Decrease in ecological damage of water throughput tubular transitions on spawning

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Abstract. Intensive growth of traffic demands decrease in negative impact of water throughput constructions on ecology. Conditions of the correct installation of the tubular transitions made from steel corrugated elements (MCE) on spawning waterways which performance will allow to ensure ecological safety at movement of fish are defined. Recommendations about the organization of overcoming by fishes of difference and a velocity pressure when moving in MCE culverts are made. The obtained data on speed on a transit part of a water throughput construction are of interest at problem solving on easy access of fishes through culverts to up-stream and design of culverts. Results of pilot hydraulic studies of MCE pipes of round shape according to depths and speeds are presented on an outlet from a pipe for different operating modes, at existence and lack of a protective tray in a ground part of pipes with helical (HC) and a normal (NC) form of a corrugation. It is established that if 10% of cross sectional area of a corrugated pipe are occupied with stone dumping, then flow rate is reduced approximately by 10 - 12%. Based on results of laboratory researches and published materials, data for assessment of value of roughness coefficients of composite section of a round culvert in the form of one-point transition are provided and the targets of future researches on melioration of culverts are planned. Received results can be used at hydraulic calculations and optimization of water throughput designs in nature protection and also highway engineering.

1. Introduction

On highways the most perspective and economic is performance of water throughput constructions (such as pipes - culverts, arches, arches pipes) from metal corrugated elements (MEC) [1-3]. For an exception of hydrological and environmental disasters, safety at road and nature protection construction, it is important to inform designers and operators on operating conditions of pipes from MCE with different type of a corrugation (normal – NC and helical – HC), correctness of their hydraulic calculation and also features of interaction of MCE with an ecosystem of a water object (a spawning waterway or a stocked reservoir).

When crossing a spawning waterway, artificial water throughput constructions from MCE should answer a number of the major requirements, namely:

- provide the free admission of fish, a necessary amount of water, free migration of fishes at any stage of their development;
- exclude considerable siltation of a pipe and suspended waters;
- provide the invariable speed of a current of water and support its size according to the prevailing breed of fishes;
- provide the minimum deformation of bed of a waterway and places of spawning;
- provide maintenance of the course of a waterway or its certain site in natural or close to natural a state at minimization of perturbations in a flow;
- provide observance of legislatively established requirements to passing of fish and basic provisions of laws regarding environmental protection, protection and use of water biological resources.

On ability of the movement of fishes in a culvert influence: design of entrance and output head; size and form of pipe cross-section; length, roughness, bias and constructive registration of a benthonic part; speed, extent of filling of a pipe and biophysical parameters of fishes. Optimal conditions can provide to the migrating fish also anti-vortex devices before a tubular construction from MCE, existence of a step cascade behind it, the fish pass device on a transit part or in a diversion channel behind a culvert, etc.

It is known that pipes from MCE work in 4 main hydraulic modes: free-flow, semi-pressure head, partial and pressure head and pressure head [1–3]. As design in Russia for road pipes accept the free-flow mode which takes place at not flooded entrance to a head. At the same time the recommended restriction of filling of entrance and output section of NC should not exceed respectively 0.75 and 0.9 from height or pipe diameter. Spawning water currents at the admission of a design flowrate require a possibility of passing of fish on a pipe against the current. About 80% of water throughput pipes in the flat area of the Russian Federation have a bias 5...10% therefore it is possible to assume that work as NC and HC in the semi-pressure head and pressure head mode when crossing highways through a spawning waterway most likely economically will be ineffective. It is caused by big costs of the devices for filtration reduction, ensuring resistance of an embankment to water filtration, strengthening of the bed at the inlet and an outlet from a pipe. Therefore we will consider hydraulic aspects of passing of fishes through the road culverts from MCE working generally in the free-flow mode or partially pressure head mode (which can arise at hypothetical hydrological accident on a water object).

