Janusz & Tchórzewska-Cieślak, 2014; Rajeev et al., 2014).

In papers by Khoruzhiy, Tkachuk and Kosinov (1993) and by Kosinov (2016), an algorithm for an indirect (predictive) calculation of the number of structural elements in the pipeline sections was started and created. This calculation enables taking into account indirect design features (conditions for laying a pipeline section, the number of water consumers connected to it and their groups, the presence of water sampling points for fire extinguishing, shut-off regulatory pipeline valves). This technique provided for the calculation of the number of structural elements not only in the nodes, but also on the linear part of the pipeline. At the same time, the authors did not distinguish between a structural subordination of individual structural elements included in the linear part of the pipeline (pipe section), and individual water supply units on it, i.e. the technique assumed a gradual hierarchical complication of the calculation algorithm, starting from an elementary section to an entire pipeline line and ending with a whole water supply network.

However, the methodology proposed by these authors did not give any classification of all structural elements of the pipeline, nor the degree of complexity and the impact of a method of their connection with each other on reliability of the water supply system.

The technique did not lead to staging the algorithm for this calculation. The authors of this article improved individual formulas for calculating the number of structural elements in the composition of water supply units and delineated the linear part of the pipeline and individual water supply units and gave a numerical indicator to take into account the degree of complexity of the water supply unit.

Further development of the algorithm for designing nodes on the water supply network and establishing their optimal number at each pipeline section in the work by Kosinov (2016), it was proposed to improve the formulas for calculating the number of structural elements not only in the nodes, but also on the linear part of the network. For this, a classification of structural elements of the same type was carried out – into water supply units and linear part. It is proposed to establish the length of the elementary section of a pipeline between two nodes, which assumes a minimum of butt joints on it. The concept of elementary section of the linear part has been introduced, which excludes the presence of nodes on it and is limited to nodes at both ends. This is necessary in order to exclude the influence of the structural elements of the nodes on the reliability indicators of the linear part of the pipeline. Thus, in a logical way, the analysis of the structural composition of the nodes and the linear part of the pipeline was separated.

Consequently, the analysis of existing methods for establishing the optimal level of structural complexity, both of individual sections of the water supply network, and the entire network as a whole, does not ensure sufficient improvement of its reliability.

This article is a continuation of the studies described in publications by Khoruzhiy, Tkachuk and Kosinov (1993) and by Kosinov (2016) on the method of assessing the impact of the structural arrangement of the water supply unit on the reliability of the water supply system. It expands on the previously discussed topic and demonstrates new solutions related to the classification of nodes into simple and complex, with the subsequent determination of the structural coefficient. This classification enabled to intensify the methodology for determining the overall dimensions of water supply units and to analyse the effect of their sizes on the reliability of the water supply system.

The purpose of the scientific article (this study) is following:

1) to propose a fairly simple criterion for a mathematical assessment of the degree of complexity of the structural arrangement of water supply units placed in the chambers of water supply wells (unit design index);
2) to propose a methodology for determination of the constructiveness index for nodes of varying complexity and to establish criteria for assessment of an optimal location of pipeline equipment when designing new pipelines and in the case of reconstruction of existing ones;
3) to propose a classification of water supply units in accordance with the coefficient of constructiveness and to provide results of the analysis of its determination for each group of water supply units of the same type;
4) to propose criteria by which the designer-researcher will be able to determine the degree of complexity and the optimal required quantity of elements of the water supply network nodes without preliminary assembly of schemes of the nodes.

Therefore, the purpose of this study is to improve the methods of calculation of the schemes and design features of the water supply network, taking into account the variability of the design structure of network's individual sections.

MATERIAL AND METHODS

Definition of coefficient of constructiveness

In order to exclude a possibility of impact of the indicators of the structural reliability of water supply units on the indicators of the structural reliability of the linear part of the pipeline, the following should be taken:

$$l_d = l_d^{\min} = l_{a.w.w.},$$

where $l_{a.w.w.}$ is the minimum distance between two adjacent water wells, according to the standard DBN V.2.5-74:2013 [m].

