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WAY TO REDUCE SUBGRADE IN HIGHWAY CONSTRUCTION

Abstract

There is formulated the dement of minimum of land works in road construction. For it is suggested new method to construct road pipes and new method of their hydraulic design.

Keywords: subgrade, soil volumes, pipe, flow, width, depth, water discharge

1. Introduction

Lack of land for the layout of traffic installations and soil for the construction of roadbeds has become in many ways a primary and dire problem preventing construction of new highways. It can put off the construction works for a long time, sometimes even years.

2. Main text

The issue of gradual, inconspicuous switch to universal planning of highways on embankments has already been discussed before [1]. This switch has not been recorded in any regulations, but it seems that roads constructed at ground level have somehow vanished from said regulations. Already in the Highway Planning manual for engineers [2] this cross section type is mentioned (and only on a diagram – see Fig. 1), but only once, and subsequent regulations do not touch upon it.

In the Highway Cross Section Design Principles section of the book it is said that "the general optimality criterion in planning the formation line of a highway cross section can be determined as":

$$Exp_t = C_0^{rb} + C_0^{mi} + C_0^{str} + C_0^{la} + C_0^{p} + \sum_{T=1}^{T}\frac{1}{(1+Ed)^T}\cdot\left(E_e^{sn} + E_e^{tr} + E_e^{t} + E_e^{a}\right) \qquad (1)$$

Where: Exp_t = total expenses for the target period (т); C_0 = cost of, respectively; rb = roadbed; mi = man-made installments; str = strengthening constructions; la = land appropriated for the highway construction; p = paving; E_e^{sn}, E_e^{tr} = annual snow defense and transportation expenses respectively; E_e^{t}, E_e^{a} = financial losses caused by the passenger time loss and road traffic accidents respectively; Ed = discounting coefficient.

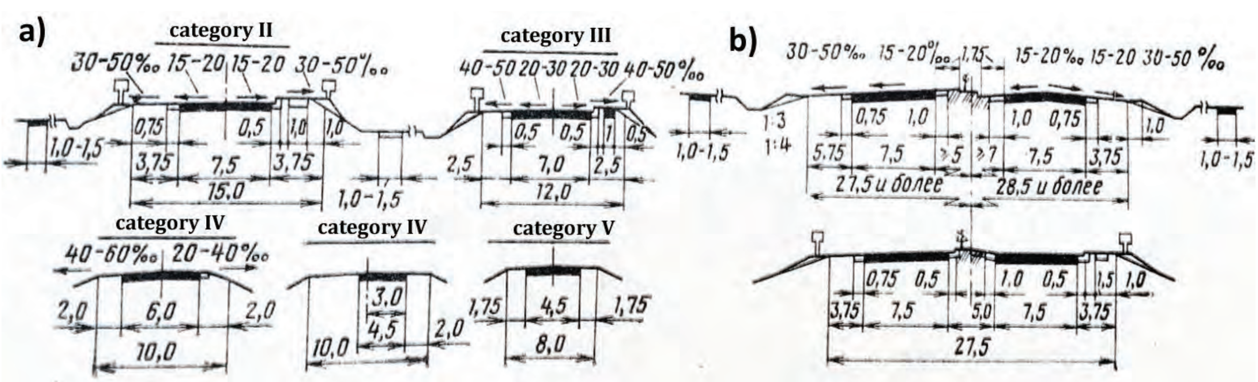

Fig. 1. Highway cross-sections: a) categories II – V; b) category I

In the equation (1):

$$K_0^{rb} = \sum_{i=1}^{n} q_i V_i$$

$$K_0^{str} = \sum_{i=1}^{n} k_i^{str}\left(l_i^{sl} + l_{i+1}^{sl}\right)\cdot\frac{l_i}{2}$$

$$K_0^{la} = \sum_{i=1}^{n} k_i^{la}\left(\frac{[Wi + Wi{+}1]}{2} + 2\right)\cdot l_i$$