2. Materials and methods
Modern models of passing of fish on a culvert are one-dimensional as are constructed on a ratio of ability of swimming of fish to the average speed of a flow arising in a one-point pipe. In that case carrying out physical modeling and performance of a detailed research of distribution of flow rate in process of filling of pipe cross-section and change of depth of a flow longwise of a water throughput metal pipe from MCE with the normal corrugation which is (rather in detail investigated), and with helical, a little investigated, a corrugation is necessary. For this purpose at first it is necessary to evaluate efficiency of modern methods of calculation of roughness of the "corrugated pipe-an abrasive covering of a ground part" complex and composite "a ridged surface of a pipe - benthonic area from stone dumping", in relation to a water throughput pipe from MCE which is in Russia which is almost not explored and standardly not approved so far.

The operating experience, design and calculations of NC and HC in Russia and abroad allows to draw a number of conclusions on increase in efficiency of hydraulic work of road water throughput pipes from MCE depending on a form of a corrugation, diameter and a bias of a pipe, existence at the bottom of reinforced-concrete smooth flumes or gravel and pebble dumping. Pilot studies are conducted in laboratory of department of hydraulics of Moscow Automobile & Road Construction State Technical University (MADI) [3] on pipe model with a normal and helical corrugation diameter in nature of 1 m and 1.2 m according to a linear scale factor 5. The sizes of a normal corrugation were in NC 130X32.5 mm, in HC – 125X25 mm. The bias of pipes changed in the range from 0.01 to 0.1. The central corner \( \varphi \) at installation of a smooth tray made 120\(^\circ\), when dumping gravel and pebble mix - \( \varphi = 90^\circ \). After the research of influence of a design of entrance head on NC, the main part of experiments with HC has been conducted [3] with entrance to heads with a cut perpendicular to a pipe axis, and day off – in the form of a portal wall. The maximum error of measurements of a hydrostatic pressure \( H \), depths \( h \), an
expense Q, water temperature did not exceed 4%. The program complex allowed to build pressure heads in the automatic mode, to calculate expense parameters \( \theta = \frac{Q}{\sqrt{g d_p^{5/2}}} \) (\( d_p \) - the rated diameter of models), to determine resistance coefficients, normal depths, roughness coefficients by Manning \( n \). At installation of a smooth tray on bottom of pipes and values of a Reynolds number more than 350,000 for pipes with a normal corrugation, and more than 400,000 for helical corrugation pipes there came the square area that was well coordinated with natural data of Ch. Neill [4]

3. Results and Discussion

Results of laboratory researches have shown that the value of coefficient of roughness \( n \) at the free-flow and pressure head movement for NC and HC can be a miscellaneous and is considerable differ from recommended in standardizing document (SD) in Russia. It is confirmed with model and natural researches in which the value of roughness coefficient \( n \) at the free-flow movement in some cases is less, and sometimes it is more, than at pressure mode. Installation of a smooth tray on a bottom of corrugated pipes is regulated by SD for protection against abrasive destruction that allows to provide decrease in hydraulic resistance and to reduce value of coefficient of roughness \( n \). At the same time it leads to reduction of the extent of a throat area and cross sectional area of a pipe. A tray, occupying a part of internal perimeter of a pipe (Figure 1a), creates the added resistances depending on the central corner \( \delta \) and the minimum thickness of a smooth tray \( \delta \) which is 5 cm in the USA, in the Russian Federation – \( \delta = 10 \) cm. With change of filling of a corrugated pipe the ratio between the sizes of a smooth tray and corrugated sheet in equipotential section changes, i.e. between wetted perimeters of the smooth and corrugated parts of a pipe therefore the nature of change of roughness coefficient \( n \) depends on the sizes of a smooth tray and filling of the pipe \( h/d \).

