

Safety of Operation of Reinforced Concrete Culverts Based on the Results of Static Tests

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Abstract— This study evaluates the safety and performance of reinforced concrete culverts manufactured using advanced German (MBK) and Danish (PEDERSHAAB) technology. A 1.0 m diameter culvert with a flat base was subjected to static tests to evaluate crack resistance and strength. The culvert was made of concrete of class B33.5 with a compressive strength of 43.2 MPa, reinforced with steel bars of A400 class. No cracks were observed at the crack resistance test load of 143 kN, but the first crack appeared at a load of 268.8 kN with a width of 0.05 mm, well below the allowable limit of 0.2 mm. The strength tests showed that the culvert withstood a load of 332.1 kN, exceeding the design load of 294.6 kN without reaching the limit state. These results confirm that the culvert complies with safety standards (SP RK 3.03-112-2013 and GOST 8829-94) and is suitable for installation under embankments up to 7.0 m high. Finite element modeling (FEM) in MIDAS FEA NX 2023 confirmed the experimental data. A 1.5 m diameter culvert compared to a 1.0 m diameter culvert has a higher energy intensity after cracking, which is due to a complex of factors. The study emphasizes the effectiveness of modern manufacturing techniques in improving the durability, crack resistance and load-bearing capacity of reinforced concrete culverts, ensuring their reliability in road and railway infrastructure under various environmental conditions.

Index Terms — safety, reinforced concrete culvert, crack resistance, strength.

I. INTRODUCTION

THE transportation volume in the world is constantly growing. The development of road communications is connected with the development of production, business, strengthening of interregional ties on a national scale.

Culverts are an important part of industrial road construction. The requirements for mechanical strength and stability must be met, so that during their operation there are no risks of collapse and damage to building structures, which

may endanger the movement of vehicles, affect the economic efficiency of maintenance of facilities, lead to violation of requirements for the protection of human health, creation of safe working conditions for maintenance personnel and environmental protection. Properly organized drainage of water from the road ensures its safety and increases its service life. Structural designs of bridges and pipes shall meet the requirements of safety, serviceability and durability, as well as additional requirements specified in the design task. Any inaccuracy in the design or construction of culverts is a risk for problems such as misalignment and deep cracks in the structure [1].

Research on the use of culverts has been actively pursued by scientists, which has made significant progress in design, construction and materials. At present, ductile iron pipe, cast iron pipe, steel pipe, concrete pipe, polyethylene pipe, composite pipe, etc. are widely used. [2] During operation, culverts accept permanent and temporary loads (from the mass of embankment and vehicles), which change in time, depend on the temperature and humidity of the environment, the action of water flow and ice, seismic loads.

Paper [3] revealed that errors in the regulatory requirements for the design of highway bridges and culverts led to the formation of a soil arch. Paper [4] considered the effect of soil arching when the fill height is changed. The designs of culverts are relatively simple, but the interaction between soil and structure can be complex [5]. Structural damage may result from improper soil treatment strategies. Factors that can cause pipe damage include trench slope, trench bottom width, culvert size, and stiffness of the backfill adjacent to the culvert [6]. Paper [7] presents the effects of friction forces acting on the side walls of buried box culverts determined using the Finite Element Method (FEM). It was found that the soil-structure interaction at the culvert-soil interface has a significant effect on the total soil pressure acting on the bottom slab. Paper [8] formulated equations to predict the rate of soil load reduction, including the optimum soft zone geometry and treatment of backfill and side fill. The effect of automobile load on the culvert is considered in paper [9], scientists have theoretically described the phenomenon of transient radiation emitted by mechanical load in a heterogeneous medium (soil layer).

Paper [10] created a truck load simulation, with each culvert subjected to a monotonically increasing load. The instrumentation included tensiometers, a high-resolution laser deflection sensor and automated data acquisition. The test results determined the loads at which each crack nucleated and propagated. Paper [11] conducted a comprehensive study to evaluate the shear strength of precast reinforced concrete box culverts. Six culverts were tested to failure by applying a wheel load to each culvert to determine

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the critical shear location. Shear cracks appeared in the test specimens at loads twice the standard loads.

Test results [12] showed that when the strength of a concrete slab is increased from 35 to 75 MPa, the shear strength increases by 7-20% depending on the loading case, i.e. concentric or eccentric loads. The tensile fracture properties of concrete are characterized by a parameter called characteristic length and brittleness of concrete. The brittleness factor of a concrete slab is required to be considered in any rational expression of shear calculation to reflect the dimensional effect factor and filler type.

In order to fulfill the safety requirements, the structures are supposed to have such initial characteristics that under the appropriate degree of reliability and various design effects during construction and operation of bridges and pipes, any kind of destruction or disruption of performance associated with harm to life and health of citizens, property and the environment is excluded. For this purpose, culverts are tested for strength and crack resistance. The assessment process usually includes visual inspection, non-destructive testing and laboratory analysis of concrete samples.

Soon-Jin Han et al. [13] experimentally analyzed prefabricated tunnel structures with reasonable longitudinal connection compared with monolithic tunnel structures and found that the crack distribution, mid-span load-deflection curve, ultimate load curve and other mechanical properties are very similar, and the longitudinal segmentation and support connection methods are reliable.

The aim of the study [14] is to investigate the effect of steel corrosion on the long-term structural behavior of an underground reinforced concrete culvert based on a multiscale computational model. When reinforcing bars expand under the influence of corrosion products, tensile stresses are induced in the surrounding concrete, which leads to cracking of the coating and reduction of the bond strength between reinforcement and concrete, resulting in deterioration of the structural performance of reinforced concrete elements.

Various destructive factors such as water and sulfates are present in the soil, which leads to a gradual decrease in the durability of concrete over time [15]. Moreover, when the interior of a reinforced concrete structure is dry and the surrounding soil is wet, differential shrinkage occurs in concrete due to the asymmetric environment, resulting in cracking of the concrete surface. Strength reduction and cracking can cause and accelerate corrosion of reinforcing bars in concrete. Corrosion reduces the effective cross-sectional area of the reinforcement, deteriorates the bond between reinforcement and concrete, which negatively affects the structural performance of reinforced concrete elements.

In order to study the operational safety of reinforced concrete culverts based on the results of static tests, the rest of the paper was organized as follows: first, information on the dimensions, strength and deformation characteristics of reinforcement and concrete of the reinforced concrete culvert was given [16]. Then static tests were carried out to study the bearing capacity of the pipe. Next, the pipe was calculated and the experimental and design characteristics were compared.