Where: q_i = grading unit cost on the ith section of the cross section; V_i = cross sectional volume of the ith section of the roadbed; k_i^{str} = strengthening unit cost; l_i^{sl}, l_{i+1}^{sl} = lengths of the cross slope parts in the ith and i+1th sections that need to be strengthened; l_i = length of the ith section; k_i^{la} = land appropriation unit cost for the ith section; W_i, W_{i+1} = combined width of all the elements of the roadbed on the ith and i+1th sections (summand 2 means that the uniform appropriation includes an additional meter of land to each edge of the roadbed). K_0^{mi} element is a cost function of the construction of the box culvert portal and body.

From the analysis of these equations we can see that the main factors contributing to a possible rise in expenses (which should be avoided) are: roadbed construction cost, man-made installments cost, strengthening units cost, land appropriation cost, annual snow defense cost and partially road traffic accidents losses. All these components correspond directly to the elevation (working) point of the traffic-bearing surface. This includes losses caused by accidents with vehicles driving off the road. The remaining components (paving cost, annual transportation cost and passenger time loss) are not affected by the elevation level of the formation line of the cross section.

All the former costs will naturally may be minimized by the roadbed be constructed on the ground level.

It should also be mentioned that cutting down (but not eliminating!) embankment construction will considerably lower or eliminate completely the demand for soil excavation works, building of temporary soil transfer tracks, lessen the environmental pressure at the time of construction, prevent 'road fragmenting' (i.e. cutting into nature isolated parts) of the areas of the country. The issue of snow defense on highways should be given special consideration in a separate study.

Automatically controlled highway cross section planning is based on the location of reference fixed points [2, 3], a type of which is the minimum level of the roadbed elevation over the small-scale culverts. In the flat land with shallow washes and stream beds of small regular and, more importantly, irregular streams employment of the usual culverts leads to the unnecessary elevation of the formation line and as a result to the construction of embankments where a formation line could be laid out at the ground level. Eventually it raises the cost of the roadbed, increases the land demand, terrain fragmentation and environmental disasters.

The reference point of the cross section derives from the sum of the height (diameter) of the pipe culvert and the minimal acceptable layer of soil fill above it. The minimal bore diameter of a pipe culvert is 1 meter; the minimal layer of soil fills - 0.5 meters. Hence the minimal level of the embankment is 1.5 meters and with the required leveling of the side slopes it goes up to 2 meters.

One of the main reasons for raising the reference points is the stream narrowing principle employed at the hydraulic design of the highway culvert pipes. It means that the pipe opening of the culvert is considerably smaller than the width of the river bed. The steam narrows and its nature depth increases. The flow velocity increases also that it needs the construction of river bed protection. Pipe carrying capacity secures by increase of height pipe (diameter of pipe). But this culvert design principle makes it impossible to minimize (to the ground level of neighboring terrain) the embankment level of the small-scale washes or stream beds.

There is only one way to lower embankments of the small-scale stream beds I is a refusal from steam narrowing principle in the hydraulic design of road pipes and to use the stream widening principle. But it would change the flow before and behind the water pipe.

So, before we turn to the design of the culvert let us first examine the flow of water before it enters the portal of the culvert and inside of it.