![Figure 1](image)

**Figure 1.** Options of transitions from MCE on spawning waterways: (a) - NC with a smooth tray at the bottom: 1 – a metal pipe with a normal corrugation; 2 – packaged units of a tray; 3 – protecting cover; 4 – bolts; (b) - stone dumping in the absence of a tray in a round pipe

Lack of culverts from MCE on a spawning waterway is that tubular transitions, constraining a flow, cause it to pass through smaller cross sectional area. It leads to loss of the habitat, natural substrate and zones of a quiet current where fish could have a rest earlier. For compensation of these losses in addition to installation of a pipe with the corresponding bias as it is possible closer to a natural channel of a stream, it is necessary to bury on spawning waterways a culvert bottom below a waterway bottom (on depth not less than 2 … 3 rated diameters of a stone or 0,1…0,2 from pipe diameter). And also for preservation of the native habitat of fishes to cover a tray part of NC with the natural material steady against rated speeds of water in a pipe (a stone, gravel, coarse sand, etc.) (Figure 1a). All this provides more natural bed of substrate and increases roughness of a water throughput pipe, reducing the average speed of a flow which would be in not buried water throughput pipe of similar cross sectional area.

Forecasting of values of coefficient of roughness \( n \) for round pipes diameter \( d \) from MCE with a gravel layer at the bottom is quite difficult task what numerous researches (Strickler, testify 1923 to;
Meyer-Peter and Muller, 1948; Limerinos, 1970; Bray, 1979; Bruschin, 1985; Abt et al., 1987; Julien, 2002, etc.). These methods have been developed first of all for use in the rivers with a gravel bottom and have received widely varying results. Generally they treat model range 0.027 < n < 0.031 when material of a surface course is linearly scaled. In practice natural values of roughness coefficient n of real melioration objects, for example, in Manitoba [5], varied from 0.035 to 0.041. It is possible to call roughness of this kind composition. For reliable assessment of roughness coefficient of a composite "a ridged surface of a pipe - benthonic area from stone dumping", it is necessary to evaluate experimentally values n in different operating modes of tubular transitions from NC and HC and to verify the existing methods of forecasting of roughness of a similar composite.

On the basis of the researches executed in MADI earlier (Figure 2) [3] it is possible to assume that at 10% the size of a gravel bed and filling of a pipe approximately 0.15 d, (that corresponds to filling of a zone of a smooth tray or gravel sketches), the value of coefficient of roughness n is expected should strive for value of coefficient of roughness for the gravel open course of a natural waterway. Thus, [1-6] recommendations provided in works are not enough for correct assessment of change of coefficient of roughness in all the range of fillings of water throughput metal pipes from NC at the different amount of gravel registration of its bottom and various modes of the movement of water in a construction.

Preliminary pilot studies have really shown reduction of flow capacity of a water throughput pipe from MCE at addition of a gravel layer that is caused by reduction of the area of a flow and increase in roughness of a composite. At the same time it has turned out that at 10% occupation of the area of NC its flow capacity is reduced by stone dumping approximately by 10 - 12% both for pipe bias i = 0.005, and at i = 0.01.

It is established that the value of coefficient n even in pipes with the uniform evenly laid gravel dumping can change for 28% only because of change of depth of a flow. Researches have shown that as in a pipe section compound – composite, the value n depends on depth of water and varies on model in the range of 0.0230 < n < 0.0256, and in some experiences when filling from 0.4 d to 0.75 d reaches 0.029 for the gravel course, i.e. about 0.039 in nature. It is necessary to remind that for NC in the absence of additional devices in a transit part of a pipe the value of coefficient of roughness n does not depend on filling of a pipe (filling change, and respectively and the mode occurs at the free-flow mode in the range of change of filling of h/d = 0,12...0,52, and at semi-pressure mode - h/d = 0,52...0,82). Its weighted average is approximately identical and is on model n = 0.0268, and in real culvert n = 0.035. And at the pressure mode movement for this design the value 12% lower and is in real culvert n = 0.03. For HC without protective smooth tray at the bottom for assessment of stability of hydraulic work of water throughput transitions of round section it is expedient to accept at a pressure mode of n = 0.027, and at free-flow – n = 0.03.
Figure 2. Dependence of coefficient of roughness across Manning $n$ from change of the relative depth $(h/d)$ in culverts from corrugated metal with a composite coating of a transit part at $i = 0.03 \ldots 0.05$: 1, 3 – according to NC and HC without tray on a bottom; 2, 4 and 6 – NC and HC with a smooth tray on a bottom; 5 – NC with gravel dumping on a bottom.

