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PEAT CONSOLIDATION – NEW APPROACH

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The problem of consolidation of soil has been widely investigated. The basic approach was given by Terzaghi who assumed soil of constant physical and mechanical parameters. In the case of peat consolidation, the permeability coefficient of soil and the elasticity modulus are functions of the settlement which is an important additional factor. The model proposed here assumes varying the elasticity and permeability coefficients. Moreover, the settlement is described by the so-called elementary curve which was approximated empirically based upon laboratory tests. The model allows to consider the case when the filtration in the peat body goes in horizontal direction. It happens so when the charging layer does not receive outgoing water from the pores. The model includes also the case when the load involving consolidation varies in time i.e. the charging layer grows up gradually. The model has been applied practically in several cases and it comes that there is a good agreement between calculated and measured settlement of the consolidated peat layer.

Key words: ground improvement, soil consolidation.

1. Introduction

Soil consolidation is the phenomenon associated with the ground settlement especially in the case of its improvement. Consolidation consists basically of two processes:
– soil settlement due to outflowing water from the pores (forced filtration) and
– elasticity modulus increase due to diminishing of soil void ratio.

It was assumed that the soil settlement and the forced filtration results from the external load (charging layer). The basic theory of the soil consolidation is given by Terzaghi [5]. In the Terzaghi's description of the phenomenon the basic assumptions are:
– constant soil parameters i.e. elasticity modulus and permeability coefficient, and
– constant load.

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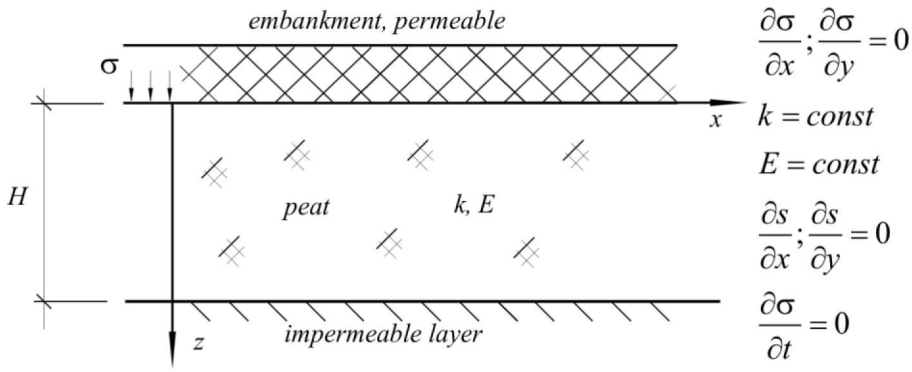


Fig. 1. Soil profile conditions in Terzaghi's theory.
Rys. 1. Profil gruntowy przyjęty w teorii Terzaghii

The recent research shows that it is hard to keep those assumptions. In the literature several models trying to avoid the above mentioned assumptions are presented. Such presentation is given by den Hann [1]. However, the problem is still waiting to be solved, because of the con-cave character of the curve at the load-settlement.

In the Dep. of Geotechnics at the Technical University of Szczecin, the research has been carried out in purpose to estimate the real consolidation process. The city of Szczecin is situated at the Odra River mouth, and so a large area is covered by soft soils – peat. The urban development seeks new territories and so new technologies of peat improvement are needed, also for better understanding of this phenomenon.

2. Mathematical description of soil consolidation

The basic model at consolidation was given by Terzaghi [5]. The physical assumption and the geometry are shown in Fig. 1, Fig. 2. and Fig. 3.

Assuming constant soil properties, the basic equation takes the form:

$$\frac{\partial u}{\partial t} = \frac{kE}{H^2 \cdot \gamma_w} \cdot \frac{\partial^2 u}{\partial z^2} \tag{2.1}$$

In the above equation: u– denotes pore pressure, k – permeability coefficient, H – peat layer depth, E – elasticity modulus of peat, γ_w- water density, t – time, z – vertical coordinate going downward.

