Method to incorporate the climatic changes for determining freezing depths of road constructions

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Abstract
The problem of road structures deformation and demolition is still of vital importance nowadays. The reason of various demolitions, in most cases, especially during the period after winter, is oversaturation of the earth subgrade roadbed level with water and its load-bearing ability consequent losing. Due to the mentioned problem and related ones, this publication is devoted to the issues of defining calculated characteristics of the structures for regulating moisture and thermal regime of the road structure – shallow laying drainages. In the following article one can find an improved method of calculating the freezing depth of a road construction within the layers of its pavement and ground belonging to the active zone of the earth subgrade roadbed. On the basis of the statistical analysis of climatological indices for the last ten years, it is the first time within the territory of Ukraine when road-climatic maps have been developed to study the ground freezing depth under the road pavement. These maps have been built for all technical categories of roads according to the adopted regulatory documents. The renewed approach permits developing reasonably improved measures concerning regulating moisture and thermal regime of a road structure and eliminating the time-consuming process of receiving the arrays of meteorological information and their statistical processing.
Key Words: ROAD STRUCTURE, EARTH FREEZING DEPTH, ROAD-CLIMATIC MAPS.

Background. The most effective way of decreasing the cost of road pavement arrangement is in increasing a modulus of elasticity and decreasing upheaval of the earth subgrades, and also in decreasing the water income by regulating moisture and thermal regime of the earth subgrade roadbed. When designing the earth subgrade roadbed and the road pavement, their geometrical dimensions should be substantiated and soil modulus E_p is to be specified. At this, a possibility of oversaturation for the earth subgrade roadbed on different depths of the active zone is not taken into account, which can lead to the violation of the endurance and road pavement deformations. The endurance and the long life of road pavements largely depend on the strength of the earth subgrade roadbed. Due to the moisture level and the earth subgrade roadbed strength tending to change in the course of a year, when designing the earth subgrade roadbed and the road pavement, it is necessary to apply the technological and constructive measures concerning regulation of moisture and thermal regime, which are capable of providing small in the range and given values of earth humidity changes and the previously accepted soil modulus.

Moreover, this problem is becoming especially important under conditions of changing climate, global warming and the resulting increase in the amounts of rain precipitations as the transformation in moisture accumulation processes is occurring and the shift of moisture and thermal regime is taking place, affecting the operation conditions of a road structure in general. Currently, the calculations of drainage structures, in particular drainage structures of shallow laying for regulating moisture and thermal regimes on roads, are carried out with application of the aged data and the norms worked out during the times of the former Soviet Union. If we want to take into account the mentioned changes when projecting road structures, we need a renewed approach concerning calculated characteristics of the structures dedicated to prevention of the moisture accumulation in the road.

In the works of many scientists, there has been studied moisture accumulated in road constructions and the results of this phenomenon in the winter period. One of the directions of these studies and researches is the improvements of road structures with additional drainage subgrades to provide the optimal timelines of drying [1]. Proposed in [2] approach to apply mobile laser scanning system (MLS) allows determining the depth of water flow distribution and revealing the conditions of drainage structures and surface runoffs. The experimental researches on the water flow in the drainage constructions, the distribution of the velocity field and the prognosticated consumption of the surface runoff are reported in [3]. The methods for determining hydraulic calculated parameters of the entire drainage system [4] are the foundation for effective hydraulic engineering measures aiming at the distribution of the water flow on the surface. The numerical 3D simulation for the hydrodynamic processes of water flow distribution within a drainage system was carried out and they allowed incorporating the parameters of both the longitudinal and transversal geometry of motor vehicle roads [5].

The scientifically-based suggestions concerning drainage systems adaptation on motor roads before the climate change, oftener critical rain precipitations, changes in the freezing and thawing cycles are described in [6]. The approaches to continuously incorporate the dynamics of the changes in the climatic index during the year cycle, hydraulic model to calculate the fluid run into reservoirs attaches to roads, prognostication of moisture accumulation within road constructions, allow suggestions on drainage system improvements.

