Vacuum consolidation for construction of motor road embankments in peat soil

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Abstract. One of the efficient methods to accelerate primary filtration consolidation of peat is vertical draining combined with vacuuming.

This article presents the results of laboratory analysis of vacuuming impact onto the peat deformation rate in the bases of motor road embankments. It demonstrates that the duration of peat vacuuming increases and its efficiency decreases with the increase of pressure exerted by surcharge sand layer.

The results of compression tests have shown that relative peat deformation after vacuum consolidation is 0.24…0.37; this means the deformation rate of the road base in the course of operation will be significantly lower.

The effect of vacuum consolidation on peat settlement rate during motor road embankment construction was assessed by numerical simulation in PLAXIS software, which enables accounting for consolidation and creep processes in motor road base courses. The results of numerical simulation were used to compare the efficiency of preloading the peat using surcharge sand with the efficiency of vertical draining combined with vacuuming, considering the allowable embankment settlement rate during motor road operation. Due to a low settlement rate, the vacuum consolidation method ensures normal road operation and allows increasing the maintenance interval.

1. Introduction
Preparation Construction of motor roads on peaty soils requires some extra base preparation activities. Surcharging the peat with sand during embankment construction is accompanied by prolonged settlement [1-10]. Site preparation on peaty soils may include the following: full or partial removal of weak soils, peat dewatering, peat surcharging with sand combined with water depression activities, construction of drains for quicker consolidation.

Sand drains have certain disadvantages: process complexity, low performance, and high cost. Replacement of weak soils is the most expensive method of base preparation. Peat surcharge with sand leads to long embankment settlement and road structure deformation.

Practice has shown that vertical draining using band drains is the cheapest way to accelerate peat base consolidation before constructing the road pavement. In most cases, peat surcharge with sand does not ensure the allowable settlement speed.
To increase the consolidation rate of motor road peat bases, it is reasonable to employ vacuum preloading. Vacuum in the peat base at construction sites is created by a vacuum pump connected to vertical drains with tubes. An airtight geomembrane is placed between the base and the embankment to prevent pressure drop [11-17]. Pressure build-up in the base combined with water pumping causes partial water removal from peat. Vacuuming ensures high base settlement rate due to reduced peat consolidation time.

2. Laboratory experiments
To evaluate the effect of vacuum preloading on settlement dynamics, we conducted laboratory tests in a tray measuring 0.4×1.5×1.0 m (Figure 1). We used poorly decomposed peat sample taken from the depth of 0.5 to 0.1 at a raised bog. Peat decomposition degree was 6 to 8%, density 1.00 to 1.02 g/cm³, particle density 1.47 to 1.52 g/cm³, moisture content 13 to 14, void ratio 17.8 to 19.8.

For vertical drains, we used plastic drains 20 mm in diameter, perforated at the bottom. The drains were combined via a plastic main pipe, to which a vacuum pump, a receiver, a pressure gauge, and a drum to collect pumped water were connected.

Figure 1. Peat vacuuming survey unit configuration: 1 – laboratory tray, 2 – peat, 3 – stamp, 4 – tubular drain, 5 – main pipe, 6 – water collecting drum, 7 – pressure gauge, 8 – receiver, 9 – vacuum pump.

Peat in the tray was pre-compacted under the pressures of \( p_0 = 8 \) and 16 kPa, which correspond to surcharge sand thickness 0.5 and 1.0 m required to carry out the works on site. After surcharging for 10 days, drains were inserted into the peat followed by vacuuming and water pumping. The duration of vacuuming in the first case was 3 hours at maximum suction pressure \( p \leq 60 \) kPa, and in the second case – 6 hours at \( p \leq 80 \) kPa. The values of relative deformation and moisture content of peat after vacuum consolidation are summarized in Table 1.

| Parameter                          | Natural-structure peat | Peat vacuuming at pressure exerted by | 8     | 16     |
|------------------------------------|------------------------|--------------------------------------|-------|--------|
| Moisture content, unit fractions   | 15.3…16.3              | 9.3…12.4                             | 8.6…11.5 |
| Porosity coefficient               | 21.8…23.2              | 13.4…17.8                            | 12.4…16.5 |
| Relative deformation               | 0                      | 0.241                                | 0.367  |

The table shows that the void ratio and moisture content reduced from 30.7 to 35.8 % during vacuuming at surcharge layer pressure \( p_0 = 8 \) and 16 kPa. As the surcharge sand layer thickness increases, the vacuuming duration extends considerably, which is explained by reduced water permeability of peat. It is well known that peat permeability decreases significantly with compaction.
It is known that the permeability of peat during compaction is significantly reduced, and at a pressure of 100 kPa peat is a waterproof soil [18-20].

After peat vacuuming, samples were taken from the tray for compressibility survey. Peat compression tests were carried out using samples with the height of 3.5 cm and the area of 40 cm². The loads of 32 kPa, 50, 75 and 100 kPa were applied to the samples in a single stage. The pressure of 32 kPa corresponds to 2 m of sand poured onto the peat surface after vacuuming. To prevent peat decomposition, the tests were carried out at the temperature of 5 ºС to 10 ºС. The samples were held under the load for 25...35 days until the conventional stabilization of deformation at 0.05% of the initial sample height was achieved (1.8 mm/day). Besides, peat compressibility was studied on samples of undisturbed structure, which were not subjected to vacuuming.

