Improved design for accelerated consolidation of subgrade when building a highway on a weak base

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Abstract. This article deals with the design of the foundation of the subgrade of a motor road on a weak foundation (peat, sapropel) in difficult climatic and engineering-geological conditions. The features of physical and mechanical properties of soft soils imply the creation of non-typical design solutions using modern technologies and building materials. As a result, the theoretical studies of the processes of accelerated consolidation of weak soils were carried out and a design of the subgrade was proposed based on the use of electro-physical and filtration properties of various aggregates, namely the cathode layer (crushed stone from blast furnace coke or conductive coal), the drainage layer (sand) and the anode layer (crushed stone from dolomite limestone or basalt). The developed structure will allow reducing the consolidation time of a weak base and providing the necessary strength of the base by increasing shear resistance, which will increase the durability and reliability of the road, as well as reduce the technological construction time.

1. Introduction

The construction of high-quality and reliable highways is an urgent task for providing the population of our country with favorable conditions of existence in modern economic relations of any industry.

The motor road is an expensive transport structure, and therefore it is necessary to shorten the technological construction time as much as possible while ensuring the regulatory requirements for it, without reducing the service life to subsequent major repairs.

This is provided for in the national project "Safe and high-quality roads" on the basis of the Decree of the President of the Russian Federation dated May 7, 2018 No. 204 "On national goals and strategic objectives of the development of the Russian Federation for the period up to 2024", in particular the section of the project design passport "Road network".

The vast territory of the country is characterized by various climatic, engineering-geological and economic conditions that create significant difficulties in the design of construction, reconstruction and repair of highways. Since most of the projected sections have difficult conditions, it becomes necessary to create non-typical projects with the latest construction technologies and improvement of the main elements of the highway.

Many research organizations and scientists both in our country and abroad have dealt with problems of designing roads in difficult conditions, including automobile ones. Starting from the middle of the 20th century, characterized by the development of new territories of Western Siberia, the discovery and development of oil and gas fields and development of the oil and gas industry led to
development of the regional transport infrastructure, which was difficult in terms of engineering and geological conditions.

There is a tendency in the central regions of our country to reduce the use of valuable agricultural land as a right of way for the construction and reconstruction of highways that has led to the refusal to bypass of projected complex sections.

At the same time, the volume of earthworks associated with technologies for removing soft soil and an increase in the length of the route increased, that led to some rise in the cost and low rate of road construction, an increase in labor intensity and the duration of work. Therefore, from this period, a new direction in the design of highways in difficult conditions has been developing, based on the accumulated vast practical experience and the development of modern research in the field of soil science, engineering geology, as well as the theoretical basis of soil mechanics, rheology and physical and chemical mechanics.

Great contribution to the development of theoretical sections of soil mechanics on a weak foundation was made by Soviet scientists N.N. Maslov, N.A. Tsytovich, Yu.K. Zaretsky, N.M. Gersevanov, as well as foreigners K. Tertsagi, L. Lemb, A. Bishop, R. Peck and others [1].

From the point of view of the fundamental and practical use of the theory for specific purposes, the development of research in the field of constructing foundations of irrigation and drainage structures was of great importance, as well as industrial and civil buildings. It was carried out by B.I. Dalmatov, M.Yu. Abelev, K.P. Lundin, I.I. Vikhedaev [2]. As for road construction, a new direction of research with the development of new devices and structures for transport structures was carried out by the following scientists: V.D. Kazarnovsky, I.E. Evgenyev, D.M. Dobrov [3].

In turn, the development of new structures and methods for calculating foundations in difficult engineering conditions was carried out in foreign countries, namely the USA (L. Casagrande, w.Web, etc.), Canada (K. Anderson, I. Mac Farlane, R. Redforth), Switzerland (A. Moos, F.J. Aeckin, etc.), France (F. Bourges, G. Piot, etc.), Germany (A.D. Cicker, etc.), the Netherlands, Japan and others [3].

After analyzing the existing problems of improving and building new transport facilities, it becomes necessary to create atypical projects with implementation of the latest construction technologies and improve the structures of the main elements of the highway, especially those passing through difficult natural conditions.

2. Problem statement
One of the most important elements of the road is the subgrade. Its construction constitutes the bulk of construction costs, which affects the cost of construction and the payback of the project.

At the same time, the subgrade is to conform to building standards, since the further operation of the transport structure depends on its high quality. Particularly problematic is the construction of a subgrade in swampy areas, which relate to difficult engineering and geological conditions, since the base of the structure is a weak soil, consisting mainly of peat, sapropel, marl, etc. and having special physical and mechanical properties.

Analysis and study of the features of soft soils will make it possible to create rational engineering solutions for structures of the subgrade and improve technologies for its construction.

In this case, it is necessary to take into account the influence of these properties on the stress-strain state of a weak base, the quantitative value of which depends on the following factors:

- physical and mechanical characteristics of base soils;
- the magnitudes and values of the transferred traffic load;
- engineering geological conditions of the structure of the soil layer (the level of groundwater, the outline of the roof of the underlying rocks, conditions affecting the compression of the water-soil mass);
- construction technologies and compliance with operational measures for the existence of a transport structure.
The analysis and study of the features of soft soils and their joint stress-strain interaction with the main elements of the road will make it possible to create rational engineering solutions for the structures of the roadbed and improve the technologies for its construction.