For absorbing and removing that moisture which penetrates into the earth subgrade roadbed under the layers of road pavement during the most unsuitable for road constructions time periods, the drainage constructions of shallow laying are arranged. The main sources of forming the specific volumes of excessive moisture within road constructions are infiltration of rain precipitations and the moisture at thawing of earth subgrade roadbed in after winter period. The issues regarding the development of methods to define the specific volumes of moisture excess and how to incorporate the information on the changes in moisture and thermal regime throughout the seasons are studies in [7, 8].

Publication Purpose. This publication aims at development of a new approach capable of incorporating the Ukraine's climate changes with the objective to define road construction freezing depths at setting construction parameters for regulating moisture and thermal regime.

In order to reach the target set, it is reasonable to perform the following tasks:

- based on the Ukraine's statistical meteorological data of the past ten years, to determine the indicators of the earth subgrade roadbed freezing depths and those of the road construction in general;
- to build the maps of road construction freezing depths according to the typical solutions for road pavements of various categories;
- to develop the methods capable of incorporating climatic index when determining freezing depths, information on which can be utilized for designer's solution adoption for the constructions of moisture and thermal regime regulation.

The research concept is based on information of typical constructions in complete agreement with normative documents of *Album of the Typical Road Pavement Structures of Non-Rigid Type for the Estimated Loads A1, A2, B*, applied for Ukraine road climatic maps development related to calculations of road construction freezing depths. This allows drastic reduction in the labour loads directed to improvement of the design solutions concerned with the search, collection and statistical processing of initial meteorological data of the building sites and motor roads territories for reconstruction.

Results and Discussion. The calculations on the freezing depth value for the road construction begin with collecting the data necessary for determining climatic and geological indicators.

Nowadays, the common practice of freezing depth calculation with incorporating the climatic index is performed through the use of one climatic map dated as far as 80-s of the previous century. The tests on freezing resistance are being carried out in accordance with the requirements of *VBN V.2.3-218-186-2004 Transport Constructions. Road Pavement of Non-Rigid Type*.

Thus, it becomes obvious that there is the necessity to improve the methods of design calculations meeting the contemporary requirements and the changes in climatic conditions.

In order to perform the previously mentioned tasks, the authors collected the 2007-2016 meteorological data by Central Geophysical Observatory of Ukraine and processed them statistically according to the standard techniques.

The time period of earth subgrade roadbed freezing T_{fr} has been calculated through statistical climatic data for the territory of the building site and it has taken into account the number of 24-hour periods from the time when average daytime temperatures reach below -5°C in autumns and up to the average day temperatures higher than 0°C in springs [8].

Based on *Methodological Recommendations on Moisture and Thermal Regime within the Sub-Base of Motor Roads (Ukrainian Document),* the approach as reported below has been applied for defining the freezing depths.

The general freezing of road construction z_{fr} (cm) is defined according to the dependence given below provided that the results of many years of observations are available:

$$z_{fr}=\sqrt{\frac{4.86\cdot\lambda_{fr}\cdot T}{\delta\cdot W\cdot\rho}\cdot\left[t_{ice\ forming}-t_{air}+\left(t_{air}-t_{soil}\right)\cdot\frac{R_{coat.-air}+R_{pav}}{R}\right]}\cdot 100 \qquad (1)$$

where λ_{fr} – is the coefficient of frozen soil thermal conductivity ($W/(m\cdot K)$); T – the freezing period (hours) (*the same as* T_{fr} *and expressed in hours)*; δ – hidden heat of ice formation, which equals 334 kJ/kg; W – soil moisture (unit fraction); ρ –soil density, kg/m^3; t_{air}, t_{soil}, $t_{ice\ forming}$ – respectively the temperature of air (°C), the temperature of soil (°C) (according to the data of meteorological observations) and the temperature of ice formation (°C); $R_{coat.-air}$ – the thermal resistance to characterize heat exchange with air ($K\cdot m^2/W$); R_{pav} – thermal resistance of road pavement ($K\cdot m^2/W$); R – general thermal resistance ($K\cdot m^2/W$).

