Numerical modelling of a test embankment on soft ground

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The construction of an embankment situated on soft subsoil with a high groundwater level leads to a rise in pore pressure. This "undrained behaviour" can made the effective stress to remain low and intermediate consolidation periods to be adopted so that the construction of the embankment is safe. During a consolidation process the dissipation of the excess pore pressure is observed in order to increase the shear strength of the soil to continue the construction process [4].

The behaviour of a test embankment founded on a soft soil in Warsaw, on the Ursynowska Scarp, in the Campus SGGW (Warsaw University of Life Sciences) site was simulated with a use of a finite element analysis [6]. This study presents an experimental work, a construction of a flood-control embankment on organic soil represented by peat. The modelling of an embankment behaviour is carried out by the program PLAXIS (Finite Element Code for Soil and Rock Analysis). Measurements were taken of pore pressure, dissipations rates and displacements in the foundation peat. Predictions of these were made using a simple Soft Soil Model. Moreover, the calculation of the safety factor, the effect of the drains on the consolidation process and an update mesh analysis were investigated.

The results suggest the significant impact of drains on the speed of the consolidation course. The commonly accepted Mohr-Coulomb Model and Soft Soil Model, which involve typical parameters obtained from in-situ and laboratory testing, can be successfully selected for examination the behaviour of flood-control embankment situated on soft soils. The Updated mesh and Updated water pressure analysis reduces the settlements and allows for a more realistic study of settlements, while the positive effects of large deformations is considered. However, there is a great need to compare the numerical simulation with the real existing embankments located on problematic soils.

Keywords and phrases: numerical modelling, embankment construction, soft soil.

Introduction

Peat is an organic soil, which mostly consists more than 70% of organic matters. Peat deposits can be found where conditions are favourable for their formations [7]. In Poland there are large areas with soft organic soils where different types of embankment have to be constructed [8]. Organic soils pose serious problems in construction due to their high compressibility and low shear strength, what causes large vertically and horizontally deformations, that may occur during and after the construction period [14]. Hence, peat is considered unsuitable for supporting foundations in its natural state. To maintain embankments over peat deposits and avoid a risk connected with bearing failures various construction techniques have been carried out. Excessively large settlements of these embankments, stability difficulties during construction such as slip failures and localized bearing failures must be always taken into account while building on soft soils [7].

The development of advanced numerical techniques, especially two-dimensional and three-dimensional finite element analysis, has greatly enhanced the ability to model complex geotechnical problems, for example as mentioned above, the use of soft soil as a building material. These sophisticated methods, however, offer a number of challenges including: evaluating the effects of numerical error and instability; the time for setup, verification, and execution; and, computer memory requirements. Traditional models, such as one-dimensional consolidation theory, propose the advantage of simplicity, although they are severely limited in their ability to model complex situations [3]. Nowadays, there is a relevant huge amount of various programs for numerical modelling of geotechnical problems, like: GEO5- Engineering Software for Geotechnics and Tunnelling; MIDAS GTS — System for Analyzing Geotechnical and Tunnelling Problems; GGU Software-a very useful tool for geologists, geotechnics, hydrogeologists and engineers or PLAXIS. PLAXIS Software comes from the Netherlands and is one of the best known, as well as the most frequently applied by engineers. It is based on the finite element method (FEM) and intended for two-dimensional and three-dimensional geotechnical analysis of deformation and stability of soil structures, likewise groundwater and heat flow, in geo-engineering applications such as excavation, foundations, embankments and tunnels [11]. A FEM tool like PLAXIS provides the benefit of idealising the material behaviour of soil, which is non-linear with plastic deformations and stress path dependent, in a more rational manner. The FEM can also be particularly useful for identifying the patterns of deformations and stress distribution in and around the reinforcing elements, during deformation and at ultimate state. It can be extremely helpful when improvement measures like drains or counter fills are studied, since the method automatically locates the new critical surface [2, 3].

The main aim of this paper is modelling of the behaviour of earth works, such as embankments, founded on soft soil, peat. While soft soils are loaded by embankments problems of two types mostly occur: stability and settlement. The technical aspects essentially deal with the study of the settlements of constructions . After a short review of the features of the model used, the parameters of the soft soil and the results of the finite element analysis will be presented.