According to the Fig. 3 the boundary conditions are defined as:

$$\left.\begin{array}{l} \text{for } z = 0;\ u = 0 \\ \text{for } z = H;\ \dfrac{\partial u}{\partial z} = 0 \text{ (no flow)} \\ \text{for } t = 0;\ u = \sigma \quad \text{and} \\ \text{for } t \to \infty;\ u \to 0 \end{array}\right\} \tag{2.2}$$

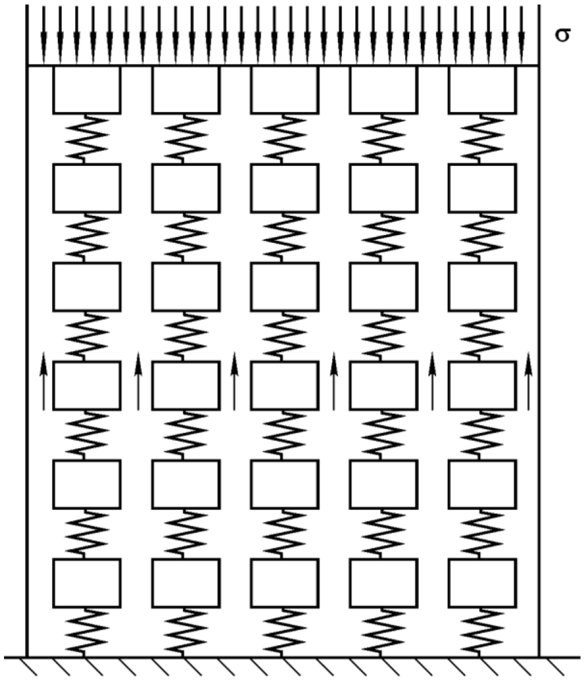


Fig. 2. Physical model [5].
Rys. 2. Model fizyczny [5]

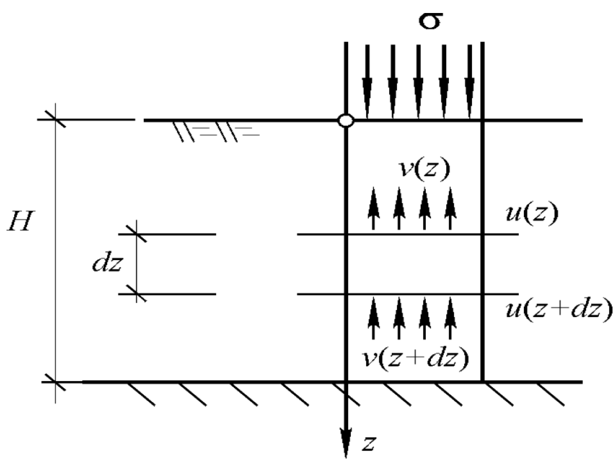


Fig. 3. Water flow direction.
Rys. 3. Kierunek przepływu wody w modelu

The typical solution of Eq. 2.1 including boundary conditions (2.2) is given in terms of Fourier series. The settlement $S(t)$ of the considered consolidation of peat is

$$S(t) = \int_0^H \frac{\sigma - u(t,z)}{E} \cdot dz \text{ so (3)}$$

$$S(t) = \frac{\sigma H}{E} \cdot \left\{ 1 - \frac{8}{\pi^2} \sum_{n=0}^{n=\infty} \left[\frac{1}{2n+1} \cdot \exp\left(-(2n+1)^2 \cdot \frac{\pi^2}{4} \cdot \frac{t}{T_0} \right) \right] \right\} \tag{2.3}$$

The value of T_o is defined as

$$T_0 = \frac{H^2 \gamma_w}{E \cdot k} \tag{2.4}$$

The research by Meyer [1] has shown that the changes of the peat parameters during the consolidation process can be related to the current settlement in the following form:

$$E(s) = E_0 \cdot \left(1 - \frac{s}{n_0 H_0} \right)^{-\kappa} \tag{2.5}$$

$$k(s) = k_0 \cdot \left(1 - \frac{s}{n_0 H_0} \right)^{-\kappa_f} \tag{2.6}$$

In the above equations the following symbols are introduced: $E(s)$ – elasticity modulus of peat varying with settlement; E_0 – initial elasticity modulus of peat (for $s = 0$); n_0 – initial peat porosity; H_0 – initial depth of the peat layer; κ- coefficient to be evaluated based on experimental data, and furthermore; $k(s)$- permeability coefficient of peat with varying settlement; k_0 – initial permeability coefficient of peat (for $s = 0$); κ_f – coefficient to be estimated based upon experimental data.