The thermal resistance of road pavement R_{pav} ($K\cdot m^2/W$) can be defined by the dependence as below:

$$R_{pav} = \frac{h_1}{\lambda_1} + \frac{h_2}{\lambda_2} + \ldots + \frac{h_n}{\lambda_n}; \quad (2)$$

where h_1, h_2, h_n – the road pavement layer thickness (m); λ_1, λ_2, λ_n – the coefficients of thermal conductivity of the dedicated layers ($W/(m \cdot K)$).

The thermal resistance of $R_{coat.-air}$ describes the thermal exchange between the coating and the air ($K \cdot m^2/W$) and is accepted as dependent on wind speed v (m/s).

The general thermal resistance of R ($K \cdot m^2/W$) is as follows:

$$R = \frac{H'}{\lambda_{soil\ field}} + \frac{h_s}{\lambda_s}, \quad (3)$$

where H' – is the depth to accept the soil temperature; t_{soil} (m) (accepted per the data of meteorological observatory – the depth to measure soil temperature for meteorological observations); $\lambda_{soil\ field}$ – the coefficient of soil field thermal conductivity; h_{snow} – the height of the snow cover (m); λ_{snow} – the coefficient of snow thermal conductivity ($W/(m \cdot K)$).

When calculating the freezing depths of soil sides or those of traffic strips, one should apply formula (1) with variable R_{pav} and dependence $\frac{h_{snow}}{\lambda_{snow}}$.

The coefficient of soil thermal conductivity λ_{soil} is accepted per the data of the experimental studies at soil moisture of W, which is average for the period under calculations.

The coefficient of snow thermal conductivity λ_{snow} is determined by the empirical dependence as written:

$$\lambda_{snow} = 0.017 + 0.774 \cdot \rho_s, \quad (4)$$

ρ_{snow} in the formula is the snow density (g/cm³).

The calculations according to the given method are performed by using the statistical data of the meteorological service. For the calculations, the data has been averaged, or the extremes have been selected, depending on the purpose of the calculation.

Based on the statistical meteorological observation data of the past ten years in a row for the territory of Ukraine, we applied formulas (1-4) to obtain the freezing depth calculated parameters of the subgrade roadbed and the road structure in general. For example, for the Chernihiv station, the following calculated values have been obtained, as shown in Table 1.

Thus, the obtained freezing depth critical value of 5% reliability is $z_{fr} = 1.039\,m$.

In order to predict the moisture accumulation in the road and to select the parameters of the shallow laying drainage structures, we have constructed the maps of the freezing depth spreading for the motor roads of various categories throughout the territory of Ukraine. These maps have been developed with Surfer 13 program, which has a wide range of the discrete functions of interpolation methods and the customizability of the required additional parameters. The method of Radial Basis Functions has been used, whereby the surface is constructed on all the control points that have been input [7].

As an example can be illustrated Figures 1, 2, 3, which show the road-climatic maps of Ukraine for several categories of the general use roads.

The values of the freezing depths have been determined for the typical road pavement structures of non-rigid type regulated by normative document *Album of the Typical Road Pavement Structures of Non-Rigid Type for the Estimated Loads A1, A2, B.*

The practical effectiveness of the methodology we offer is presented in the scheme of designer's decisions on the selection of structures parameters for the regulation of the moisture and thermal regime (Fig. 4). Two approaches have been considered: 1) the first one contains four additional stages of the design calculations and is based on the existing regulatory framework; it requires updating of the outdated reference data on the climatic characteristics of the regions of Ukraine; 2) the second approach is short-cut; it allows taking into account the typical and atypical designer's decisions regarding the road pavement structure and updated climate information about the region of the construction area.

The improved method offered by the article (the right side of the scheme in Figure 4) makes it possible to exclude the stages of the input data collection on the climatic conditions of the construction area over a multiyear period of observations (air temperature, soil temperature, wind speed and snow cover height) and the statistical processing of the data to perform the calculations by the normative technique. All these elements of the design process can be replaced by the simplified use of the value maps for the estimated freezing depths of the motor road of various categories.