II. MATERIALS AND METHODS

A. Samples description

The section of reinforced concrete round pipe 2.200 with a flat base with a diameter of 1.0 m, accepted for testing, was manufactured in accordance with the requirements of [17].

Concrete of B30 class (C35/45 [18]) with the following physical and mechanical characteristics in accordance with the current standards [19] was used for production of pipe sections: $R_b=1.60$ kN/cm², $R_{bt}=1.10$ kN/cm², $R_{b,ser}=2.25$ kN/cm², $R_{bt,ser}=1.85$ kN/cm², $E_b=33.20 \times 10^3$ kN/cm².

As a working reinforcement in pipe sections the reinforcement according to GOST 5781-82 "Hot-rolled steel for reinforcement of reinforced concrete structures" of 8 mm diameter bars of A400 class (A-III - St 400 [18]) made of 25G2S and 35GS steel with the following physical and mechanical characteristics $R_s=R_{sc}=34,50$ kN/cm², $E_s=20,00 \times 10^3$ kN/cm² is accepted.

For reinforcement of the pipe section with the length of 2.0 m, according to the project, twenty coils of 8 mm diameter bars of A400 class (A-III - St 400 [18]) in the cages of external and internal reinforcement are accepted. The calculated area of working reinforcement in both frames is $A_s=10.06$ cm².

The inner radius of the pipe according to the project [17] is $r_{int}=50$ cm, the average radius of the pipe $r=56$ cm, the outer radius of the pipe $r_0=62$ cm. The wall thickness of the pipe section is $t=12$ cm.

The authors [21], based on the approaches given in [22-25], conducted a study to determine the optimal pipeline thickness at different backfill depths and pipeline diameters. The calculations were carried out by the finite element method for concrete of normal strength with a compressive stress of 34.5 MPa and specific gravity of 23.6 kg/m³, steel reinforcement with a tensile strength of 448 MPa with a concrete protective layer of 32 mm. The maximum crack width did not exceed 0.25 mm. With a pipeline diameter of 1000 mm and a backfill depth of 6.25 m, the optimum pipe thickness was 150 mm. Taking into account the reinforcement area, the optimum thickness corresponds to the pipe thickness adopted in this paper.

B. Determination of forces from the action of permanent and temporary loads

The normative bending moment in the pipe link from the effect of permanent and temporary load NK-120 is as follows [19]:

$$M=9,80 \text{ kN}\cdot\text{m}$$

The design bending moment in the pipe link from the action of permanent and temporary load NK-180 is as follows [19]:

$$M^d=11.1 \text{ kN}\cdot\text{m}$$

C. Calculation of control load for strength testing

The reference linear load for strength tests of a pipe section with a diameter of 1.0 m in accordance with [19] is determined according to the following dependence:

$$P_k = \frac{M}{0.175 \cdot r} = \frac{11.1}{0.175 \cdot 0.56} = 113.3 \text{ kN/m} \quad (1)$$

Since the length of the pipe is 2.0 m, the load during the strength test is assumed to be equal to:

$$P_k = 2 \cdot 113.3 = 226.6 \text{ kN} \quad (2)$$

The strength test load determined according to the current standards [19] is defined without taking into account the safety factor C specified in accordance with GOST 8829-94 [20]. In accordance with [20], the safety factor C in determining the strength test load is assumed to be equal to $C=1.3$.

Thus, the test load when checking the strength of reinforced concrete round pipe 2.200 is assumed to be equal to:

$$P_k = 1.3 \cdot 226.6 = 294.6 \text{ kN} \quad (3)$$

D. Calculation of the crack resistance test load

The reference linear load for crack resistance testing of the pipe section in accordance with [19] is determined by the formula:

$$P_{crack} = \frac{M}{0.318 \cdot r} \quad (4)$$

where M is the standard bending moment;
 r is the average pipe radius, m.

For a pipe section with a diameter of 1.0 m, the control load to ensure crack resistance is as follows:

$$P_{crack} = \frac{9.80}{0.318 \cdot 0.56} = 55.0 \text{ kN/m} \quad (5)$$

Since the length of the pipe link is 2.0 m, the crack resistance test load is assumed to be equal to:

$$P_k = 2 \cdot 55.0 = 110 \text{ kN} \quad (6)$$

Since the safety factor $C=1.3$ is taken into account when controlling the load for strength, respectively, the control load

when testing the crack resistance of reinforced concrete culvert with a diameter of 1.0 m also increases and is taken equal to $P_c=1.3 \cdot 110=143 \text{ kN}$.

E. Testing procedure

A winding machine made by MBK (Germany) is used for manufacturing reinforcement frames from pipe sections [21]. For concreting the pipe sections, a molding machine made by PEDERSHAAB (Denmark) was installed. To evaluate the crack resistance, strength and compliance with the design data, additional control tests were performed on a 2.200 m diameter round pipe section with a 1.0 m diameter flat base (Fig. 1).

In works [22-26] characteristics of reinforced concrete pipes based on steel, synthetic and basalt fibers are given. The mechanical properties of fibers are given.

F. Testing of the pipe section

Accepted for testing reinforced concrete round profile of pipe 2.200 with a flat base with a diameter of 1.0 m had no mechanical damage. Concrete class accepted at the plant of reinforced concrete products LLP LCI-MK [27] in the manufacture of a pipe link with a diameter of 1.0m corresponds to concrete B30 (C35/45 [18]). The strength of concrete of the pipe link with diameter of 1,0 m according to the laboratory of LLP LCI-MK at the age of 7 days after molding of the product was 39,8 MPa, on the 28th day - 41,8 MPa, and on the test day - 43,2 MPa. Thus, on the test day the concrete strength of the round pipe with cross-section 2.200 with a flat base corresponded to the concrete class according to the standard B33.5 (C 35/45 [18]).

The pipe section was loaded during the tests by two oppositely directed forces applied in the direction of its vertical diameter (Fig. 2). Since the pipe section has a flat base at the bottom, the impact from below on the pipe was transmitted as a uniformly distributed load.