According to the recommendations of the standards DSTU B.V.2.5-25:2005 and DBN V.2.5-74:2013, this distance cannot be lower than 10 m.

With a smaller distance, in order to reduce financial costs, it is advisable to combine two adjacent water supply units in one common chamber of a water supply well.

On a section of 10 m, two standard pipes with a link length of 6 m can be laid, between which only one butt joint can be arranged. In other cases (when the length of the pipeline section under consideration between adjacent water wells is greater), the number of butt joints between pipes belonging to such sections should be determined separately.

The number of butt joints of pipes of the linear part of the pipeline, according to the standard DBN V.2.5-74:2013, is determined by the formula:

$$N_{st} = N_{spl} - 1,$$

where N_{spl} is the number of standard pipe links in the considered section of the network [pcs].

The number of standard pipe links in the considered section of the network is calculated by the formula:

$$N_{spl} = \frac{l_d}{l_{spl}},$$

where:

l_d – the coefficient of constructiveness,

l_{spl} – the length of standard pipe links in the considered section of the network.

In order to analyse the role of each structural element of the same type, belonging to an assembly consisting of a linear part of the pipeline and nodes, it will be introduced a concept of coefficient of constructiveness and it will be determined for water supply node unit and linear part of the pipeline section.

It is proposed to define it by a following analytical expressions:

– for the water supply unit: $P_{con}^{node} = \frac{1}{N_{s.p}} + \frac{1}{N_{s.f}} + \frac{1}{N_{b.j}}$, where $N_{s.p.}$, $N_{p.f.}$, $N_{b.j.}$ are the numbers of similar structural elements of the assembly, namely fittings, pipeline fittings, butt joints and standard pipe links;

– for the linear part: $P_{con}^{l.p.} = \frac{1}{N_{spl}} + \frac{1}{N_{b.j.}}$.

Setting the probability of the structural arrangement of a water supply unit in a planned section of a working chamber of the water well

As an important task in predicting the variability of planned dimensions of the working chamber of a water well, it should be considered the dependence on the diameters of structural elements, their number and connection scheme.

As a working scientific hypothesis, the following has been proposed:

1. As an important characteristic of the probabilistic possibility of the geometric location of the water supply unit in the planned dimensions of the working chamber of the water well, it should be considered the area of a figure (F_{fig}) formed by projections of the extreme points of the working chamber on a plane.
   In the further part, such a plane will be called the plane of the reference points and the created figure – figure of the reference points of the node.
2. An additional condition for the probable location of the water supply unit in the planned overall dimensions of the working chamber of a standard water well is the coincidence (or sufficient proximity) of the coordinates of the geometric centers of the areas and cross-sectional area of the working chamber of the water supply unit ($F_{w.ch.}$).

To test the above working scientific hypothesis, the plan diagram of the chamber with the water supply unit has been placed in the Cartesian plane, with the OX and OY axes aligned with the inner walls of the well chamber, as shown in Figures 1 and 2.

All plumbing nodes, regardless of their indexing and classification division into typical (simple) node and conventional (complex) node water supply units (Kosinov, 2016), depending on the shape of the figure of the reference points, can be conditionally divided

