Experimental studies of dynamic properties of soils of railroad embankments

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Abstract. The safety and stability of train traffic directly depend on the reliable operation of railroads and the condition of the subgrade. The main purpose of the research was to study the influence of vibration effects on the deformation characteristics of cohesive soils used in the subgrade of railroad embankments. The paper presents the results of compression tests, as well as deformability parameters of the studied soils under static and vibrodynamic loads. The values of deformation modulus (E) for soils of natural origin and with disturbed structure are discussed. It is confirmed that the change in the modulus of deformation of non-water saturated cohesive soils under the influence of vibration depends on changes in the stress state. The modulus of deformation of non-water-saturated clayey soils under static and vibrodynamic loads is determined by the type and nature of interactions between soil particles, as well as possible changes in the process of testing. Soil humidity is one of the key factors influencing the nature of water-colloidal bonds and deformation properties of the soil sample under both static and vibrodynamic loading conditions.

Keywords: earth embankment, railroad track, dynamic loading, tangential stress, modulus of deformation, shear.

1. Introduction

The serviceability of railroad earthwork directly affects the safety and continuity of train traffic. The stress-strain state of soil structures depends not only on the impact of external factors, but also on the physical nature of the soils composing the massif. The main parameters used in stability calculations are the strength characteristics of soils - angle of internal friction and specific cohesion. The main parameters used in VAT calculations are deformation characteristics of soils - deformation modulus and transverse expansion coefficient (Poisson's ratio) [1]-[3].

The purpose of the research was to determine the deformation characteristics of cohesive soils under vibration loads, to study the influence of vibration effects on the deformation characteristics of cohesive soils and on the VAT of the subgrade of railway embankments [4]-[5].

Characteristics of physical and mechanical properties of clayey soils are determined according to standard methods and the obtained data are consistent with the data of other experts. The calculation of the VAT of the embankment taking into account the dynamic properties of the soils is based on the principles and provisions of deformable solid mechanics and experimental data [6]-[14]. Determination of physical and mechanical characteristics of embankment soils is the most important component of geotechnical engineering studies affecting the safe operation of railway infrastructure [15]-[17].

In November 2024, a group of specialists from the testing laboratory "Testing of Track and Artificial Structures" carried out a survey of the railroad embankments in the area of Burunday settlement.

Soil samples of both disturbed and undisturbed structure were taken from the body of the railroad embankments in accordance with GOST 12071-2014. Physical characteristics of undisturbed structure soils determined according to GOST 30416-2020 are presented in Table 1. Tests to determine the characteristics of deformability were performed in the compression device Kpr-1 of the Hydroproject system for samples of both undisturbed and disturbed structure with moisture and density corresponding to the natural one. The tests were conducted according to the standard methodology in accordance with GOST 12248-2010.

The novelty of scientific research is the improvement of the methodology of testing clayey soils, modeling the impact of train load and intensity of train traffic. train traffic. Identification of the regularity of the relationship between the parameters of deformability parameters of cohesive soils under static and vibration loads. As well as the regularity of the stress-strain state of railroad embankments taking into account the dynamic properties of soils of the earth bed of railway embankments.

2. Materials and methods

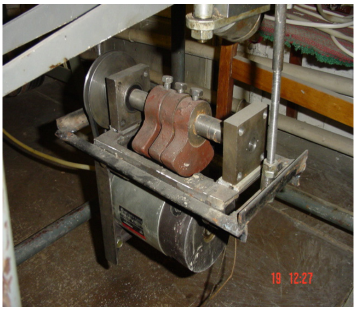
To conduct experimental studies, the authors used a modified version of a single-plane shear instrument VSV-25 designed by Gidroproekt, the general view of which is shown in Fig. 1.

The advantage of this device over domestic analogues is a more uniform distribution of stresses over the shear area due to the symmetrical impact of vertical and horizontal forces. Increasing the wall thickness of the device cages allowed to reach the value of relative shear deformation of the specimen of the value equal to 27 % of the inner diameter of the carriage.

To create vibrodynamic loading on the soil sample, an eccentric rotary vibrator (Fig. 1(b)) with a drive from a DC motor of PJK-25/3 brand was specially designed.

