The method of accounting infiltration of atmospheric precipitation to calculate drainage facilities

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Abstract
Due to changes in the global climate of the planet, increasing the content of atmospheric moisture, the intensity and duration of precipitation throughout the year, it is proposed that the calculations should be performed separately for each of the three periods: autumn period of initial accumulation of moisture; spring period of thaw and saturation; summer period of heavy rainfalls events. One of the main reasons of destruction of road coating is overmoistening of the soil of earth bed and road base due to the unsatisfactory state of drainage and drainage facilities. The investigation is devoted to the problems of designing drainage structures. This paper proposes a method for calculating the amount of water ingressing the drainage layer by infiltration of atmospheric precipitation.
To improve the structural strength of the road, fast and continuous removal of water from porous layers of road covering should be provided. The delay in water diversion reduces the bearing capacity of soil foundation and as a result, decreases the structural strength in general. The arrangement of continuous drainage layer under the road coating allows collecting excess moisture that enters the drainage layer for the entire year.
Key words: ROAD, WATER AND THERMAL REGIME, DRAINAGE FACILITIES

Introduction

There is an urgent need to develop a method of calculating the total moisture ingress to the working area of linearly extended ground buildings and structures [5-8] due to changes in the global climate of the planet [1, 2] and increase in the content of atmospheric moisture [3], increase in the intensity and duration of annual precipitation [4]. In particular, the work presents a method for determining the amounts of moisture accumulation from the infiltration of atmospheric precipitation in road constructions on highways of general use. Using the proposed method allows to adjust the moisture accumulation mode in the road design and reasonably determine the general size of the drainage structures. Accounting for significant climatic changes and application of this method allows the development of an improved method of drainage systems designing.

The objective of the article and presentation of the main material

One of the main reasons of destruction of the road coating is overmoistening of the soil earth bed and road base due to unsatisfactory state of drainage and drainage facilities. Problems of designing drainage structures were studied in [9-12]. This paper proposes a method for calculating the amount of water ingress to the drainage layer by infiltration of atmospheric precipitation.

Establishment of the boundaries of the individual certain periods [13] and determination of the calculated value of the proportion of excess water ingress the drainage layer when soil thawing is proposed to carry out in accordance with the recommendations [14].

Moisture ingress from atmospheric precipitation should be determined for each of the three periods separately: autumn (T_a), spring (T_{sp}) and summer (T_s). In each period, the various types of precepitation, which make the maximum contribution to the formation of the value of water ingress to the drainage layer should be analyzed.

From the perspective of effect on the ingress of moisture, rains can be divided into three types: 1. rainstorms are short and intense rains with duration from 2 hours to 4 hours and an average intensity of 10 mm/h to 20 mm/h; 2. heavy rains are characterized by duration from several hours to several days, the average intensity of 2 mm/h to 10 mm/h; 3. widespread rains are characterized by a long duration from 3 days to 5 days or more and a relatively low intensity (less than 2 mm/h), which varies slightly during the rain.

Widespread rains are accounted for method of determining the weighted average precipitation intensity; rainstorms and heavy rains should be taken into account for the calculation of peak loads on the drainage system.

When determining the weighted average values of the infiltration of moisture ingress to the road surface foundation, the possible total duration of precipitation 5% occurrence on statistical meteorological data for all N_{years} is defined; these years are taken into account.

The amount of rain 5% occurrence:

$$m = \frac{m_{av}}{T_{r(av)}} \cdot T_r, \tag{1}$$

where m_{av} – the average amount of rains for N_{years} years;

$T_{r(av)}$ – average total duration of precipitation, min;

T_r, min – possible total duration of precipitation of 5 % occurrence.

Average rain intensity is determined (in mm/min) according to the formula:

$$i_r = \frac{H_{r(av)}}{T_{r(av)}}, \tag{2}$$

where $H_{r(av)}$ – average monthly amount of precipitation, mm.

The amount of the surface coating moistening, mm is determined according to the formula:

$$H_{m(c)} = a_m \cdot m \cdot \sqrt[3]{d \cdot \frac{T' - T_r}{m}},$$
$$H_{m(c)} \le max H_{m(c)} = max h_m \cdot m, \tag{3}$$

where T' – duration of the calculation period, m;

a_m, $max\ h_m$ – moistening indicators of road surface, mm [15].