Description of the numerical models

The mechanical behaviour of soils can be modelled at various degrees of accuracy. The Hooke's law of linear and isotropic elasticity are considered as the simplest available stress-strain relationship. In this case, only two input parameters: Young's modulus E and Poisson's ratio ν are required, what is, however, too crude to describe essential features of soil and rock behaviour. PLAXIS offers analysis with different models, starting with basic one like Linear Elastic Model and Mohr-Coulomb Model and finishing with more advanced like Hardening Soil Model or Hardening Soil Model with small-strain stiffness. In this paper, to model the behaviour of a test embankment, Soft Soil Model for peat and Mohr-Coulomb Model for embankment are applied [11, 12].

The Soft Soil Model is a Cam-Clay type model especially meant for primary compression of near normally-consolidated clay-type soils. The main features of this model are following:

- stress dependent stiffness (logarithmic compression behaviour);
- distinction between primary loading and unloading-reloading;
- memory for pre-consolidation stress;
- failure behaviour according to the Mohr-Coulomb criterion.

Within the Soft Soil Model of PLAXIS it is believed that some logarithmic relationship between the volumetric strain ε_v and the equivalent effective stress p' exists, which can be formulated as:

$$\varepsilon_v - \varepsilon_{v0} = -\lambda \ln(\frac{p}{p'}) \quad \text{(Virgin compression)} \qquad (1)$$

The parameter λ^* is called "modified compression index" and allows to determine the material's compressibility during primary loading.

In isotropic unloading and reloading a different line is followed, verifying the equation:

$$\varepsilon_v{}^e - \varepsilon_{0v}{}^e = -\kappa \ln(\frac{p}{p'}) \quad \text{(Unloading-reloading)} \qquad (2)$$

The dimensional the validity of both expressions (1) and (2) results from using a minimum value of p' equals to a unit stress. The parameter κ^* from the equation (2) is called "modified swelling index", which allows to define the material's compressibility during unloading and subsequent reloading. The response of the soil while unloading and reloading is assumed to be elastic, as denoted by the superscript "e" in equation (2). It should be underlined that λ^* and κ^* are different parameters then conventional indexes λ and κ used by Burland (1965) [5]. This is because both equations (1) and (2) are function of volumetric strain instead of void ratio. However, the ratio $\frac{\lambda^*}{\kappa^*}$ is equal to the ratio $\frac{\lambda}{\kappa}$.

The Soft Soil Model is a plasticity model with a hardening cap. Strains consist here of elastic (reversible) and plastic (irreversible) strains. This model is suitable for simulating the behaviour of normally consolidated clays, as well as peat in primary loading. The time aspects must be with a minor importance. This model, unfortunately, doesn't account for viscous effects, i.e. creep and stress relaxation. In fact, all soils exhibit some creep and primary compression is thus followed by a certain amount of secondary compression [1].

The Mohr-Coulomb Model is a linear elastic perfectly-plastic mode, which involves five input parameters:

- Young's modulus E and Poisson's ratio ν for soil elasticity;

— friction angle ϕ and cohesion c for soil plasticity;
— dilatancy angle ψ.

This model represents a "first-order" approximation of rock and soil behaviour and is useful for a first analysis of the considered problem. For each layer one estimates a constant average stiffness or an increasing stiffness linearly with depth. This constant stiffness causes relatively fast calculations and one obtains a first estimate of deformations.

Description of the test site

The test embankment is situated on the Ursynowska Scarp, which adjoins to the Campus SGGW (Warsaw University of Life Sciences) site. This area is a part of Warszawska Scarp, which is extending on the left side of Vistula River, beginning in the small place Czersk and ending in one of the district of Warsaw-Żoliborz.

The region of terrace bay of Ursynowska Scarp consists mainly of silty clays and sandy-silty clays. In some parts of this area, under the ground surface, soft organic soils are found, mostly peat and peaty alluviums. The thickness of the soft layer does not cross over 2 m. Organic soils are underlaid by river sands.

Table 1. Physical properties of Warsaw peat.

Properties	Symbol	Unit	Value
Water content	w	%	396-554
Particle density	ρ_s	g/cm^3	1.58
Bulk density	ρ	g/cm^3	0.97-1.05
Dry density	ρ_d	g/cm^3	0.22-0.34
Organic content	I_{OM}	%	70-80
Degree of humification	R	%	50-60

The test embankment is located on peat. The specimens for the laboratory experiments were collected from the depth around 0.8–1.0 m. The physical properties of examined soft soils are performed in Table 1.

