Hydraulic calculation features of helically corrugated steel culverts

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Abstract. Algorithm of hydraulic calculation in steel culverts design with a normal and a spiral corrugations form is developed on the model hydraulic studies basis of corrugated metal culverts. Processing of experimental data was allowed to determinate flow coefficients, resistance coefficients, roughness coefficients; depths on an inlet to a pipe and on an outlet from it; critical depth; a critical bias and normal depths for different operation modes. Algorithm can be used for correction of calculations in normative documents, in new and reconstruction of the operating culverts design and for urgent relining of the damaged culverts.

1. Introduction

Culverts from metal corrugated pipes (CMP) are widely use in water-development transport projects (WDTP) of different functions and also in fish-protecting and landscape nature protection structures. Structures from helically corrugated steel pipes (HCSP) are of special interest. Hydraulic calculation is necessary for optimum design of such culvert structures and their individual elements. This calculation should be supported by experimental and natural researches [1, 5].

The aims of the research work are the following:

- to study work of HCSP under various service conditions;
- to develop algorithm of hydraulic calculation in structures design from CMP.

2. Hydraulic research of helically corrugated steel pipes (HCSP)

The following data are necessary for performance of hydraulic calculation in design: a type of a culvert structures from CMP; preliminary parameters of pipe round section (diameter, existence of a smooth tray, type and the sizes of corrugation, pipe material, existence of a covering); settlement water levels in the head race and in the tail race and the passed water consumption; the modes of water flow in pipe transit part (free-flow mode, semi-pressure head mode, partially-pressure head mode and pressure head mode); bias of a pipe bottom and pipe length; existence and design of the inlet and outlet heads; the way of the pipe line laying (opened or closed); average height (crest mark), width, contour interval of slopes and characteristic of an earth embankment soil (dam). Settlement passed water consumption is accepted on flood hydrographs.

Hydraulic research on HCSP carried out at the Hydraulics Department of the Moscow Automobile and Road Construction State Technical University (MADI) [6,7] within linear large-scale coefficient...
\( \alpha = 5 \). Researches were conducted for two types of pipe: pipe with a normal form of corrugation (CMP) and with a spiral form of corrugation (HCSP).

Researches were conducted for the pipe with diameter \( d = 1 \) m with a normal corrugation of 130x32,5 mm (CMP), length of a pipe equaled 520 cm and 414 cm and the biases \( i_p = 0,01; 0,031; 0,05 \) and 0,096. Diameter of the model \( d = 20 \) cm. The second series of experiences were conducted for the pipe with diameter \( d = 1,2 \) m with a spiral corrugation of 125x25 mm (HCSP). Internal diameter of the HCSP model made \( d = 24,0 \) cm and a spiral angle =9°21′. This model of a pipe consisted of four sections 102 cm long, connected by flanges, with a total length of 408 cm and biases \( i_p = 0,01; 0,03; 0,05 \). At the bottom of both models was a smooth tray with a thickness 12 mm and with the central angle 120°.

In the majority of experiments, the inlet to the studied pipe was issued in the form of a cut, perpendicular pipe axes, and the outlet, in the form of a portal wall. During the experiments performing the next parameters were measured: pressure \( H \) before a pipe; depth at the inlet to the pipe \( h_{in} \) concerning of a smooth tray on the bottom over the first corrugation; depth at the outlet from the pipe \( h_{out} \) concerning of a smooth tray on the bottom over the last corrugation; indications of piezometers; value of the past water consumption \( Q \) and water temperature.

Processing of skilled data consisted in flow coefficients determination, resistance coefficients, roughness coefficients; depths at the inlet to a pipe and at the outlet from it; critical depth and also a critical bias and normal depth at the free-flow mode, semi-pressure head mode, partially-pressured head mode and pressure head mode.

3. Algorithm of hydraulic calculation in structures design from corrugated metal culverts

The executed pilot hydraulic studies of the specified models working as a flat "short" culvert allowed to develop the flow chart of hydraulic calculation algorithm in the culverts design with a normal and a spiral form of corrugation (Figure 1).