The most important problem of using varying soil parameters is to estimate the coefficients: κ and κ_f. They can be defined by statistical method i.e. by using the least square method. This method gives one single optimal point. And the example of this approximation is given in Fig. 4.

The optimization of the coefficients κ and κ_f, allows also to estimate the initial values: E_0 and k_0. As an example for the peat samples taken at Szczecin region the values are: E_0= 166 kPa ÷ 210 kPa and k_0= $10^{-6} m/s$÷ 1.16 $\cdot 10^{-s} m/s$.

The aforementioned equation (2.5) allows also to calculate the terminal settlement of the considered peat column in the case when the elasticity modulus varies. We have then

$$S(\sigma) = n_0 \cdot H_0 \left[1 - \left(1 + \frac{\kappa - 1}{n_0} \cdot \frac{\sigma}{E_0} \right)^{\frac{-1}{\kappa-1}} \right] \tag{2.7}$$

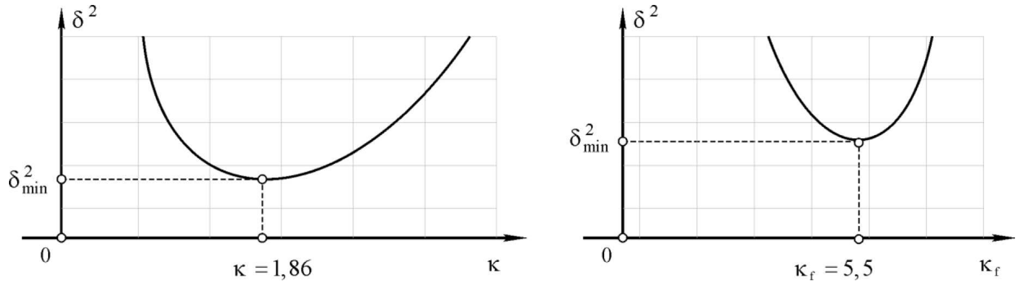


Fig. 4. Optimization of: $\delta^2 = f(\kappa) \cdot \delta^2 = f\left(\kappa_f\right)$.
Rys. 4. Optymalizacja parametrów $\delta^2 = f(\kappa) \cdot \delta^2 = f\left(\kappa_f\right)$

It can be seen that due to the reinforcement of the peat the settlement given by Eq. 2.8 is smaller that the one coming from Terzaghi solution.

We can also include the load varying with time i.e. the charging layer depth which is growing up with time. We have

$$S(t) = \sum \left\{ \frac{\sigma_j}{E} \cdot H \left[1 - F\left(t - t_j\right) \cdot \eta\left(t - t_j\right) \right] \right\} \tag{2.8}$$

In the above equation the function $F(t)$ is the function which appears in the first parentheses in Eq. 2.4. The value σ_j is the sequent load, and t_j is the time at applying the sequent load σ_j.

The function $\eta(t)$ is defined as

$$\eta(t) = \begin{cases} 1 \text{fort} - \mathrm{t_j} > 0 \\ 0 \text{fort} - \mathrm{t_j} < 0 \end{cases} \tag{2.9}$$

An example of the influence of varying load on settlement is given in Fig. 5.

3. Consolidation with horizontal filtration

The particular case of consolidation of peat is when the out-flowing water from the pores is filtrating horizontally. It appears when the charging layer is impermeable and it does not allow water to flow through that layer. In practice it appears when the load is applied, by layer of ash. The description of flow in this case is given in Fig. 6 and Fig. 7 and Fig. 8.

