Expansion of pipeless drainage functions for draining poorly permeable soils

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Abstract. Due to climate change, in the next 30-50 years, an increase in precipitation during the growing season is predicted in the Non-Chernozem zone of Russia. However, even now, traditional methods of draining poorly permeable soils in a number of cases have proved to be ineffective due to the insufficiency of operational and capital measures to accelerate the removal of surface water and the weak hydraulic connection between the arable layer and drains. The experience of operation of drainage systems in the Nonchernozem zone of Russia has shown that at large distances between channels, the removal of surface runoff is difficult. A rational solution is to reduce the distances between the conductive channels. In this case, instead of open collectors, we propose to use cavityless collectors for drainage, which do not interfere with the movement of heavy agricultural machinery. A complete analysis of the functioning of cavityless collectors has been carried out. In the part of hydrology, accounting for the increase in precipitation is discussed and a method is given for calculating the maximum average daily module of drainage flow for the early spring and summer-autumn periods. A geotechnical calculation of the settlement during the passage of a heavy general-purpose tractor of the 5th traction class K-744R1 (Kirovets) was performed. It is shown that under the design conditions, the settlements will be about 1 cm. An example of a hydraulic calculation of the reservoir with the calculation of the initial and maximum depth of the filtration flow in it is given. Hydraulic calculation is carried out according to a proven method, the theoretical foundations of which were developed by the authors in previously published articles. An important feature is that all possible filtration modes are taken into account in the hydraulic calculation: laminar, transitional and turbulent.

1 Introduction

In recent years, the results of observations of changes in climatic conditions in the Non-Chernozem zone of Russia indicate an increase in precipitation during the growing season in the next 30-50 years [1]. Consequently, the water regime of the drained lands will undergo certain changes by the middle of the 21st century [1, 2]. There will be an increase in drainage flow (volume, intensity and duration). The continentality of the climate will

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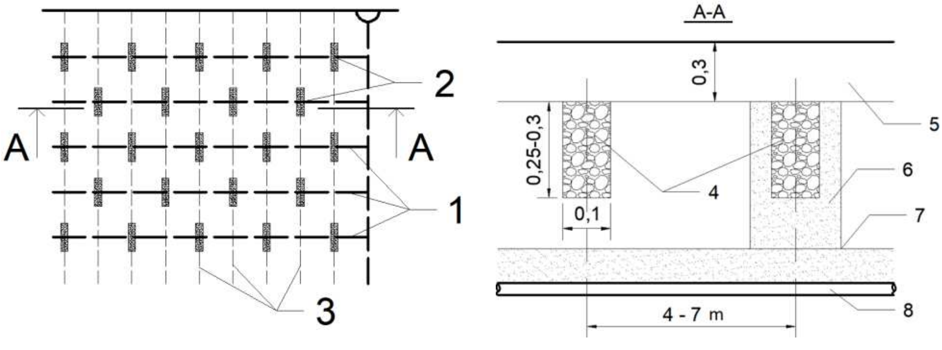
decrease in the North-West and in the Center of the ETS. It becomes closer to the Baltic type. The estimated water inflow to the drainage will increase by 10 - 15% (estimated drainage flow module).

As practice has shown, even under the prevailing conditions, traditional methods of drainage in poorly permeable soils turned out to be insufficiently effective. The main reason is the insufficiency of capital and operational measures to accelerate the removal of surface water, that is, a violation of the basic principle of draining poorly permeable soils.

In addition, closed drainage, arranged in such soils without well-filtering backfills, is not able to timely remove excess water from the root layer in the required time frame. The currently accepted parameters (first of all, the distance between drains of 10 m or more) cannot ensure its efficient operation and, as a result, the actual water inflow to the drainage will be 1.5-2.0 times less than recommended. Laboratory and field studies have established that in poorly permeable soils, in the presence of a well-filtering backfill, up to 70% of water enters the drain through the arable layer. Accordingly, in the absence of a reliable hydraulic connection between the arable layer and drains, a little more than 30% of the total volume to be removed falls into the drainage during the calculated period, which leads to waterlogging [3]. According to the calculations of British, Irish, Czech and other experts, in order to achieve a drainage rate on soils with a filtration coefficient of 0.001-0.03 m/day, drainage should be built with a distance between drains of about 5 m [3]. Drainage of poorly permeable soils is also considered in [4]

This is evidenced by the experimental data of SevNIIGiM, obtained in the course of joint research with Finnish specialists in the late 80s of the 20th century at the Zaitsevo experimental site in the Leningrad Region. The most efficient of the two dozen experimental systems turned out to be a two-tier drainage system based on cavityless drainage, which is also more environmentally friendly than traditional tubular drainage and is not afraid of negative temperatures.

