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The results of monitoring the properties of road embankment soils

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For five full-scale objects, research methodology and geotechnical control results of physical and mechanical characteristics of in layers compacted silty loam within the road embankment after its construction and before the operation start are presented. According to the statistical analysis of the two-factor experiment data sample, empirical coefficients values of the analytical dependence of stabilized moisture for loams' in layers rolling on the value of soil skeleton density within the embankment and the plasticity index of these soils were obtained. It has been proven that this parameter corresponds to the maximum molecular moisture capacity in clay soils, at which it is most expedient to do in layers compaction to ensure subgrade long-term strength

Keywords: road embankment, soil base, silty loam, soil compaction, soil moisture, soil skeleton density, maximum molecular moisture capacity, long-term strength, plasticity index, cutting ring method, laboratory soil testing

Результати контролю властивостей ґрунтів дорожнього насипу

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Для п'яти натурних об'єктів подано методику досліджень і результати геотехнічного контролю фізико-механічних характеристик пошарово ущільненого суглинку пилуватого в межах дорожнього насипу за час після його зведення та до початку експлуатації. За статистичним аналізом вибірки даних двочинникового експерименту отримано величини емпіричних коефіцієнтів аналітичної залежності стабілізованої вологості суглинків для їх пошарового укочування від значення щільності скелету ґрунту в межах насипу та числа пластичності цих ґрунтів. Доведено, що цей параметр відповідає вологості максимального вмісту зв'язаної води в глинистих ґрунтах, за якої найбільш доцільно пошарово ущільнювати їх для забезпечення тривалої міцності земляного полотна. Також проаналізовано найбільш популярні тренди сучасної транспортної геотехніки: модифікації конструкції дорожнього насипу відповідно до його призначення, матеріалу, геометричних параметрів, природних умов експлуатації, небезпечних інженерно-геологічних процесів і т. ін.; комбінації пошарового ущільнення ґрунту з геосинтетичними стками чи просторовими (3D) георешітками; попереднє фізичне моделювання процесу ущільнення ґрунту для оптимізації режиму зведення насипу конкретним ущільнюючим механізмом; стандартний лабораторний тест певного грунту для визначення оптимальної вологості його ущільнення з наступним польовим контролем якості ущільнення; пошарове ущільнення ґрунту з позицій забезпечення тривалої міцності земляного полотна, тощо. Відзначено оригінальні особливості в проектуванні земляного полотна, як-то: використання емпіричних рівнянь взаємозв'язку між фізичними та механічними властивостями ущільнених ґрунтів у насипу; прийняття ортотропної моделі ґрунтового середовища; моделювання методом скінчених елементів процесу ущільнення ґрунтів для насипу; застосування ймовірностних підходів з оцінювання неоднорідності штучно створеного середовища й ризиків його експлуатації

Ключові слова: дорожній насип, ґрунтова основа, суглинок пилуватий, ущільнення ґрунту, вологість ґрунту, щільність скелету ґрунту, максимальна молекулярна вологоємність, тривала міцність, число пластичності, метод ріжучих кілець, лабораторне випробування ґрунту

Introduction

A road embankment is an artificial earth structure, the entire surface of which is located above the earth's surface. During the entire period of operation, it must effectively resist various influences without changing its geometric parameters and destruction. The strength of the subgrade depends mainly on the granulometric composition, moisture and density of the soil skeleton ρ_d. In the case of in layers clayey soils compaction, the soil skeleton density is usually normalized as some reference value, which is determined for their varieties according to the Proctor test or its modifications [1-4].

But the standards accept an optimal moisture W_{opt} and the maximum soil skeleton density ρ_{dmax} as the optimal compaction parameters, not including the actual mechanisms features. In compacted soil, the pores of which are filled with water, free water evaporates over time, which causes additional subgrade subsidence. On the other hand, when compacting low-moisture soil, even with modern rollers, it is not always possible to achieve the design coefficient of soil compaction, due to which additional subsidence deformations are also realized when such an embankment is compacted [1-4]. Thus, for road embankment erection it is important not only to achieve the maximum soil skeleton density, but also to ensure the long-term strength of the subgrade, when the properties of the soil acquired by compaction are preserved during the standard period of operation, and excessive deformations of the artificial structure do not occur.