Conclusions. The global transformations of the climatic conditions require taking into account the changes in the climate index when making the

Table 1. The Freezing Depths of the Ia Road Structure

	Year									
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Freezing Depth (m)	0.862	0.401	0	0	0.938	0.734	0.881	0.499	0.543	0

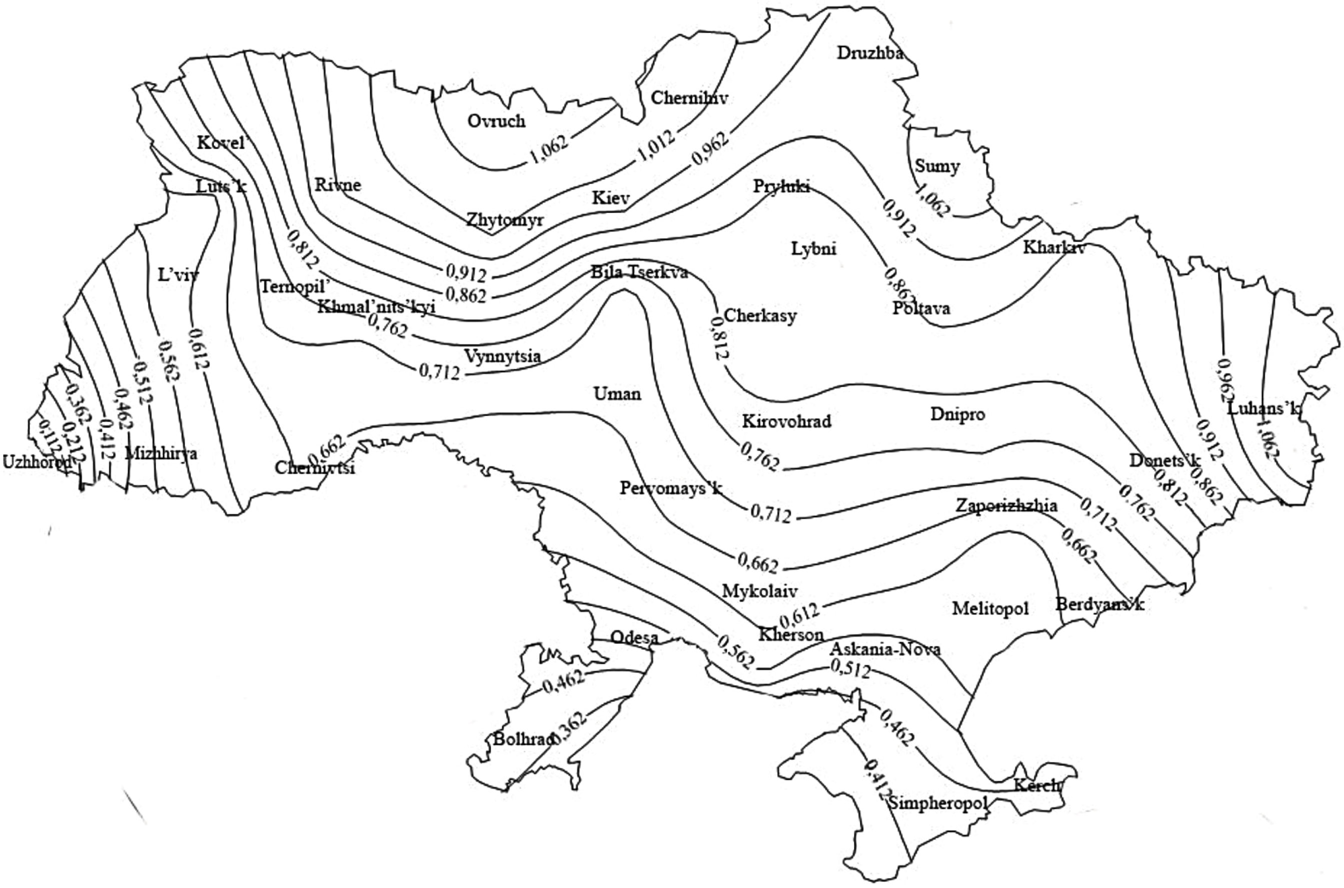

Figure 1. The Freezing Depths of the Road Structure within the Road (m) of Ia Category