Figure 2 shows the graphs of settlement versus time at a pressure of 50 kPa for samples of natural-structure peat and after vacuuming.

As an example, Table 2 shows settlement rates for peat samples after vacuum consolidation with preliminary surcharge of 8 kPa, as well as for peat samples of natural-structure.

| Time, days | Average rate values, mm/day, at pressure, kPa | Relative deformation, unit fractions, at pressure, kPa (υs = 1.7 mm/day) |
|------------|---------------------------------------------|---------------------------------------------------------------|
|            | 32  | 50  | 75  | 100 | 32  | 50  | 75  | 100 |
| natural-structure peat | 5   | 5   | 5   | 5   | 0.416 | 0.485 | 0.561 | 0.638 |
| 3           | 4   | 5   | 4   | 4   | 3    | 3    | 3    | 3    |
| 15          | 1   | 2   | 2   | 2   | 0.211 | 0.298 | 0.411 | 0.498 |
| 20          | 6   | 6   | 7   | 6   | 0.211 | 0.298 | 0.411 | 0.498 |
| peat after vacuuming with surcharge of 16 kPa | 4   | 6   | 6   | 6   | 0.211 | 0.298 | 0.411 | 0.498 |
| 3           | 4   | 4   | 4   | 5   | 0    | 3    | 3    | 3    |
| 15          | 2   | 3   | 3   | 3   | 0.211 | 0.298 | 0.411 | 0.498 |

The test results have shown that peat relative deformation after vacuum consolidation is 22...49 % higher as compared to the deformation of natural-state samples; this means the deformation rate of the motor road base in the course of operation will be significantly lower.

3. Numerical simulation

Numerical simulation is capable of providing a reliable prediction of peat settlement in the motor road bases. For example, PLAXIS 3D software package allows taking into account the processes of consolidation and creep in the motor road bases. Numerical simulation was performed for a 3 m high motor road sand embankment, which corresponds to 50 kPa pressure. The embankment is to be constructed on a 4 m thick peat layer underlain by clay soils.
According to technical regulations, the settlement rate of motor road embankment for construction of permanent pavements shall not exceed 20 mm/year. Therefore, we used "Soft soil Creep" model for peat calculations. The main parameters of soil model are as follows: modified compressibility factor $\lambda$, modified swelling factor $k$, compressibility factor $\mu$, as well as specific cohesion $c$, and internal friction angle $\phi$. Strength parameters are assumed in accordance with the results of peat sample shearing tests as follows: $c = 12.9$ kPa, $\phi = 15.2$ deg.

Settlement calculation was performed for two cases:
- surcharging natural-state peat with sand,
- surcharging peat with sand with preliminary vacuum consolidation of peat.

Preliminary vacuum consolidation of peat was accounted for by "Soft soil Creep" model parameters - $\lambda$, $k$, $\mu$, the values of which are given in Table 3.

**Table 3.** Peat parameters for "Soft soil Creep" model.

| Parameter | Natural-structure peat | Peat vacuuming at pressure exerted by surcharge layer, kPa |
|-----------|------------------------|----------------------------------------------------------|
| $\lambda$ | 0.193                  | 0.234, 0.252                                             |
| $k$       | 0.039                  | 0.047, 0.051                                             |
| $\mu$     | 0.0180                 | 0.0179, 0.0183                                           |

Verification of the adopted "Soft soil Creep" model was performed by numerical simulation of testing in compression devices. The deviation of the results of compression tests from the results of numerical simulation in the PLAXIS 3D program is on average 40%. Therefore, an increment factor of 1.4 was applied to the precipitation values of the highway embankment.

A one-year break between the start of embankment pouring and pavement construction was assumed. The calculation results of road embankment behavior in time from the start of operation are given in Table 4.

As we can see, the road embankment deformation rate in the second year of operation is 63 mm/year in case of surcharging natural-state peat and 38...45 mm/year in case of vacuum preloading. Based on the allowable embankment settlement rate, the road operation may commence 4.5 years after the embankment dumping in the first case or after 2.5...3 years in case vacuum consolidation is employed.

**Table 4.** Road embankment settlement rate according to numerical simulation results.

| Time elapsed from road pavement construction, years | Embankment settlement rate, mm/year |
|---------------------------------------------------|-----------------------------------|
|                                                   | Natural-structure peat            | Peat vacuuming at pressure exerted by surcharge layer, kPa |
|                                                   | 8                                 | 16 |
| 1...2                                             | 6.3                               | 4.5, 3.8 |
| 2...3                                             | 3.5                               | 2.5, 2.2 |
| 3...4                                             | 2.4                               | 1.8, 1.5 |
| 4...5                                             | 2.0                               | 1.4, 1.3 |

4. Conclusions
1. Vertical draining with vacuum preloading ensures significant acceleration of peat consolidation.
2. To shorten the period of water pumping and peat consolidation, vacuuming shall be performed before road embankment construction.
3. As compared to peat surcharging, vacuum consolidation allows reducing the road embankment settlement rate in the course of operation by 25...40 % and increasing the service life of pavement.
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