It is established, for NC with a corrugation of 130x32.5 mm and a smooth tray on a bottom influence of a bias of a pipe on value $n$ has an appearance

$$n = 0.02 + 0.034i$$  \hspace{1cm} (1)

During the experiments it is received that at a free-flow mode of NC with a smooth tray on a bottom with biases $i = 0.01 \ldots 0.1$ and design filling at the inlet $h/d = 0.75$ value of coefficient of roughness can accept $n = 0.019$. During the work of NC with a smooth tray on a bottom in the free-flow mode with fillings at the inlet $h/d = 0.9 \ldots 1.0$ coefficient of roughness in the range of change of a bias $i = 0.01 \ldots 0.096$ are almost identical and can be accepted with a small stock equal $n = 0.021$. For HC with $d = 1.2$ m, a corrugation of 125x25 mm and a smooth tray on a bottom value of coefficient of roughness at the free-flow movement of water it is possible to accept $n = 0.0207$ (at $i = 0.03$) and $n = 0.0226$ (at $i = 0.05$), and at pressure mode – $n = 0.0234$. Results on increase in coefficient of roughness with increase in filling of a pipe from MCE with a smooth tray on a bottom qualitatively coincide with the available foreign experimental data.

Comparison of values of flow rates $V_{out}$ at outlet from smooth and corrugated pipes shows that at the free-flow and semi-pressure head modes of their value are close only at bias $i = 0.01$ and the parameter of an expense $\theta = \frac{Q}{\sqrt{ghd_{o}^{2}}} \lessgtr$ less than 0.7, and at change of a bias of pipe $i$ from 0.03 to 0.1 in a corrugated pipe of speed it is less. At pipe bias $i = 0.03$ for the free-flow mode reduction reaches 18%, for semi-pressure head – 13%. At $i = 0.1$ at all modes and parameters of an expense reduction of speed for the free-flow and semi-pressure head modes considerably also is according to 50% and 38%, and for the first partial and pressure head mode (when the pipe bulk from entrance the head works in pressure, and at the outlet – the free-flow movement) – 30%. At the same time it is necessary to consider that existence of an protected from an erosion smooth tray on a bottom in NC can increase the flow capacity of such constructions at the free-flow and semi-pressure head modes respectively by 10% and 14 … 18% in comparison with the existing recommendations for pipes from culverts without smooth tray.
Thus, at pipe bias \( i > 0.01 \) it is established that average speed at the outlet at a corrugated pipe is less, than at smooth pipe for all modes. It allows reduce at design length of fastening of the taking-away course behind a corrugated pipe, to choose optimum and simpler type of strengthening of protection of the downstream against washout and it is more correct to define hydraulic characteristics of a flow on strengthening of an end part of tubular transition.

**Figure 3.** The schedule of dependence of \( V_{out} = f(Q) \) for natural pipes diameter of \( d = 1.5 \) m with biases \( i = 0.03 \) and \( i = 0.01 \): --- for the smooth pipe working in the semi-pressure head mode; --- for NC working in the first partial and pressure head mode; --- for a pipe from MCE with a smooth tray on a bottom.

In the hydraulic relation in modern nature protection construction and at reconstruction of road bypass tubular constructions in the course of a relining it is preferable to use a corrugated pipe instead of smooth one that is confirmed also by long-term practice of operation of corrugated pipes in Canada, France, Japan, the USA and other countries [7, 8].