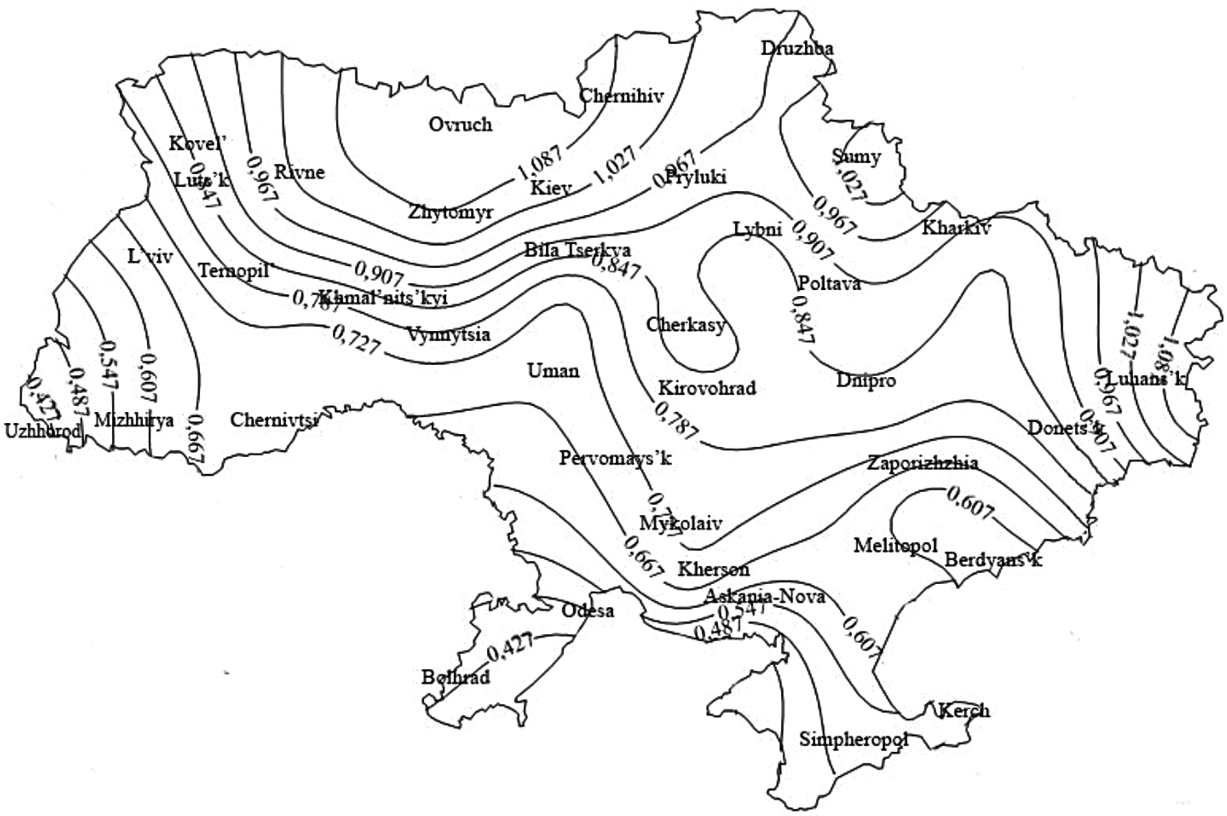

Figure 2. The Freezing Depths of the Road Structure within the Road (m) of III Category