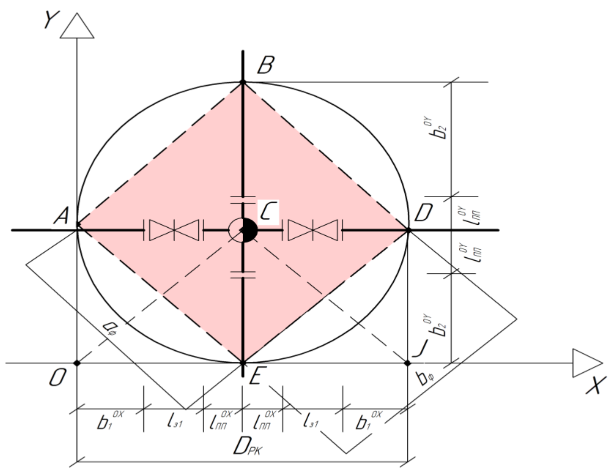


Fig. 1. Example of a plane-symmetric plumbing unit

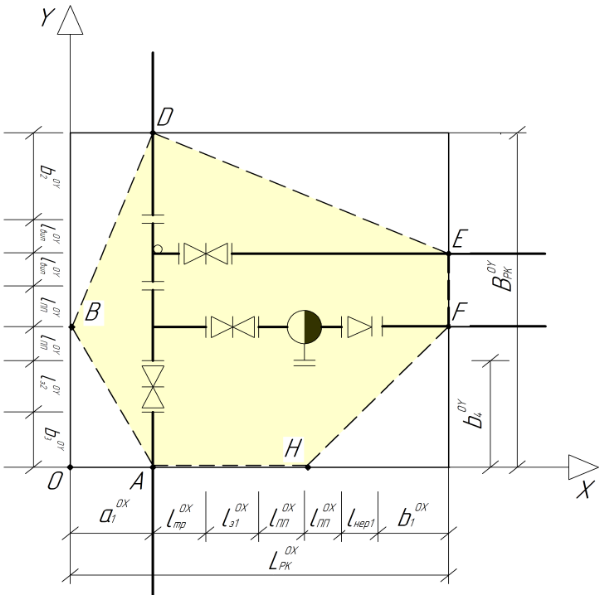


Fig. 2. Example of a plane-asymmetric water supply unit

into two groups: plane-symmetric and plane-asymmetric.

Plane-symmetric plumbing nodes must necessarily be symmetric with respect to any coordinate axis. Plane-asymmetric plumbing nodes create an asymmetric figure of the reference points.

Ideally, plane-symmetric plumbing nodes create: an equilateral triangle, a rhombus, a rectangle, a circle as the figure of the reference points. The plane-asymmetric nodes theoretically create more complex shapes.

It should be noted that typical (simple) water supply units, whose classification and indexing according to the coefficient of constructiveness is already given in paper by Kosinov (2016), in most cases are plane-symmetric units. The figure of the reference points for such water supply units is either a circle, or a rectangle, or an equilateral triangle. The geometric center of such simple plumbing units almost always coincides with the geometric center of the figure formed by the inner walls of the working chamber of the water well.

Thus, the task of checking the possibility of location of a water supply unit in the overall dimensions of a standard working chamber can be reduced to establishing the area of the figure of the reference points (F_{fdn}) with its subsequent correlation to the cross-sectional area of the working chamber of the water supply unit ($F_{w.ch.}$).

In this case, the satisfaction of the limiting condition of the form should be guaranteed $P_{c.p.} = \frac{F_{w.ch.}}{F_{fdn}} \geq 1$.

It has been proposed to call the value of $P_{c.p.}$ as the guaranteed probability of constructive location of a water supply unit in the planned dimensions of a standard working chamber of a water well. At the same time, it is obvious that the closer to 1 the value of $P_{c.p.}$ is, the more difficult it is to mount a water supply unit in such a chamber, because it becomes cramped for it. On the other hand, in this situation, the estimated cost of such a water well chamber becomes minimal. It has been proposed a method for determination of this criterion $P_{c.p.}$ for simple and complex water supply units.

RESULTS AND DISCUSSION

Determination and comparison of the coefficient of constructiveness of a conventional (complex) node water supply unit with the coefficient of constructiveness of a typical (simple) node water supply unit

The coefficient of constructiveness determines the degree of repeatability of an element of the same type as part of an elementary structural part, its constructive importance. The coefficient of constructiveness can be treated as an additional indicator of reliability.