The basic equation in this case takes the form:

$$k_x \cdot \frac{\partial^2 u}{\partial x^2} + k_y \cdot \frac{\partial^2 u}{\partial y^2} = \frac{\gamma_w}{E} \cdot \frac{\partial u}{\partial t} \tag{3.1}$$

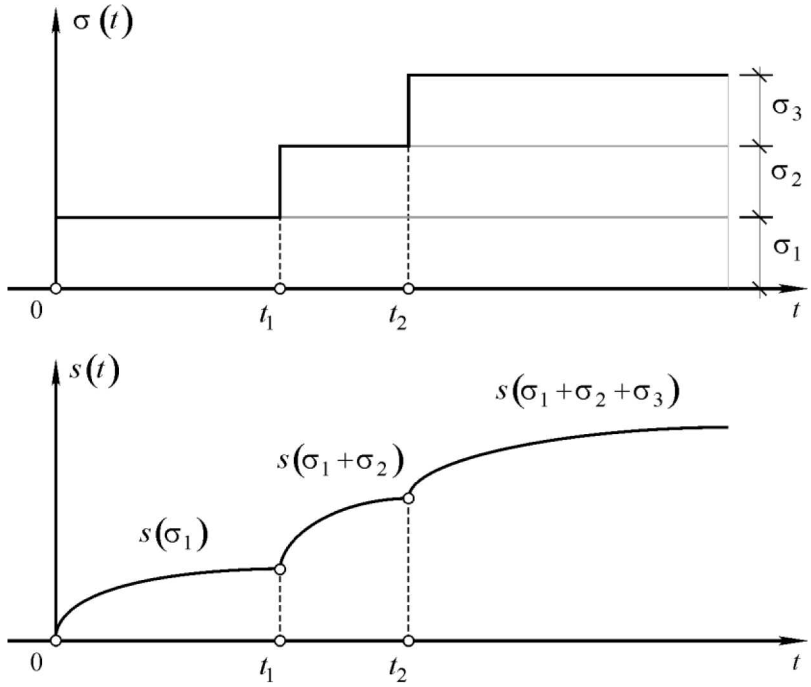


Fig. 5. Varying load influence on settlement.
Rys. 5. Wpływ zmiennego obciążenia na osiadanie

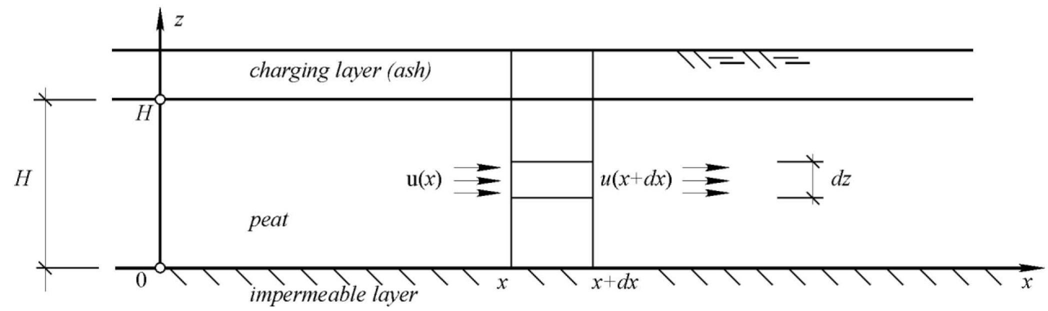


Fig. 6. Consolidation with horizontal water flow.
Rys. 6. Konsolidacja w warunkach filtracji poziomej