When $H_{m(s)} \geq i_r \cdot T_r$, all precipitation go to moistening, penetration is missing.

When $H_{m(s)} < i_r \cdot T_r$, penetration of precipitation into the coating occurs.

The average duration of the penetration of moisture into the coating at one rain, min:

$$t_{mi(c)} = \frac{i_r \cdot T_r - H_{m(c)}}{i_r \cdot m}. \tag{4}$$

The amount of water penetrating into the coating, mm:

$$H_{mi(c)} = 0.013 \cdot m \cdot ln(1 + a_0 \cdot i_r) \cdot 10^{0{,}4 ln t_{mi(c)}}, \tag{5}$$

where a_o – parameter, which amounts to 120 for summer, 100 for the spring and 80 for autumn periods.

The runoff intensity from the coating, mm/min is defined by the following formula:

$$i_{ro(c)} = i_r - \frac{H_{mi(c)}}{m t_{mi(c)}}. \tag{6}$$

The intensity of the flow of water on the roadside taking into account the runoff from the roadway (in mm / min) is determined as follows bellow:

$$i_{wf} = i_r + i_{m(c)} \cdot \frac{a}{l}, \tag{7}$$

where a – width of one-slope or dual-slope road surface to the side of slope, m;

l – length of the side of the road in the direction of the slope, m.

The moistening value of roadsides surface, mm is defined as follows

$$H_m = a_m \cdot m \cdot \sqrt[3]{d \cdot \frac{T' - T_r}{m}},$$
$$H_m \le max H_m = max h_m \cdot m, \tag{8}$$

Where a_m, $max\ h_m$ – indicators of road surface moistening, mm;

$H_m \geq i_{mi} \cdot T_r$ - all the water falling on the sides of the road, goes to moistening, ingress is missing.

When $H_m < i_{mi} \cdot T_r$, ingress of water into the soft takes place.

Coefficient of ingress in the soil of road bed:

$$C = 6000 \cdot \frac{\sqrt[3]{K}}{W_T^2}\left(1 - \sqrt{\frac{W_{opt}}{W_{mi}}}\right) + 30 \cdot K, \tag{9}$$

where K – soil filtration coefficient;

W_L – soil moisture content at the soil liquid limit, %;

W_{opt} – optimum soil moisture content,%;

W_{cm} – complete soil moisture content, %.

Complete soil moisture content, % is calculated using the following formula:

$$W_{mi} = \frac{n \cdot \rho_w}{\rho_s} \cdot 100 \tag{10}$$

Where n – soil porosity;

ρ_w – water density , g/cm³;

ρ_s – density of solid soil particles, g/cm³.

K, W_L, W_{opt}, ρ_s values are determined experimentally. Determination of water ingress rate in the roadsides, mm/min is done according to the following formulas:

$$(i_{wi} \le 0.02 \cdot C), \quad i_{mi} = i_{wi},$$
$$(i_{wi} > 0.02 \cdot C), \quad i_{mi} = C \cdot \left(0.02 + 10^{0.02 + 0{,}68 \cdot lg\frac{i_{wi} - i_{mi}}{\varphi(l)}}\right) \tag{11}$$

Where *φ(l)* – function of surface slope.

$$i_{st} = i_{wi} - i_{mi} \tag{12}$$

Ingress intensity is determined by selecting method. The amount of water ingressing the roadsides (in mm):

$$H_{mi(rs)} = A_{har} \cdot i_{mi} \cdot \left[T_r - \left(\frac{H_{m(c)}}{i_r} - \frac{H_m - H_{m(c)}}{i_{wi}}\right)\right], \tag{13}$$

Where A_{har} – coefficient taking into account the type of the roadsides hardening.

Intensity of evaporation of water from the roadsides when soil moisture content exceeds an optimum (in mm/min):

$$i_{rs} = 25 \cdot 10^{-5} \cdot (E - e) \cdot \lg\left(1 + \frac{80}{d}\right) \cdot (1 + 0.15 \cdot v), \tag{14}$$

Where E – pressure of saturated water vapor on the border with the evaporation surface, mbar;
e – water vapor pressure, mbar;

d – air moisture deficit, mbar;

v – wind speed, m/sec.

In the first month of spring, the difference between the temperature of air and soil surface is insignificant. Therefore, during this period it is possible to calculate evaporation by the simplified formula by taking the values of E as pressure of saturated water vapor at air temperature.

