The efficiency of using ductile iron water pipes in soft soil

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Abstract. At the present stage of reforming the housing and public services, toughening the requirements for the life and reliability of pipelines of the municipal life support systems, the issues of developing the requirements for choosing the material and type of pipes in relation to specific operating conditions of urban water supply systems become very relevant. The reliability and safety of the public water supply have been the main requirements applicable to these systems as the most important components of public health and one of the main priorities of the state social policy [1,2]. Of great importance in providing for the reliability of water pipelines is the expert choice of the pipe material. The paper states that for many years the main pipe materials used in the public water supply of Russian cities have been steel and cast iron. In recent years, ductile iron pipes widely used abroad and in Russia, in particular in the Moscow water supply system, have been competing with steel pipes (among metal ones). The paper presents the information on the condition of the water pipelines in the Russian cities, on the characteristics of ductile iron pipes and their use in soft and subsiding soils.

1 Introduction

Problems with the condition of the public water utilities in the cities and communities in Russia have been known to most water industry experts. In general, the condition of public water supply and wastewater disposal systems in a considerable number of cities and communities in Russia in terms of their wear and tear and reliability causes concern [3,4,5,6].

Currently, more than 18 billion cubic meters of water are supplied annually to the water distribution networks in the Russian Federation; however, 30.5 million people, or 19% of the population, are not provided with public water supply. In 2021, the share of all the sources of public drinking water supply that did not meet sanitary and epidemiological requirements amounted to 15%. The share of water samples from public drinking water supply sources that did not meet the sanitary and chemical standards of the hygienic regulation was 25.79% in 2022 [7].

There are also economic problems. According to the information submitted by the Russian Association for Water and Wastewater, 48% of water utilities are state-run or municipal unitary enterprises. Almost all of them have accounts payable, including water utilities of many large regional centers [8].

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It is obvious that at present the problem of providing the population with drinking water of the standard quality in sufficient amounts and the environmental safety of the water use has been the most urgent for Russia as before. These are not only technical problems of the obsolete equipment and general technical backwardness, but, above all, legal, organizational and economic problems. In general, the financing gap in the water industry has been estimated at 4.6 trillion rubles until 2030.

It should be noted that in 2023 with account of all available mechanisms for financing housing and public utilities (including national projects and the infrastructure menu), the total amount of budget investments in the upgrade of this sector will rise steeply. 440 billion rubles will be allocated for the upgrade of the communal infrastructure, which is 2.5 times more than last year (170 billion rubles).

However, this amount will cough up only a tenth of the funding required for the renovation of the worn-out infrastructure of the housing and public utilities to solve their problems, [9].

Ensuring the reliability of water pipelines is a separate problem. In terms of the length of the underground pipelines, Russia ranks second in the world, and one of the first in terms of worn-out pipes. About 70% of pipes are made of steel.

Operating municipal water supply systems shows that violations of the normal level of water supply are mainly associated with failures in pipeline sections of the municipal water distribution network being the most functionally significant and vulnerable elements of an urban water supply system. Currently 40% of the water distribution and sewer networks in the cities and towns of Russia, i.e., 391 thousand out of the total 940 thousand km need repair. Leaks and unaccounted-for-water in the domestic water supply systems in a number of cities and towns in Russia reach 40 percent of the water amount supplied to the network. There is a consistent tendency towards an increase in the funds needed to eliminate failures. To solve the problem of network wear and tear, the renovation rate should be improved from the current 1.5-2% to 5% annually [10].

Pipe material in no small degree determines the reliability and durability of water pipelines. Domestic and foreign experience shows that one of the main ways to improve the reliability of pipelines in public water supply systems is to crank up the construction and renovation of pipelines with the priority use of ductile iron pipes. To date, ductile iron pipes have been the most promising in terms of "price-quality-reliability-durability". The shares of pipeline systems made of ductile iron in the water supply systems of the major world centers range from 75 to 97%. [11].