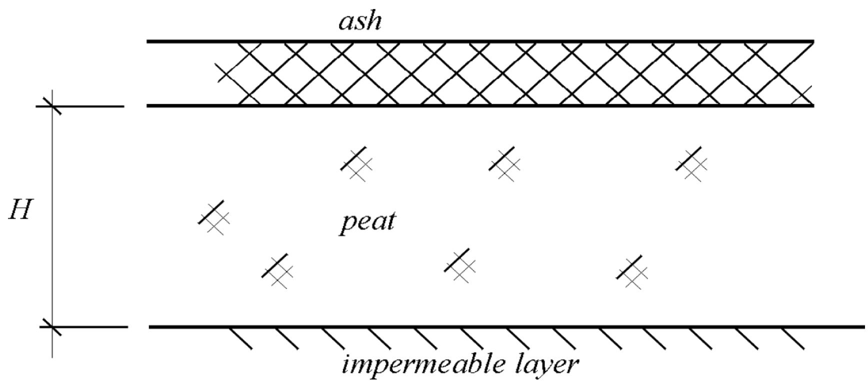


Fig. 7. Soil profile.
Rys. 7. Profil gruntowy modelu

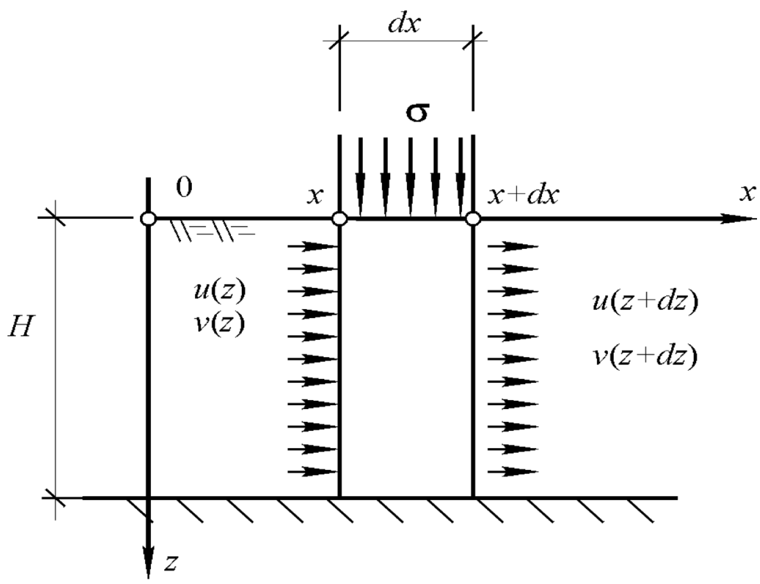
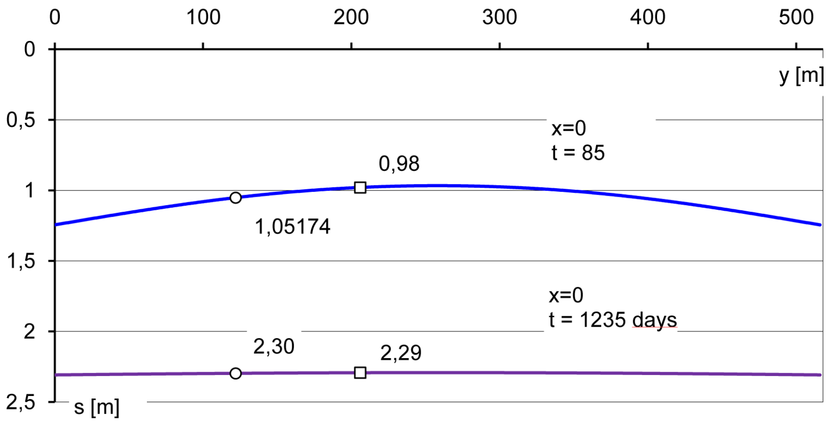
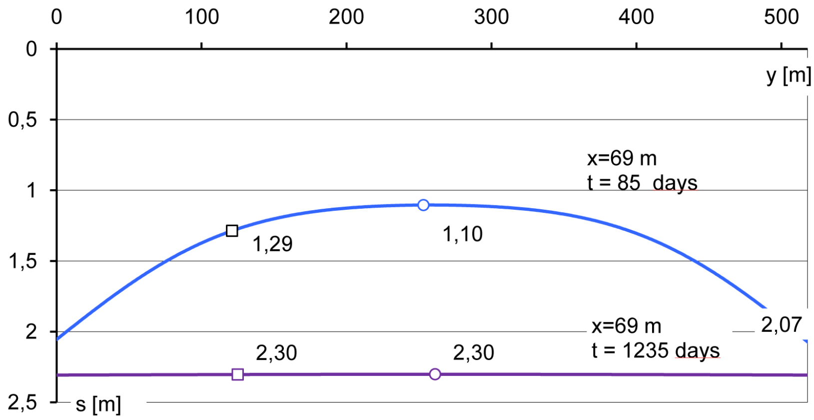


