Numerical simulation of perimeter drainage system considering peat water permeability change over time

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Abstract. A reliable forecast of water depression in waterlogged areas depends on the due consideration of specific peat properties: a considerable change in the water permeability of peat once water hydrostatic uplift is removed, clogging over time, decomposition and other factors. The article presents an example of numerical simulation in Plaxis software of a perimeter drainage system, where groundwater level has been monitored for 1 year. Piezometers were installed on site at the distance of 7, 17 and 30 m from the drain pipe of a building under construction. Deformation-strength properties and filtration properties of peat were determined on samples taken from excavated pits. Besides, the samples were tested using filtration tubes to identify changes in water permeability of peat over time and depending on the amount of water filtered through peat. The survey took 90 days at the ambient temperature of 6 to 12 °C, which allowed avoiding rapid peat decomposition. The laboratory test results have shown that water permeability of natural-state peat samples has decreased by a factor of 2.7 to 3.1 with 450 to 580 liters of water filtered. The deviation of the design groundwater level calculated in Plaxis from its actual position did not exceed 0.07 m. Numerical simulation with due consideration of decreased water permeability of peat over time allows obtaining forecast results closer to the actual groundwater level.

1. Introduction
The essential construction site preparation method for waterlogged areas includes creating a layer of sand over peat by filling or jetting.

Peat is highly porous and compressible, with prolonged consolidation under load and variable water permeability when compacted. In non-compacted condition, the natural-state peat is water permeable, but its permeability decreases hundreds of times as it is compacted under load [1-3]. Many types of peat feature anisotropic permeability both in vertical and horizontal directions [4, 5].

In addition, experimental results show that water permeability of natural-state peat without load can vary over time. Studies indicate that this process is related to peat clogging over time with fine particle transfer; swelling; adsorption; pore clogging with air bubbles; and peat decomposition [6, 7]. Microbiological processes at temperatures above 20 °C in full water saturation conditions lead to a considerable increase in peat decomposition rate [8, 9]. Under natural conditions, peat temperature over a year is 5-10 °C, and the decomposition process is slow.

This article presents the observation data and the results of perimeter drainage calculations with due account for peat permeability variation over time.
2. Materials and methods

A perimeter drainage system is installed in the basement of a high-rise building under construction at the depth of 2.7 m from the grade elevation (Figure 1). The layer of peat 2.5 to 3.5 m thick is surcharged with a layer of man-made soil 0.7 to 1.2 m thick. The peat is underlain by impermeable clay soil. The drainage system includes a tubular drain with inspection wells meant for pipe cleaning. Drain pipes are perforated corrugated polyvinyl chloride pipes with the inside diameter of 140 mm, wrapped in geotextile with the density of 100 g/m². A 100 mm thick layer of foamed plastic pellets is used as aggregate around the pipe. The aggregate is wrapped in geotextile with the density of 250 g/m². The drain pipes are backfilled with sand.

There is a four-storey building 43 m away from the high-rise building, which has a perimeter drainage system buried to the depth of 3 m. The drainage system includes asbestos-cement pipes 150 mm in diameter with crushed stone filling.

Three piezometers were installed to monitor the water level: at the distance of 7, 17, and 30 m from the high-rise building drainage system (Figure 1). The piezometers were made of perforated plastic pipes 50 mm in diameter and 3 m long. The water level was measured every 60 days during one year.

![Figure 1. Perimeter drain design.](image)

Samples of undisturbed structure were taken from excavated 1-m deep pits in the area without a surcharge sand layer. The density of sphagnum peat was 1.02 to 1.03 g/cm³, moisture content was 11.6 to 12.6, and porosity coefficient was 17.4 to 18.9.

A Mohr-Coulomb model was used for peat when running a numerical simulation of the drainage system in PLAXIS software. The following parameters were set for peat:
- Modulus of deformation, $E$
- Specific cohesion, $c$
- Internal friction angle, $\phi$
- Permeability factor, $k_f$
- Coefficient accounting for the change in the permeability factor during compaction, $c_k$

Numerical simulation of water depression in the drainage system area was performed using Plaxis 2D software package. The application of numerical techniques allows accounting for the change in water permeability of peat over time.

For numerical simulation purposes, permeability factor for natural-state peat was assumed. The $c_k$ factor of 4.2 was assumed to account for the change in the permeability factor with compaction in the pressure range of 0-25 kPa.
The assumed PLAXIS calculation model takes into account the variation of peat water permeability after it is surcharged with sand. In addition, the permeability factor was reduced by a factor of 3 based on the findings of laboratory studies of peat permeability change. Infiltration was calculated on the basis of the actual amount of precipitation during the observation period considering partial evaporation. The amount of evaporation was determined on the basis of the ambient air temperature using Mayer data [10].

Peat compression tests were carried out using samples 8.7 cm in diameter and 70 mm in height. The sample height was adopted to ensure the integrity of natural peat structure was preserved when taking samples. The tests were conducted using compression and filtration test units with bottom-to-top water flow. The samples were loaded in increments of 5, 12.5, 25, 50, and 100 kPa. Each load stage was held until the deformation was assumed to have been stabilized.