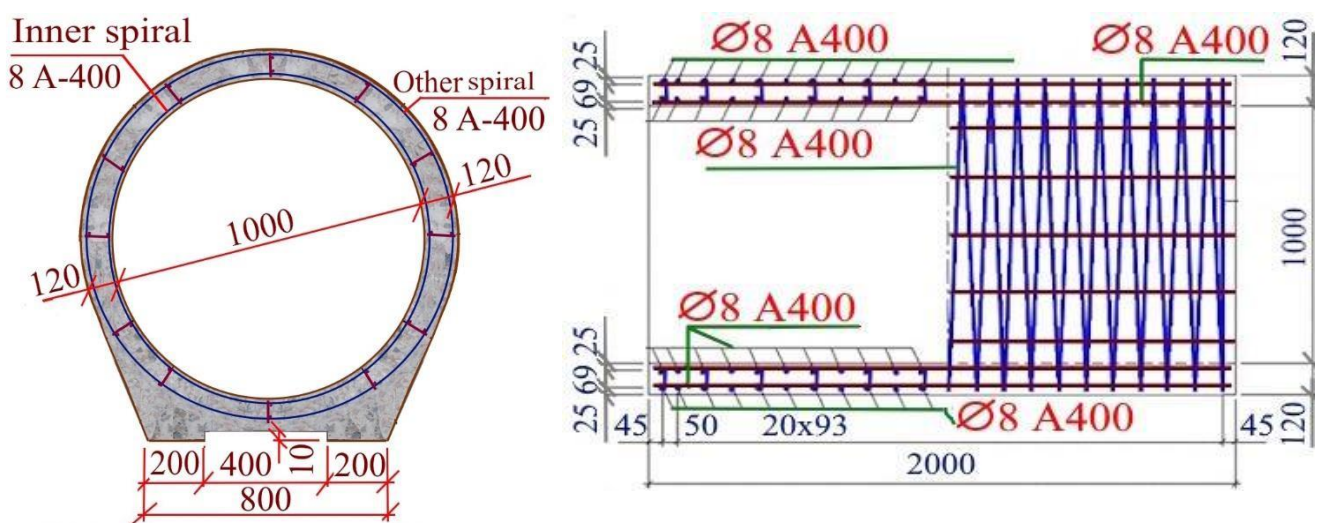


Fig. 1 Formwork dimensions and reinforcement of a reinforced concrete 2.200 circular pipe section with a flat base

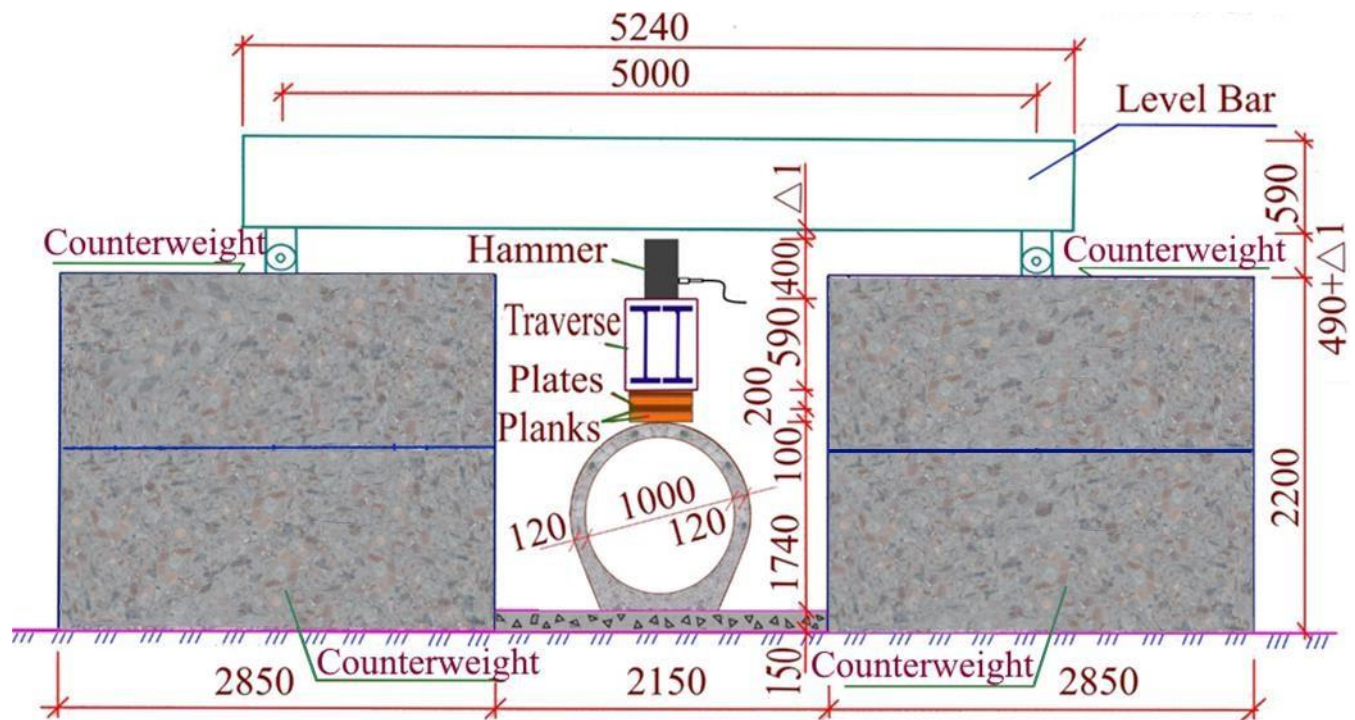


Fig. 2 Diagram of the power plant with the test section of the circular pipe 2.200 with a flat base with a diameter of 1.0m

Pipe tests were carried out at the production base of LLP LCI-MK, where a power bench was equipped. The test load was transferred to the prototype by means of a pumping station and a hydraulic jack with a capacity of 1000 kN. The load was recorded by a pressure gauge mounted on the pumping station.

The change of vertical and horizontal diameters of the pipe section during the tests was determined with the help of deflection gauges of Aistov system and Kucherenko Central Research Institute of Structural Engineering with the value of division 0.01 and 0.1 mm, respectively.

The pipe sections were loaded in steps equal to 7-10% of the control load. After each step, the product was held under load until the stress-strain state stabilized.

The deflection meter readings were taken after the next load step was applied and after holding under load. Crack opening in the pipe concrete was determined using a Brinell microscope with a division value of 0.05 mm.

A schematic diagram of the power plant with the tested section of round pipe 2.200 with a flat base of 1.0 m diameter is shown in Fig. 3. The vertical load on the pipe section was transferred by a hydraulic jack DG-100 through a steel crossbeam and wooden plates. Under the load, the jack rested on the thrust beam, which was attached to the counterweights of the power bench on both sides of the pipe.

