Study of Deformability of Weak Soils Underlying the Embankment at Construction Sites in Nakhodka City, Primorsky Region

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Abstract. The article presents the dependences of the weak soil settlement (peat, silty sand) on their capacity, the capacity of artificial embankment and the dynamic effects of transport and construction machinery on the planned area, which were identified due to long-term observations over settlement of ground reference marks and benchmarks. The recommendations are given to determine the settlement of weak soils under the embankment pressure when planning a residential area.

1. Introduction

The coastal zones in the south of the Far East are under intensive construction, which results in the need to develop the areas formed by the masses of weak, structurally unstable soils (peat, peaty and silty sands, etc.). Bases composed of saturated organic-mineral and organic soils (which include peat) or including these soils, should be designed with due regard to the requirements of Code Specification (SP) 22.13330.2016 p. 6.4 [1]. Such bases are known for a significantly long development of the settlement and a possible risk of instability.

When building the structures on foundations composed of weak, water-saturated organic and organic-mineral soils, it is necessary to carry out the engineering preparation of the territory, including a creation of ballast in the form of a dam made of local material or washed sand directly on the surface of the site as well as drainage and other measures that improve the properties of weak bases [2-7]. The density of dry soil in ballasting dams is to be at least 1.65 t/cm³ [1, p. 6.4.26]. Such bases should be estimated by both bearing capacity and deformation. To ensure the normal operating conditions of buildings and structures on weak soils, it is necessary to forecast not only the settlement of the objects themselves, but also the settlement of the area as a whole under the influence of a complex of factors.

2. Conducted research

The problem of reliable determination of settlements arose in the course of the construction of the large-panel construction (KPD) plant and a residential neighborhood in the city of Nakhodka, where the actual settlements exceeded the estimated ones.
Engineering and geological conditions of the construction site at the Salt Lake in Nakhodka are as follows. Morphologically, the construction site is a buried lagoon surrounded by slopes. According to the engineering and geological surveys, the site is composed of the following lithological differences (from top to bottom): 1. The bulk layer is the soil made of a mixture of crashed stone, landwaste, inclusions of blocks with loamy aggregate in various percentages. The thickness of the layer is 1.1-3.0 m; modulus of deformation \( E = 6.0-10.0 \) MPa. 2. The 0.1-0.3 m-thick topsoil layer. 3. Wet peat, in places water-saturated and slightly decomposed with thickness of 0.4-0.8 m. 4. Silty sand is of medium density and loose. The thickness of the layer is 5.6-5.8 m; modulus of deformation \( E = 6.0 \) MPa; internal friction angle \( \varphi = 20^\circ \); specific cohesion \( C = 1.0 \) kPa. 5. Flowing sandy silt. Layer thickness is 0.4-1.1 m; modulus of deformation \( E = 2.5-3.0 \) MPa; internal friction angle \( \varphi = 11-12^\circ \); specific cohesion \( C = 5.0 \) kPa. 6. Soft and fluid plastic layer of loam with landwaste- and gravel up to 35%. The thickness of the layer is 2.2-2.4 m; modulus of deformation \( E = 15.0 \) MPa. 7. Landwaste and coarse medium gravels with the thickness of 1.4-4.5 m. 8. Basement rock of siltstone and porphyrite. Opened layer thickness is 0.2-0.6 m.

Groundwaters are represented by topwatering, and the silt of consistency from fluid to soft-plastic serves as an aquifuge. In periods of intense moisture formation like snowmelt and rainfall, a sharp rise in the level of groundwater is possible. The maximum level of groundwater in summer is the daylight surface.

When developing the residential area, the entire site was filled with a soil layer of 1.1-3.0 m. The pressure from the weight of the bulk layers on the roof of the underlying bed reached 50-125 kPa, which was the sufficiently significant value for weak soils.

Preliminary studies carried out at the construction sites of the KPD-80 plant and the residential neighborhood in Nakhodka showed that the relative compressibility of bulk soils is 5-7% of thickness of the layer, of the peat - up to 40%, and of the sand - 1.0-1.5%.

Since it was necessary to identify the cause of the discrepancy between the design and the actual amount of work on the formation of the area, this research was aimed at identification of the factors causing deformation of the soils at the construction site at the comprehensive development. At the same time, it was necessary to determine the possible values of settlement from various factors with an accuracy that allows to determine additional volumes of soil for the formation of the territory.