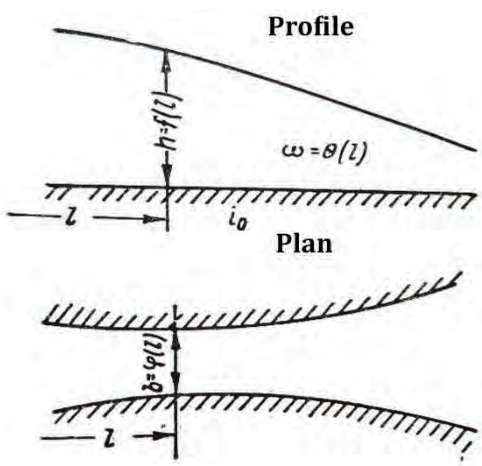

Fig. 2. Plan and cross section of a widening water stream

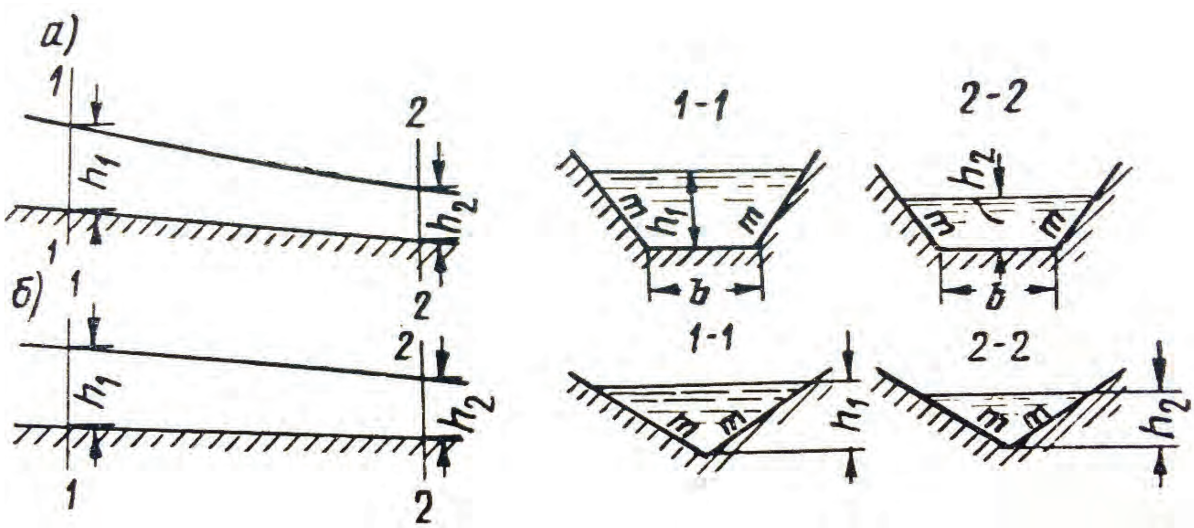

Fig. 3. Types of (prismatic) cross sections of ravines and river beds entering small-scale culverts

The changing of the width and depth of the flow (Fig. 2), when water discharge is constant, is making a flow by irregular.

By changing these characteristics we will change free flow cross-section area. As a rule cross sections of ravines and river beds are non-prismatic (their banks are more softly shaped), but we shall examine prismatic trapezium- and triangle-shaped cross sections (Fig. 3) that simulate reality well enough.

The water flow in these streams can be defined by the equation (at zero slope):

$$\frac{dh}{dl} = \left(i_o - \frac{Q^2}{\omega^2 \cdot C^2 \cdot R} \right) / \left(1 - \left[\frac{\alpha \cdot Q^2}{g} \right] \left[\frac{W}{\omega^3} \right] \right) \qquad (2)$$

where: h = depth of the stream; l = length of the stream bed under examination; Q = flow rate; ω = square area of the water cross section; C = Chezy's velocity factor; R = hydraulic radius of the stream, $R = \omega / \chi$; g = gravitational acceleration; α = coefficient (velocity factor); χ = wetted perimeter of the water cross section.

Specific energy Э in the cross section is a continuous function of the depth h of the stream and has minimum when its depth is critical – h_{cr}:

$$\alpha \cdot Q^2 / g = \omega_{cr}^3 / W_{cr} \qquad (3)$$

where: ω_{cr} = square of free cross section at the critical depth; W_{cr} = width of the stream at the free water level at the critical depth.