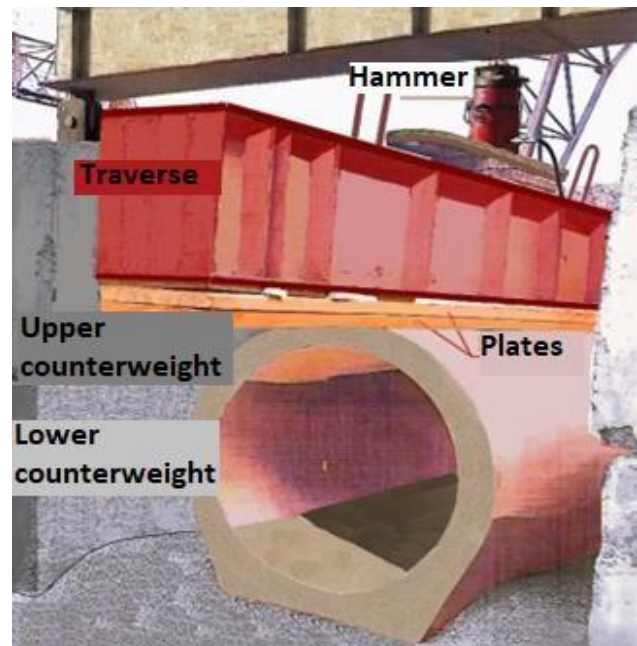


Fig. 3 Fragment of the power rack and a section of pipe with a diameter of 1.0 m

condition is met, under which the maximum crack opening width should not exceed the control one, multiplied by the coefficient 1.05.

In accordance with clause B.12 of GOST 8829-94 [20], the crack opening width control load is defined as the most unfavorable combination of standard loads, and all loads are assumed to be short-term.

According to Table 40 of SP RK 3.03-112-2013 [19], the limiting width of crack opening in culvert links, which ensures normal operation of the structure, corrosion resistance of reinforcement and durability of the structure under the action of standard loads, should not exceed the

III. RESULTS AND DISCUSSION OF THE PIPE SECTION TESTS

A. Evaluation of crack resistance

In accordance with Table 40 of the Construction Norms and Rules of the Republic of Kazakhstan SP RK 3.03-112-2013 [19], the category of crack resistance requirements for pipes of all purposes with non-tensioned reinforcement is 3v.

According to clause 9.3.4 of GOST 8829-94 [20], the products subject to the requirements of the 3rd category are considered suitable if under the action of the control load the

value of $a_{cr}=0.2$ mm.

Fig. 4 shows the graphs of vertical and horizontal diameters change at the end of the pipe section under step load application. Consideration of these graphs shows that starting from the loading step equal to $P = 175$ kN, there is a slope of the graphs, indicating the beginning of accelerated growth of elastic-plastic deformations of concrete at further increase in load.

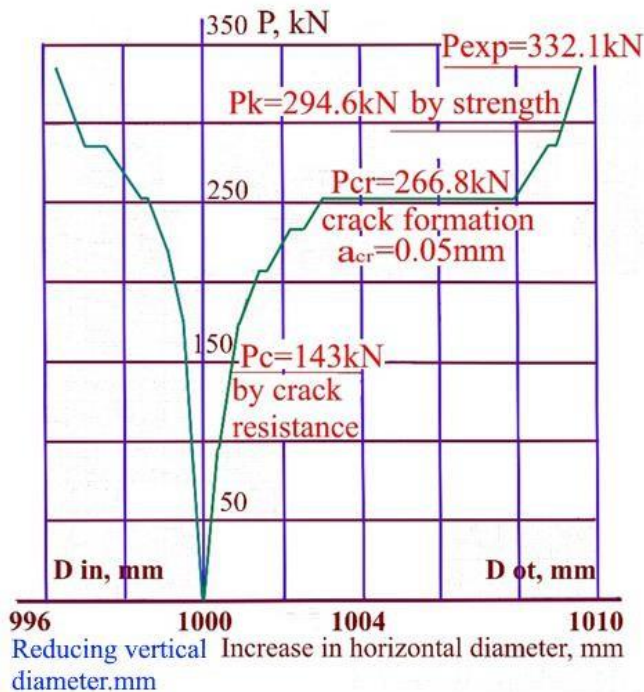


Fig. 4 Graphs of changes in vertical and horizontal diameters at the end of the pipe section with stepwise application of load

The control load when assessing the crack resistance of the pipe of circular section 2.200 with a flat base was assumed to be equal to $P_c = 143$ kN. The control load should also include the mass of loading devices, the value of which during testing of the pipe section amounted to $R_{l,d} = 15.8$ kN.

When a round pipe with a cross-section of 2,200 with a flat base was loaded with a test load equal to $P_c = 143$ kN, no cracks appeared in the tensile concrete.

When the load $P_{cr} = 266.8$ kN was reached, a crack was formed in the tensile concrete zone at the base of the pipe. The crack opening width measured with a Brinell microscope at load $P_{cr} = 266.8$ kN had a value of $a_{cr} = 0.05$ mm.

The tests showed that the reinforced concrete section of round pipe 2.200 with a flat base with a diameter of 1.0 m on crack resistance meets the requirements of standards SP RK 3.03-112-2013 "Bridges and pipes", the project and GOST 8829-94. Crack resistance of round pipe section 2.200 with a flat base is provided by.

In [28-31] the results of tests of pipes with fibers under long-term loading are presented. It is shown that polypropylene fibers improve mechanical properties of pipes manufactured by dry method in terms of characteristics after cracking.

B. Strength assessment

According to paragraph B.1 of Annex B of GOST 8829-94 [20], when testing reinforced concrete structures for

strength, the value of the control load is taken equal to the value of the load causing forces in the main sections, equal to the maximum of the design loads, multiplied by the safety factor C.

In accordance with the calculation, the control load without taking into account the safety factor C when testing a round pipe section 2.200 with a flat base for strength in accordance with the requirements of building codes and regulations of the Republic of Kazakhstan is a value equal to $P_c = 226.6$ kN.

According to Table B.1 of Appendix B of GOST 8829-94 [20], when reinforcing the pipe section with reinforcement of class A400 (A-III), the safety factor C is assumed to be equal to $C = 1.3$.

Thus, the control load during strength testing according to GOST 8829-94 [20] is the value $P_c = 226.6 \cdot 1.3 = 294.6$ kN.

Consideration of the graphs of change of vertical and horizontal diameters of the pipe section showed that when the experimental load reaches the value $P_{exp} = 332.1$ kN, the vertical diameter decreased by 3.7 mm, and the horizontal diameter increased by 9.6 mm.

During the tests of the pipe profile, the experimental load $P_{exp} = 332.1$ kN was achieved. The analysis of the pipe profile state under this load showed that the limit state in the experimental product was not reached, and the round pipe profile 2.200 with a flat base had reserves in load-bearing capacity.

The tests showed that the reinforced concrete pipe section with a diameter of 1.0 m meets the strength requirements according to the norms of SP RK 3.03-112-2013 "Bridges and pipes", the project and the standard GOST 8829-94. The strength of the circular section of the pipe with a diameter of 2.200 m with a flat base was ensured.