To solve the problem, long-term observation of the settlement of the built-up area was made to research the soil settlement of the construction site as a whole and stress-related properties of peat under load, and reports on current researches were studied [8, 9]. Based on the observations and previous studies reports, the dependences between the settlement amount, on the one hand, and the thickness of the embankment and peat layer, on the other hand, were determined.

The settlement of the site surface as a whole \( S \) can be represented as the sum of settlements of different nature:

\[
S = S_1 + S_2 + S_3 \tag{1}
\]

Where \( S_1 \) is the settlement of freshly placed soil;

\( S_2 \) – the settlement of the underlying layers, caused by pressure of the weight of the bulk layer;

\( S_3 \) is the surface settlement caused by additional loads.

The long-term observations (for almost three years) over the settlement of the studied construction site showed the following.

**Settlement \( S_1 \) of the freshly placed layer** of soil is caused mainly by the builders' failure to follow the technology of layer-by-layer compaction of bulk soils with rollers, as well as low compaction efficiency in winter due to the soil freezing. This suggests the need for careful monitoring of the degree of compaction of the embankment and compliance with the required compaction coefficient \( K_{pc,\%} \).

**Settlement \( S_2 \) of the underlying layers** caused by the pressure of the weight of the bulk layer can be represented as

\[
S_2 = S_{2T} + S_{2II} \tag{2}
\]

Where: \( S_{2T} \) is the settlement of the peat layer;


\( S_{2\Pi} \) – settlement of the layer of soils, lying under the peat (in this case - a layer of sand).

If there is a peat layer in the underlying soils (the relative compressibility of peat is up to 40\% of the thickness of the layer, while the relative compressibility of peat and sand is only 1.0-1.5\%), it can be assumed that the settlement occurs mainly due to the compaction of the peat.

SP 22.13330.2016 (clause 6.4.30) provides formula (6.18) for determining the final settlement of organic and organic-mineral soils in a stabilized state \( S_{cm} \), m, caused by washed sand or by the filled soil:

\[
S_{cm} = \frac{3ph}{3E + 4p},
\]

(3)

where \( p \) is the pressure from the ballasting dam on the surface of organic-mineral and organic soil, kPa;

\( h \) is the thickness of the layer of organic and organic-mineral soil, m;

\( E \) - modulus of deformation of organic and organic-mineral soil at full moisture capacity, kPa.

However, this document does not specify a period of peat stabilization.

The expected settlements of construction sites of the KPD plant and residential neighborhood in the city of Nakhodka were calculated according to [1], however, the actual deformations of the development area turned out to be slightly higher.

To identify the causes of this discrepancy, DalNIIS researchers studied the previous researches reports on the deformability of weak clay soils and peats, the methods of estimating settlement [10-14], and conducted long-term in-situ observations of the settlement of the areas.

The observations showed that the relative settlement of peat can vary widely - from 26-27\% to 48-50\% - depending on the thickness of the peat layer \( h_t \), the height of the embankment \( h_n \), the load of the damped area by pressure \( p \) and the time.

When analyzing the process of development of settlement \( S \) of the area under construction, the researchers used the data of monitoring of the settlements of bulk soil \( S_1 \), peat \( S_{2T} \) and settlements of a layer of sandy soil lying under the peat \( S_{2\Pi} \).

To assess the compressibility of bulk soils and peat at the KPD plant and residential area construction sites, 8 ground reference marks have been installed (4 marks were immediately destroyed by a bulldozer). The marks were installed on the roof of peat and covered with soil. The change in the height of the mark showed the settlement of the soil underlying the embankment, that is, the settlement composed of the settlement of peat \( S_2 \) and the settlement of the soil underlying the peat \( S_4 \). The measurement of the settlement of the ground marks was carried out according to the current regulations [15, 16].

Observations over ground marks settlements (Table 1) showed that the settlements of soils underlying the embankment developed most intensively in the first 5-6 months of observation (in the warm period of the year). The complete stabilization occurred within 2-3 years.