The soft soil is represented in this study by peat and has been classified as low peat, sedge-rushes, supplied by ground — as well as surface water. It has been characterized as medium decomposed peat with the amorphous-fibrous structure [13].

The parameters for the models used in the study are evaluated from the laboratory tests carried out in geotechnical laboratory in Department of Geotechnical Engineering of WULS. Laboratory tests included routine oedometer tests and CD triaxial tests. The material properties of the test embankment and subsoil are summarized in Table 2.

Numerical simulation of the embankment behaviour

The test embankment is 16.0 m wide and 4.0 m high. The inclination of the slopes is 1:3. The problem considered in this paper is symmetric, due to only one half (the right half) has been chosen to model the behaviour of an experimental embankment (Fig. 1). The embankment itself consists of sand, the same one which is located under the soft soil layer. The subsoil is composed of 2.0 m of peat. Under the soft soil layer there is a sand layer of which 4.0 are included in the finite element model. The phreatic level is situated 2.0 m below the ground surface. In this study the influence of the drains on the consolidation process is also investigated. Drains are defined in the peat layer and the distance between each two is 2.0 m. Because of the symmetry, the first drain is set at 1.0 m distance from the boundary of the model.

In Fig. 2 the mesh layout is presented.

Table 2. Material properties of the test embankment and subsoil.

Parameter	Name	Embankment	Peat	Unit
Material model	Model	MC	Soft Soil	-
Type of behaviour	Type	Drained	Undrained	-
Soil unit weight above phreatic level	γ_{unsat}	17.0	10.5	kN/m^3
Soil unit weight below phreatic level	γ_{sat}	20.0	14.0	kN/m^3
Initial void ratio	e_{init}	0.5	5.9	-
Horizontal permeability	k_x	1.0	-	m/day
Vertical permeability	k_y	1.0	-	m/day
Young's modulus	E_{ref}	$2.5 \cdot 10^4$	-	kN/m^3
Poisson's ratio	ν	0.3	-	-
Modified compression index	λ^*	-	0.0990	-
Modified swelling index	κ^*	-	0.0549	-
Cohesion	c_{ref}	1.0	4.5	kN/m^3
Friction angle	φ	33.0	27.5	^{0}
Dilatancy angle	ψ	3.0	0.0	^{0}
Advanced: Set to default	Yes	Yes	Yes	Yes

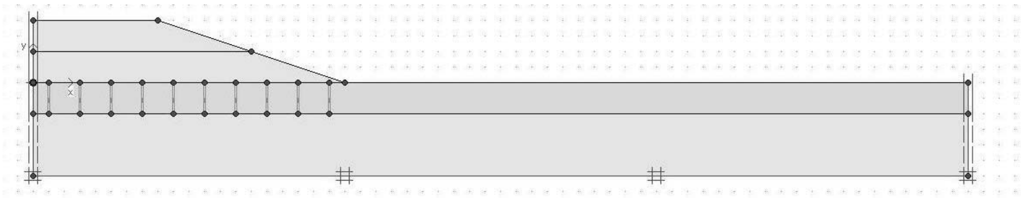

Fig. 1. Model of the test embankment.

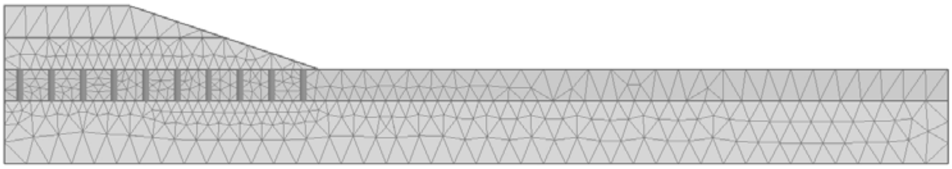

Fig. 2. Finite element mesh.

Calculations and results

The construction of the test embankment is divided into two phases. When the first construction phase is finished, the 30 days consolidation period is presented to allow to dissipate the excess pore pressure. After the second construction stage another, shorter consolidation period is introduced, which permits to determine the final settlements. Apart from the initial phase, four calculation phases are defined in this study.

After the whole process of calculations is finished, the deformed mesh after the undrained construction of the final part of the embankment can be shown (Fig. 3). The deformed mesh presents the uplift of the embankment toe and hinterland due to the undrained behaviour.