The results of tests of reinforced concrete round pipes with diameters of 2000 mm and 1000 mm are given in [32, 33]. Thus, in [33], lower values were obtained for a round pipe of 1000 mm diameter, 120 mm wall thickness, concrete compressive strength 31.7 MPa, 8 A-400 reinforcement with an area of 5.54 cm² than for the single pipe in the present work.

In particular, the normal crack in the tensile zone was formed at 102 kN/m ($26.68 \cdot 0.5 = 13.34$ kN/m in the present work), the increase in elastic-plastic strains occurred from 73.2 kN/m ($175 \cdot 0.5 = 87.5$ kN/m in the present work). And the limit state began at 214.5 kN/m when the horizontal diameter increased to 10 mm and the vertical diameter decreased to 14 mm (in this work at $332.1 \cdot 0.5 = 166$ kN/m there was a decrease in the vertical diameter by 3.7 mm and an increase in the horizontal diameter by 9.6 mm; at the same time in the experimental product the limit state was not reached). Relatively high indicators of strength and deformation characteristics of reinforced concrete pipe, given in this paper, should be explained by a combination of factors: higher strength of concrete, large area of working reinforcement, as well as the manufacture of the pipe on more modern equipment.

IV. PIPE CALCULATION IN THE MIDAS PROGRAM AND USING REGRESSION CURVES

The tests were simulated using the MIDAS FEA NX 2023 software package, taking into account the physical nonlinearity of concrete and reinforcement characteristics.

First, a finite element model of the pipes was created with finite element dimensions of approximately 50×50 mm.

Concrete Smeared Crack model was adopted to describe the nonlinear loading behavior of concrete. The Concrete Smeared Crack model is used to describe the nonlinear behavior of reinforced concrete under tension and compression. This model is based on the concept of distributed material damage and allows to take into account the formation and development of cracks without explicitly modeling their geometry.

In determining the stiffness of the sections, nonlinear σ - ϵ laws were adopted for concrete: in compression - by Thorenfeldt diagram, in tension - by Brittle diagram, in shear - by Al-Mahaidi diagram. A nonlinear von Mises work model was adopted for the reinforcement.

Figure 5 shows the three-dimensional model of a 2.200 pipe link built in the MIDAS FEA NX 2023 software package. Figure 6 shows the three-dimensional pipe body when subjected to different loads. Figure 6 shows the formation of cracks in the pipe body under different test loads.

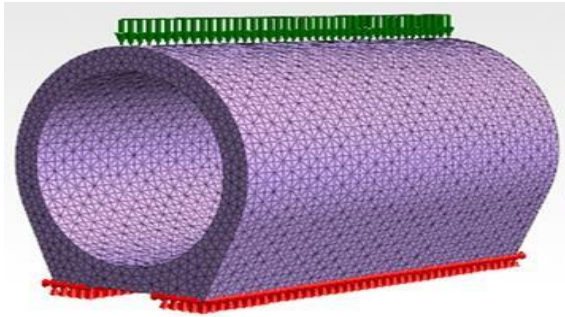


Fig.5 - Three-dimensional model of pipe link 2.200

Analysis of the data in Figure 6 shows that cracks by the finite element method are formed earlier than in the experimental specimen. This can be explained by incomplete consideration of the transverse reinforcement of the pipe in the FEM.

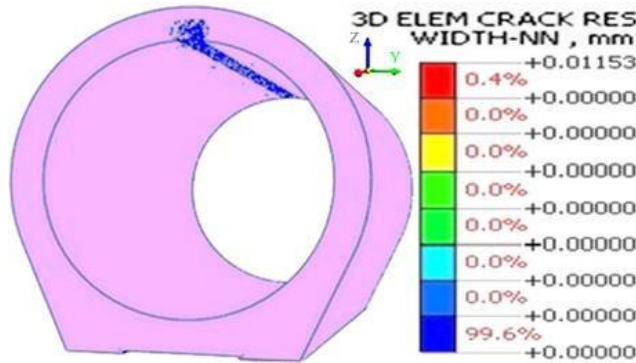
The plots of the vertical and horizontal diameters of the 1.0 m diameter 2.200 pipe link obtained from the experimental and calculated data are shown in Fig. 7.

Both graphs (calculated and experimental) presented in Figure 7 show a similar trend of strain change under load. This indicates the correctness of the selected calculation model.

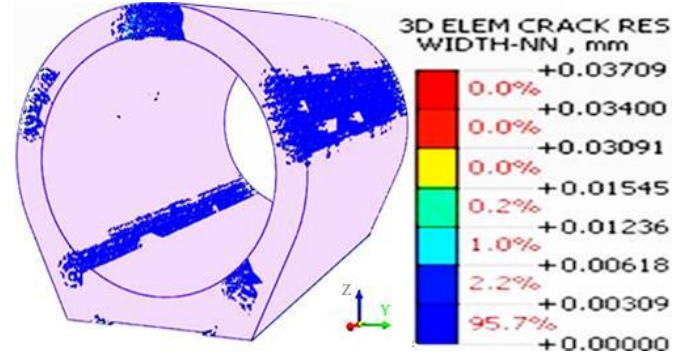
Based on the presented graph, it can be noted that the change in the vertical diameter of the pipe according to the calculated data practically coincides with the experimental data. The coincidence of curves in the area of vertical diameter reduction indicates the correct description of stress and strain distribution in the numerical model.

Analysis of the graph shows that the change in the horizontal diameter of the pipe according to the calculated data also shows close agreement with the experimental data at the initial stages of loading. When the load increases, the calculation model shows slightly smaller values of horizontal diameter increase compared to the experimental data, which indicates that there is some discrepancy between the results of modeling and testing. This may be due to a simplification of the calculation model or to material features that were not fully accounted for in the numerical analysis. Nevertheless, the general character of the horizontal diameter change is reproduced correctly.