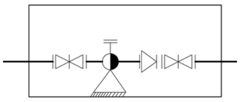
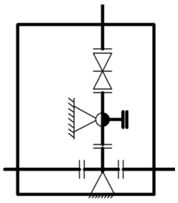
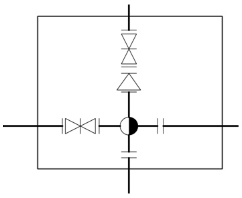
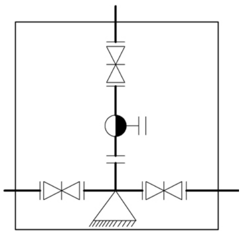
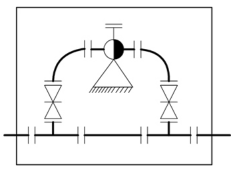
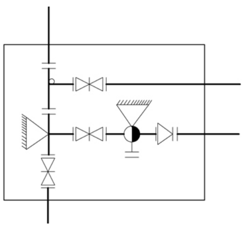
In general, for a certain water supply unit, it indicates the degree of its structural significance in the composition of the pipeline section and its structural reliability.

The coefficient shows not only the complexity of the equipment of the water supply unit, but also its influence in calculating both the estimated cost of the site and indicators of structural reliability.

The proposed systematisation is based on the following conditions:

1) the water supply unit of each type group (subtype) should be simple in its construction and combine the minimum number of similar structural elements;
2) the number of fittings, pipeline fittings and butt joints of these elements should be attributed to the main elements of the same type;

Table 1. Classification of conventional (complex) node water supply units according the shouldnumber of structural elements of the same type in the unit

Class	Detailed scheme of well	Number of structural elements of the same type in the assembly						Coefficient of constructiveness (P_{con})
		shaped parts		pipeline fittings		butt joints		
		$N_{f.}$	$n_{f.}$*	$N_{p\cdot f.}$	$N_{f.}$	$n_{f.}$*	$N_{p.f.}$	
1		2	6	3	5	4	3	1.17
2		2	7	2	3	3	7	1.14
3		2	7	3	5	2	8	0.96
4		2	6	4	7	4	10	0.85
5		5	13	3	5	6	5	0.73
6		4	11	4	7	6	11	0.59

*The number of exits from a structural element is given per one structural unit.

3) the number of outlets (connecting structural ends) of each structural element should be taken into account;
4) it is necessary to exclude the possibility of re-counting the same element in the calculations of the quantitative composition of the water supply unit due to the elimination of structural combination elements.

Table 1 shows classification of conventional (complex) node water supply units.

The number of structural elements of the same type in the composition of conventional (complex) node water supply unit should be calculated in a following way:
- in a direct calculation with a compilation of a separate table of the first type;
- by a division of a (complex) water supply unit into several typical (simple) ones.

Figure 3 shows dependence of the coefficient of constructiveness on the type of water supply unit.

For a typical (simple) water supply unit, the analytical equation will be following:

$$P_{con}^{typ} = -0.1931 \cdot n_t + P_{con.s.n.}^{\max},$$

where:

n_t – identifier of the complexity type of a typical water supply unit (n_t = 1, 2, 3, 4, 5, 6, 7),

$P_{con.s.n.}^{\max}$ – maximum value of the structural factor for a typical (simple) node.

For a conventional (complex) water supply unit, the analytical equation will be following:

$$P_{con}^{con} = -0.1259 \cdot n_t + P_{con.c.n.}^{\max},$$

where:

n_t – identifier of the complexity type of a typical water supply unit (n_t = 1, 2, 3, 4, 5, 6),

$P_{con.c.n.}^{\max}$ – maximum value of the coefficient of constructiveness for a conventional (complex) water supply unit.

According to the plotted graphs, for typical (simple) nodes, the minimum value of the coefficient of constructiveness is 1.3 and the maximum value is 2.54. The largest value of the coefficient of constructiveness for the conventional (complex) node is 1.45, the minimum value is 1.13.