![Figure 1. The flow chart of hydraulic calculation algorithm in design culvert CMP and HCSP with the usual and increased abrasive stability.](image)

Value of a roughness coefficient \( n= 0,0248 \) for a real pipe at any constructive solutions of heads in HCSP without smooth tray at the bottom of a pipe when pipe filling is less \( 0,15h_{0}\)/d. With a growth of pipe filling to 0,45\( h_{0}\)/d according to the available bias of the pipe and the head construction value type of a roughness coefficient can increase form 0,0267 when a pipe bias \( i_p = 0,01 \) and to the maximum 0,03 when a pipe bias \( i_p = 0,05 \), i.e. approximately for 12,5%.
With installation of a smooth tray at the pipe bottom, the critical bias of HCSP depends on the flow parameter $\theta$ (Figure 2). Flow parameter $\theta = \frac{Q}{\sqrt{g d_{p}^{3/2}}}$.

![Graph](image)

**Figure 2.** Critical bias $i_k$ dependence from the flow parameter $\theta$ in HCSP with a smooth tray at the pipe bottom at the free-flow mode and different types of head construction: (a) - cut off on a slope with a ledge; (b) - cut off on a slope without ledge.

Flow coefficient $m$ at the free-flow mode is defined according to the offered settlement dependence

$$m = 0.37 + 0.15 f_{p}$$

Flow coefficient $m$ for HCSP can be accepted depending on the head type and the presence of the smooth tray: without smooth tray at the pipe bottom respectively $m= 0.34; 0.345$ and $0.365$, and with installation of the smooth tray at the bottom is 10% more.

In the process of a roughness coefficient for HCSP working finding in the pressure head mode it is necessary to consider both parameters: pipe bias and construction of the head. If the inlet head of the pipe is a cut perpendicular pipe axes and with the maximum value of hydraulic coefficient resistance $\lambda$ value of a roughness coefficient $n \approx 0.028$. And for a bell-shaped inlet head construction and a portal wall entrance head construction $n \approx 0.027$.

It is necessary to accept 11% less, than at free-flow mode at pipe bias $i_{p} = 0.03$ in HCSP the maximum value of a roughness coefficient for all studied modes almost identical $n \approx 0.027$, but at the pipe bias $i_{p} = 0.05$ maximum value of a roughness coefficient at the pressure head movement of water.

Water depth at the inlet to HCSP without smooth tray at the bottom is determined depending on type of an inlet head and flow parameter $\theta$ (see table 1), thus the bias of a pipe is not considered.

Water depth at the outlet of HCSP ($h_{w}/h_{i}$) rather precisely is determined depending on a pipe bias, (see Table 2), and thus head construction can be not considered.
Table 1. Relative depth on an inlet to HCSP without smooth tray at the bottom.

| \(i_p\) | Head type       | \(h_{w/d}\)   | \(h_{w/h}\)  |
|--------|----------------|---------------|--------------|
| 0.03   | Without head   | 0.22 + 1.87 \(\theta\) | 0.61+0.16 \(\theta\) |
|        | Portal wall    | 0.22 + 1.8 \(\theta\)  | 0.61+0.160 \(\theta\) |
|        | Bell-shaped    | 0.25 + 1.43 \(\theta\) | 0.61+0.135 \(\theta\) |
| 0.05   | Without head   | 0.22 + 1.84 \(\theta\) | 0.63+0.045 \(\theta\) |
|        | Portal wall    | 0.25 + 1.75 \(\theta\) | 0.58+0.16 \(\theta\) |
|        | Bell-shaped    | 0.28 + 1.38 \(\theta\) | 0.58+0.165 \(\theta\) |

Table 2. Relative depths \(h_{w/d}\) at the outlet from HCSP at various biases of the round pipes \(i_p\).