Cast iron and has been known to mankind and used since ancient times. The history of cast-iron pipelines started in 1664, when, on the orders of the French king Louis XIV, the first 15-mile gray iron pipes were cast and laid from the pumping station on the Seine to the palace complex of Versailles. That pipeline supplied the royal fountains for over 330 years.

Ductile iron with nodular graphite differs from gray cast iron with a lamellar form of graphite in that graphite inclusions are in the form of balls with a diameter of 10 to 50 microns. This is provided by modifying liquid iron with magnesium, calcium, rare earth metals, or a combination of these substances. Spherical inclusions of graphite to the least extent weaken the working section of the casting; they do not exert a strong incisive effect on the metal base, unlike lamellar graphite; they aid reducing the stress concentration around, thus eliminating the risk of formation and propagation of cracks. Ductile iron pipes in terms of their mechanical properties are not inferior to steel pipes being superior to pipes made of gray cast iron. According to foreign and domestic data, their service life is 90...100 years. [13]

In Russia, class K-9 ductile iron pipes with a diameter of up to 1000 mm are manufactured at one plant - Svobodny Sokol Lipetsk Ironworks.

Pipelines made of ductile iron have the following features:

- the lowest failure rate compared to pipelines made of other materials;
- high laying rate and ease to install;
Service life up to 100 years
- sanitary reliability of transported water;
- impact resistance, ductility, cold resistance up to -600;
- high resistance to external loads and changes in hydraulic pressure with peak values up to 550 N/mm^2;
- high economic efficiency owing to the low installation and operation costs.

The design strength of ductile iron pipes is 300 kg/cm^2 (170 kg/cm^2 of steel pipes); the load bearing capacity of RJS-type lock-on socket connection ensures nondetachable connection while subject up to 25 atm. These pipes are characterized with a high plasticity.

Easy installing ductile iron pipelines should be noted - no energy costs, no special equipment or highly skilled personnel are required. Ductile iron pipes can be laid directly into the soil to a depth of 8–10 m eliminating any bed preparation; works at low temperatures are allowed [12].

The analysis of the available data on the reliability of pipelines in public water supply systems in the developed countries of North America and Europe (Canada, USA, Germany, France) shows that these countries have most reliable water supply systems in the world. This is primarily due to the wide use of ductile iron pipelines in these countries over the past 40 years. If we refer to the experience of laying pipelines in densely populated megacities, then ductile iron pipes are world leaders, one can say, non-competitive ones [11].

Most of the pipelines in the water distribution networks of large world cities are made of ductile iron (Tokyo - 97 %, Singapore -95 %, Venice - 90 %, Hong-Kong - 90 %, Istanbul - 90 %, New-York -85 %, Paris - 85 %, Damascus - 80 %, London - 80 %, Vilnius- 80 %, Prague - 80 %, Algiers - 75 %, Toronto -75 %).

In turn, rapidly developing China has got already more than 10 ironworks manufacturing cast iron pipes. China has become the second (after USA) biggest exporter of ductile iron pipes.

Considering the high performance and reliability of ductile iron pipes, the domestic production and use of ductile iron pipes has been growing in Russia in recent years.

Fig. 1. Laying ductile iron pipes.

Thus, more than 3,000 km of ductile iron pipelines have been are currently in operation in the Moscow water supply system. Their failure rate is the lowest compared to other pipelines [13].

Ductile iron pipes have butt socket connections with the gasket and socket of a special shape. The advantages of these connections are the ability of the connection to stay airtight at any pressure the pipe itself can resist, and the possibility of angular rotation (3-5 °), that provides for the flexibility of the assembled pipeline section and large radius turns thus eliminating the use of fittings.

Ductile iron pipes have a socket part on one side and a smooth end on the other or flanges on both sides for the following types of connections in the pipeline:

– socket connection *TYTON - DN80-DN1000 mm*;
– socket connection *RJ - DN 80-DN 500 mm;*
– flange connection - DN 80-DN 1000 mm.