Fig. 8. Mass exchange in elementary volume [2].
Rys. 8. Wymiana masy w elementarnej objętości gruntu [2]





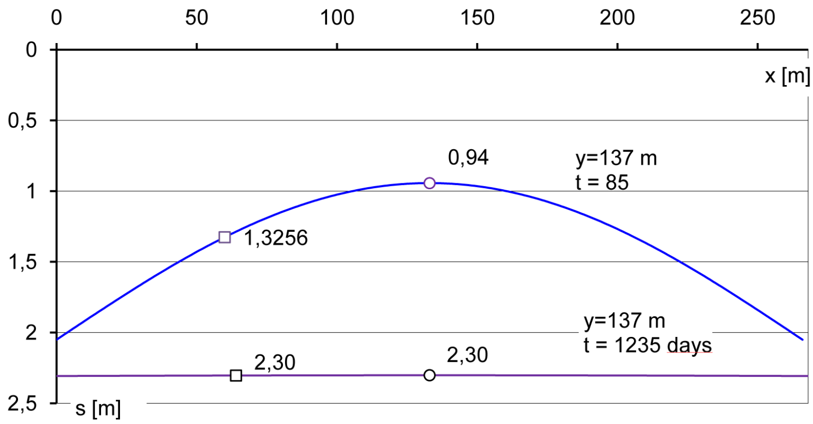


Fig. 9. Settlement in different profiles 1 and 2 [2].
Rys. 9. Osiadanie w profilach 1 oraz 2 [2]

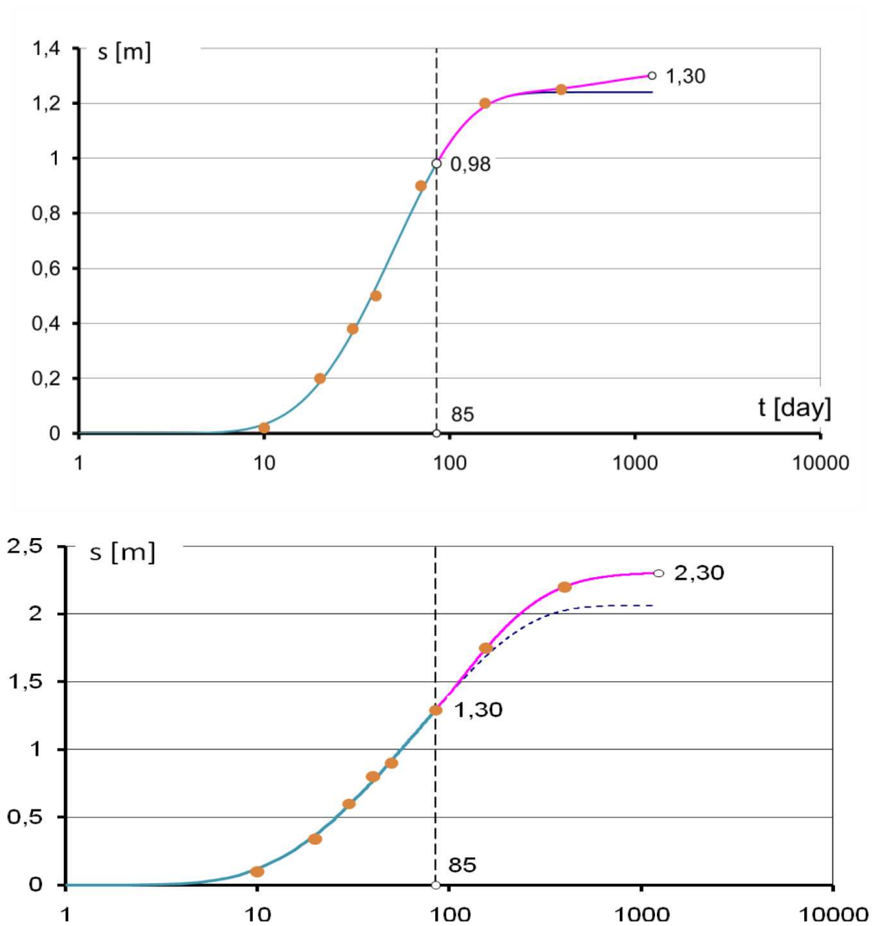


Fig. 10. Settlement at reference points [2].
Rys. 10. Osiadanie wybranych punktów [2]

The exact solution of the problem is given in the previous paper [2]. The results of practical calculations are given in Fig. 9 and Fig. 10.

