Numerical Simulation of Sand Fill to Allow Operation of Pile Driving Rigs on Peaty Soil

A Nikitin

1Northern Federal University named after M.V. Lomonosov (NArFU), Severnaya Dvina Emb., 17, Arkhangelsk, 163002, Russia

E-mail: nikitinavvsaf@yandex.ru

Abstract. Construction sites in undeveloped areas underlain with a thick peat bed require some preparation, usually surcharging with sandy soil. In such conditions, the buildings are erected on pile foundations. To ensure safe operation of pile driving rigs, method statements must specify a minimum sand fill thickness. Numerical simulation of the sand fill was performed in PLAXIS 2D software to establish the required fill thickness over peat. The analysis was performed for sphagnum peat, the samples of which had been taken from undeveloped wetlands. Peat shear strength was determined with a standard vane and was found to be 6 to 10 kPa. Strain and strength properties were calculated on the basis of laboratory tests. To estimate the strength properties, a laboratory unit was built to include a peat sample box measuring 0.5×0.5×0.5 m, a stamp and a linkage system. The pressure applied to the peat was assumed within the range of 12.5 to 35 kPa. Upon load application, a four-bladed vane was submerged into the peat through a hole in the stamp to carry out a torsion shear test. Using the results of sample testing in the laboratory unit, the values of the internal friction angle for sphagnum peat were obtained. A Soft Soil model was used for peat in the numerical simulation. Peat thickness was assumed within the range of 2 to 6 m, and shear resistance – 6 to 10 kPa. The analysis was performed for the most common models of drop hammer and static pressure pile driving units. The design criterion was the minimum sand bed thickness at which peat bearing capacity was ensured. In addition, the maximum soil settlement was estimated that would allow normal operation of pile driving equipment.

1. Introduction

Construction on peaty soils requires certain engineering preparations. As full peat removal is a very expensive and technologically complex operation, the most frequently applied method of preparation is surcharging peat with sand [1, 4, 5]. The embankment is formed by sand filling or pulp jetting onto the peat surface. Engineering preparation must take into account that peat is highly compressible and has low strength properties [6-8]. As a rule, all structures are erected on pile foundations. The required sand fill thickness allowing the operation of pile driving equipment is determined mainly on the basis of building experience in the given area. The article summarizes the results of calculating the minimum sand fill thickness over sphagnum peat for safe operation of pile driving units.
2. Laboratory experiments

The samples of poorly decomposed sphagnum peat of undisturbed structure were taken from wetlands at the depth of 0.5 to 0.7 m. The peat had the following initial physical properties: degree of decomposition 8 to 10%, density 1.00 to 1.02 g/cm³, particle density 1.48 to 1.52 g/cm³, humidity 12 to 13, porosity coefficient 16.6 to 18.4. The peat shear strength according to the standard vane test varied from 6 to 10 kPa.

The deformation properties of the samples were established on the basis of laboratory compression tests. Peat compressibility was determined on samples measuring 60 cm² in area and 5 cm in height. The pressure was applied to the sample in stages of 12.5, 25, 50, and 75 kPa. Each pressure stage was held for at least 20 days until the deformation was assumed to stabilize. The results of peat compression tests are given in Table 1.

| Pressure, kPa | Deformation, mm | Relative deformation | Oedometric modulus of deformation, E_œd, MPa, within pressure range |
|--------------|-----------------|----------------------|---------------------------------------------------------------|
| 12.5         | 10.40           | 0.208                |                                                               |
| 25           | 15.65           | 0.313                |                                                               |
| 50           | 22.95           | 0.459                | 0.080 0.109                                                   |
| 75           | 26.85           | 0.537                |                                                               |

The strength of peat soil is generally estimated by shear resistance. The test includes making a torsion shear along a cylindrical surface with a manual vane in field conditions (Figure 1, b). The vane consists of two rectangular plates measuring 120×60 mm, arranged at right angles to each other, and welded to a rod. The torque is transmitted via a pre-calibrated handle. Computer-aided numerical simulation requires setting an internal friction angle (ϕ) and a specific resistance (c). To determine the said characteristics, torsional shear test in peat was carried out at several load stages and at normal vane shear plane.

To determine peat strength properties, a laboratory unit was built (Figure 1, a). A peat sample is placed in the box measuring 0.5×0.5×0.5 m. The sample is loaded via a stamp using a linkage system with 1:10 leverage ratio. The lever is made of two paired steel angles. The lever is hinged to a rigidly fixed frame. The sample is loaded with weights placed on the loading platform. The stamp has six holes to determine peat shear resistance. The vane goes down through these holes, and torsional shear test is performed. At each load stage, six torsional shear tests are carried out.

The transition from vertical stress to the stress normal to the vane shear plane is performed using formula [3]:

\[ \sigma_x = \sigma_v \cdot \xi, \]

\( \sigma_x \) – vertical stress,
\( \sigma_v \) – stress normal to the vane shear plane,
\( \xi \) – lateral pressure coefficient, \( \xi = \frac{\nu}{1-\nu} \),
\( \nu \) – Poisson's ratio.

In view of the fact that the load from pile driving equipment is transmitted to peat instantly, peat strength properties were determined for unconsolidated shear conditions. Peat test results are given in Table 2.
Figure 1. Peat vane test laboratory unit: (a) – unit design, (b) – standard vane.

The ultimate shear resistance of peat was determined by formula:

$$
\tau = \frac{M}{B},
$$

$M$ – maximum torque,
$B$ – constant vane coefficient.