Changing the location of eccentrics on the drive shaft allows changing the amplitude of the pulsating load. The device operates in the controlled deformation mode (kinematic mode) and has additional equipment for temporary fixation of absolute shear deformations of the soil sample. The shear rate can vary from 0.5 to 0.01 mm/min. Variation of shear rate is regulated by changing the current of the power supply VSA-5K.

a) General view



b) Eccentric rotary vibrator

Fig. 1. VSV-25 single plane shear instrument

The reciprocating motion of the lower movable cage of the device is created by the reduction reducer MPK-13I-5 through the spindle. The general drive of the shear force system is carried out by a DC motor D-10ARU. At vibrodynamic influence frequency of oscillations is regulated by laboratory automatic transformer “LATR”. The value of the oscillation frequency is determined by the tachometer. The tachometer is driven through the speedometer cable of the GAZ-53 car connected to the driven shaft of the rotary vibrator. The device design allows to create vibration frequency in the range from 0 to 30 Hz.

Control and measuring equipment allow to obtain quantitative values of alternating normal load N±DN both at static and vibrodynamic influences, as well as horizontal shear force T and displacement of the device cage U.

2.1. Test methodology

The curves plotted in Figs. 2-4 with sufficient accuracy are approximated by equations of the form:

$$\tau = m_0\varepsilon^4 + m_1\varepsilon^3 + m_2\varepsilon^2 + m_3\varepsilon + m_4, \tag{1}$$

where $\tau = f(\sigma, \varepsilon)$; m_0, m_1, m_2, m_3, m_4 – coefficients; ε – relative deformation.

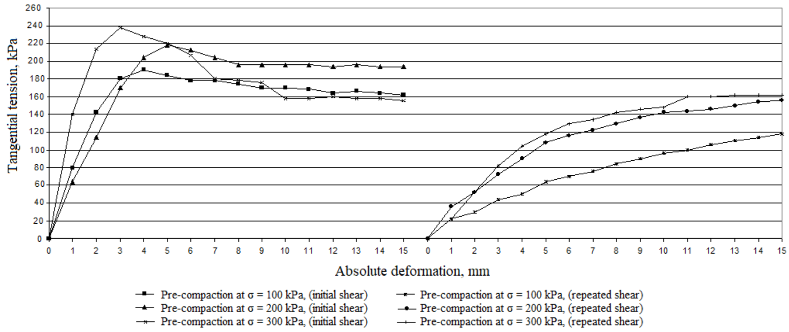


Fig. 2. Graph of the relationship between absolute strain and tangential stress (plastic sandy loam from km 4048, PK 5, unloaded experiment)

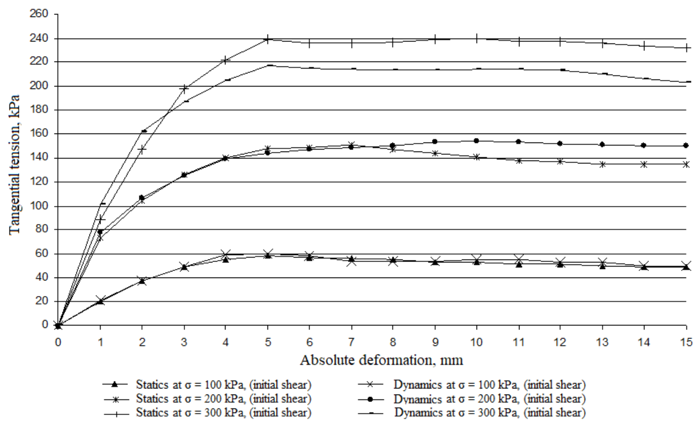


Fig. 3. Graph of the relationship between absolute strain and tangential stress (plastic sandy loam from km 4048, PK 5)

Transition from shear modulus G to strain modulus E_0 is made by the following dependences:

$$\gamma = \frac{\tau}{G}, \quad G = \frac{\tau}{\gamma}, \quad G = \frac{E_0}{2(1+\mu_0)}, \quad E_0 = 2G(1+\mu_0), \tag{2}$$

where γ – angular strain, τ – shear stress, G – shear modulus, E_0 – deformation modulus, μ_0 – coefficient of transverse soil expansion (Poisson's ratio).

3. Results of the study

The results of the compression tests are presented in Table 1.