The use of cavityless drainage is also effective in draining areas with ground pressure supply [5-7].



1 - tubular drains of the lower tier; 2 – junction nodes of drains of the upper tier with tubular drains; 3 - voidless drains of the upper tier after 4-7 m; 4 - hollow drains of the upper tier; 5 - arable layer; 6 - junction of drains of the upper tier with tubular drains; 7 - volumetric filter of tubular drain H=0.2 m; 8 - tubular drain of the lower tier.

Fig. 1. Double drain.

The design and parameters of the system are shown in Figure 1. The following data testify to the effectiveness of such a system. Compared to the control (systematic drainage), during the thaw period in February 1990, the two-tier drainage removed 2.9 times more water. The following maximum modules of drainage flow were recorded: two-tier drainage with cavityless drains of the upper layer 4.8 l/(s*ha), control 1.86 l/(s*ha). In terms of cost, a two-tiered one with a distance between the drains of the upper tier of 5 m and a lower 30 m competes with a narrow trench with a drain spacing of 10 m, a volume filter of 0.2 m and absorption columns every 5 m. The effectiveness of cavityless drainage is also evidenced by field studies presented in the paper [8].

The aim of the work is to create and justify structures of cavityless drainage that provide effective drainage of poorly permeable soils. Hydrological, hydraulic and geotechnical calculations of cavityless collector channels have been performed.

2 Materials and methods

If we consider the scenario of climate warming, accompanied by an increase in the amount and intensity of precipitation by 10-15% in the Non-Chernozem zone of the Russian Federation (Russian Federation) [2], to be considered sufficiently substantiated, then the calculated "hydrological load" on drainage systems should also increase, which, obviously, will require "thickening" of drainage, additional arrangement of various designs of absorption elements, introduction of more advanced drainage schemes. Runoff volumes will increase, primarily during periods of winter thaws, as well as in the pre-sowing period of the year.

One of the topical issues is the development of methods for calculating the characteristics of surface runoff from drainage systems. Many years of experience in the operation of drainage systems in the Non-Chernozem zone of the Russian Federation has shown that a rare conductive network of channels located, as a rule, at least 300 m apart, is not able to effectively receive and divert surface runoff from large inter-channel strips of the drained territory, especially in conditions of weak relief. . Absorption devices, hollows and temporary furrows in these inter-channel areas do not completely solve the problem of surface drainage. A rational way out of this situation is to reduce the distances between the conductive channels to an average of 90-200 m, with the obligatory application of all necessary measures to organize surface runoff.

For the hydrological substantiation of the conductive channels of such systems, one should proceed from the features of the formation of surface runoff from the interchannel strips. The runoff from them will occur as from an elementary runoff area with the practical absence of reduction phenomena and a significant influence of the terrain conditions. The maximum average daily modulus of spring runoff of calculated availability (qp%) in the early spring period, which is advisable to use in the calculations of the conductive network of drainage systems (unlike other hydraulic structures), is calculated taking into account the instructions of the SP (Set of Rules) [9].

For an elementary drained watershed limited by canals, we have:

$$q_{p\%} = 10 \cdot K_0 \cdot \mu \cdot h_{p\%} \cdot \gamma \text{, l/s•ha} \qquad (1)$$

Where K_0 is a parameter characterizing the friendliness of the flood; μ is the coefficient taking into account the inequality of the statistical parameters of the layer and the maximum runoff modules; $h_{p\%}$ - estimated layer of spring runoff (mm) p% of supply; γ is the conversion factor from instantaneous to average daily flow rates of melt water runoff.

With a catchment area $F = 5$ ha, γ is 0.4, with $F = 1$ ha or less, it is 0.3–0.4 [10, 11].

The value of K0 for elementary watersheds (less than 1 km^2) in the North-West of the Russian Federation varies on average from 0.003 to 0.005, at $p = 10\%$ the coefficient $\mu = 0.93$ [10]. Estimated spring flood layer for the North-West of the Russian Federation $h_{10\%} = 150\text{-}250$ mm [11].