Review of the research sources and publications

The problematic situation described above was one of the discussions at a number of world and European geotechnical conferences of the last decade, in particular: 18th International conference on Soil Mechanics and Geotechnical Engineering (Paris, 2013) [5-12], «XVI ECSMGE Geotechnical Engineering for Infrastructure and Development» (Edinburgh, 2015) [13-18], 19th International conference on Soil Mechanics and Geotechnical Engineering (Seoul, 2017) [19-23], 20th International conference on Soil Mechanics and Geotechnical Engineering (Sydney, 2022) [24-27]. Reports TC 202: Transportation Geotechnics are especially profitable in this direction.

Therefore, it makes sense to highlight some of the most popular trends in modern transport geotechnics aimed at solving the described problem:

– modifications of the construction of the road embankment in accordance with its purpose, material, geometric parameters, natural operating conditions, dangerous engineering and geological processes, etc. [9, 25, 26];

– combinations of in layer soil compaction with geosynthetic stacks or spatial (3D) geogrids [20, 22, 25, 26];

– preliminary physical (full-scale) modeling of the soil compaction process to optimize the embankment construction mode with a specific compaction mechanism [16, 19];

– a standard (tested by geotechnicians of many countries) laboratory test with a certain soil to determine its optimal compaction moisture (i.e., plotting the dependence of «soil moisture - soil skeleton density») with subsequent field geotechnical control of the compaction quality [5, 7, 9, 10, 12, 24]. At the same time, by the way, it is interesting to pay attention to examples of cracking over time of the soil surface already compacted to the design parameters [14];

– in layer soil compaction precisely from the standpoint of the subgrade long-term strength ensuring [8, 15, 17, 18, 28, 29, 30], etc.

We will also note original features in the subgrade design, such as:

– empirical equations applying of the relationship between the physical and mechanical properties of compacted soils in the embankment [6, 13, 21, 31];

– adopting an orthotropic (anisotropic) model of the artificial soil environment [32, 33];

– finite element modeling of the soil compaction process for embankment [11, 21, 23, 31, 33];

– the application of probabilistic approaches to assessing the artificially created environment heterogeneity and the risks of its exploitation [27, 34].

Previously, the authors [28, 29], based on the data of laboratory studies, obtained an analytical dependence of the stabilized moisture W_k of the compacted subgrade loam on the soil skeleton density ρ_d and its plasticity index I_P

$$w_k = a_0 + a_1\left(\frac{\rho_d}{\rho_{d0}}\right) + a_2 \cdot I_p\,, \tag{1}$$

where $\rho_{d0} = 1$ g/cm^3; $a_0 = 0.531$; $a_1 = -0.279$; $a_2 = 0.570$ – empirical coefficients.

It has been proven [28, 29] that the stabilized moisture is the parameter that corresponds to the maximum molecular moisture capacity, at what it is advisable to do the subgrade clay soils multilayer consolidation for their long-term strength ensuring.

Definition of unsolved aspects of the problem

However, there are currently no results of field research on the patterns of water migration in the massif of in layer compacted clay soils depending on the plasticity index, soil skeleton density, the height of the embankment, the time factor, etc.

Problem statement

Therefore, the purpose of this work is by controlling the physical and mechanical parameters of in layer compacted types of silty loam within full-scale road embankments during their «rest» (after construction and before operation) to reveal possible patterns of changes in the moisture regime in the artificial layer depending on the skeleton density and the soil plasticity index.

Basic material and results

Research methodology

Full-scale experiments to assess possible water migration in massifs with in layer rolling of highway embankments and sites were carried out at five sites

(Fig. 1) in Poltava, Kharkiv, and Chernihiv regions. Indicative characteristics of loams for rolling; optimal parameters of their rolling; the required number of determinations of soil properties in the embankment were determined. The selection (Fig. 2) of compacted soil samples from the embankment into cutting rings in pits (3 samples per 300 m^2) with their subsequent examination (Fig. 3) by standard methods [35] was performed immediately after rolling each layer and after 0.5 – 1 month of «rest».

The physical parameters of the soil and technological factors that significantly affect the physical properties values of the compacted clay embankment soils, etc., were also highlighted.

a

b

Figure 1 – Embankment erection (object №4):
a – compacting mechanism – roller on the basis of MOAZ 6014 scraper; b – subgrade after rolling