The socket connection of ductile iron pipes is made so that the contact pressure between the sealing ring and the pipe metal, as well as the water pressure ensure water tight integrity of the connection.

A socket connection is not rigid and allows the connected pipes deviating at an angle of up to $1.5^{//}$ - $5^{//}$ while maintaining complete tightness.

An important role in the introduction of ductile iron pipes in the construction and reconstruction of water transporting pipelines in cities and towns of Russia is assigned to the availability of a comprehensive regulatory and procedural framework. Designing and constructing pipelines made of ductile iron is regulated by Code of Practice - CP 66.13330.2011 "Design and construction of pressure water supply and sewer networks using high-strength ductile iron pipes " [14].

2 Methods

The experience of using this document, new developments in constructing ductile iron pipelines, pipe joints of new design that allow angular deviation (bending) have shown that ductile iron pipelines can be laid in karstic areas.

It should be noted that designing, constructing buildings and engineering networks in soft and subsiding soils, and ensuring their strength and normal operation, is one of the most important and complex problems of the present-day civil engineering. In accordance with “Soils. Classification.” GOST 25100-2020 soft and low-strength soils include soils with uniaxial compressive strengths from 15 to 1 MPa and less [15].

These soil types include loess water-saturated soils, silt, peat, banked ground, glacial clay. They are distributed over a large area of the European part of Russia, Western Siberia, and the North Caucasus, and intensive industrial and civil construction is being carried out on them. However, just while constructing on soft and subsiding soils a large number of accidents occurred, both during the construction process and during the operation of water transportation pipelines.

Laying traditional pipes on the soils of the above-referenced categories is rather labor-intensive and associated with laying pipes on an artificial bed of sand and backfilling of imported soils; with installing concrete or pile foundations. This applies to welded steel pipes and pipes with socket and coupling connections.

Amendment No. 2 to CP 66.13330.2011 establishes requirements for the use of ductile iron pipes in public water supply and wastewater disposal systems while constructing in soft and subsiding soils. The amendment provides for a method for calculating the strength and deformability, and also for the design of pressure ductile iron pipelines with diameters up to 1000 mm with RJ and *RJS* reinforced lock-on connections for laying in soft and subsiding soils.

Ductile iron pipelines in potentially dangerous karst-suffusion areas should be calculated by the bearing capacity and deformability of the pipes in the annular and axial directions, for the combined deformation of the pipeline and the subsoil. The pipes must be calculated for the formation of one karst sinkhole of a 6 m diameter anywhere under the pipeline; herewith the bearing capacity of the pipe in the longitudinal direction must ensure the strength and tightness of the butt swivel joint in case of the subsidence of the soil of the natural ground. The most dangerous in this calculation is the formation of a sinkhole at the pipe junction that can cause the break of tightness.

To eliminate such a situation, each pipe 6 m long downstream the socket is laid on racks or piles buried in the natural ground. With the assumed design length of 40 m of the dangerous section, the design load scheme is accepted for pipes with laying of each pipe on the reinforced concrete pillow supports; the calculation and design being executed in accordance with the instructions of section 6.10 of CP 66.13330.2011.

The transverse bending strength of the pipe is determined as for a tubular beam and should not exceed 300 MPa, and the calculated allowable deflection due to external loads should not exceed 20 cm.

Reinforced concrete columns and piles should be used as pile supports, and column-type reinforced concrete slabs should be used as foundations for columns. While laying piles in the natural ground, piles to 30 m deep and higher should also be used constructed of ductile iron pipes. On dangerous or potentially dangerous sections of a laid pipeline, the use of toe and gravity blocks is not allowed.