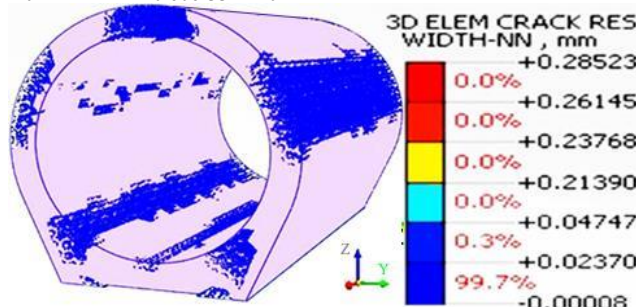
a - Crack formation character in the model of a pipe link with diameter 1.0m under load $0.303 \cdot 332 = 100.6$ kN



b - Crack formation character in the model of a pipe link with diameter 1.0m under load $0.515 \cdot 332 = 171.0$ kN



c - Crack formation character in the model of a pipe link with diameter 1.0m under load $0.606 \cdot 332 = 201.2$ kN



d - Crack formation character in the model of a pipe link with diameter 1.0m under load $0.697 \cdot 332 = 231.4$ kN

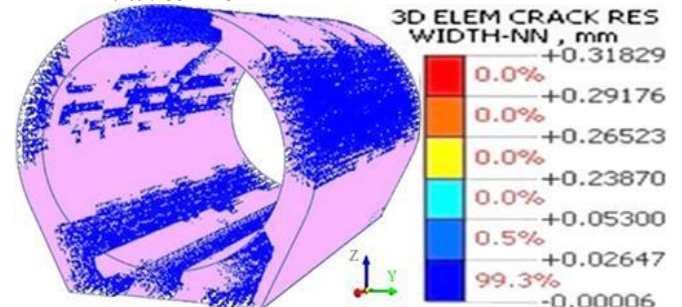


Fig.6 - Nature of crack formation in the model of a 1.0m diameter pipe link under different loads

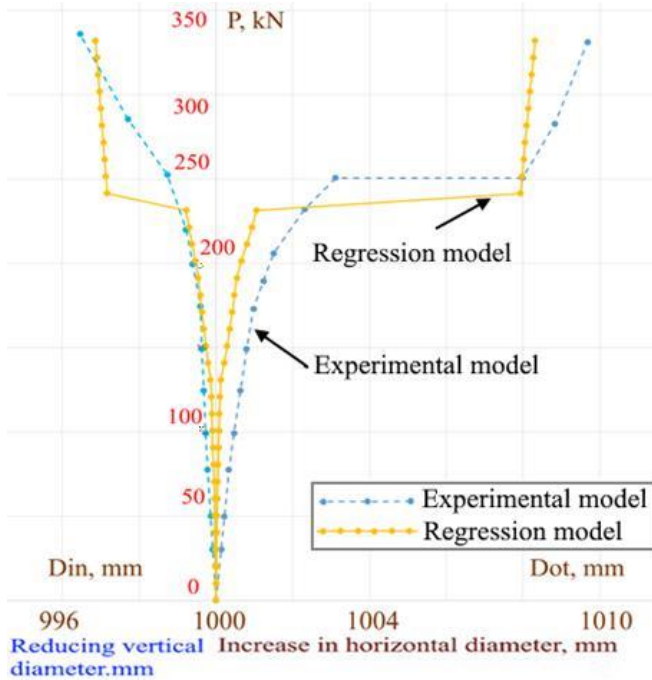


Fig.7 - Graphs of change of vertical and horizontal diameters of the pipe link 2.200 with diameter 1,0 m, obtained on the basis of experimental --- and calculated --- data

The discrepancies in the slope of the graphs at the final stages on both the left and right sides are explained by the fact that the Concrete Smeared Crack model with the Brittle tensile model was used in the calculation. This increases the stiffness of the model, as it prematurely terminates the tensile resistance of the concrete and does not take into account the gradual opening of cracks and the redistribution of forces.

The present paper [34] is devoted to the study of the influence of fiber orientation on crack propagation in reinforced concrete beams reinforced with basalt fiber-reinforced plastic (BFRP). The paper employs the finite element method and the golden section concept to analyze the crack propagation patterns. The main conclusions drawn are that the cracking pattern can be described through the golden section, that there is a dimensional effect in crack distribution, and that the modelling method can accurately predict crack development.

In [35], the development of a numerical model to analyse the bond-slip effect in steel-reinforced concrete composite beams under cyclic loads is presented. A modified finite element model that accounts for slip without necessitating an increase in the number of nodes in the mesh is proposed. The primary conclusions drawn from this study are that the proposed model accurately predicts the distribution of stresses and strains and exhibits good agreement with earlier analytical and experimental studies.

For a pipe with a diameter of 1.5 m (Fig.8) with practically

the same physical and mechanical characteristics the following test data were obtained:

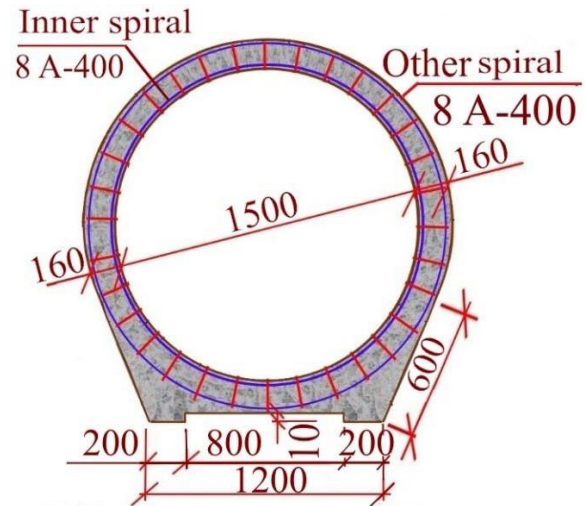


Fig.8 - Diagram of a pipe with a diameter of 1.5 m

The crack resistance design load is 257.4 kN with crack opening width not more than $a_{cr}=0.2\text{mm}$.

At loading of the pipe link ZKP6.200 with the crack resistance control load equal to 257.4 kN, there were no cracks in the stretched concrete.

When the load $P_{cr}=300.5\text{ kN}$ was reached, a crack was formed in the tensile zone of concrete in the pipe support zone. The crack opening width measured with the help of Brinell microscope at the load $P_{cr}=300.5\text{ kN}$ had the value $a_{cr}=0.05\text{mm}$.

The analysis of the graphs of vertical and horizontal diameters of the pipe link showed that when the experimental load equal to the value of $P_{exp}=525\text{ kN}$ was reached, the vertical diameter decreased by 13.7 mm, and the horizontal diameter increased by 20.1 mm.

The analysis of the pipe link condition at this load showed that the limit state was not reached in the experimental product and the pipe link had reserves of bearing capacity.

To compare the test data, consider the following table 1.

Comparison of the test results shows that although the ultimate limit state was not reached in each pipe at the maximum test loads, the 1.0 m diameter pipe has a higher margin in both crack resistance (1.86) and strength (1.127) compared to the 1.5 m diameter pipe (1.167 and 1.006).

Also the reduction of vertical diameter in the tests for 1.0 m diameter pipe is more than 2 times less than for 1.5 m diameter pipe.