Calculations have shown that the calculated module of melt runoff in the conductive network, depending on the runoff-forming factors and the agricultural use of the drained area, varies on average from 3 to 5 (l/s*ha). During this period, the operation of conductive channels with a full cross section is allowed.

When determining the parameters of the conductive network on drained lands used for arable land without winter crops, for the spring period, it is recommended to take the pre-sowing module (flow rate) of water in conductive channels as a calculated one.

In wet years, after precipitation in the pre-sowing period, the arable layer becomes waterlogged and an intensive drainage runoff is formed, which must be passed in a timely manner by a conductive network of channels with a margin of up to 0.5 m from their edges and in the absence of melt runoff. Therefore, it seems appropriate to take the calculated drainage runoff module as the calculated pre-sowing runoff module.

The maximum average daily module of rain runoff in the summer-autumn period, also passed in the edges of the canals, can be approximately calculated by the empirical method [11] according to the formula adapted to the drained agricultural lands,

$$\begin{aligned} q_{p\%} &= 0{,}116 \cdot \alpha_q \cdot O_{p\%} \\ \alpha_q &= \alpha_{q_0} \cdot K_1 \cdot K_2 \cdot K_3, \end{aligned} \tag{2}$$

Where $O_{p\%}$ - the maximum daily amount of precipitation for the warm period of the year with a calculated (p%) supply, mm; K_1, K_2, K_3 - correction factors, taking into account, respectively, the nature of use, relief and slope of the surface; α is the normalized melt runoff coefficient [10].

The calculated dependence (2) was obtained based on the generalization of field research data, as well as the results of calculations using the State Hydrological Institute formula, taking into account the specifics of runoff formation on drained lands [10].

The value of $O_{p\%}$ is determined according to the data of climate reference books. For the North-West of the Russian Federation at p = 10%, it varies approximately within 40–50 mm [11]. The normalized values of the surface runoff coefficient obtained for grasslands with a surface slope of ≈ 1% vary depending on the value of $O_{p\%}$ and the type of soil in the range from 0 to 0.7. For loams and clays at p = 10% αqo, = 0.3…0.5. For other conditions, correction factors are introduced: for arable land $K_1 = 0.8…0.9$, $K_2 = 0.9$ and 1.1…1.2 with slopes < 0.5% and > 3%, respectively. For a well-planned surface $K_3 = 1.1…1.2$, with poor planning with deep micro and meso relief depressions $K_3 = 0.8…0.9$.

For the North-West of the Russian Federation, the value of q10% varies on average from 4 to 6 (l/s*ha), which is approximately 20-30% more than the maximum average daily module of melt runoff.

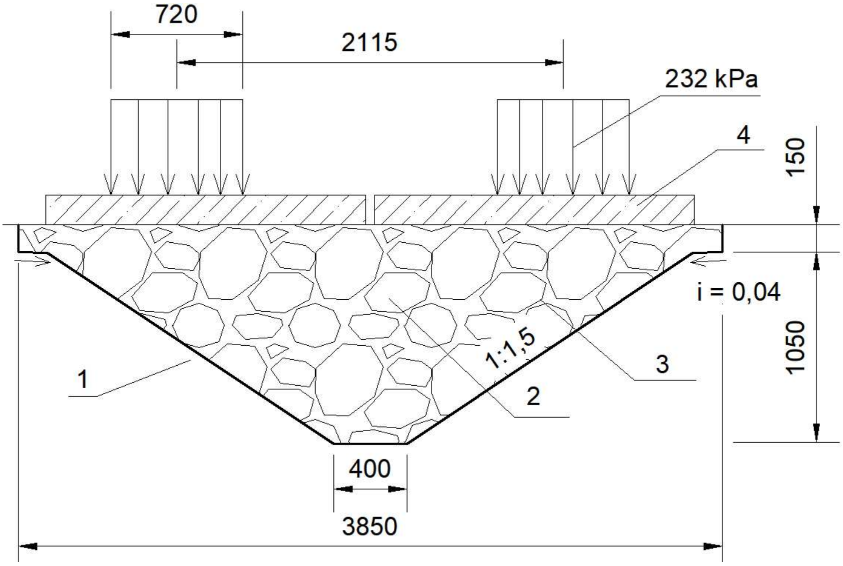
When using this characteristic of rain runoff from small inter-channel watersheds in the calculation of canal parameters, the duration of flooding of the territory adjacent to the canal will not exceed several hours during the calculated day with precipitation Op%, which will not lead to significant losses in crop yields in the years of calculated availability. Calculations have shown that during the period of flooding, the maximum instantaneous module of rain runoff can exceed the daily average by an order of magnitude or more. However, when substantiating the parameters of the drainage network, it seems economically unreasonable to take the maximum instantaneous modulus as a calculated one.