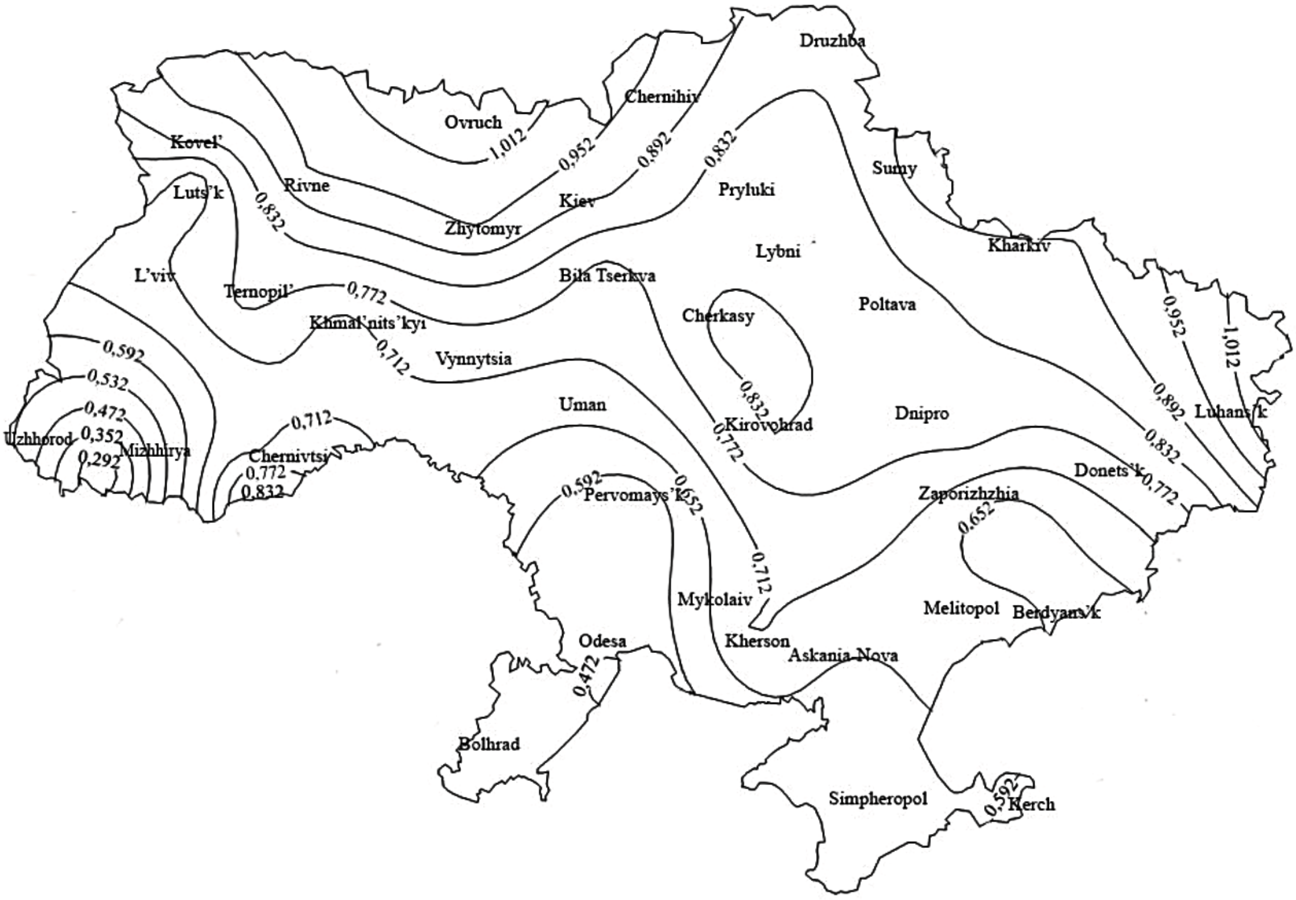

Figure 3. The Freezing Depths of the Soil (m) at the Roadside

designer's decisions regarding the structures for the regulation of the moisture and thermal regime of a road.

As a result of the research, conducted by using the standard calculation methods on the basis of the available statistical meteorological information for ten years in a row, the updated estimated values of the soil freezing depths of the road structures have been obtained and classified according to the categories of the motor roads.

Applying Surfer 13 software system, based on the Radial Basis Functions, the maps of the road structure freezing depths have been built in accordance with the typical designer's decisions for the road pavements of various categories adopted on the territory of Ukraine.

In order to find the optimal designer's decisions, the methodology has been developed to take into account the changes in the climatic characteristics when determining the freezing depth of the road. The implementation of the results achieved with the reported development allows optimizing the shallow laying drainage structures with the improved characteristics based on the improved characteristics of the climatic index, processed by the contemporary methods of the mathematical statistics.