| Presence of the tray | \(i_p = 0.01\) | \(i_p = 0.03\) | \(i_p = 0.05\) |
|----------------------|----------------|----------------|----------------|
| Without tray         | 0.38           | 0.349          | 0.341          |
| Protective tray on the bottom | 0.375 | 0.314 | 0.278 |

In the semi-pressure head mode for CMP and HCSP with a smooth tray at the bottom passed water consumption \(Q\)

\[
Q = \mu_0 \omega \sqrt{2g(H_0 - \varepsilon d)}
\]  

\(\mu_0\) is the flow rate coefficient considering local resistance on the inlet to a culvert; \(\omega\) is the area of a stream section; \(H_0\) is hydrodynamic pressure; \(\varepsilon\) is the coefficient connected with type of head.

Usually neglect high-speed pressure before a pipe and substitute value of hydrostatic pressure in the formula (2) instead of hydrodynamic pressure. It is necessary to employ coefficients: \(\varepsilon = 0.73\) and \(\mu_0 = 0.65\) (for the inlet without head), \(\varepsilon = 0.72\) and \(\mu_0 = 0.67\) (for a portal wall head), \(\varepsilon = 0.7\) and \(\mu_0 = 0.68\) (for a bell-shaped head) at calculation of HCSP at the semi-pressure head mode with the pipe bias less than \(i_p \leq 0.1\).

Calculation of passed water consumption \(Q\) of pipes at the partial-pressure head mode is carried out from formulas (3) and (4).

\[
Q = \mu \omega \sqrt{2g(H_0 + il - \eta d)}
\]  

\[
\mu = \frac{1}{\sqrt{1 + \zeta_{\text{det}} + \lambda \frac{l}{d}}}
\]  

\(\zeta_{\text{det}}\) is the resistance coefficient depending on type of the inlet head; \(\lambda\) is the Darci's coefficient; \(\eta\) is the coefficient considering pressure distribution in the outlet section of a pipe.

Value of coefficient \(\eta\) for corrugated pipes depends on the flow parameter \(\theta\) [2, 7]: at \(\theta \geq 1.35\eta = 0.5\), and at \(\theta \leq 1.35\) coefficient \(\eta\) is calculated from the formula (5)

\[
\eta = 1.35 - 0.63 \theta.
\]  

The length of a trailer site \(l\) depends on flow parameter \(\theta\) and pipe bias for HCSP (Figure 3). At \(\theta \geq 1.4\) it is possible to consider \(\eta = 0.5\).

4. Conclusion

Conditions of hydraulic work and parameters of stream are experimentally studied for different modes of operation and with installation a protective tray at the bottom of a culvert transit part.

Introduction of the provided recommendations are limited to the cross section form of transit part of a tubular structure. It is impossible to use for hydraulic calculation of the pipe with non-round section; for culverts with other form and the sizes of a corrugation and also for different tray modifications such as the trays made of different materials with riprap or gabion elements.
Development of the corresponding recommendations requires is carried out additional hydraulic researches.

Figure 3. Relative length dependence of a trailer free-flow site on flow parameter θ for the studied HCSP models: 1, 2, 3 - the HCSP model at the pipe bias $i_p = 0.05$ with the inlet without head, respectively portal head and bell-shaped head; 4, 5, 6 - the HCSP model at the pipe bias $i_p = 0.03$ with portal head, bell-shaped head and without inlet head respectively; 7, 8 - the HCSP model at the pipe bias $i_p = 0.01$ with portal head and without inlet head respectively.

The algorithm and the basic principles of settlement justification of constructions from metal corrugated pipes with a normal and spiral form of corrugation is developed. The algorithm considers geometrical and hydraulic characteristics of the basic constructive elements of culvert structures and allows facilitate the right choice of innovative technical solutions in the design, options comparison, reconstruction of hydraulic engineering transport structures of complex appointment and the fast-built constructions from prefabricated metal corrugated elements. It allows carrying out calculations for real structures of different tubular transitions correctly and to ensure functional, constructive and information reliability of culvert from metal corrugated pipes.

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