In order to reduce the movement of agricultural machinery across fields with poorly permeable soils, especially during periods of waterlogging, it is recommended [3] to fill a part of open channels that act as collectors with crushed stone and turn them into hollow collectors (Figure 2). At the same time, in the case of hayfields, with a distance between hollow collectors laid with slopes of at least 0.002, equal to 80-100 m, in some cases it is possible to confine ourselves to field profiling and other measures to organize surface runoff. The cross-sectional dimensions of the collector, calculated for a runoff modulus of 4.4 (l / s * ha), the value of which corresponds to those recommended for the North-West of the Russian Federation as the maximum average daily rainwater runoff modulus passed in the canal edges, are shown in Figure 2. As mentioned above, within the same limits (on average from 3 to 5 l / s * ha) is the estimated module of melt runoff, which during this period in the conditions of the North-West of the Russian Federation is also allowed to pass through the edges of hollow collectors.

The maximum surface and drainage runoff of melt water ends, as a rule, 5-15 days before the start of pre-sowing work, and the drainage runoff, which is formed during the drainage of predominantly subsurface soil horizons, enters the canals. The drainage runoff module during this period is (0.1-0.3) l / s * ha, but it must be passed through a conductive network of channels, and in this case, voidless collectors, with a margin of up to 0.5 m from their edges.

The distance between voidless collectors is assumed to be 90 m. The voidless collectors will simultaneously be part of the on-road network in the fields. Strengthening the base for the passage of wheeled vehicles is of great importance, since the running systems have a harmful effect on the soil [12, 13].

Field roads for heavy equipment are proposed to be arranged in the same way as temporary roads for construction sites. In this case, a through or ring traffic pattern is used and the roads are designed for one-way traffic, that is, a width of 3.5 m. The estimated load is up to 12 tons per axle. Roads are made by laying slabs in two rows, as shown in Figure 2.



1 - soft-plastic loam; 2 - cavityless collector from crushed stone of fractions 5-40 mm; 3 - geotextile along the perimeter of the cavityless collector; 4 - reinforced concrete inventory slab [14].

Fig. 2. Field road combined with a cavityless collector.

Geotechnical settlement and stress calculations were performed using the Plaxis software. The plane problem was solved numerically.

Physical and mechanical parameters of the soil mass are given in Table 1.

Table 1. Physical and mechanical parameters of soils adopted for the calculation of the model.

Characteristic	Soft-plastic loam	rubble	Note
Deformation modulus, MPa	17	40	The loam porosity coefficient is taken equal to 0.65
Bulk density, t/m^3	1.9	1.35	
Angle of internal friction, degrees	19	40	
Coupling, kgf/cm^2	0.25	0.02	
Poisson's ratio	0.35	0.29	

For the maximum actual load, the pressure from the passage of an agricultural general-purpose tractor of the 5th traction class K-744R1 (Kirovets) was taken. The operating weight of such a tractor is 118 kN (7 tons per axle).

The calculations were performed according to the following schemes:

- 1a - the plates are laid in two rows, the load is applied symmetrically with respect to the seam between the plates;
- 1b - the plates are stacked in two rows, the load is maximally shifted to the right edge, the edge of the wheel is above the edge of the right plate.

The results of the calculation are summarized in Table 2, in which, for various depths, the values of settlement h on the road axis are given.

Table 2. Maximum settlements at the estimated depth according to the results of calculations (h, mm).

Design scheme	Estimated depth, counting from the bottom edge of the slab, m			
	0	**0.45**	**0.9**	**1.8**
1a	13	12	11	8
1b	14	12	10	8

Recommended crushed stone fractions:

- For hollow collectors 20-40 mm.
- For hollow drains inside the field 10-20 mm.

In the case of tilled crops, in order to ensure the removal of excess moisture from the arable layer within the required time, it is necessary to provide a drainage network based on closed drainage, including the use of two-tier drainage, between the void-free collectors.

3 Results and Discussion

Let's perform a verification calculation for compliance with the reserve requirement of at least 0.5 m from the water level in the cavityless collector to the top of its filler.