The diagram, depicted on Figure 4 illustrates changes in the stream energy in relation to the change of depth. If the depth exceeds h_{cr} specific energy of the stream increases (dE/dh > 0), if it becomes less than h_{cr} specific energy of the stream decreases (dE/dh < 0).

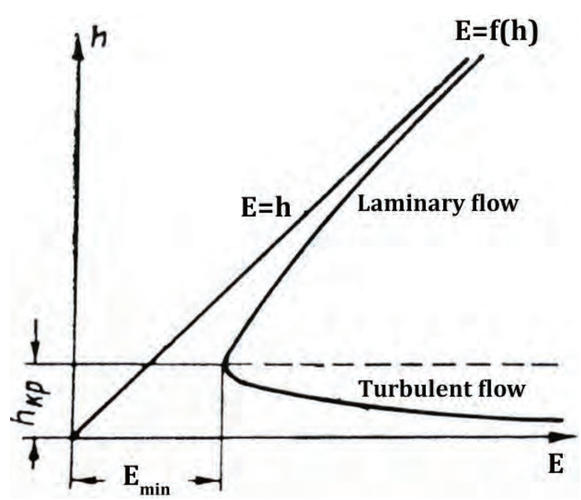

Fig. 4. Specific energy change at the cross section E in relation to the depth of the stream; h = depth of the stream, h_{cr}= critical depth.

If the depth of the stream exceeds the critical depth the flow is considered laminar, otherwise – turbulent. The minimal energy critical width (as well as the depth) of the stream can be calculated with the equation

$$\left(\alpha \cdot Q^2 / g \right) (W_{cr} / \omega_{cr}^3) = 1 \qquad (4)$$

The product of this equation is referred to as the kinetic factor P_k. It can also be defined as $P_k = 2(\alpha \cdot v^2/2g) / h_{av}$. The kinetic factor, hence, is the ratio of the doubled specific kinetic energy to the average depth. In the case of a two-dimensional rectangular section problem average depth h_{cp} equals the stream depth h. Then

$$P_k = 2\,(\alpha \cdot v^2 / 2g) / h = \alpha \cdot v^2 / gh = Fr \qquad (5)$$

Therefore the average Froude number (Fr) defines the ration of the doubled kinetic energy to the specific cross section potential energy. After the insertion of the kinetic factor to the equations 4 and 5 they can be rewritten as (at zero slope)

$$dh/dl = (i_0 - Q^2/K^2)/(1 - P_k) \quad (6)$$

where: $K = \omega \cdot C\sqrt{R}$, the discharge characteristic at the stream depth h.

While the flow rate Q remains constant, the values of the variables K and P_k in the right hand side of the equation (6) depend only on the characteristics of the water cross section: ω, W, R, C, which in their turn are functions of the stream depth h. Hence we can pick the value of the stream depth so that the numerator on the right-hand side of the equation (6) becomes zero.

As the width of the stream grows and its depth decreases the hydraulic grade line shifts too. This process deserves our utmost attention. The unevenly smoothly changing flow of water in the open non-prismatic riverbed is defined by the equation [4]

$$dE/dl = dh/dl - (\alpha Q^2/g\omega^3)(W\, dh/dl + \delta\omega/\delta l) \quad (7)$$

which for the prismatic riverbed can be extended to the function

$$dh/dl - (\alpha\, Q^2/g)\,(W/\omega^3)dh/dl +$$
$$+ (Q^2/2g\omega^2)\,(\delta\alpha/\delta h)\cdot dh/dl = i_0 - Q^2/\omega^2C^2R$$

