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Consolidation of loose foundation soil for esplanade project in Kaliningrad

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Abstract. The article presents the practical experience of pre-construction compaction of loose water-saturated clay foundation soils during the construction of Paradnaya Embankment in Kaliningrad. The engineering and geological conditions of the embankment construction site were complicated by the occurrence of a significant thickness (up to 15 m) of highly compressible flowing silts from the surface. The base preparation was carried out by preliminary compaction of loose soils with the ballasting embankment using vertical geodrains. The geotechnical monitoring system at the site was implemented after the construction of the ballasting embankment, in connection with which the designers made a premature conclusion that 90% of the degree of consolidation of soft soils according to the readings of pore pressure sensors was reached only 2 months after the filling of the ballasting embankment. The authors of the article analyzed the calculation methods of the consolidation process used in the design and the results of geotechnical monitoring. A repeated prediction of deformations of the soil mass from its compaction by the ballasting embankment was performed by a numerical method, taking into account the nature of the transfer of the load to the foundation, as well as the presence of shore protection structures of the embankment. A non-standard method was used to assess the total settlement of the ballasting embankment and the degree of consolidation of the foundation in the absence of correct monitoring data, which consists in determining the top elevations of loose soils by drilling control observation wells and comparing them with the results of engineering and geological surveys performed before the start of construction.

1 Introduction

In the run-up to FIFA World Cup 2018, in 2016-2017 the city of Kaliningrad started the construction of a football stadium project, with Paradnaya Esplanade as one of its facilities. Paradnaya Esplanade is located in the western sector of Oktyabrsky Island on the right bank of the Staraya Pregolya River. Its pedestrian area has a length of nearly 1,500 m and the width of about 30 m.

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Structurally, the Esplanade consists of shore protection structures, sub-grade, paved pedestrian area, and paved vehicles area (Fig. 1).

Fig. 1. The view of Paradnaya Embankment.

Engineeringly and geologically, the right bank of the Staraya Pregolya River is characterized by high ground water level and the occurrence of loose layers of clay soils (silt) as thick as 16 m, underlain by sandy soils and, occasionally, loam.

For the purpose of compliance with regulatory requirements with regard to foundation strength and deformation in conditions of fairly thick layers of loose, water-saturated soils, the project resorted to a common method for pre-construction compaction of loose soils with ballasting embankment using vertical geodrains [1-7].

In construction practice, successful implementation of this compaction method in loose soils largely depends on the accuracy of background surveying data; adequate choice of technique; accuracy of prediction calculations; timely on-site geotechnical monitoring; and the quality of monitoring data analysis during the soil consolidation process.

2 Consolidation of loose soils of the foundation during the construction of the embankment

2.1 Object of study

Structurally, the embankment represents a bank protection structure in the form of an anchored bulwark with sub-grade and structural elements on top. The front wall of the bulwark consists of a Ø1020x10 mm tubular welded sheet pile with a length between 19.0 m and 22.0 m. The anchor wall consists of a Ø1020x10 mm welded tubular sheet pile with a length between 15.0 m and 19.0 m. The distance between the front sheet piling and the anchor sheet piling is 22 m to 28 m. The front wall and the anchor wall are connected by Ø60-80 mm anchor rods, spaced at 2.4 m intervals.

The pre-construction compaction of the loose foundation soils involved the arrangement of sand ballasting embankment of varying height: +4.00 m BS in the pedestrian section and

+5.00 m BS in the vehicles section (Fig. 2 and 3). The sand for the embankment was medium-sized (min. 5 m/day filtration coefficient.

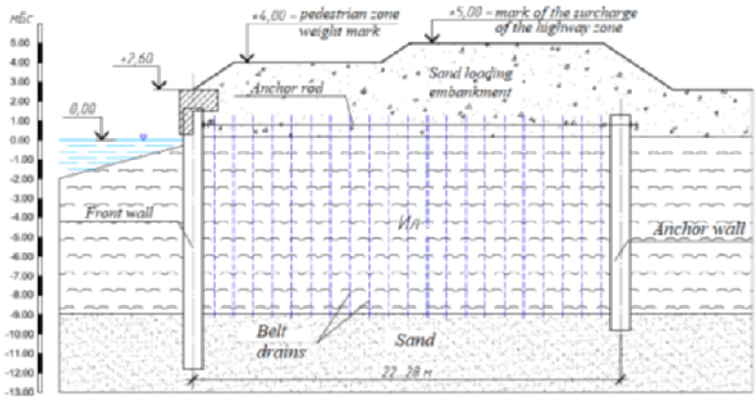

Fig. 2. The structural design of the embankment referenced to on-site engineering and geological conditions.

