Hydraulic parameters of culverts from pipes with normal and spiral form of corrugation

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Abstract. The research paper is devoted to study of culverts from metal corrugated pipes (CMP) and helically corrugated steel pipes (HCSP). Modern design solutions of culverts from CMP and HCSP are differ as compared with used before (bottom with various types of roughness, inlet and outlet heads, type and size of corrugation) and there is not enough experimental data for their design. The aim of the study is to test CMP and HCSP models to determine their hydraulic parameters, such as roughness and resistance coefficient, critical bias and so on. The laboratory equipment and method of experimental study as well as results of the tests of CMP and HCSP with protective tray at the pipe bottom and without it under different operation modes are given in the research paper. The results of the study show that roughness coefficient under pressure hade mode can be determined using Norton equation only for HCSP, Norton and Einstein-Banks equations are corrected for CMP.

Keywords: Culverts, metal corrugated pipe, helically corrugated steel pipe, hydraulic parameters, roughness coefficient.

1. Introduction

Corrugated metal pipes (CMP) and helically corrugated steel pipes (HCSP) are used as culverts nowadays along with concrete culverts (Figure 1) [1, 2].

![Figure 1. Scheme of culverts from CMP (left scheme) and HCSP (right scheme).](image)

The lengthening or replacement (relining) of old culverts and small bridges by metal pipes with normal and spiral forms of corrugation are carried out during reconstruction or repair works. Such pipes allow carrying out all necessary works in short time without stop of a traffic flow. Area of
cross section of transit part of the pipes, which was reduced after reconstruction or repair works, has to provide the necessary estimated water flow according to hydrograph of waterway [3]. Therefore, it is necessary to take into account ecological and economic efficiency of using CMP and HCSP or culverts with variable cross section in every particular case, for example, if we place a tray with increased abrasive stability in the pipe bottom [4].

When we design culverts from CMP and HCSP, it is necessary to estimate their design solution and durability. If the durability is not enough, the initial design solution is changed and the durability is estimated again. If the durability is enough (not less than 50 years), terms of water flow, pressure, depth and speed in the pipe as well as other parameters are identified [5].

CMP or HCSP have a wide range of design features: type and sizes of corrugation, form and sizes of the pipe cross section, length of the pipe elements and types of their joints, types of inlet and outlet head, presence of protection from fish and garbage, presence of protective tray in the pipe bottom, type of internal surface of the pipe. Besides, such pipes have some available operating modes. Therefore, only experimental data can be taken as the basis for design of such pipes in modern software, which is used independently or with software for design of highways and railways nowadays [6].

We cannot use present guides to make hydraulic calculation of CMP or HCSP with different sizes of corrugation and presence of the tray in the pipe bottom because the corrugation size influences on the hydraulic resistance. This is due to the fact that the guides of hydraulic calculation are reliable only when we calculate pressure head mode, but if we calculate free-flow mode, semi-pressure head mode or partially-pressure head mode we have to use other methods. Besides, the guides for calculation of roughness coefficient under pressure head mode and free-flow mode for HCSP with the corrugation size 125x25 mm, which is widely used in Russia, have not experimental data [5, 7-11].

In spite of a large volume of the culverts construction from CMP or HCSP, there are not guides for hydraulic calculation of HCSP and methods of assessment its durability. Therefore, the culverts design is not based on hydraulic calculation, which is necessary according to normative documents. It causes reduction of their durability.

Taking into account the above, the aim of research work is the experimental study of CMP and HCSP models to obtain the necessary data and hydraulic parameters of such pipes, which can be used for hydraulic calculation in design of culverts from CMP or HCSP. The object of the study is the metal pipes with normal and spiral forms of corrugation. The subject of the study is the pipe hydraulic parameters, such as flow, resistance and roughness coefficients, critical bias and Reynolds number under different modes of operation.

The following tasks are defined to obtain the above aim:
- Review of existing guides for hydraulic calculation of CMP and HCSP;
- Experimental study of CMP and HCSP models;
- Analysis of experimental data, obtained under different operation modes;
- Determination of hydraulic parameters and their dependency on the operation modes;
- Development of guideline of using the obtained parameters for hydraulic calculation in design of the culverts.