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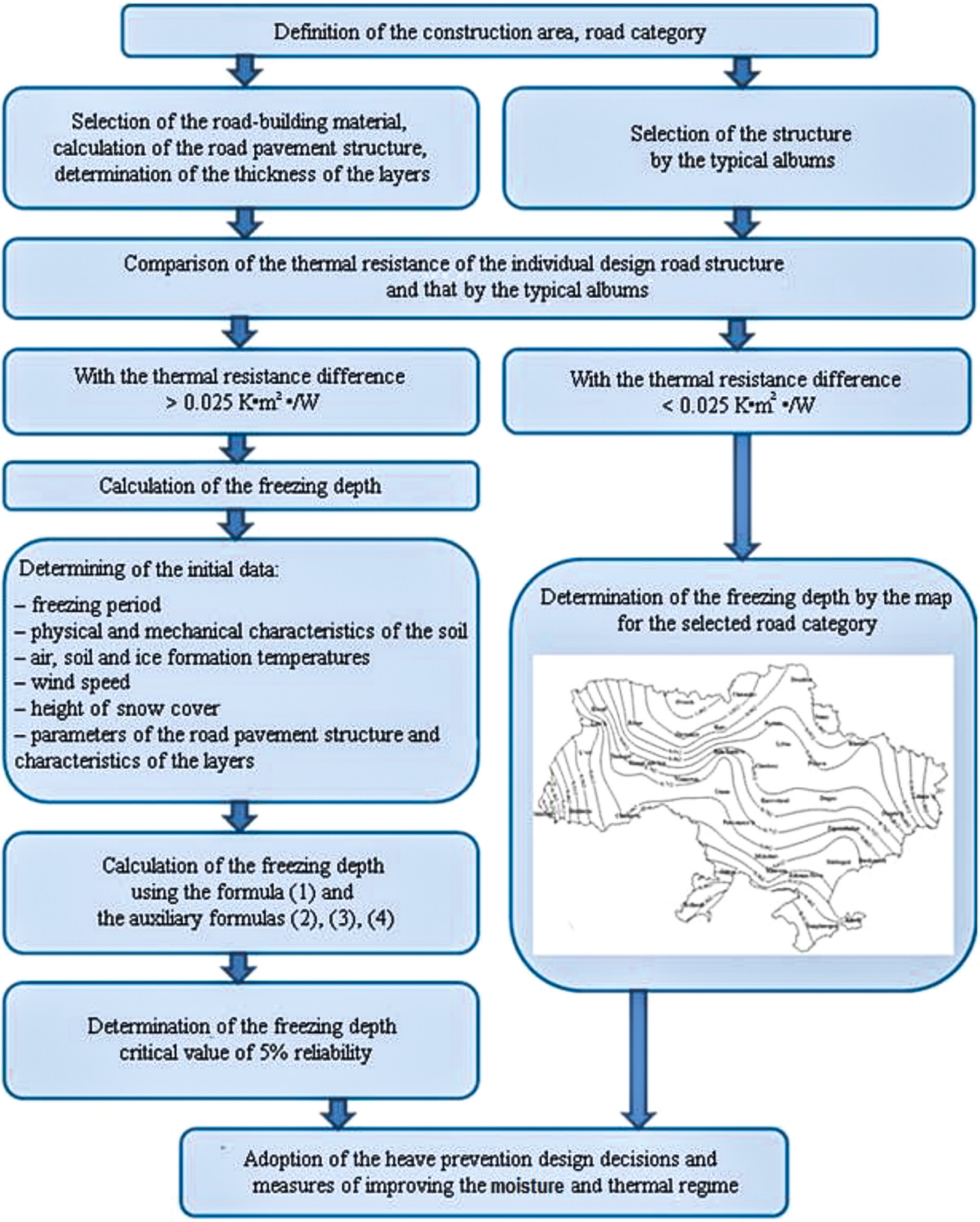

Figure 4. The Scheme of the Designer's Decisions: the Selection of the Structure Parameters for Regulating the Moisture and Thermal Regime

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