Fig. 3. The view of ballasting embankment for pre-construction compaction of loose soils.

Due to the large thickness and low water permeability of the loose soil layers (silts), 10 cm wide vertical geosynthetic drains were installed to accelerate the process of their consolidation. The drains were arranged in a square pattern with a spacing of 1.0 m. Their length ranged from 10 to 15 m, corresponding to silt layer thickness in some areas.

To enable the construction process in the waterlogged conditions, the site preparation works involved arrangement of a 1.0-1.5 m thick working layer, from which the vertical geodrains. The installation of the vertical geodrains was followed by filling of the main bulk of the ballasting embankment to its design height – a process that lasted for 6 months. It should be noted here that there had been unacceptable delay in installation on the site of geotechnical monitoring system Thus, the piezometers for measuring excessive pore pressure across the thickness of loose soils were installed only after the completion of the ballasting embankment, for which reason it wasn't possible to measure the pore pressure peak. Nor was it possible to ensure that sensors are spaced at equal distances from the vertical geodrains. The reference benchmarks for monitoring vertical deformation in the ballasting embankment were installed on the surface of the working layer six months after its filling, so the analysis of subsidence appeared incomplete. Further, as the ballasting embankment grew in height, the reference benchmarks got lost; the subsequent monitoring covered only the surface of the ballasting embankment, which did not allow us to estimate the total degree of compaction in loose soils.

The above shortcomings had led to the on-site geotechnical monitoring service mistakenly estimating the compaction degree to be 90% as early as 2 months after the installation of the ballasting embankment, based on the pore pressure sensor readings. That said, the ballasting embankment was measured to subside at a rate of 15 mm per month. In that situation, the construction project had timely turned to the authors of this article for critical analysis of their design solutions and geotechnical monitoring, conducted as part of the R&D support at the pre-construction soil compaction stage.

2.2 Prediction calculation methods and results

According to the project estimation, the loose soils were expected to achieve 90% compaction over ~6 months, with the final consolidation settlement varying between 1.58 m and 3.79 m.

The final settlement was calculated by the project using Konovalov formula (Konovalov, P.A. 1995. Construction engineering on peaty soils):

$$s = \frac{3ph}{3E + 4p}, \quad (1)$$

where p = sand fill pressure on the organomineral soil, kPa; h = organomineral layer thickness, m; E is organomineral soil deformation modulus at total moisture capacity, kPa.

The above formula is suitable for sand fills higher than 5h. In the design case under analysis, the ratio of sand fill width (22 ... 28 m) to minimum loose soil layer thickness (8.6 m) equals 2.6 to 3.3, which renders Konovalov formula inappropriate for the design conditions in question, as was further evidenced by numerical calculations and geotechnical monitoring results.

The final settlement was calculated by the authors using numerical modeling in finite-element software PLAXIS. Given the length of the facility, the calculations followed two-dimensional formulation using Coulomb-Mohr elastic-plastic model.

The chosen calculation method made it possible to take into account the nature of the load transfer from the ballasting embankment to the foundation, as well as the presence of shore protection structures made of sheet piles. The presence of sheet piling along the edges of the compacted foundation soil had a significant impact on the nature of the development of its deformations, in particular, it helped to limit the lateral expansion of the soil and, accordingly, reduce the overall settlement of the foundation (Fig. 4).