Determination of the area of the figure of the reference points – *F* (dimensions) for plane-symmetric typical water supply units

For the practical implementation of this technique, the calculations have been performed in a tabular form (Table 2). Using the MS Excel software package, the minimum overall dimensions of the working chamber in plan were established in the directions OX and OY. It was provided the basis for choosing the standard internal dimensions of the working chamber made of precast reinforced concrete elements. Using MS Excel software package as well, model analytical

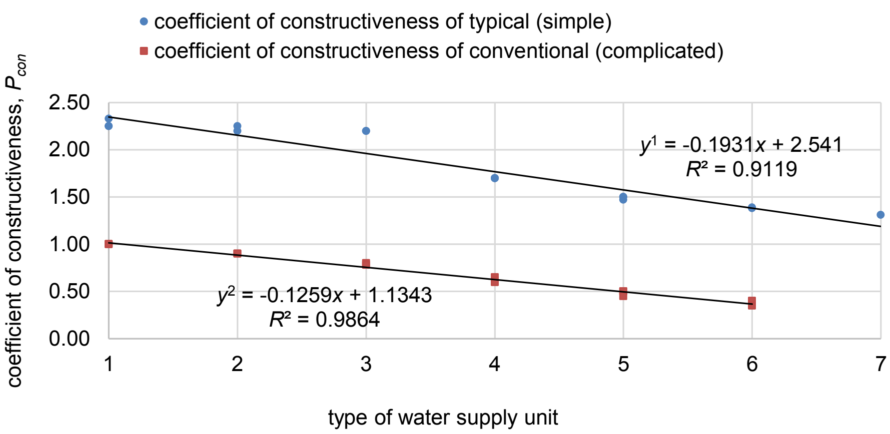


Fig. 3. Dependence of the coefficient of constructiveness on the type of water supply unit

Table 2. Recommended the dimensions of the working chamber in plan for a plane-symmetric typical water supply unit (proposed method), according to the standards DSTU B.V.2.5-25:2005; DSTU ISO 5752:2008; DSTU B.A.2.4-1:2009

n_d	D	l_{nn}^{ox}	l_{nn}^{oy}	l_{fit}	$\Delta b_2^{oy} - \Delta b_1^{ox}$	$L_{p.k.}^{ox} - B_{p.k.}^{oy}$	$L_{p.k.}^{ox}$	$B_{p.k.}^{oy}$	D_{rec}
	mm								
1	100	200	200	190	190	380	1 360	980	1 500
2	125	225	225	200	200	400	1 400	1 000	1 500
3	150	250	250	210	210	420	1 540	1 120	2 000
4	200	300	250	230	230	510	1 520	1 010	2 000
5	250	300	300	250	250	500	1 600	1 100	2 000
6	300	300	300	270	270	540	1 680	1 140	2 000

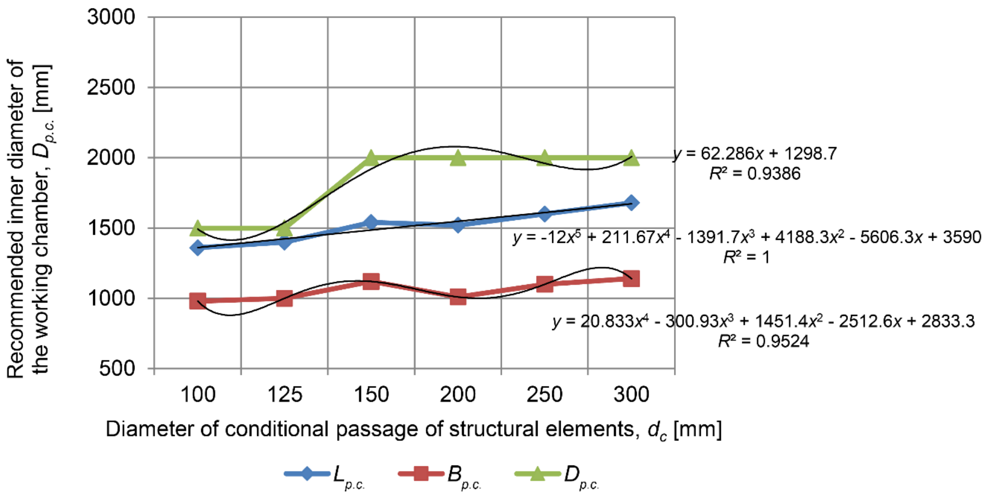


Fig. 4. Prediction of the internal dimensions of the working chamber of a water well (for a plane-symmetric typical water supply unit)

dependencies were obtained for predicting variability of chamber dimensions in plan. Figure 4 shows prediction of the internal dimensions of the working chamber of a water well.