The value of $B$ was calculated by formula:

$$
B = \left( \frac{\pi D^2}{2} \right) \left( H + \frac{D}{3} \right),
$$

$D$ – vane diameter,
$H$ – vane height.

Table 2. Results of peat strength properties determination with a vane.

| Normal stress, $\sigma$, kPa | Vane coefficient, $B$ | Torque, $M$, N·m | Average shear resistance, $\tau$, kPa |
|------------------------------|----------------------|------------------|-------------------------------------|
| 12.5                         |                      | 12.0 to 13.5     | 16.3                                |
| 25                           | $7.9 \cdot 10^{-4}$  | 14.2 to 16.9     | 19.7                                |
| 35                           |                      | 15.7 to 19.5     | 22.4                                |

According to the test results, the angle of internal friction was 15.2 degrees, and the specific cohesion – 12.9 kPa.
3. Numerical simulation

The stress-strain state of the sand fill was calculated in the PLAXIS 2D software. Soft Soil model was used for peat, and Mohr-Coulomb model was used for clayey soil underlying the peat. The Soft Soil model was configured with the following basic parameters: modified compressibility factor ($\lambda$), modified swelling factor ($k$), specific cohesion ($c$), and internal friction angle ($\varphi$). Peat thickness was assumed 2 to 6 m for calculation purposes. Calculations were performed for peat with shear resistance of 6 to 10 kPa. Simulation was performed for a drop hammer pile driving unit SP-49 (Figure 2, a) and a static pressure pile driving unit Sunward ZYJ 240 (Figure 1, b). The drop hammer unit SP-49 based on a crawler tractor applies the load of 60 kN/m to the soil. The static pressure unit Sunward ZYJ 240 allows loading the pile with up to 244 tons. The own weight of the static pressure unit without the counterweight is 109 tons. The unit allows driving the piles with various forces. The required driving force depends on the soil type, the design bearing capacity and cross section of the piles. As an example, calculations for unit weight 150 and 180 tons were performed.

![Figure 2](image-url)

Figure 2. Design layouts of pile driving units in PLAXIS 2D:
(a) – drop hammer unit SP-49, (b) – static pressure unit Sunward ZYJ 240.

N. P. Kovalenko has established that peat consolidation under the load leads to a considerable improvement of peat strength properties [2]. Depending on the peat thickness, its shear resistance increases 3 to 5 times. Rapid shear resistance growth is observed in the initial period.

According to N. P. Kovalenko, numerical simulation accounts for the increase in the ultimate peat shear resistance (specific cohesion) based on the sand embankment thickness. The minimum sand bed thickness at which the peat bearing capacity is ensured was assumed as the design criterion. The simulation also estimated the allowable soil settlement that ensures safe operation of pile driving equipment (the ability to move around the construction site).

Based on the numerical simulation results, the minimum sand fill thickness over the peat layer was determined that would allow the operation of pile driving units (Table 3).

Peat shear resistance at heavy loads from pile driving units on the base has a considerable impact on the required sand fill thickness.

The results of numerical simulation in Plaxis 2D software can be used to determine the sand fill thickness for construction in moss peat areas. In advance, during the geotechnical survey, one must determine the peat resistance by torsional shear test method.
Table 3. Minimum sand fill thickness for SP-49 and Sunward ZYJ 240 units.

| Peat shear resistance, $\tau$, kPa | Unit SP-49 | Sunward ZYJ Weight 150 t | Sunward ZYJ Weight 180 t |
|-----------------------------------|------------|-------------------------|-------------------------|
|                                   | 2  | 4  | 6  | 2  | 4  | 6  | 2  | 4  | 6  |
| 6                                 | 0.6 | 0.6 | 0.6 | 0.9 | 1.1 | 1.5 | 1.2 | 1.6 | 1.7 |
| 8                                 | 0.4 | 0.5 | 0.6 | 0.5 | 0.8 | 1.3 | 0.9 | 0.7 | 1.5 |
| 10                                | 0.5 | 0.5 | 0.6 | 0.3 | 0.7 | 0.9 | 0.4 | 0.7 | 1.3 |

4. Conclusion

The sand fill thickness on peaty soils to allow the operation of pile driving units can be determined by numerical simulation based on the deformation-strength properties of peat.

References

[1] Nevzorov A L, Nikitin A V and Zaruchevnyh A V 2012 City on the swamp (Arkhangelsk: NArFU) p 157
[2] Kovalenko N P, Hydyakov A B and Gorelyakov V S 1971 Preliminary loading of a peat (Russia) p 97
[3] Tsitovich N A 1983 Soil mechanics (Moscow: Vysshaya Shkola) p 283
[4] Bronin V N 1982 Investigation of the long creep of a peat IV Symposium on Soil Rheology (Russia) pp 10 – 13
[5] Kovalenko N P, Fedotov A N 1979 Peculiarities of construction management in complicated geotechnical conditions of Arkhangelsk Proceedings of the scientific and technical conference "Complex utilization of forest resources and their regeneration in the European North (Arkhangelsk: RIO ALTI) p 72
[6] Wong L S, Hashim R, Ali F H 2009 A review on hydraulic conductivity and compressibility of peat Journal of Applied Sciences vol 9(18), pp 3207–3218
[7] Huttunen E, Kujala K 1996 On the stabilization of organic soils Proceedings of the 2nd International Conference on Ground Improvement Geosystem (IS-Tokyo 96) vol 1 pp 411–414
[8] Harwadi F, Mochtar N E, Compression Behavior of Peat Soil Stabilized with Environmentally Friendly Stabilizer 2010 Proceedings of the First Makassar International Conference on Civil Engineering (MICCE 2010) pp 9-10