According to [4] δα/δh in this equation with some bogey value

$$\delta\alpha/\delta h = (\alpha_2 - \alpha_1)/(h_2 - h_1) = a = const$$

We get

$$dh/dl = (i_0 - Q^2/K^2)/(1 - P_k + \alpha Q^2/2g\omega^2) \quad (8)$$

The curve of the hydraulic grade line of the widening stream with a constant flow rate can be calculated with the Chézy formula

$$Q = \omega C \cdot \sqrt{Ri} \quad (9)$$

The depth of the stream after some transformations of the equation (9) [4] can be defined by the formula

$$h = \sqrt[3]{(Q^2/\,W^2\;C^2 i)} = (n^2\;Q^2/\,W^2 i)^{10/3} \quad (10)$$

where: W = the widht of the stream at the cross section under examination; n = river bed hydraulic roughness coefficient (table 1); i = longitudinal slope of the riverbed at the section under examination; C = Chézy coefficient, roughly defined by the Manning formula as $C = h^{1/6}/n$.

Let us use equation (10) and make graphs of the change in depth and velocity of the widening water flow (Fig. 5, 6) at the water area before a pipe. The width of the flow (initially) is 1 m, the width of the following sections is 2.0, 3.0, and 4.0 m as shown on Figures 5 and 6. The roughness (n) and slope (i) of the riverbed remain constant (0.02 and 0.01 respectively).

$h^{5/3} = Q\,n\,/\,W\,i^{1/2}\,; \quad C = h^{1/6}/\,n; \quad v = C\,(\,R\,i\,)^{1/2} = 5\,h^{2/3}$

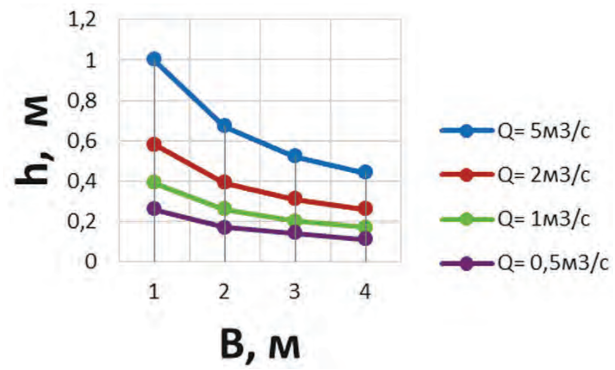

Fig. 5. Change of the depth of the flow as it widens

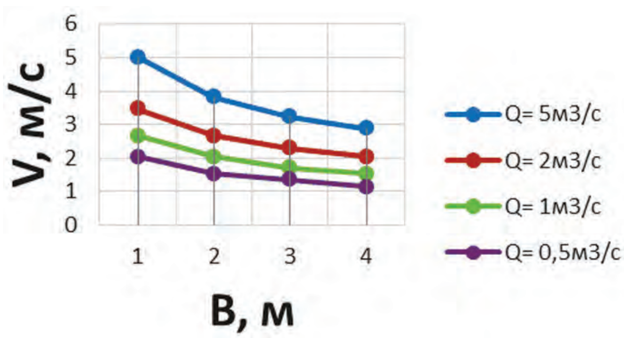

Fig. 6. Change of the velocity of the flow as it widens

The graphs show a sharp fall in the depth and velocity of the flow. In the majority of cases dry creeks have gentle slopes covered with grass, sometimes with a soil riverbed. During a flood the water flow may transport a lot of polluting particles such as dry branches and bottom sediments that can clutter the portal of the pipe.

Bottom sediments in the flow are influenced by two forces, fluid resistance (drag) and lift. Subject to these forces the particles move along the flow and rise to the surface. Drag and lift forces depend on the flow velocity, particles' size (d), density and viscosity of the liquid (ρ and v respectively). According to M.A. Velikanov [4] drag force F can be described as

$$F = k_1 \cdot \rho \cdot d^2 \cdot v^2,$$

lift force S as

$$S = k_2 \cdot \rho \cdot d^2 \cdot v^2,$$

where k_1 and k_2 are coefficients of the drag and lift forces calculated experimentally with regard to the liquid viscosity μ and dynamic velocity v_d. Dynamic velocity is defines as the minimum value of the bottom velocity (v_{bot}) that initiates movement of the separate particles of soil, so that it becomes the starting velocity. For loose soil with particles sized from 0.1 to 5 mm the starting velocity can be calculated using the equation [4]:

$$v_d = \sqrt{15 + 6/d} \cdot \sqrt{gd} = a_d \sqrt{gd} \qquad (11)$$

where: d = diameter of the load particles, mm; a_d = 15 + 6/d.