On evaluating the total displacements increments, it can be noticed that a failure mechanism is just developing (Fig. 4).

In Fig. 5 it is clear seen that the highest excess pore pressure occurs under the embankment centre.

The settlements of the embankment and original soil surface increases considerably during the fourth phase of consolidation analysis. This is caused because of the

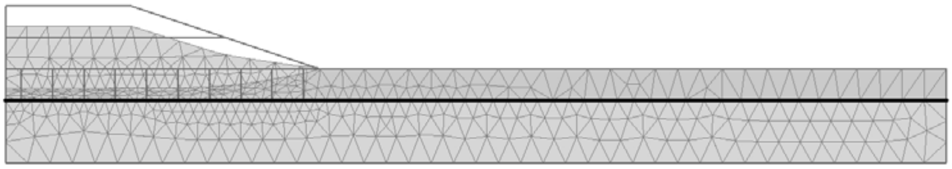

Fig. 3. Deformed mesh after undrained construction of embankment-phase 3.

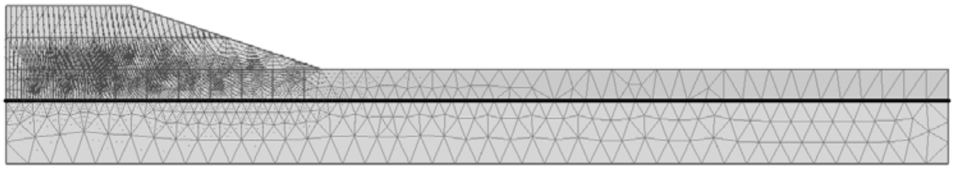

Fig. 4. Displacement increments after undrained construction of embankment.

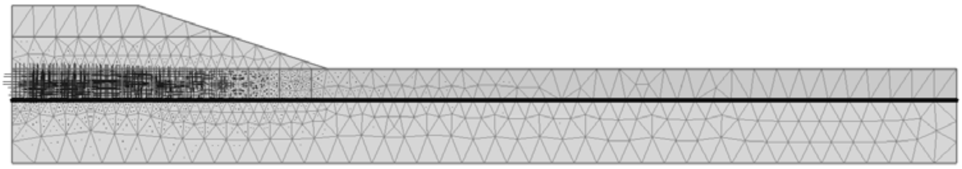

Fig. 5. Excess pore pressure after undrained construction of embankment.

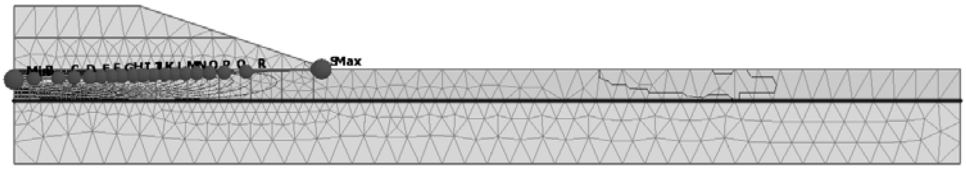

Fig. 6. Excess pore pressure counters after consolidation to p_{excess} < 1.0 kN/m².

dissipation of the excess pore pressure, which leads to further settlements of the soil. In the Fig. 6 the remaining excess pore pressure distribution after consolidation is presented.

During the construction phases the excess pore pressure increases with small increase in time. However, during the consolidation process the excess pore pressure decreases with time. In reality, consolidation occurs already during construction period, as this involves small time intervals. From the curve in the Fig. 7 can be observed that around 45 days are needed to reach the full consolidation.

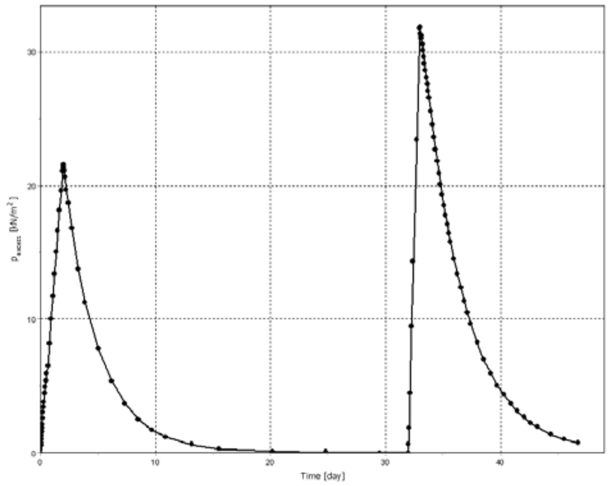

Fig. 7. Development of excess pore pressure under the embankment.