3 Results

An example of calculating the strength of ductile iron pipelines in the process of underground laying on a weak base. Basic data:

- K-9 class pipe;
- Outside diameter $D_н$ = 63.5 cm;
- Pipe wall thickness h = 9.9 mm;
- Young's modulus $E = 1.7 \cdot 10^5$ MPa;
- Bearing capacity of the pipe to internal pressure P^0 = 9.7 MPa;
- Specific weight of the pipe 72.6 kN/m^3;
- Design tensile strength of the pipe material $R_р$ = 300 MPa;
- Depth of the pipe from the ground level to the top of the pipe H = 2 m;
- Specific gravity of backfill soil in the bank γ = 16.7 kN/m (fine sands, soil category G-II CP 66.13330.2011);
- Backfill soil deformation modulus $E_{гр}$ = 1 MPa;
- Design internal hydrostatic pressure in the pipeline $P_{раб}$ = 1.6 MPa;
- Atmospheric pressure while vacuum is formed in the pipeline $P_{вак}$ = 0.1 MPa;
- Laying pipes in a bank;
- Load safety factor n = 1.15;
- Coefficient considering the lateral earth pressure ξ = 0 (CP 66.13330.2011).

Computing chain

1. The parameter that characterizes the pipeline stiffness is determined by Formula (1):

$$P_л = 2E\left(\frac{h}{D-h}\right)^3 \tag{1}$$

$$P_л = 2 \cdot 1.7 \cdot 10^5 \left(\frac{9.9}{635-9.9}\right)^3 = 1.35 \text{ МПа.}$$

Resultant vertical load of the soil pressure in the bank:

$$Q^{в}{}_{гр} = n\gamma H D_н К_н,$$

where $K_н$ – soil pressure concentration factor, $K_н$ = 1 (CP 66.13330.2011); $Q^в_{гр}$ = 1.15·16.7·2·0.635·1 = 24.4 kN/m.
2. Resultant calculated pipe dead weight vertical load is determined by Formula (2):

$$Q_3 = n\pi\gamma_т hD_{ср}, \quad (2)$$

$$Q_3 = 1.15 \cdot 3.14 \cdot 72.6 \cdot 0.0099 \cdot 0.635 = 1.64 \text{ kN/m}.$$

3. Resultant calculated vertical load of transported water mass Q_2, vertical load, is determined by Formula (3):

$$Q_2 = n\frac{\pi}{4}\gamma_н D_в^2; \quad (3)$$

$$D_в = D_н - 2h,$$

where $D_в$ – pipe inner diameter, m; $\gamma_н$ – specific gravity of transported water equal to 9.8 kN/m^3.

$$Q_2 = 1.15 \cdot 0.785 \cdot 9.8(0.635 - 2 \cdot 0.0099)^2 = 3.3 \text{ kN/m}.$$

4. Calculation of bending moments.

The soil effect moment while the pipe is supported on a flat base (2α = 30°) determined by Formula (4):

$$M_г = 0.252Q^в_{гр}r_{ср}, \quad (4)$$

where $r_{ср}$ – pipe median radius, $r_{ср} = \frac{D_н - h}{2}$= 0.312 m

$$M_г = 0.252 \cdot 24.4 \cdot 0.312 = 1.91 \text{ kN·m}$$

Pipe and water mass effect moment is determined by Formula:

$$M = 0.199\ (Q_3Q_2)\ r_{ср} = 0.199(1.64 \cdot 3.3)0.312 = 0.27 \text{ kN·m}.$$

5. Calculation of the total moment

$$M_0 = 1.91 + 0{,}27 = 2.18 \text{ kN·m}.$$

Calculated equivalent load $Q_{экв}$, kN·m, is determined by Formula (5):

$$Q_{экв} = \frac{M_0}{0.318r_{ср}}; \quad (5)$$

$$Q_{экв} = \frac{M_0}{0.318 \cdot 0.312} = 21.97 \text{ кН} \rightleftarrows/\rightleftarrows \text{ м}.$$