The amount of water evaporating from the roadsides during the calculation period (mm) is determined by the equation:

$$H_{rs} = B_{har} \cdot i_{rs} \cdot (T' - T_r), \tag{15}$$

where B_{har} – coefficient taking into account the effect of the type of the hard shoulder on the evaporation process.

Specific excess water (m³/day per 1 m²) coming into the base from the atmospheric precipitation is determined by the following relationships:

a) through the coating:

$$q_{inf}^{rw} = \frac{H_{mi(c)}}{1000 \cdot T''} \tag{16}$$

b) through the roadsides:

$$q_{inf}^{rs} = \frac{(H_{mi(rs)} - H_{rs})}{1000 \cdot T''} \tag{17}$$

where T'' – duration of calculation period, day.

The amount of moisture ingress from the unfortified divisor q_{inf}^{d} without receiving waters is calculated similarly to roadsides considering direction of runoff from the roadway and slope and elevation point of the dividing line location with respect to the roadway.

Specific excess infiltration moisture from atmospheric precipitation (m³/day per 1 m²) ingressing through the roadside covering of the roadway, divisor is determined by the dependence:

$$q_{inf}^{av} = \frac{q_{inf}^{b} \cdot a + q_{inf}^{rs} \cdot l + q_{inf}^{d} \cdot b}{a + b + l} \tag{18}$$

Where a – width of single-slope or half of dual-slope roadway, m;

l – width of road side, m;

b – width of divisor.

To determine the peak loads rainstorms (duration T_r is less than 5 hours, intensity - H_r from 10 mm/h to 20 mm/h) and heavy rains (duration T_{hr} is more than 5 hours to 5 days, intensity - H_{hr} from 2 mm/h to 10 mm/h) are taking into account.

The calculation steps are as follows:

According to the statistics of meteorological observations the amount of air moisture deficit of 5% occurrence (d, mbar) should be determined.

According to the data of statistical meteorological observations, it follows that for heavy rains (lasting more than a day) i_{hr5} – intensity of the heavy rain of 5% occurrence, mm/min.

To determine the intensity of the precipitation according to meteorological observations duration of precipitation of observation period T_{hri}, min and total amount of precipitation of one rain before this observation period H_{hri}, mm should be taken into account. Intensity of this rain i_{hri} should be determined by the following ratio:

$$i_{hri} = \frac{T_{hri}}{H_{hri}}. \tag{19}$$

For the obtained values of i_{hri} value of i_{hr5} should be determined, that is intensity of heavy rains precipitation of 5% occurrence, mm/min. In subsequent calculations for such types of precipitation as estimated duration of rain, one day should be taken (*T_{pd}=1140 min*).

According to the statistics of meteorological observations, the intensity i_{35}, mm/min is determined for the heavy rains (intermittent rains, duration of less than 5:00).

Total amount of precipitation for one heavy rain H_{hr} with a repetition once in N years should be determined by the following formula:

$$\mathrm{H}_{hr} = 0.046 \cdot \sqrt[3]{\overline{H}^2 \cdot N}, \tag{20}$$

Where $\overline{H}$ – annual precipitation for this area (according to the meteorological statistical observations),

N – number of years during which H_{hr} is repeated once.

Duration T_{hr}, min of heavy rains of 5% occurrence is determined from the following ratio:

$$T_{hr} = \frac{H_{hr}}{i_{hr}}. \tag{21}$$

Further calculations should be performed by a single algorithm taking into account that T_r – estimated duration of the rain (for rainstorm – T_r, for heavy rain– T_{hr}), i_r – estimated rain intensity (for rainstorm – i_{r5}, for heavy rain – i_{hr5}).

The value of the surface coatings moistening h_m (mm) should be equal to the maximum moistening value *max* h_m.

The average duration of moisture ingress into the coating at one rain, min:

$$t_{\mathrm{mi(c)}} = \frac{\mathrm{i_r} \cdot \mathrm{T_r} - h_{\mathrm{m(c)}}}{\mathrm{i_r}} \tag{22}$$

The amount of water ingress into the coating, mm:

$$h_{\mathrm{mi(c)}} = 0.013 \cdot \ln(1 + a_0 \cdot i_{\mathrm{r}}) \cdot 10^{0{,}4\ln t_{\mathrm{mi(c)}}}, \tag{23}$$

where a_o – parameter that is 120 for summer, 100 – for spring and 80 – autumn periods.