From the results given in Fig. 9 and Fig. 10 it comes out that it is possible to reach good agreement between modeled and measured values. An interesting question is how the changing layer parameters do influence the time of consolidation. The comparison can be done using the value of T_o given by Eq. 2.5:

– for the case with vertical filtration (Terzaghi) we have

$$T_{oz} = \frac{H^2\gamma_w}{E \cdot k_z} \text{and} \tag{3.2}$$

– for the case with horizontal filtration we have

$$T_{oz} = \frac{\gamma_w}{E \cdot k_{xz}} \cdot \left(\frac{L}{2}\right)^2 \tag{3.3}$$

In the above equations: k_z – denotes the permeability coefficient in vertical direction and k_x – in horizontal direction; L – is the horizontal extent of the consolidated area. So finally we can write

$$\frac{T_{oz}}{T_{ox}} = \left(\frac{k_x}{k_z}\right) \cdot \left(\frac{L}{2H}\right)^2 \tag{3.4}$$

The detailed calculation for the real case gives the following result

$$T_{oz} = 0.4 T_{ox} \tag{3.5}$$

The results are shown in Fig. 11

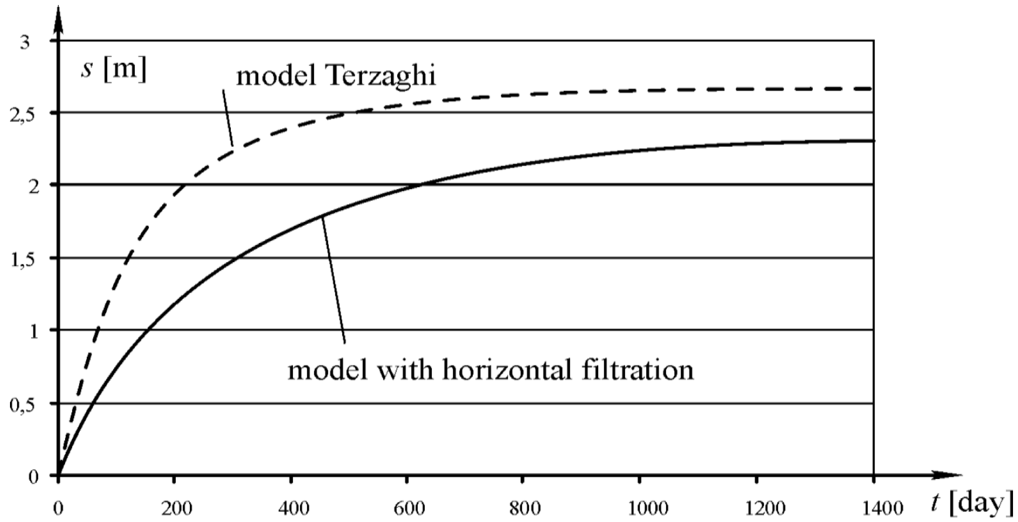


Fig. 11. Comparison of consolidation time [2].
Rys. 11. Porównanie czasu konsolidacji [2]

4. Empirical model of peat settlement

The model describing peat settlement during consolidation process assumes simplifications. The assumptions taken in order to obtain solution were specified in the previous chapters. Laboratory experiments and field measurements indicate that besides of changing soil parameters: $E(s)$ and $k(s)$, another factor should be included.

That is the reological movement of peat body. It appears after long time of settlement: i.e. one or two years.