2. Materials and methods of research

Experimental hydraulic research of the culvert models from CMP and HCSP with smooth tray at the pipe bottom and without it were carried out at the Hydraulics Department of the Moscow Automobile and Road Construction State Technical University (MADI) within linear large-scale coefficient \( \alpha = 5 \).

The first culvert model was RMP with diameter \( d = 1 \) m with a normal corrugation \( l_c \times \Delta c = 130 \times 32.5 \) mm. Such pipes are widely used in Russia. When CMP had diameter \( d = 20 \) cm, measured between the corrugation centers, internal diameter of the pipe was \( d_i = 19.35 \) cm. The lengths of the tested pipes were \( l_p = 520 \) cm and 414 cm, the biases of the pipes were \( i_p = 0.01; 0.031; 0.05 \) and 0.096. Piezometers were placed at the pipe bottom between the corrugation edges, 24 piezometers for CMP with \( l_p = 520 \) cm and 20 piezometers for \( l_p = 414 \) cm.

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The second culvert model was HCSP with diameter $d=1.2$ m and spiral corrugation of 125x25 mm. An internal diameter of the model was $d_i=24$ cm and a spiral angle $\varphi=9^\circ 21'$. This model consisted of four sections with the length of each section 102 cm, joined by flanges, and had the whole length $l_p=408$ cm and biases $i_p=0.01; 0.03; 0.05$. The end sections had normal corrugation of 68x13 mm. 22 piezometers were placed at the pipe bottom.

A smooth tray with thickness of 12 mm and central angle of 120° was place at the pipe bottom, it filled one third of internal perimeter of CMP and HCSP. Diameter of cylindrical pipe, which area of cross section was equal to area of internal cross section of the corrugated pipe with exception of area of the smooth tray, was accepted as an estimated diameter. The estimated diameter was $d_e=18.6$ cm for CMP and $d_e=23.2$ cm for HCSP. An inlet head of the pipe was a cut perpendicular pipe axes, an outlet head had a form of portal wall in the tests.

Processing of skilled data consisted in determination of flow, resistance and roughness coefficients; depths at the inlet to the pipe and at the outlet from it; critical depth; critical bias and normal depth at the free-flow mode and semi-pressure head mode (Figure 2 and Figure 3).

**Figure 2.** Graph of water surface in CMP with the smooth tray under free-flow mode.

**Figure 3.** Graph of water surface in HCSP with the smooth tray under free-flow mode.
The following measurements were made during the tests:
- Pressure before the pipe $H$;
- Depth at the inlet to the pipe concerning of the smooth tray on the bottom over the first corrugation $h_{in}$;
- Depth at the outlet from the pipe concerning of the smooth tray on the bottom over the last corrugation $h_{out}$;
- Indications of piezometers;
- Value of the passed water consumption $Q$;
- Water temperature.

Maximum relative error of measurements of hydraulic parameters did not exceed 3.5%.

3. Results and discussion
The laboratory test results show that the resistance coefficient $\lambda$ is functionally connected with Reynolds number $Re$ when we place the smooth tray at the bottom under pressure head mode. The quadratic resistance area is noticed when $Re \geq 350000$ for CMP and $Re \geq 400000$ for HCSP.

The resistance coefficient reaches maximum value $\lambda = 0.072$ in CMP with the smooth tray at the bottom, it complies with the roughness coefficient $\eta = 0.0238$ for corrugation of 130x32.5 mm. The research results testify to the fact that calculation of the roughness coefficient under pressure head mode in such culverts can be determined by using Einstein-Banks and Norton equations, if we take exponent outside bracket equal to 0.64 (instead 0.67) (1) [12, 13, 14].

$$\eta = \left(\frac{x_t \eta_t^3 + x_c \eta_c^3}{x_t + x_c}\right)^{0.64}$$

where $x_t$ and $x_c$ – the pipe cross section perimeters for the smooth tray and the corrugation; $\eta_t$ and $\eta_c$ – roughness coefficients for the tray and the corrugation respectively.