6. The ultimate crushing load on a pipe laid in the ground is determined by Formula (6):

$$Q^0_{пр.} = \frac{mRh^2}{0.95 \cdot \eta \cdot D_н} \quad (6)$$

where R - design strength equal to 300 MPa;

m - coefficient of the pipe material working conditions equal to one at confidential probability $P > 0.997$;

η - coefficient characterizing the lateral horizontal pressure of soft soil (soil pressure) CP 66.13330.2011, $\eta=1$

$$Q^0 = \frac{300 \cdot 10^3 \cdot (0.0099)^2}{0.95 \cdot 1 \cdot 0.635} = 46.3 \text{ kN·m} \quad (7)$$

For K-9 class pipe: Q^0 = 47 kN·m.

Conclusion: The bearing capacity of K-9 class pipe for external load is sufficient to ensure reliable operation of the pipeline.

4 Conclusions

1. The choice of the material, strength class and pipe diameters for water supply systems should be carried out solely on the basis of technical, economic and static calculations, data on the aggressiveness of the soil and transported water, operating conditions of the pipelines and requirements to the water quality, reliability and environmental safety of the pipes. The pipe material should be chosen taken together with necessary anticorrosive measures, i.e., the type of insulation protective coating, and electrochemical protection.
2. The material of pipes and protective coatings of pipelines must ensure maintaining for a long period the physical integrity of pipelines, fittings and structures in the network. In case of accidental failure of the physical integrity of the pipeline system, the conditions for the prompt restoration of the reference parameters of the network operation must be provided by using advanced flushing, cleaning and renovation methods, including modern trenchless technologies. At the same time, the hydraulic integrity of the pipeline system should not be violated which implies maintaining the design parameters of the water flow (velocities, flow rates, pressures, etc.).
3. Pipe material contributes greatly to the reliability and durability of water supply pipelines. Domestic and foreign experience shows that one of the ways to improve the reliability of pipelines of the public water supply systems is to increase the volume of construction and renovation of pipelines with the priority use of ductile iron pipes.

To date, pipes made of ductile iron are the most promising in terms of "price-quality-reliability-durability".

Reference

1. O. Primin, E. Pupyrev, Chistaia Voda: Problemy i Resheniia **3(4)**, 40 (2012)
2. Natural resource complex of the Russian Federation. Analytical report. *NIA-PRIRODA* (2018)
3. A. Demin, Supplying Russia with drinking water. Priroda Rossii. National Portal (2019)
4. On the state of sanitary and epidemiological well-being of the population in the Russian Federation in 2021: https://www.rospotrebnadzor.ru
5. M. V. Vasilyeva, R. I. Zinurova, Bulletin of Kazan Technological University **14**, (2013)
6. The concept of the strategy for the development of the water supply and sanitation sector of the Russian Federation for the period up to 2030: Government.ru/docs/11914
7. Applied: https://applied-research.ru
8. Raasn: https://www.raasn.ru
9. Portal VodaNews: https://info@vodanews
10. Iu. Skolubovich, E. Primin, E. Gogina, Vodosnabzhenie i Sanitarnaia Tekhnika **1**, 6 (2023)
11. IngTrade: https://ingtr.ru/files/doki/vchshg/dinamika_razvitiya.pdf

12. S. Khramenkov, O. Primin, V. Orlov, *Reconstruction of pipeline systems* (ASV, Moscow, 2008)
13. S. Khramenkov, A. Aliferenkov, O. Primin, *Ductile iron pipes for water supply and wastewater disposal systems* (Moscow: MISI-MGSU Publ., 2015)
14. *Code of Practice 66.13330.2011 (with Amendment 2) Design, construction of pressure water supply and sewer networks with the use of ductile iron pipes*. Order of the Ministry of Construction of Russia dated November 7, 2016 N 775 / pr "On approval of Amendment No 2 to CP 66.13330.2011
15. GOST 25100-2020 *Soils. Classification* (2020)