CONCLUSIONS

1. The calculation of the optimal number of structural elements as part of the water supply pipeline system should be carried out after structural division of each individual pipeline into elementary structural parts. An elementary structural part for the analysis of its constructiveness should be considered as a linear section of the pipeline with a length of 10 m, corresponding to the minimum distance between two adjacent water supply wells. It is proposed to divide all water supply units as part of the network sections into typical (simple) nodes and conventional (complex) nodes and determine the calculation of the number of constituent structural elements separately with their subsequent summation.
2. To establish the role of each structural elements of the same type in the pipeline section, it is necessary to determine the coefficient of constructive-

ness. The coefficient of constructiveness tends to decrease in regression with an increase in the number of input constituent elements in the composition of the water supply unit. The conventional (complex) node water supply unit can be divided into six types in size.

3. For the above water supply units, working chambers of a round shape are recommended, what practically enables to reduce the overall planned dimensions of a water well in comparison with a rectangular shape of the same chamber.

Authors' contributions

Conceptualisation: V.K. and Y.T.; methodology: V.K.; validation: V.K. and Y.T.; formal analysis: V.K. and R.T.; investigation: V.K.; resources: V.K.; data curation: V.K.; writing – original draft preparation: Y.T.; writing – review and editing: V.K. and Y.T.; visualisation: R.T.; supervision: V.K. and R.T.; project administration: Y.T.; funding acquisition: V.K. and R.T.

All authors have read and agreed to the published version of the manuscript.

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ANALIZA BUDOWY WĘZŁÓW SIECI WODOCIĄGOWEJ I MODELOWANIE WYMIARÓW GABARYTOWYCH KOMÓR ROBOCZYCH

STRESZCZENIE

Ważnym zadaniem przy projektowaniu sieci wodociągowych jest ustalenie miejsca niezbędnego do zainstalowania studni wodociągowych wraz z umieszczonymi w nich węzłami wodociągowymi w celu określenia liczby elementów konstrukcyjnych w składzie poszczególnych rurociągów. Zaproponowano zastosowanie metodyki planowego obliczania wielu elementów konstrukcyjnych sieci wodociągowej za pomocą znaków pośrednich. Udoskonalenie tej techniki przeprowadzono poprzez klasyfikacje elementów konstrukcyjnych na proste i złożone z określeniem dla każdego z nich wskaźnika urządzenia konstrukcyjnego. W celu przeanalizowania roli każdego elementu konstrukcyjnego tego samego typu, należącego do zespołu składającego się z części liniowej rurociągu i węzłów, wprowadzono pojęcie współczynnika konstruktywności. Uzyskano zależności analityczne i graficzne do przewidywania wartości współczynnika konstruktywności. Dla typowych (prostych) węzłów minimalna wartość współczynnika konstruktywności wynosi 1,3, a maksymalna 2,54. Największa wartość współczynnika konstruktywności dla konwencjonalnego (złożonego) węzła wynosi 1,45, a minimalna wartość to 1,13. Przedstawiono zalecenia dotyczące oceny złożoności instalacji wodociągów w praktyce przy projektowaniu nowych sieci wodociągowych i przebudowie istniejących. Dla wspomnianych wodociągów zalecane są komory robocze o okrągłym kształcie, co w praktyce pozwala na zmniejszenie planowanych gabarytów studni w porównaniu z prostokątnym kształtem tej samej komory.

Słowa kluczowe: sieć wodociągowa, armatura, węzeł wodociągowy, współczynnik konstruktywności