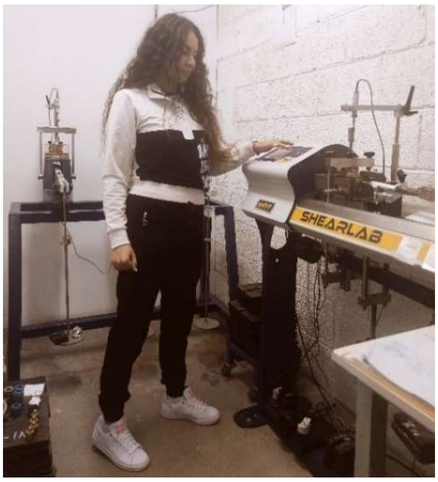
a

b

c

Figure 2 – Selection of soil in cutting rings from the road embankment:
a – subgrade surface; b – removing the top layer and pressing the ring into the soil;
c – cutting the soil from the upper and lower edges of the ring

a



b

Figure 3 – Equipment for the soil mechanical parameters determining:
a – odometer (for performing consolidation, swelling, collapse of soil);
b – machine for direct shear and consolidation

During the geotechnical control of soil embankment compaction quality, the following were recorded: the initial thickness of each soil layer; lowering its surface under the roller; the initial soil skeleton density within each layer after filling and planning to the horizontal level; the number of roller passes for one track; geometric dimensions of the working body and its mode of operation, etc.

At *object №1* the silty loam with the following indicative characteristics was used as a subgrade material:

– natural water content $W = 0.21$;
– liquid limit $W_L = 0.40$;
– plastic limit $W_P = 0.23$;
– index of plasticity $I_P = 0.17$;
– optimal soil moisture is obtained $W_{opt} = W_P = 0.23$;
– the average soil skeleton density in the embankment is $\rho_d = 1.65$ g/cm^3.

Due to the fact that the natural soil moisture is less than optimal, it was moistened to $W_{opt} = 0.23$ using a water washing machine with a technological break of 2-3 hours for uniform distribution of moisture over the entire layer thickness.

The layer thickness after soil leveling with a grader and a bulldozer to the horizontal level was 0.2 m. The soil was rolled in 14 passes in one track with a HAMM 3520 single-drum cam self-propelled vibratory roller and a Hamm HD 150 TT pneumatic wheel roller.

At *object № 2* the silty, clayey loam with the following indicative characteristics was used as a subgrade material:

– natural water content $W = 0.17 – 0.20$;

– liquid limit $W_L = 0.27$;

– plastic limit $W_P = 0.20$;

– index of plasticity $I_P = 0.07$;

– the average soil skeleton density in the embankment is $\rho_d = 1.64$ g/cm^3.

Soil moisture is close to $W_{opt} = W_P = 0.204$. The thickness of the soil layer after planning 0.25-0.3 m. It was rolled for 6-10 passes in one track with a loaded KrAZ-256 car.

At *object № 3* the silty, clayey loam with the following indicative characteristics was used as a subgrade material:

– natural water content $W = 0.175 – 0.195$;

– liquid limit $W_L = 0.34$;

– plastic limit $W_P = 0.19$;

– index of plasticity $I_P = 0.15$;

– optimal soil moisture is obtained $W_{opt} = W_P = 0.19$;

– the average soil skeleton density in the embankment is $\rho_d = 1.705$ g/cm^3.

The soil layer thickness after planning 0.25-0.3 m. It was rolled through the passes of loaded KrAZ and MAZ in one track.

At *object № 4* the silty, clayey loam with the following indicative characteristics was used as a subgrade material:

– natural water content $W = 0.21$;

– liquid limit $W_L = 0.355$;

– plastic limit $W_P = 0.22$;

– index of plasticity $I_P = 0.135$;

– the average soil skeleton density in the embankment is $\rho_d = 1.60$ g/cm^3.

The soil layer thickness after planning 0.25-0.3 m. It was rolled for 6 - 10 passes with a roller based on a MOAZ 6014 scraper with a mass of 25 tons per track.

At *object № 5* the silty, clayey loam with the following indicative characteristics was used as a subgrade material:

– natural water content $W = 0.225$;

– liquid limit $W_L = 0.27$;

– plastic limit $W_P = 0.19$;

– index of plasticity $I_P = 0.08$;

– the average soil skeleton density in the embankment is $\rho_d = 1.57$ g/cm^3.

Research results and their interpretation

The moisture of compacted clay soils, collected in rings from the embankment after 1 month of its «rest» was on average at the objects:

– №1 – $W_k = 0.17$;

– №2 – $W_k = 0.13$;

– №3 – $W_k = 0.15$;

– №4 – $W_k = 0.17$;

– №5 – $W_k = 0.15$.

Basically, the moisture of silty loams after their in layer rolling before the start of embankment operation decreased to the maximum molecular moisture of these soils. Values of indicative parameters (natural soil moisture W, liquid limit W_L, plastic limit W_P, index of plasticity I_P) of silty loams used as a material for the subgrade of full-scale objects, the average soil skeleton density in the embankment ρ_d and the stabilized (after «rest») moisture W_k of the compacted road embankment loam is summarized in the table. 1.