The value of the toughness coefficient for HCSP under pressure head mode can be rather correctly determined by using Norton equation ($\eta = 0.028$) unlike CMP. The toughness coefficient for CMP and HCSP without the tray at the bottom under free-flow mode can be more or less than under pressure head mode depending on the pipe bias (about 11%).

A hydraulic jump after the compressed cross section of the pipe did not occur under free-flow and semi-pressure head modes in CMP; it means that the pipe bias $i_p = 0.096$ was more than critical bias. The pipe filling changed in limit of $h_o/d_i \approx 0.12...0.52$ under free-flow mode and $h_o/d_i \approx 0.52...0.82$ under semi-pressure head mode.

The test results testify to conclusion about dependency of the roughness coefficient on the CMP filling under free-flow mode. Meanwhile, the roughness coefficient values for CMP without the tray in the studied limit ($h_o/d_i \approx 0.12...0.52$) are almost the same under free-flow and semi-pressure head modes.

The comparison of experimental graphs of dependency $\eta = f(h_o/d_i)$ for the corrugated pipe, working by partial cross section with or without the tray, shows that maximum value of the pipe filling coincides semi-pressure head mode in the moment before the filling of CMP (fig. 4).

The roughness coefficient value, obtained in the tests for HCSP under pressure head mode ($\eta = 0.028$) is significantly more than the roughness coefficient value ($\eta = 0.022$), recommended by AISI for such pipes [15, 16]. The HCSP filling influences on $\eta$ under free-flow mode. The roughness coefficient reaches maximum value when $h_o/d_i \geq 0.45$ (fig. 5). It can be taken as estimated value.

The test results of CMP with the tray under free-flow mode with the pipe bias $i_p = 0.01...0.096$ and the estimated filling in the pipe inlet $h_o/d_i \approx 0.75$ show that the roughness coefficient can be accepted equal to $\eta = 0.019$, for $h_o/d_i \approx 0.9...1$ – $\eta = 0.021$.

The roughness coefficient can be taken equal to $\eta = 0.0207$ when the pipe bias $i_p = 0.03$ and $\eta = 0.0226$ when $i_p = 0.05$ for HCSP with $d = 1.2$ m and corrugation of 125x25 mm with the tray at the bottom under free-flow mode. This value can be taken equal to $\eta = 0.0234$ for pressure head mode.
Figure 4. Graph of dependency $\eta = f (h_o/d_i)$
1, 2 – test points for the pipe model with $d_e=0.1935$ m and $i_p=0.096$ under free-flow and semi-pressure head modes; 3, 4, 5 – test points for the pipe model with the tray at the bottom, $d_e=0.186$ m, length 5.2 m, $i_p=0.031$, 0.096, 0.01 respectively; 6 – test points for the pipe model with the tray at the bottom, $d_e=0.186$ m, length 4.14 m, $i_p=0.05$.

Figure 5. Graph of dependency $\eta = f (h_o/d_i)$ for the culverts models with $i_p=0.05$ and $i_p=0.03$ under free-flow mode
1, 2 – for HCSP with the tray at the bottom; 3, 4 – for HCSP without the tray; 5, 6 – for CMP with the tray at the bottom.
4. Conclusion
The research results of culverts from CMP and HCSP show their high efficiency and give the necessary estimated data for engineers to design the culvert construction. The estimated data about hydraulic resistance in CMP and HCSP with the smooth tray at the bottom were obtained during the tests. Values of the resistance coefficient along the pipe length under pressure head mode in CMP and HCSP with the tray are functions of Reynolds number. If $Re \geq 350000$ for CMP and $Re \geq 400000$ for HCSP respectively value $\lambda$ will be maximum.

According to the research results, the roughness coefficient under pressure head mode can be rather correctly determined using Norton equation only for HCSP, but for CMP it can be determined only with particular corrections. The roughness coefficient can be equal to 0.019 and 0.021 for the estimated filling in the pipe inlet $0.75$ and $0.9$ respectively for CMP with the tray under free-flow mode with the pipe bias $i_p=0.01…0.096$.

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