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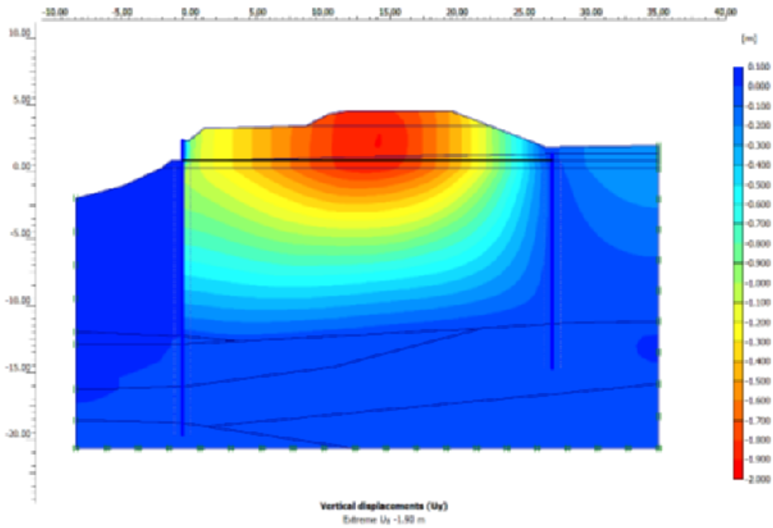

Fig. 4. Isofields of the development of vertical deformations of the soil mass from its compaction by a ballasting embankment.

According to the results of calculations, the maximum final settlement in the loose soils underneath the ballasting sand fill vary, depending on the loose soil layer thickness, from 1.22 m to 2.37 m.

Table 1. Final consolidation settlement calculated using different methods.

Site No.	Loose soil layer thickness, m	Ballasting sand fill thickness, m	Final settlement, m	
			Formula (1)	Numerical method
1	12.3	3.1	2.77	2.19
2	8.6	3.1	1.93	1.22
3	9.7	2.9	2.16	1.37
4	12.2	3.7	3.1	1.90
5	13.8	3.3	3.24	2.37

As can be seen from Table 1, the final settlement calculated by the project using formula (1) appear overestimated by 26% to 63%.

The follow-up calculation of filtration consolidation used analytical and numerical methods.

The calculation of the settlement in foundation soil over time used analytical method that made use of silty soils consolidation coefficient c_r=1.8 m^2/year, determined in laboratory conditions as part of the engineering and geological surveys.

Since the ratio of the minimum design thickness of the consolidated loose layer ($h_{s\,\min}$ = $H_{\min}/2$ = 8.6/2 =4.3 m) to the distance between the drains (d=1.0 м) equals, in the given geological and engineering conditions, is higher than 3, only the radial pore water filtration was taken into account in the calculations. The vertical filtration flow towards the draining boundary layers was not considered in the calculations due to the large thickness of the loose layer with vertical geodrains.

In the computational model, the consolidated foundation had the form of a soil cylinder with diameter d_e, compressed by a vertical, evenly distributed load with a radial filtration flow directed towards the drain.

Depending on the distance between drains d in the square grid, the actual (effective) diameter of geodrain d_e was calculated using the following formula:

$$d_e = d\sqrt{\frac{4}{\pi}} = 1{,}13d = 1{,}13 \cdot 1{,}0 = 1{,}13 \text{ м} \tag{2}$$

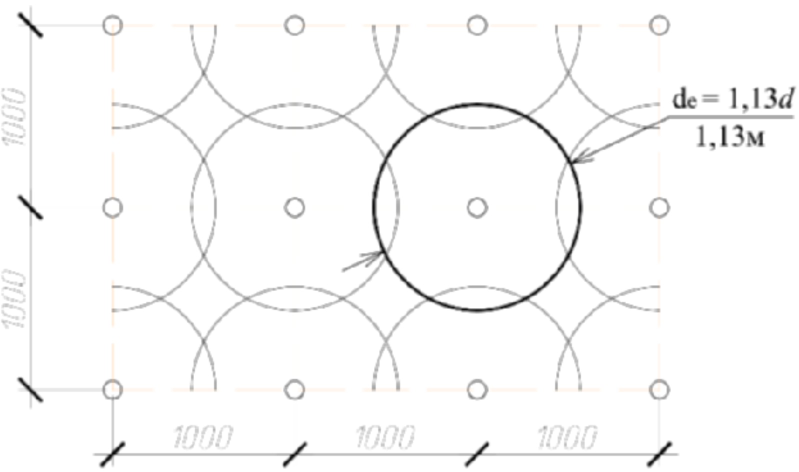

Fig. 5. The square-grid geodrain design layout.