Let us give an example of a hydraulic calculation of a cavityless collector. First, to the maximum hydrological load, which is diverted by the cavityless collector in its edges, and then the test for the diversion of the maximum drainage flow, which should be discharged at water levels in the cavityless collector, which are at marks 0.5 m below the marks of their edges.

The main calculation case.

Given: filler material of a cavityless drain - crushed stone 20-40 mm; the diameter of the filler particles, less than which its composition contains 17% of the particles by weight d_{17} = 2.8 cm; coefficient of heterogeneity η = 2.1; porosity n = 0.48; particle shape factor ψ = 1.68; Shezy coefficient C_0 = 78 cm$^{0.5}$/s; water viscosity v = 0.0131 cm^2/s; slope factor m = 1.5; bottomless collector width b = 0.4 m; length L = 200 m; specific inflow $q = 0.3 \cdot 10^{-4}$ m^2/day; the slope of the bottom of the cavityless collector i = 0.002. The distance between the cavityless collectors is 90 m. Aggregate filtration coefficient, respectively, in laminar and turbulent modes: K_l = 4.47 m/s; K_t = 0.095 m/s. Estimated diameter of the filtration passage d_u = 0.99 cm.

Calculations showed that the maximum water depth in a cavityless reservoir (with a water depth at its mouth equal to 0.4 m) at a maximum hydrological load is 1.02 m, and the height of the filler layer is 1.2 m. With an increase in hk, the maximum water depth also increases in the collector.

Check calculation. The original placeholder data remains the same. The hydrological load on the outlet network from the drainage flow changes. The maximum hydrological load for the North-West of the Russian Federation on the drainage network from drainage during these periods, as a rule, did not exceed 1 l/s•ha. With a distance between collectors equal to 90 m, q = $0.9 \cdot 10^{-5}$ m^2/s. The value of hk is taken equal to 0.1 m.

In this case, the depth of water at the source of a cavityless collector is calculated by the formula [15]:

$$h_0 = L\sqrt{\frac{\left(t_k^3 - i\cdot t_k^2 + U_l\cdot t_k + U_t\right)^{(1-F_1)}}{\left(t_k - K_1\right)^{(1-3F_1)}}}\cdot \exp\left[-\frac{M}{\sqrt{N_1}}\left(\frac{\pi}{2} - \text{arctg}\frac{2t_k + K_1 - i}{\sqrt{N_1}}\right)\right], \qquad (3)$$

Where $t_k = \frac{h_k}{L}$, is the ratio of water depth at the mouth of a cavityless reservoir to its length; $U_l = \frac{q}{K_l\cdot b_e}$, $U_t = \frac{q^2}{K_t^2\cdot b_e^2}$ - complex parameters; $b_e = b + m\cdot\beta\cdot h_н$ - equivalent width of the cavityless collector; K_1, F_1, N_1 and M are the total complex parameters, the formulas for calculating which are given in [15].

For the calculation, it is necessary to set the estimated value hн and if at the end of the calculations according to formula (5) we confirm this value, then it is taken as the desired one.

In the case under consideration, the following values of the parameters listed above were obtained during the calculation: t_k = 0.0005; b_e = 0.72 m; $U_l = 0.28 \cdot 10^{-5}$; $U_l = 1.73 \cdot 10^{-8}$; $P = 9.28 \cdot 10^{-9}$; $K_1 = -1.8 \cdot 10^{-3}$; F_1 = 0.164; $M = 0.141 \cdot 10^{-2}$; $N_1 = 24.12 \cdot 10^{-6}$.

As a result, according to formula (3), we get $h_н$ = 0.3 m. Accordingly, the mark of the maximum water level in the cavityless collector is less than the mark of its edge by 0.9 m, that is, the difference in marks is more than 0.5 m. If the drainage capacity of the cavityless collector turns out to be insufficient, it can be increased by introducing a drainage pipe of the appropriate size into the collector. The hydraulic calculation technique described in [15] makes it possible to do this.

4 Conclusion

Thus, with a decrease in the distance between the conductive channels, closed cavityless collectors filled with crushed stone can cope with the diversion of the drainage and surface runoff coming to them, which can simultaneously be used as the foundation of field roads for heavy agricultural machinery. The maximum settlement from the Kirovets heavy agricultural tractor does not exceed 14 mm, practically does not depend on the loading pattern, is evenly distributed along the length of the collector and will not have any significant effect on changing the slope of its bottom.

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