Safety analysis

Besides the final stability, the stability during each construction stage is important while designing of an embankment. Usually, a failure mechanism starts to develop after the second construction phase. Safety calculations generate additional displacements. The total displacements do have any real physical meaning, in contrast to the incremental displacements, which give in the final step an indication of the probable failure mechanism (Fig. 8).

Safety analysis allows to evaluate a global safety factor at each stage of construction of the embankment. The safety factor is normally defined as the ratio of the collapse load to the working load. However, a more appropriate definition, especially for the embankments, is following:

$$Safety\_factor = \frac{S_{\max imum\_available}}{S_{needed\_for\_equilibrium}} \qquad (3)$$

where: S — shear strength.

By introducing the standard Coulomb condition, the safety factor is obtained:

$$Safety\_factor = \frac{c - \sigma_n \tan \varphi}{c_r - \sigma_n \tan \varphi_r} \qquad (4)$$

where: c, φ — input strength parameters;
σ_n — actual normal stress component;
c_r, φ_r — reduced strength parameters.

Reduced strength parameters should be large enough to maintain equilibrium. This principle is generally used in PLAXIS to evaluate a global safety factor. In this approach the cohesion and the tangent of the friction angle are reduced in the same proportion, controlled by the total multiplier ΣMsf:

$$\frac{c}{c_r} = \frac{\tan \varphi}{\tan \varphi_r} = \Sigma Msf \qquad (5)$$

The total multiplier increases step by step until failure occurs and determines the safety factor, provided that at failure an approximately constant value is received for a number of successive load step [10].

In this study for each step of calculations more and less constant value of a safety factor is obtained:

— for the 1st ΣMsf ≈ 1.05;

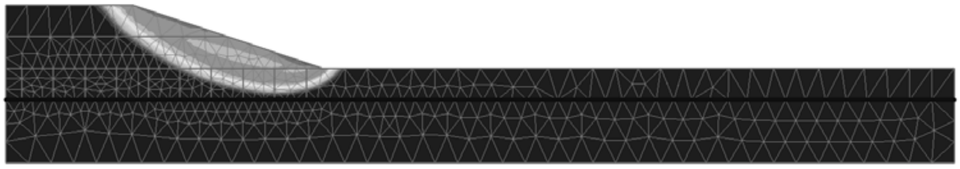

Fig. 8. Shadings of the total displacements increments pointing the most applicable failure mechanism of the embankment in the final stage of its construction.

— for the 2nd ΣMsf ≈ 1.00;
— for the 3rd ΣMsf ≈ 1.50;
— for the 4th ΣMsf ≈ 2.00.

Effect of drains

In this paper the influence of the drains on the consolidation process is also investigated. The chart of Fig. 9 gives a clear view of the effect of drains in the time required for the excess pore pressure to dissipate. It can be noticed that the excess pore pressure dissipates very quickly, just after the first stage of construction.

An updated mesh analysis

In Fig. 10 it can be seen that the settlements are less while using the option *Updated mesh* and *Updated water pressures*. The *Updated mesh* analysis includes second order deformation effects, due to which the changes of the geometry are considered. On the other hand, the *Updated water pressures* procedure results in smaller effective weights of the embankment. The use of these two additional analysis allows for the more realistic calculations of settlements, taking into consideration the positive effects of large deformations.

Conclusions and future work

In this paper a two-dimensional numerical analysis of a test embankment founded on the soft soil in Warsaw, on the Ursynowska Scarp is presented. The numerical model includes the soft ground-peat, the embankment as well as drains in the further analysis to verify their impact on the consolidation process. The modeling of the embankment behaviour is conducted by the