The geodrain diameter d_ω, which is equivalent to a circular sand drain, was determined from the ratio of their perimeters. For the 100×3.5 mm cross-section geodrains, the equivalent diameter was calculated as follows:

$$d_\omega = \frac{2 \cdot (100 + 3{,}5)}{\pi} \cdot 0{,}75 = 49{,}4 \text{ мм} \approx 5 \text{ см} \tag{3}$$

where 0.75 is transition coefficient.

In our case, the ratio of the diameter of the zone of influence d_e to the equivalent diameter of the combined drain d_ω is:

$$\nu = \frac{d_e}{d_\omega} = \frac{1{,}13}{0{,}05} = 22{,}6 \tag{4}$$

As can be seen from Figure 4, with the design soil consolidation degree Q = 0.9 and ν=22.6, time factor T_r = 0.7.

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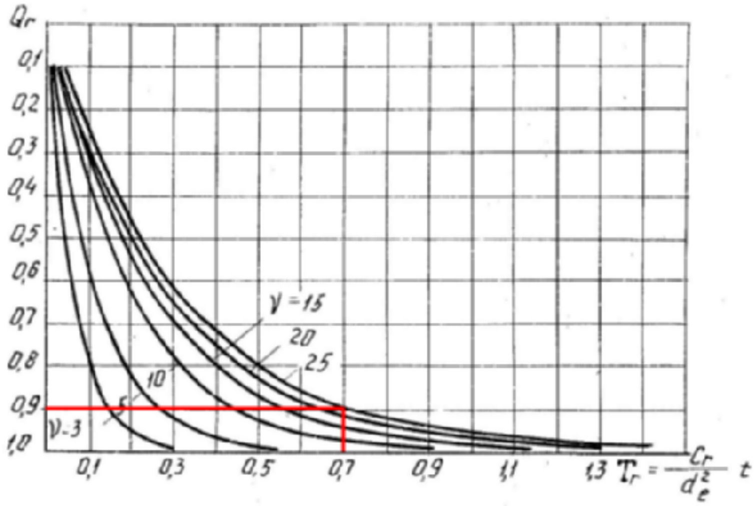

Fig. 6. The graphs for determining the soil consolidation degree using geodrains for instantaneous load application case.

Using time factor

$$T_r = \frac{c_r}{d_e^2} t \tag{5}$$

and loose layer consolidation coefficient $c_r = 1.8$ m^2/year, let us calculate time t (year), at which loose soil consolidation will reach 90%:

$$t = \frac{T_r d_e^2}{c_r} = \frac{0,7 \cdot 1,13^2}{1,8} = 0,5 \text{ года} \tag{6}$$

As part of the R&D support at the pre-construction soil compaction stage and additionally to the calculations made with use of analytical method, we used PLAXIS numerical method to calculate the settlement development over time in axially symmetric formulation. For consolidation calculations, PLAXIS uses as background data the filtration coefficient, the value of which was not provided in the engineering and geological survey report. For the purpose of numerical calculations, the filtration coefficient was back-calculated by us using the data on laboratory compression tests on silt soil samples, according to the formula:

$$k = c_v m_v \gamma_w, \tag{7}$$

where c_v = soil consolidation coefficient with vertical drainage, m^2/year; γ_w = specific gravity of water, kN/m^3; and m_v = relative soil compressibility coefficient, m^2/kN.

The averaged, back-calculated value of the loose soil filtration coefficient amounts to $2.5 \cdot 10^{-4}$ m/day.

The time for the filtration consolidation to achieve Q=0.9 with the use of vertical geodrains, calculated numerically, amounts to 6 months, which is consistent with the result of analytical calculations and the project-calculated value. In the scenario with no vertical geodrains, this time period amounts to 7 to 16 years, depending on the location and its soil conditions. Thus, the use of vertical geodrains can shorten the filtration consolidation period by 14 to 32 times, which indicates the expediency of the draining solution used.