Permeability factor was calculated after each load stage under variable head gradient conditions. Water permeability of sphagnum peat was studied in vertical direction only. According to V.V. Kramarenko [5], sphagnum peat is not anisotropic in terms of permeability.

Peat strength properties were checked using a shear test unit. Shear resistance limit was determined at the vertical pressure of 12.5, 25, and 50 kPa. Strength parameters were assumed in accordance with the results of peat sample shearing tests as follows: $c = 11.4$ kPa, $\phi = 14.7^\circ$.

Laboratory tests were conducted to identify any variation in water permeability of compacted peat over time. Figure 2 shows sample test setup. Filtration tubes were made of polypropylene pipes 105 mm in diameter. The adopted peat sample height was 300 mm. Water permeability was determined at the head gradients of 2.5 and 4. Constant water level in the tubes was maintained by make-up water supply from a tank. The samples were covered with a 30 mm thick layer of gravel.

The tests were conducted at the ambient temperature of 6 to 12 ºС. This temperature corresponds to the soil temperature in natural conditions and prevents quick decomposition of peat.

The total duration of tests was 90 days. Permeability factor was determined before the test start and then after 15 to 150 liters of water filtered through the peat. The total amount of water filtered through the samples was 450 to 580 liters.

![Figure 2](image)

**Figure 2.** Test setup to determine peat permeability change over time.
3. Results

Relative peat deformation against pressure is plotted in Figure 3, and permeability test results are summarized in Table 1.

![Figure 3. Peat compression curve.](image)

The tests have shown that peat can be compressed to 55% of its original height under the pressure of 100 kPa.

| Pressure on sample, kPa | Porosity factor | Permeability factor, m/day |
|-------------------------|-----------------|---------------------------|
| 0                       | 17.4 to 18.9    | 0.30 to 0.37              |
| 5                       | 17.0 to 18.4    | 0.23 to 0.33              |
| 12.5                    | 15.5 to 16.7    | 0.10 to 0.14              |
| 25                      | 13.8 to 15.1    | 0.041 to 0.046            |
| 50                      | 10.1 to 11.8    | 0.002 to 0.008            |
| 100                     | 6.9 to 8.0      | 0.0002 to 0.0008          |

The data obtained demonstrate that the permeability factor reduced by a factor of 450 to 1800 at the pressure of 100 kPa, and the peat turned into impervious soil. Reduced water permeability of peat is attributed to the decrease in the pore size with the increasing pressure.

The coefficient accounting for the variation of permeability factor due to compaction was determined in accordance with the results of compression and filtration testing using formula:

\[
\log \left( \frac{k}{k_0} \right) = \frac{\Delta e}{c_k},
\]

where \( \Delta e \) is the porosity coefficient change,
\( k_0 \) is the initial permeability factor,
\( k \) is the permeability factor at the pressure stage.
The test results are given in Figure 4.

![Figure 4](image_url)

**Figure 4.** Variation of peat water permeability over time: a – head gradient 4; b – head gradient 2.5.

The test results indicate that the permeability factor reduced by a factor of 2.7 to 3.1. The most rapid change was observed at the initial stage of filtration. As filtration went on, permeability rate slowed down considerably.

Water level measurement results in piezometers are summarized in Table 2. Groundwater table depth in the table is given against the grade elevation in the immediate vicinity to the building under construction.

| Date of measurement | Water table depth, m, at the distance from drain pipes, m |
|---------------------|---------------------------------------------------------|
|                     | 7           | 17         | 30         |
| 07.19               | 1.92        | 1.59       | 1.73       |
| 09.19               | 1.85        | 1.41       | 1.61       |
| 11.19               | 1.74        | 1.35       | 1.59       |
| 01.20               | 1.99        | 1.53       | 1.66       |
| 03.20               | 1.98        | 1.43       | 1.64       |
| 05.20               | 1.79        | 1.38       | 1.54       |
| 07.20               | 1.96        | 1.62       | 1.75       |

Table 3 provides the results of numerical simulation of the depression curve in the perimeter drainage operating area.

| Water table position determination method | Water table depth from grade elevation above drainage system, m, at the distance to building under construction, m |
|-------------------------------------------|------------------------------------------------------------------------------------------------------------------|
|                                           | 7           | 17         | 30         |
| Monitoring                                | 1.89        | 1.47       | 1.65       |
| Numerical simulation                      | 1.95        | 1.44       | 1.58       |
The deviation of the design groundwater table depth from its actual position does not exceed 0.07 m. The best repeatability of the design depression curve and the actual groundwater table depth was achieved through the application of the reduction factor accounting for the change of permeability factor over time.

4. Summary
A reliable forecast of water depression in the perimeter drainage system operating area requires due consideration of peat water permeability variation over time caused by surcharge load, clogging processes, removal of hydrostatic uplift, decomposition in the zone of aeration, and other factors.

Laboratory test results have established that water permeability of peat can decrease several times if there is a filtering flow in the drainage system operating area.

Consideration of water permeability change over time brings the forecast water depression values closer to the actual depression curve.

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