For a detailed comparison of the performance of 1.0 m and 1.5 m pipes under load, a regression model was calculated for each of them. The results are presented in Fig. 9.

TABLE I
Comparison of Test Data for Pipes with Diameters of 1.0 and 1.5m

Pipe diameter, D, m	Crack resistance test load P_{cr} , kN	Experimental crack resistance load P_{cr} , kN	Ratio $\frac{P_{cr}}{P_c}$	Strength test load P_k , kN	Experimental strength load P_{exp} , kN	Ratio $\frac{P_{exp}}{P_k}$	Reduction of vertical diameter during testing, d_v , mm	Ratio $\frac{d_v}{D}$	Increase in horizontal diameter test, d_h , mm	Ratio at $\frac{d_h}{D}$
1.0	143	266.8	1.86	294.6	332.1	1.127	3.7	0.0037	9.6	0.01
1.5	257.4	300.5	1.167	522	525	1.006	13.7	0.009	20.1	0.013

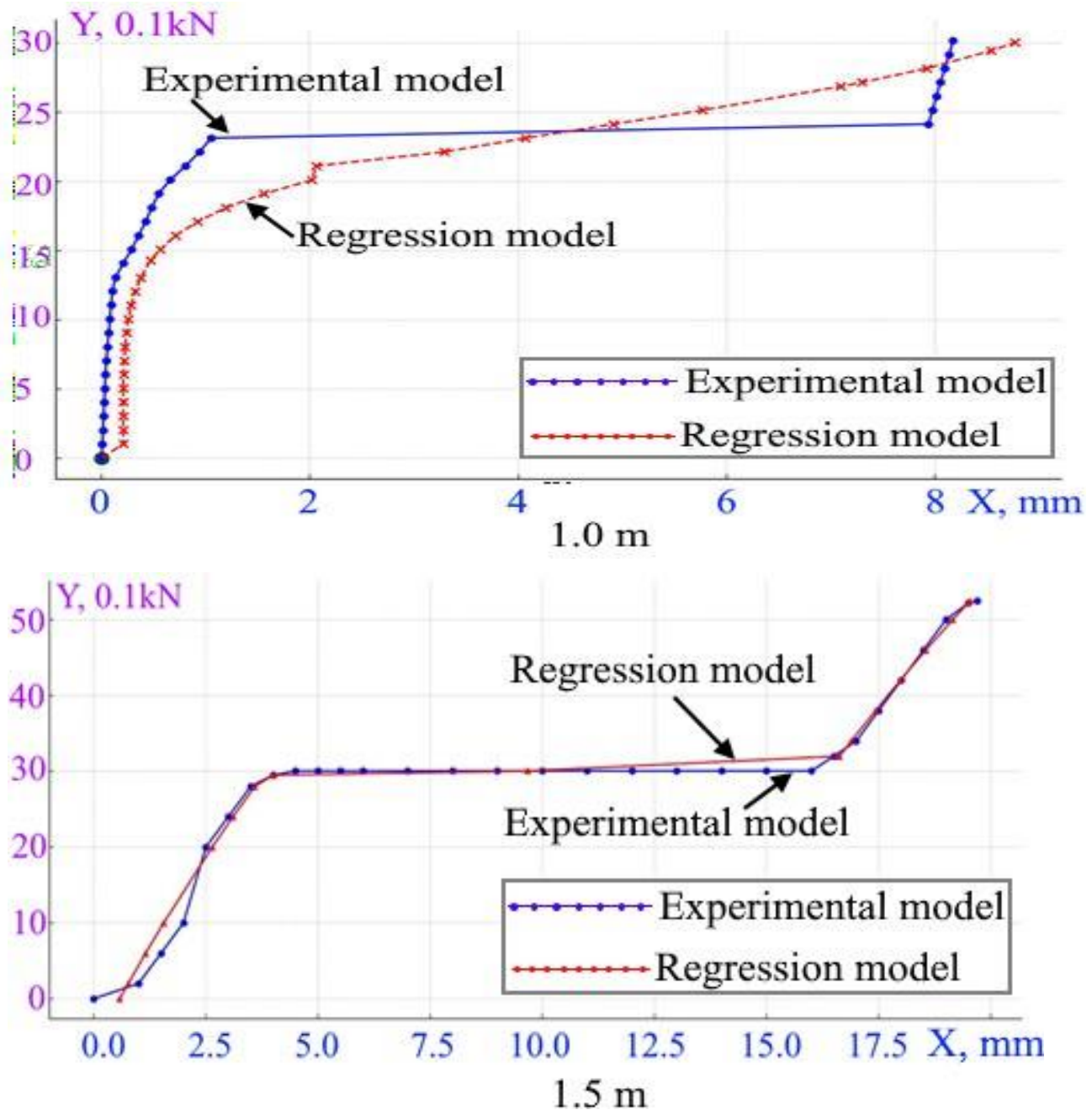


Fig.9 – Comparison diagram of the experimental (blue) and regression (red) models of horizontal diameter increase

For both graphs, the dependence of the increase in length X (mm) on load Y (0.1 kN) is described by a regression model with two logistic functions. For a pipe with a diameter of 1.0 m, this dependence is defined as:

$$y(x) = \frac{6.57}{1 + e^{-0.10(x-31.29)}} + \frac{6.32}{1 + e^{-1.40(x-24.91)^{-0.23}} \quad (7)$$

with a coefficient of determination $R^2 \sim 0.93$

And for a pipe with a diameter of 1.5 m, the relationship is written as:

$$y(x) = \frac{839.8}{1 + e^{-0.0105(x-442.86)}} + \frac{12.55}{1 + e^{-7.03(x-30.07)}} - 8.69 \quad (8)$$

with a coefficient of determination $R^2 \sim 0.85$.

For pipes with a diameter of 1.5 m, there is a significant correlation between the experimental and regression values.

This is despite the fact that the coefficient of determination for a diameter of 1.5 m is lower than for 1.0 m.

To compare the efficiency of the pipes, we will integrate the functions and calculate the resistance capacity in terms of crack resistance and strength.