2.3 Surveys to assess the degree of consolidation

Given the absence of accurate observations data on loose soil consolidation process, authors have proposed and implemented the following measures in order to estimate the actual consolidation degree:

- to determine the actual settlement in the sand fill along the esplanade, a number of observation wells were drilled at 50-100 m intervals, and record was kept of the absolute heights of the sand fill toe. Two wells were drilled in each section line, one in the pedestrian zone and one in the vehicles zone. The section lines were located along the axis of the wells that were drilled during the initial engineering and geological surveys. Having compared the absolute heights of the loose soils layers, recorded during the initial engineering and geological surveys and the follow-up surveys, we measured the settlement in the organomineral soil based on the pressure from the sand fill. This method for determining the sand fill settlement is an exception, but acceptable, given the significant compression in the loose foundation soil layer.
- in order to keep record of the deformation in loose foundation soils during their compaction, geodetic observations were made of the settlement in surface benchmarks, installed on the surface of the ballasting sand fill.

3 Discussion and conclusions

After 6 months from completion of the filling, the settlement in loose soil layer, determined with the help of observation wells, measured 0.98 to 2.91 m in the vehicles zone and 0.64 to 2.18 m in the pedestrian zone. The consolidation degree achieved by the loose soils was determined by way of comparing the actual settlement with the calculated settlement and amounted to 85% to 96% (Table 2). Based on the results of geodetic monitoring of the surface soil benchmarks, the deformation process was found to have stabilized: over the last month of observations, the rate of deformation in the foundation soil was measured less than 5 mm/month, which fully met the project requirements.

Table 2. The actual vs. calculated settlement in sand fill within the vehicle zone.

Site No.	Actual settlement, m	Final design settlement, m	Consolidation degree
1	-2.1	-2.19	96%
2	-1.08	-1.22	90%
3	-1.16	-1.37	85%
4	-1.65	-1.90	87%
5	-2.23	-2.37	94%

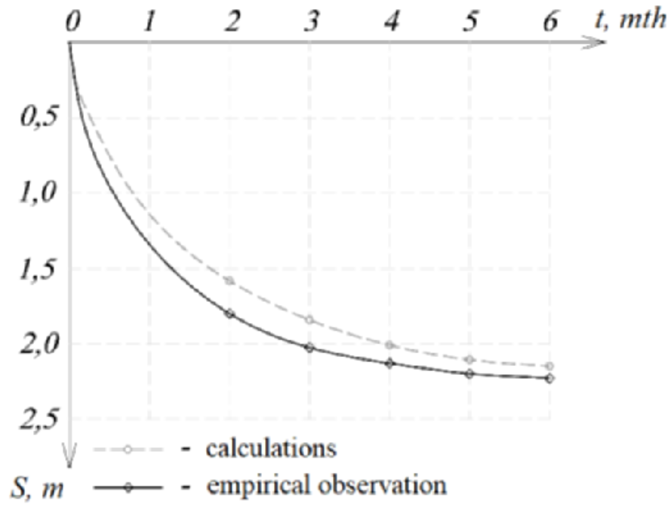

Fig. 7. Settlement vs. time graph for one of the characteristic sites.

According to the results of plate load tests, carried out upon completion of the consolidation process, the average deformation modulus of loos, fluid silts was found to have increased from 0.5 to 8 MPa.

The use of the numerical method in solving the problem of filtration consolidation showed good convergence of sediment development over time. Discrepancy between calculated and measured sediments is based on rash of 5% to 15%.

The method of pre-compaction of the thickness of loose water-saturated soils with a ballasting embankment using vertical geodrains has shown its effectiveness and allow:

- improve the deformation characteristics of loose foundation soils. The modulus of deformation has increased by an average of 16 times;
- reduce the period of filtration consolidation as a result of the use of vertical geodrains up to 32 times.

The organization of an integrated system of geotechnical monitoring before the start of construction allows timely and most reliable assessment of the parameters of the process of consolidation of a loose water-saturated foundation according to the criteria of settlement and reduction of excess pore pressure. In the case of organizing geotechnical monitoring after the construction of the ballasting embankment, the parameters of the consolidation process are evaluated only by the criterion of settlement and require non-standard engineering approaches.

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