Eventually the drag force can be calculated using the formula

$$F = \rho \cdot \lambda \cdot v_{bottom}^{2}/8\xi^2 \qquad (12)$$

where: v_{bottom} = flow bottom velocity; ξ = relative velocity, $\xi = v_{bottom}/v$; λ = Darcy coefficient.

According to M.A. Velikanov, A.I. Losievsky, M.A. Dementiev [4] lift force is calculated using the formula:

$$S = k_3 \cdot \rho \cdot v_{bottom}^{2} \cdot s \cdot k_4 \qquad (13)$$

where: k_3 = proportionality factor; s = ratio between the area under the lift force to the combined area of the particles' projections on the bottom; k_4 = solidity factor, that determines density of the particles' allocation at the bottom.

To estimate erosion of the cohesive soil one must also take into account the cohesion force between solid particles. Numerous studies have established velocities of the flow in order for the beginning of movement of the cohesive and loose soil particles to commence (permissible velocity). The data is presented selectively in tables 3, 4 [5].

In order to determine the discharge of the bottom sediments experimental results (based on the mathematical statistics methods) are used. The most frequently used formulas are [4, 5]:

V.N. Goncharov's

$$q_l = 2{,}08\ (v/v_s)^3 \backslash (d/h)^{1/10}\ (v - v_s)\ d, \qquad (14)$$

I.I. Levi's (for d/h > 1/300)

$$q_l = 2\ (v/gd)^3\ (d/h)^{1|4}\ (v - v_s)\ d \qquad (15)$$

where: q_l = sediment discharge in kg/s per one meter of the depth of the flow; v_s = average velocity corresponding to the velocity required for the particles to begin moving.

This analyse of the water flow shows that its width expansion before pipes considerably reduces the depth and power of flow by cutting water velocity. It gives favorable and more safe conditions for decrease of river bed deformation.

Meanwhile the study has also shown that it is necessary to expand the process of planning the small-scale culverts (and the highway surface drainage system on the whole) by including into it (in addition to the hydraulic calculations, portal engineering calculations, flow velocity calculations and strengthening the riverbed at the spillways) evaluation of the water flow at the area upstream in relation to the portal (riverbed condition evaluation, calculation of the widening of the flow, specifying the critical depth and velocity of the flow in front of the culvert). In this case planning of each small-scale culvert turns into a unique engineering project, excludes routine solutions from highway cross section planning while preserving all the automatically controlled planning methods. Small-scale culverts' portal planning and extended calculation methods may be included into the existing programmes of highway planning. Admittedly it would require an extended research into the examination of the floodplains of the small-scale regular and irregular flows (in addition to the evaluation of the outline and area of the drainage: collecting data about soil, bottom soil, types of vegetation, longitude grades and cross slopes of the riverbed).

Changing the hydraulic approach (principle) for the planning of the small-scale pipes requires developing new structures, different to the existing ones, allowing minimizing the level of the reference point of the crossing between a highway and a shallow riverbed. The height of the portal can be reduced to 0.5...0.2 m and limited in technical terms only by the exploitation requirements: access to the litter and load cleaning techniques. The width of the structure is determined by the demand and possibility of widening of the river flow in front of the portal till it reaches its critical depth when its energy comes to its lowest value.

3. Conclusion

Proposed method of road pipe construction is permit to construct roads in earthwork zero on the large sections. For example for many sections of new road Moscow – S. Petersburg, Moscow Central Ring road the decreasing of volumes of land works to 60000-70000 m^3/km.

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