### 3. Results

**Table 1.** Settlements of ground marks at the construction sites of the KPD plant and residential neighborhood.

| No. of ground marks | 1 | 2 | 3 | 5 | 6 | 7 | 8 |
|---------------------|---|---|---|---|---|---|---|
| Thickness of peat \( h_t \), m | 0,8 | 0,6 | 0,4 | 1,0 | 0,8 | 0,8 | 0,0 |
| Thickness of embankment \( h_n \), m | 2,8 | 4,5 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 |
| Settlement in 5 months, mm | 85 | 300 | 85 | 361 | 300 | 280 | 5 |
| Total observation time, months | 11 | 5 | 21 | 15 | 15 | 7 | 7 |
| Total settlement, mm | 121 | - | 197 | 375 | 325 | 300 | 16 |
Based on the other researchers’ reports [17-19], data from previous field tests and laboratory tests of the physical and mechanical properties of the peat deposit in various areas of the construction site, an empirical formula was obtained for calculating the final stabilized settlements of the peat layer $S_{км}$ by weight of the embankment in each case:

$$S_{км} = 0.361 \times h_t \times \log(1 + 4.49 \frac{h_n}{h_t}) \quad (4)$$

where $h_t$ is the thickness of the peat layer, cm; $h_n$ is the thickness of the bulk layer, cm.

To forecast the deformability of the peat underlying the embankment, the final stabilized settlements of the peat layer $S_{км}$ were calculated using formula (4) (Table 2).

| Thickness of a peat layer $h_t$, m in-situ | Thickness of embankment $h_n$, m |
|------------------------------------------|---------------------------------|
| 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0          | 0.20 0.60 0.80 1.00 1.20 1.40 |
| 78 100 111 120 127 132 137 142          | 147 201 236 260 275 298 308 321 |
| 184 267 321 361 394 419 440 462         | 199 295 355 403 442 472 508 520 |
| 208 320 382 430 477 512 543             | 211 320 361 403 442 472 508 520 |

In order to verify the design formula (4), data of observations over ground marks at the water pipeline along the Nakhodka-Vladivostok route were used (Table 3). Comparison of the actual and estimated values of the settlement showed a high degree of convergence of the results (the discrepancy between the value of the final stabilized settlement obtained from the observations and that one calculated by the formula was 5-10%) and made it possible to recommend the formula (4) to forecast the settlement of peat layers.

Table 3. Settlement of ground marks at the water pipeline along the Nakhodka-Vladivostok route.

| No. of ground mark | 9 | 10 | 11 | 12 | 13 | 14 |
|--------------------|---|----|----|----|----|----|
| Thickness of peat $h_t$, m | 0.8 | 0.2 | 0.2 | 0.4 | 1.0 | 1.2 |
| Thickness of embankment $h_n$, m | 1.5 | 1.2 | 1.0 | 1.0 | 2.0 | 3.0 |
| Total observation time, months | 21 | 21 | 21 | 21 | 40 | 40 |
| Total settlement, mm | 271 | 101 | 90 | 50 | 331 | 498 |

Thus, we can assume that after three years, the actual final stabilized settlement of the peat layer $S_{км}$ calculated by formula (4) will exceed the value of the settlement of organic-mineral and organic soils in stabilized state $S_{ст}$ calculated by formula (3) by the amount of $\Delta S_{ст}$, which results in the actual increase in the volume of earthworks in the planning area.

$$\Delta S_{ст} = S_{км} - S_{ст} \quad (5)$$

$$\Delta V = \Phi_{пл} \times \Delta S_{ст} \quad (6)$$
where $\Delta V$ is the additional volume of soil dumping when planning the territory; 
$\Phi_{пл}$ - dumping area; 
$\Delta S_{ст}$ - the difference between the actual and design settlement.

The settlement $S_3$ caused by additional loads, static and dynamic ones, is defined as: 
$$S_3 = S_{3Р} + S_{3G}$$

(3)

where: 
$S_{3Р}$ – the settlement caused by the weight of structures is determined according to [1] p. 5.6; 
$S_{3G}$ is the settlement caused by the effects of machines and mechanisms calculated according to [20, 21].

4. Conclusion
A comprehensive study of the compressibility of soils on the construction site revealed patterns of settlement occurrence and the nature of their occurrence in the designed territory, which made it possible to reliably determine the volume of earthworks during the formation of the construction area.

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