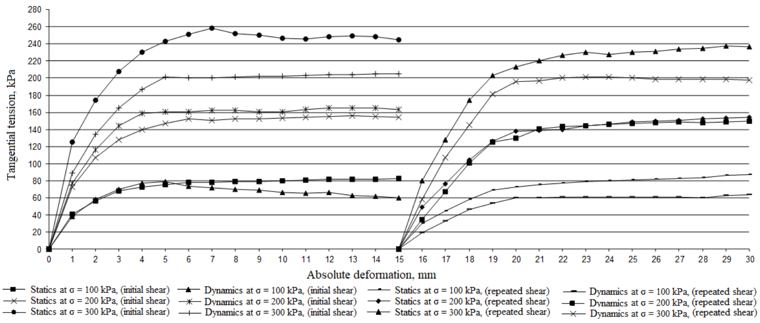


Fig. 4. Graph of the relationship between absolute strain and tangential stress (Plastic sandy loam from km 4048, PK 5)

It can be seen from the table that the value of modulus of deformation E for disturbed soil is slightly lower than that of the soil of natural composition.

This can be explained by the destruction of structural bonds between soil particles.

Table 3 shows the deformability parameters of the studied soils under static and vibrodynamic loading.

Table 1. Physical properties of soils

Selection site	Body of the railroad embankment of Burunday settlement		
Km, PK	4048 PK 5	4049 PK 6	4049 PK 4
Sampling depth, m	1,5	12,6	9,0
Natural moisture content, W, d.u.	0,213	0,234	0,233
Velocity limit, W_L, e.d.u.	0,247	0,302	0,257
Rolling limit, Wp, e.d.u.	0,188	0,189	0,207
Plasticity number, J_p, e.d.u.	0,059	0,113	0,050
Yield index, J_L, d.unit.	0,424	0,398	0,520
Density, ρ, g/cm^3	1,57	1,79	1,68
Solids density, ρ_s, g/cm^3	2,70	2,71	2,70
Dry density, ρ_d, g/cm^3	1,29	1,45	1,36
Porosity, n, %	52,2	46,5	49,5
Porosity coefficient, e	0,91	0,64	0,98
Moisture content, Sr	0,63	0,99	0,64
Soil type and condition	Plastic sandy loam	Tight plastic loam	Plastic sandy loam

4. Discussion of the results

It can be seen from Fig. 2 that the peak value of tangential stress at initial shear at $\sigma = 100$ kPa, reaches a value of 190 kPa, at $\sigma = 200$ kPa, reaches a value of 219 kPa, at $\sigma = 300$ kPa, reaches the value of 239 kPa, and at the repeated peak value of tangential stress at $\sigma = 100$ kPa, reaches the value of 119 kPa, at $\sigma = 200$ kPa, reaches the value of 157 kPa, at $\sigma = 300$ kPa, reaches the value of 160 kPa. It means that the tested soil (plastic sandy loam) resists better at initial (unbroken structure) shear forces than at repeated passage of the carriage (broken structure).

Fig. 3 shows that the peak value of tangential stress under static loading conditions under initial shear at $\sigma = 100$ kPa, reaches a value of 58 kPa, at $\sigma = 200$ kPa, reaches a value of 150 kPa, at $\sigma = 300$ kPa, reaches the value of 218 kPa, and under dynamic repeated loading, the peak value of tangential stress at $\sigma = 100$ kPa, reaches the value of 60 kPa, at $\sigma = 200$ kPa, reaches the value of 152 kPa, at $\sigma = 300$ kPa, reaches the value of 240 kPa. The difference between static and dynamic tests of the tested soil (plastic loam, unbroken structure) is not significant at $\sigma = 100$ kPa and $\sigma = 200$ kPa, and at $\sigma = 300$ kPa, the value of tangential stress under dynamic influence decreases by 11 %.