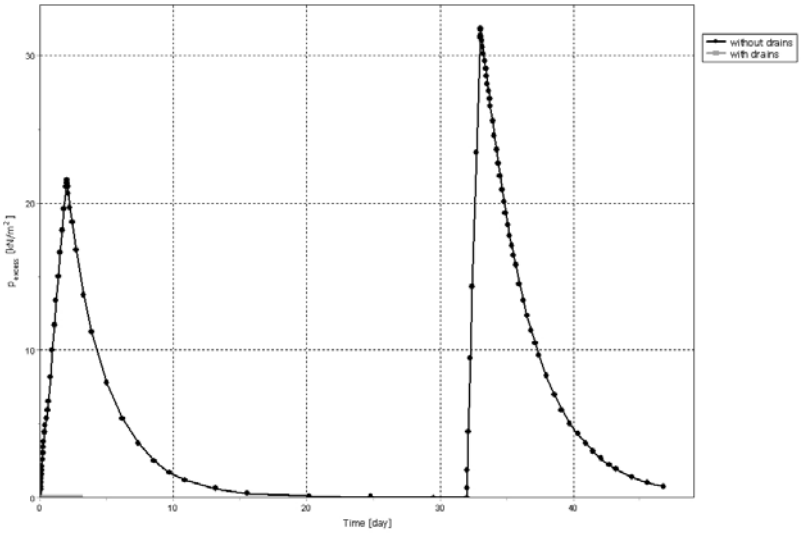

Fig. 9. Effect of drains.

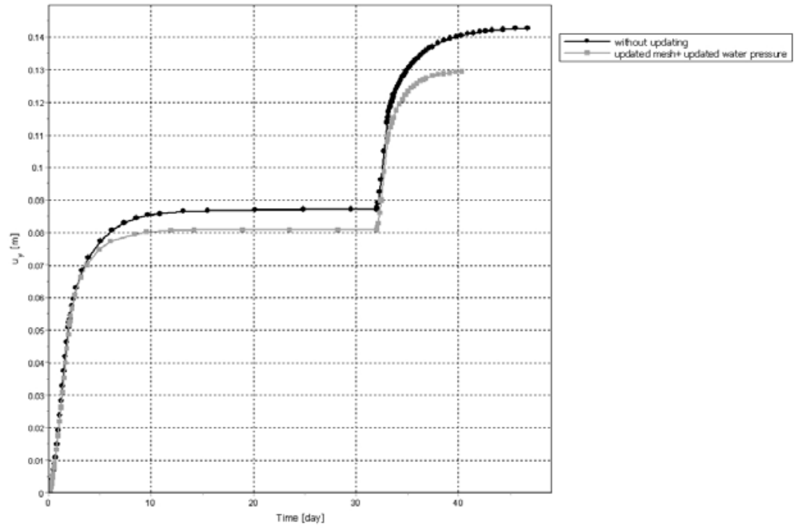

Fig. 10. Effect of Updated mesh and Updated water pressures analysis on the settlements.

program PLAXIS with the application of a simple Soft Soil Model.

It is important to notify that the studied case is fictitious. The main purpose of this work is to perform a realistic simulation of the non-existing embankment situated on the soft subsoil. After the analysis the following points can be concluded:

- after the third calculation phase while consolidation analysis due to the undrained behaviour the uplift of the embankment toe and hinterland can be observed;
- taking the total displacement increments into account, a development of a failure mechanism can be seen;
- the highest excess pore pressure occurs under the embankment center;
- during the fourth calculation phase the settlement of the original soil surface increases because of the dissipation of the excess pore pressure;
- the excess pore pressure while constructing an embankment increases with time during the construction period but decreases during the consolidation process:
- to reach full consolidation around 45 days are necessary;
- safety factor from safety analysis for each step of the embankment construction has more and less constant value;
- the effect of the drains on the consolidation process during the undrained construction can be noticed- with drains the excess pore pressure dissipates very quickly and finishes after the first phase;
- the Updated mesh and Updated water pressure analysis reduces the settlements and allows for a more realistic investigation of settlements, while the positive effects of large deformations is considered.

Future work should include a validation of the numerical model by comparing with experimental results. Moreover, a comparison of the numerical results with current design methods should be made and enclosed.

In summary, these results show and confirm, presented in the scientific literature, capability and usefulness of PLAXIS Software as the FEM tool. Finite Element Analysis has so far been used to quite little extent, especially in geotechnical practice in Poland. However, this example with the embankment founded on problematic soils, like peat, does encourage in further application of FEM to predict the behaviour of organic soil under different engineering constructions.

Concluding, PLAXIS is a powerful tool to study and model various, mostly complex, geotechnical problems. The development of the numerical modelling has contributed to a better understanding of the interaction between soil and buildings or structures located on it. Investigations using the numerical modelling, where the simulations with variety of improvements, ex. drains, can be made, provide an economical solution in practical applications.

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