Water speed at the outlet from a water throughput pipe should be close to flow rate in a spawning waterway. If speed at the outlet from a water throughput pipe exceeds maximum, then fish will not be able to overcome a current and to come into culvert, i.e. for providing a quiet outlet of fish from culvert the outlet should have whenever possible low speeds of a current of water.

To provide free passing of fish through a water throughput construction it is necessary to expel the following reasons causing negative impact of a culvert on a fish flow from MCE:
- existence of difference of water levels in a waterway and pipe;
- formation of a threshold between the river and a pipe both from tale race, and from an upper race;
- small pipe diameter;
- too big bias of a pipe;
- unacceptably high speed of a current of a water flow in a pipe;
- insufficient depth of water in a pipe;
- lack of a creek for rest of fish is lower than a culvert;
- insufficient roughness of an inner surface and bottom of a pipe.

Water throughput pipes NC on spawning waterways it is more expedient to use a round or arch design (if flow rate less than admissible washing away). The round design demands increase in diameter (from 1.5 to 7 m) in comparison with hydraulic calculation. For creation of necessary illumination in a pipe it is necessary to provide excess of a crown of a pipe over water level in 1 m and more.

Water level difference reduction (or its full elimination) and also blockings of the center of erosion lowering bottom level on the fountain site with formation of falls requires holding special constructive
events. So the difference of water level can be corrected by the construction of a retaining cascade by means of boulders or logs. For adult fishes each step should increase water level no more than on 25 … 30 cm. For clearing of an excess energy behind a tubular construction on a spawning waterway at heavy flow rates of water it is better to use a gravel pond.

4. Conclusions
High technical-and-economic indexes and favorable conditions for hydraulic work of corrugated pipes give the grounds to recommend them for application, at any biases in hydro amelioration and nature protection tubular constructions including with difference on spawning waterways and also at biases $i > 0.01$ in road transitions.

Design data of water throughput constructions from MEC are appointed taking into account type of a spawning waterway, the specific list of the fishes living or coming on spawning into a small waterway, width of roadway covering. The mode of operation of such constructions is proved taking into account requirements of hydrobiontes. The dependences of coefficient of roughness based on their interrelation with a pipe bias are given. It is shown that existence of a smooth tray or the stone dumping protecting a ground part of corrugated pipes from abrasive destruction by a multiphase flow significantly changes conditions of hydraulic work: hydraulic resistances at the free-flow movement change with change of extent of filling of a pipe, as well as an flow rate and a technique of hydraulic calculation.

On the basis of preliminary results of model researches and also the published data, recommendations which will allow to eliminate migration barriers in headwaters of the small river are offered and will serve as the management for future researches of water throughput transitions from metal corrugated structures (NC, HC) on spawning waterways. Application of such culverts gives the simplest method of maintenance of migration conditions, nature, favorable for fishes, by partial deepening of a pipe is lower than a bottom of a waterway and filling of a part of pipe cross-section with gravel dumping.

Values of roughness coefficient in a composite metal corrugated water throughput pipe with gravel dumping at the bottom are for the first time received. It is established that depending on a pipe bias and the mode of course of water in the buried pipe which bottom is covered with gravel not less than for 10% the value of coefficient of roughness turns out approximately in 1.1... 1.4 times are more than values $n$ for corrugated transitions in the absence of any tray at the bottom. It gives the chance to apply the specified values $n$ at preliminary design stages and when calculating in the existing program systems.

It is necessary to continue researches, varying the average diameter of material sketches ($D_{50}$), deepening of a pipe, a corner of the sector of the fixed site of a bottom of a water throughput pipe and its size ($d$) in the wide range of values. For development of norms and methodical recommendations about hydraulic calculation of tubular water throughput transitions from corrugated metal structures of the increased sizes with a helical and normal corrugation, the directions for of their operation and to monitoring working in the conditions of stocked water currents it is necessary to investigate experimentally pipes which ground part is strengthened by rock filling and gabion elements.

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