Table 2. Indices of soil compressibility

Km, PK, sampling location, sampling depth	Normal pressure P, MPa	Soil of undisturbed structure			
		Porosity coefficient, e	Compressibility (compaction) coefficient, a, MPa $^{-1}$	Relative strain, ε	Strain modulus, E, MPa
4048, PK 5, body embankment, 1,5 m, plastic sandy loam	0	Soil of natural composition (undisturbed structure)			
	0,05	0,907	0,986	0,0016	1,283
	0,10	0,901	0,759	0,0048	1,795
	0,20	0,826	0,654	0,0440	2,059
	0,30	0,761	0,462	0,0780	2,914
	0,40	0,715	0,284	0,1020	3,816
	0	Soil of natural composition (undisturbed structure)			
	0,05	0,958	1,546	0,0036	0,685
	0,10	0,933	1,034	0,0057	1,076
	0,20	0,878	0,893	0,0389	1,534
	0,30	0,797	0,678	0,0614	2,173
	0,40	0,615	0,326	0,0926	2,916
4049, PK 6, body embankment, 12,6 m, tight plastic loam	0	Soil of natural composition (undisturbed structure)			
	0,05	0,629	0,426	0,0066	1,486
	0,10	0,615	0,214	0,0155	2,941
	0,20	0,607	0,108	0,0203	5,618
	0,30	0,599	0,051	0,0248	10,417
	0,40	0,585	0,028	0,0337	14,873
	0	Disturbed soil			
	0,05	0,648	0,516	0,0089	1,233
	0,10	0,624	0,287	0,0178	2,536
	0,20	0,612	0,158	0,0226	4,927
	0,30	0,603	0,097	0,0274	8,751
	0,40	0,594	0,071	0,0312	12,387
4049, PK 4, body embankment body, 9,0 m, plastic sandy loam	0	Soil of natural composition (undisturbed structure)			
	0,05	0,969	1,246	0,0376	0,836
	0,10	0,952	0,416	0,0492	2,341
	0,20	0,884	0,263	0,0653	3,734
	0,30	0,836	0,135	0,0731	7,126
	0,40	0,784	0,086	0,0843	9,481
	0	Disturbed soil			
	0,05	1,084	1,437	0,0532	0,536
	0,10	1,027	0,684	0,0651	1,926
	0,20	0,973	0,495	0,0793	2,837
	0,30	0,927	0,318	0,0912	6,138
	0,40	0,871	0,237	0,108	8,874

Table 3. Deformation characteristics of soils

Sampling location	Type and condition of soil	E_{CT}, MPa	E_{din}, MPa	σ, MPa
Embankment body 1.5 m, km 4048 PK 5	Plastic sandy loam	18,46	16,78	0,1
		22,34	19,87	0,2
Embankment body 12.6 m, km 4049 PK 6	Soft plastic loam	7,34	5,89	0,1
		11,65	8,74	0,2
Embankment body 9.0 m, km 4049 PK 4	Plastic loam type and condition of soil	19,28	17,53	0,1
		24,65	21,97	0,2

From Fig. 4, it can be concluded that the peak value of tangential stress under static loading and initial shear at $\sigma = 100$ kPa, reaches a value of 80 kPa, and under dynamic reward and initial shear at $\sigma = 100$ kPa, reaches a value of 82 kPa, under static loading and initial shear at $\sigma = 200$ kPa, reaches a value of 162 kPa, and with dynamic reward and initial shear at $\sigma = 200$ kPa, reaches a value of 158 kPa, with static loading and initial shear at $\sigma = 300$ kPa, reaches a value of 258 kPa, and with dynamic reward and initial shear at $\sigma = 300$ kPa, reaches a value of 204 kPa, under static loading and repeated shear at $\sigma = 100$ kPa, reaches a value of 88 kPa, and under dynamic reward and initial shear at $\sigma = 100$ kPa, reaches a value of 64 kPa, under static loading and repeated shear at $\sigma = 200$ kPa, reaches a value of 158 kPa, and under dynamic reward and initial shear at $\sigma = 200$ kPa, reaches a value of 156 kPa, under static loading and repeated shear at $\sigma = 100$ kPa, reaches a value of 238 kPa, and under dynamic reward and initial shear at $\sigma = 100$ kPa, reaches a value of 198 kPa. This indicates that the soils in the embankment subjected to large dynamic loads are most susceptible to shear. If the shear forces reach the peak value, the process becomes irreversible, which will lead the embankment body to slump.

5. Conclusions

The results of experimental studies allow us to draw the following conclusions:

1) It is confirmed that the change of deformation modulus of non-water-saturated cohesive soils under vibrodynamic actions depends on the change of stress state.

2) Modulus of deformation of non-water-saturated clayey soils under static and vibrodynamic impacts depends on the type and nature of contact interactions between soil particles and the possibility of changes in the process of testing. At the same time moisture content is one of the main factors influencing the nature of water-colloidal bonds in the soil and deformation properties of the soil sample under static and vibrodynamic loading.

3) For calculations of VAT of railway embankments, it is reasonable to take deformability parameters obtained during vibration tests on shear or triaxial apparatus as design characteristics.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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