The runoff intensity of the coating, mm/min is defined by the following formula:

$$\mathrm{i_{ro(c)}} = \mathrm{i_r} - \frac{h_{\mathrm{mi(c)}}}{t_{\mathrm{mi(c)}}} \tag{24}$$

Further calculations are performed by formulas in sequence by (8) - (13).

The amount of water evaporating from the roadsides, mm for the calculation period is determined by the equation:

$$h_u = \mathrm{B_{har}} \cdot \mathrm{i}_u \cdot \mathrm{T_r}, \tag{25}$$

where B_{har} – coefficient taking into account the impact of the type of the roadsides hardening on the evaporation process.

Specific water excess ingressing the base from the atmospheric precipitation

(m^3/day per 1 m^2) is determined by ratios:

a) through the coating:

$$q_{inf}^{rw} = \frac{H_{mi(c)}}{1000}, \tag{26}$$

b) through the roadside:

$$q_{inf}^{rs} = \frac{(H_{mi(rs)} - H_{rs})}{1000}. \tag{27}$$

The value of moisture ingress from the unfortified divider q_{inf}^{d} without receiving waters is calculated similarly to roadsides considering direction of runoff from the roadway, slope and elevation point of the divider location relative to the roadway.

Specific excess of infiltration moisture from atmospheric precipitation that falls through the roadsides, covering of the roadway, divider, m^3/day per 1 m^2 for the peak loads on drainage system q_{inf}^{peak} is calculated by formula (18) using q_{inf}^{rw}, q_{inf}^{rs}, q_{inf}^{d} values.

As a result of the proposed method, the calculation and analytic system was developed. It was used in the preparation of the master's work of S. Prikhodko for calculations on the real object of the road of I category in the Poltava region. The calculation results are shown in Table 1.

Table 1. Results of the calculation of the specific excess of water ingress in the drainage structure

i_r	Average rain intensity	*mm/min*	0.001973285				
Q_i 5%	Total specific water excess		**24.10495373**				
$t_{mi(c)}$	The average duration of moisture ingress into the coating at one rain	min	1521.7811	1521.7811	1521.192	1523.22	1545.991
$H_{mi(rs)}$	The amount of water ingress into the road sides	*mm*	84.364774	84.364774	84.59509	83.80249	74.9055

i_{rs}	The evaporation intensity of water from the roadsides when the soil moisture content exceeds the optimum	*mm/min*	2.77672E-05				
$H_{mi(d)}$	The amount of water ingress into the divider	*mm*	105.45597	105.45597	105.7439	104.7531	93.63187
$q_{rw/inf}$	Specific excess of water ingress into base from the atmospheric precipitation through the coating	*m3/day per1 m2*	0.0403456	0.0403456	0.040331	0.040381	0.040936
$q_{rs/inf}$	Specific excess of water ingress into base from the atmospheric precipitation through the roadside	*m3/day per 1 m2*	0.0842546	0.0842546	0.084465	0.083732	0.075175
$q_{d/inf}$	Specific excess of water ingress into base from the atmospheric precipitation through the divider	*m3/day per 1 m2*	0.1052356	0.1052356	0.105484	0.104613	0.094171
$q_{av/inf}$	Specific excess of infiltration moisture from atmospheric precipitation which enters through the roadside, covering of roadway, divider	*m3/day per 1 m2*	0.0683199	0.0683199	0.068431	0.068043	0.063434

Conclusion

To improve the strength of the road structure, rapid and continuous removal of water from the porous layers of road surfacing should be provided. The delay of water draining reduces the bearing capacity of soil foundation and as a result, it decreases the structural strength in general. The arrangement of continuous drainage layer under the road surfacing allows collecting excess moisture that ingresses into the drainage layer for the entire year.

Existing methods of calculating drainage layer thickness were developed to meet the climatic characteristics thirty years ago. As a result, the research method that takes into account changes in the climatic conditions of Ukraine and an increased amount of atmospheric moisture, which is due to these changes, is proposed. Along with the average data, the use of data on the peak loads on the drainage layer during high-intensity precipitation such as rainstorms and heavy rains was suggested. Accounting of significant climate changes and the application of this method allows the development of an improved method of designing drainage systems.

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