Table 1 – Indicative parameters of loams used as embankment material, the average density of the soil skeleton subgrade, the stabilized moisture of the compacted loam of the road embankment

Soil parameters	Objects				
	№1	№2	№3	№4	№5
W	0.21	0.17-0.2	0.175-0.195	0.2	0.225
W_L	0.40	0.27	0.34	0.355	0.27
W_P	0.23	0.20	0.19	0.22	0.19
I_P	0.17	0.07	0.15	0.135	0.08
ρ_d, g/cm^3	1.65	1.64	1.705	1.60	1.57
W_k	0.17	0.13	0.15	0.17	0.15

Therefore, there is a sense in a two-factor statistical analysis, similar to the previous one [29] for the results of laboratory studies, regarding the dependence of the stabilized moisture of the compacted clay road embankment soil on the soil skeleton density subgrade and the clay soil plasticity index assessment.

By means of a two-factor statistical analysis, we again have the dependence (1) of the stabilized moisture W_k of the compacted loam of the road embankment on the soil skeleton density and the index of plasticity, the empirical coefficients of which for the case of full-scale studies were:

$a_0 = 0.490$;

$a_1 = -0.238$;

$a_2 = 0.440$.

At this multiple correlation coefficient is $r = 0.993$, and Fisher's ratio test $F = 76.73$, what more than its table-valued 19,25 at test significance $p = 5\%$ and the degree of freedom $\nu_1 = 4$ and $\nu_2 = 2$ (the number of experiments $n = 5$). Statistical values indicate about close relationship between the research data and therefore, about the equation (1) correctness for the field research results.

A comparison of the stabilized loam moisture values of the subgrade compacted to $\rho_d = 1.5$ -1.65 g/cm^3 calculated according to expression (1) for different values of the coefficients a_0, a_1, a_2 for laboratory and full-scale conditions, established that:

– with the index of plasticity $I_P = 0.07$ (light silty loam, similar in properties to sandy loam), the values of moisture W_k, determined by formula (1) based on the data of field studies, exceed the corresponding values obtained by the results of laboratory experiments by no more than by 0,015;

– at I_P = 0.17 (heavy silty loam, similar in characteristics to light silty clay), the difference in the values of W_k, obtained by (1) according to field and laboratory research data, does not exceed 0.005.

The values of the strength parameters (angle of internal friction φ, specific adhesion c) of heavy silty loam, selected in rings from the embankment at object No. 1, were also compared. The density the soil skeleton density was ρ_d = 1.65 g/cm^3.

The first group of samples corresponded to soil shrinkage at a moisture of W = 0.21, and the second - at W_k = 0.17. The samples were stored in a humid desiccator. According to their test for single-plane displacement, was received:

– for loam of the first group, the angle of internal friction φ = 24°; specific adhesion c = 34 кPa;

– for compacted loam of the second group φ = 24°; c = 41 кPa.

That is, the strength of clayey soil compacted at a moisture close to the maximum molecular moisture capacity was slightly higher than at a moisture exceeding this value. Therefore, the dependence of the stabilized moisture of silty loams for their in layers compaction on the soil skeleton density within the road embankment and the index of plasticity obtained in the laboratory experiment was confirmed.

Conclusions

Therefore, according to the geotechnical control data of physical and mechanical parameters of silty loam varieties of five road embankments for the period after their arrangement and before the start of operation, the following was established.

The moisture of silty loams, in layers compacted at plastic limit, during the «rest» period decreases to the maximum molecular moisture capacity, which corresponds to the maximum moisture of bound water, at which it is most appropriate to compact clay soils in layers to ensure their long-term strength.

New experimental data were obtained, which confirmed the analytical dependence (previously approximated by the laboratory experiments results) of the stabilized moisture of silty loams for their in layers compaction on the soil skeleton density within the subgrade and its index of plasticity. The absolute errors of this moisture values, obtained by the analytical expression based on the data of field and laboratory experiments, at I_P = 0.17 do not exceed 0.005, at I_P = 0.07 – 0.015.

The subgrade height of in layers compacted silty loams and the time of its «rest» do not significantly affect the stabilized moisture value of the embankment clay soils. The strength of clayey soil compacted at moisture close to the maximum molecular moisture capacity was slightly higher than at water content exceeding this value. The optimal criteria for in layers silty loams compaction, which ensure the subgrade long-term strength - compaction at soils' maximum molecular moisture capacity, have been improved.

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