For a 1.0 m pipe, the calculated and experimental crack resistance will be equal to:

$$Y(x_{1.0}^{cr}) = \int_0^{14.3} \frac{6.57}{1 + e^{-0.10(x-31.29)}} + \frac{6.32}{1 + e^{-1.40(x-24.91)^{-0.23}}} - 0.23 = 4.93 \text{ kN} \cdot \text{mm}^2 \quad (9)$$

$$(x_{1.0}^{cr})_{exp} = \int_0^{26.88} \frac{6.57}{1 + e^{-0.10(x-31.29)}} + \frac{6.32}{1 + e^{-1.40(x-24.91)^{-0.23}}} - 0.23 = 36.37 \text{ kN} \cdot \text{mm}^2 \quad (10)$$

For a 1.0 m pipe, the calculated and experimental strength will be equal to:

$$Y(x_{1.0\text{ cal}}^{str}) = \int_{14.30}^{29.46} \frac{6.57}{1 + e^{-0.10(x-31.29)}} + \frac{6.32}{1 + e^{-1.40(x-24.91)}} - 0.23 = 54.05 \text{ kN} \cdot \text{mm}^2 \quad (11)$$

$$Y(x_{1.0\text{ exp}}^{str}) = \int_{26.88}^{33.21} \frac{6.57}{1 + e^{-0.10(x-31.29)}} + \frac{6.32}{1 + e^{-1.40(x-24.91)}} - 0.23 = 57.78 \text{ kN} \cdot \text{mm}^2 \quad (11)$$

For a 1.5 m pipe, the calculated and experimental crack resistance will be equal to:

$$Y(x_{1.5\text{ cal}}^{cr}) = \int_0^{25.74} \frac{839.8}{1 + e^{-0.01015(x-442.86)}} + \frac{12.55}{1 + e^{-7.03(x-30.07)}} - 8.69 = 48.62 \text{ kN} \cdot \text{mm}^2 \quad (12)$$

$$Y(x_{1.5\text{ exp}}^{cr}) = \int_0^{30.05} \frac{839.8}{1 + e^{-0.01015(x-442.86)}} + \frac{12.55}{1 + e^{-7.03(x-30.07)}} - 8.69 = 65.14 \text{ kN} \cdot \text{mm}^2 \quad (13)$$

For a 1.5 m pipe, the calculated and experimental strength will be equal to:

$$Y(x_{1.5\text{ cal}}^{str}) = \int_{25.74}^{52.2} \frac{839.8}{1 + e^{-0.01015(x-442.86)}} + \frac{12.55}{1 + e^{-7.03(x-30.07)}} - 8.69 = 411.28 \text{ kN} \cdot \text{mm}^2 \quad (14)$$

$$Y(x_{1.5\text{ exp}}^{str}) = \int_{30.05}^{52.5} \frac{839.8}{1 + e^{-0.01015(x-442.86)}} + \frac{12.55}{1 + e^{-7.03(x-30.07)}} - 8.69 = 400.61 \text{ kN} \cdot \text{mm}^2 \quad (15)$$

A comparison of the performance indicators of pipes under load shows that after cracks form, performance stabilises. For a 1.5 m pipe, performance stability can be observed for both the calculated and experimental values, which is explained by the good match between the experimental and regression curves.

There are a few reasons why there's a big jump in the amount of work needed after cracks show up in a 1.5 m pipe compared to a 1.0 m pipe. The 1.5 m pipe has a significantly greater protective layer thickness and overall wall thickness (160 mm vs. 120 mm), which affects the cross-sectional geometry and, as a result, the moment of inertia and deformation capacity of the structure. This allows for more

efficient distribution of internal forces and delays the development of cracks, increasing crack resistance. In addition, the increased cross-section of the 1.5 m pipe can lead to a longer elastic working stage of the reinforcement.

The disproportionate increase in the strength characteristics of the pipe is also related to the scale factor. This is due to the non-linear distribution of stresses and the nature of crack formation.

At the same time, additional observations are necessary to know the resistance of pipes under long-term loads.

V. CONCLUSION

Culverts are the most common artificial structures on roads and railroads. The article develops questions on this type of engineering structures. The following practical conclusions can be drawn as a result of the works carried out on the construction of culverts by the method of pushing the finished sections into the embankment:

1. Reinforced concrete culvert 2.200 with a flat base 1.0 m in diameter was manufactured at the production base of LLPLCI-MK according to the new technology using the equipment of MBK (Germany) and PEDERSHAAB (Denmark). The age of concrete in the pipe section at the time of testing was 95 days. The actual strength of the concrete of the round pipe section 2.200 with a flat base on the test day was 43.2 MPa, which corresponded to the concrete class B33.5.

For reinforcement of the product, bars with a diameter of 8 mm of class A400 (A-III - St 400) are accepted. Twenty coils are taken in the outer and inner shells of the pipe profile.

The control load for testing the crack resistance of a round pipe with a cross-section of 2.200 with a flat base of 1.0 m diameter was $P_c = 143$ kN. When the pipe section was loaded with the control load $P_c = 143$ kN, there were no cracks in the tensile zone of the concrete product. The crack in the product appeared at the load equal to $P_{cr} = 266.8$ kN. The crack opening width was 0.05 mm. The crack resistance of the round profile of pipe 2.200 with a flat base with a diameter of 1.0 m meets the requirements of the project, the norms of SP RK 3.03-112-2013 "Bridges and pipes" and the standard GOST 8829-94.

2. The control load when testing the strength of the pipe profile was $P_k = 294.6$ kN. The experimental value of the load when testing the pipe of circular cross section 2.200 with a flat base was $P_{exp} = 332.1$ kN. The analysis of the stress-strain state of the pipe profile showed that the experimental product did not reach the limit state and had a safety margin. According to the strength of the link of round pipe section 2.200 with a flat base diameter of 1.0 m meets the requirements of the project, the norms of SP RK 3.03-112-2013 "Bridges and pipes" and GOST 8829-94.

3. 2.200 round pipe sections with a flat base with a diameter of 1.0 m, manufactured by the new technology, can be laid in the embankment body of highways with embankment height up to 7.0 m and provide safe passage of temporary cargoes A14, NK-120 and NK-180.

4. According to the project, for external and internal turns of round pipe section 2.200 with a flat base of 1.0 m diameter, reinforcement of class A400 (A-III) of 25G2S and 35GS grades can be used. In case of application of round pipe sections 2.200 with a flat base 1.0 m in diameter in areas with

the average temperature of the outside air of the coldest five-day period below minus 40 °C, reinforcement of class A400 (A-III) of 25G2S grade should be used for bends.

5. The change in the vertical diameter of the pipe according to the FEM calculation data practically coincides with the experimental data. Smaller values of horizontal diameter increase in comparison with the experimental data may be explained by simplification of the calculation model or material peculiarities that were not fully taken into account during numerical analysis.

6. The increased energy intensity (work) of a pipe with a diameter of 1.5 m compared to a pipe with a diameter of 1.0 m after cracks have formed is explained by geometric characteristics, as well as the complex interaction of the material, reinforcement scheme and scale effect.

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