3. Materials and methods
Many researches of both native and foreign origins are devoted to constructive solutions which allow providing the necessary technological characteristics of the subgrade on a weak basis. These works deal with theoretical studies in the field of soil mechanics, in particular the system of phase interaction in the soil mass, developed by Terzaghi, which allows the use of accelerated consolidation by creating artificial channels (drains), which are designed to remove pore water under the influence of excessive pore pressure. The physical and mechanical process is based on shortening the filtration path and changing the compaction rate of weak water-saturated soil under the embankment, since it depends on the duration of water squeezing out of its pores under the influence of a constant load, thereby reducing the embankment settling time. This increases the bearing capacity and stability of the foundation, as the resistance to soil shear increases [4, 5].

When erecting a subgrade on a weak foundation, vertical and horizontal drainage is used, this depends on the strength of the weak soil under the base of the embankment. Theoretically and practically, a relationship has been established between the types of drainage, which in most cases can be considered as the spatial possibility of combining the equation for vertical and horizontal flows in two-dimensional consolidation.

Simplified engineering methods, namely the principle of vertical drainage, were most applied. The studies in this area [4, 5, 6] have shown that for the effective operation of vertical drains, the following conditions must be met:
- the section of the drain must have high water permeability;
- the load acting on the surface of the soil being compressed must be sufficient to overcome the initial filtration gradient and carry out intensive consolidation;
- the presence of free outlet of gravity water from drains to the lower part of the embankment or to a special drainage layer.

Considering the above mentioned aspects, it is necessary to justify the influence of the hydraulic gradient, under the action of which water is squeezed out of the compressible layer when the following condition is met:

\[ \frac{u}{L} > L_0, \]  

where \( u \) is the pore water head; \( L \) is the filtration path; \( L_0 \) is the initial filtering gradient.

Compliance with this condition is ensured by the value of the initial filtration gradient in loose soil, which is expressed by the following dependence:

\[ L_0 = C_f \cdot \lg \cdot p, \]  

where \( C_f \) is the average value of the filtration coefficient of loose soil; \( p \) is embankment pressure on the base.

Based on dependencies (1) and (2), and considering that the pressure in the pore water corresponds to the pressure of the embankment base, an expression was obtained to determine the necessary filtration path or the distance between drains to ensure complete soil consolidation:

\[ L > 0.423 \cdot (100 - U_0) \cdot p \cdot \ln \cdot p/C_f, \]  

where \( U_0 \) is soil consolidation in%.

Using the obtained expression, it is possible to estimate the effect of drainage devices on acceleration of the filtration consolidation of a loose low-permeability layer, if the thickness of compacted layer \( H \) is known, the selected distance between drains is \( L \). Then, using the ratio of the duration of the consolidation period of the formation with one drain filler \( t_1 \) to the corresponding period under the action with another filler \( t_2 \), one can choose a rational distance between drains:
As the experience of designing shows, it is difficult to fulfill this condition, since the values of \( L_0 \) are large and even the use of a temporary surcharge does not allow reaching the calculated value, thereby reducing or stopping the filtration sediment process.

4. Advanced design for accelerated consolidation

The use of filter aggregates with the required physical and mechanical properties for standard drain diameters is of great practical interest in the development of design solutions. It is possible to reduce the consolidation time and accelerate the water filtration process due to the electro-physical effect of the interaction of various materials [7, 8].

It is planned to improve the constructive solution for the accelerated consolidation of a loose base by sequent arrangement of the filtration material with different electro-physical properties in vertical drains (Fig. 1): cathode layer 5 (crushed stone from blast furnace coke or conductive coal), drainage layer 7 (sand) and anode layer 6 (crushed stone from dolomite limestone or basalt).

![Figure 1. The design of accelerated consolidation of a loose base. BSD is the boundary of the surface diversion. PS is the pavement surfacing. S is the shoulder. GW is the grading width. 1 - embankment, 2 - pavement surfacing, 3 - bottoming, 4 - loose base, 5 - cathode layer, 6 - anode layer, 7 - drainage layer.]

The principle of operation of the improved design is as follows. The placed layers of the filtration material in the drainage channels will allow the creation of electrically interconnected anode and cathode layers, which will create favorable conditions under the influence of an electrostatic field formed due to the electrical properties of materials for the transformation of cohesive water into gravitational water and its rapid removal to the lower base layer from the subgrade [9, 10]. The physical meaning is as follows: since a water molecule is a dipole and has electrical bonds, therefore, under the influence of an electrostatic field between the anode and the cathode, it will be constantly removed not only from the peat cover, but from the body of the embankment, which will accelerate the precipitation process and drainage of the subgrade.
Figure 2. Influence of vertical drains with different filling on the strength of the base: 1 - combined anode-cathodic filtering filling; 2 - gravel filling; 3 - sand filling. Slimit - general resistance.

5. Conclusion
The use of a combined three-layer filling of vertical drains will not only reduce the consolidation time of a loose base, but also provide the necessary strength of the base by increasing the shear resistance, since the vertical drains are filled in the upper and lower parts with a stronger material, turning ordinary drainage slots into pile drains.

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