Sometimes, after half a year, it is observed that the settlement suddenly increases. It seems to be due to slow creeping flow of peat body and may be referred to (high) viscosity coefficient influence. The detailed analysis of this phenomenon is not a matter of the present paper. For practical calculations Meyer [3,4] proposed following empirical curve called "elementary curve".

$$S(t,\sigma) = S_{\infty}(\sigma) \cdot [1 - \exp(-Dt^{\rho} - \alpha t)] \tag{4.1}$$

In the above equation: S_{∞} – denotes the terminal settlement including reological effect, t – is the time and D, ρ, α – are parameters which can be estimated statistically based upon laboratory (oedometer) tests. The crucial value is $S_{\infty}(\sigma)$. In order to estimate it including its nature from field measurements, the following relation was used for statistical calculations:

$$S_{\infty}(t_k) = S_{\infty} \cdot \left[1 - \exp\left(-C_1 \cdot t_k^{e_2} - c_3 t_k\right)\right] \tag{4.2}$$

During the laboratory tests the longest time is denoted t_k, and the related settlement is $S(t_k)$. It can be proved that by extending time of laboratory tests t_k for each set we can calculate $S_{\infty}(t_k)$ from Eq. 4.1 and the points: $\{t_k; S_{\infty}(t_k)\}$ follow the line given in Eq. 17. So it is possible to obtain all the parameters $(c_1; c_2; c_3; S_{\infty})$. The method is described in Fig. 12 for a chosen sample.

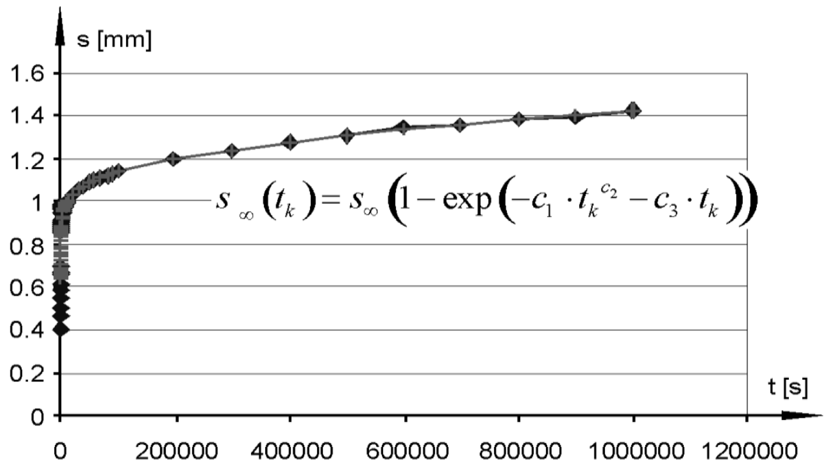


Fig. 12. Optimization of terminal settlement [4].
Rys. 12. Optymalizacja osiadania docelowego [4]

In Table 1 the calculated parameters for the four chosen peat samples are shown, and the appropriate settlement curve is given in Fig. 13.

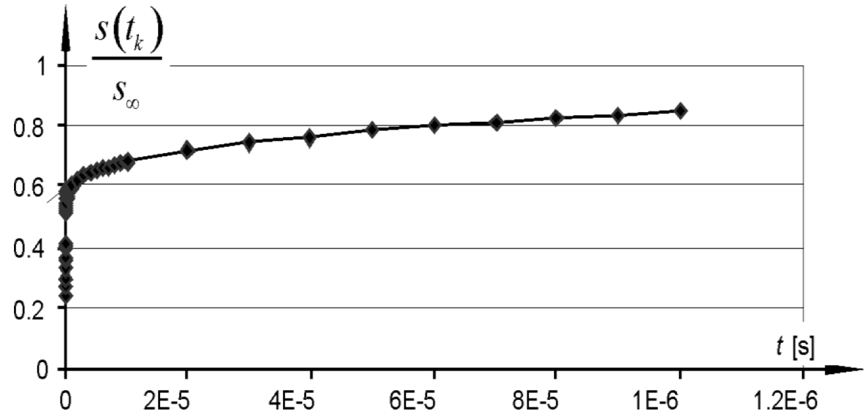


Fig. 13. Stabilization of terminal settlement [4].
Rys. 13. Ustalanie się osiadania docelowego [4]

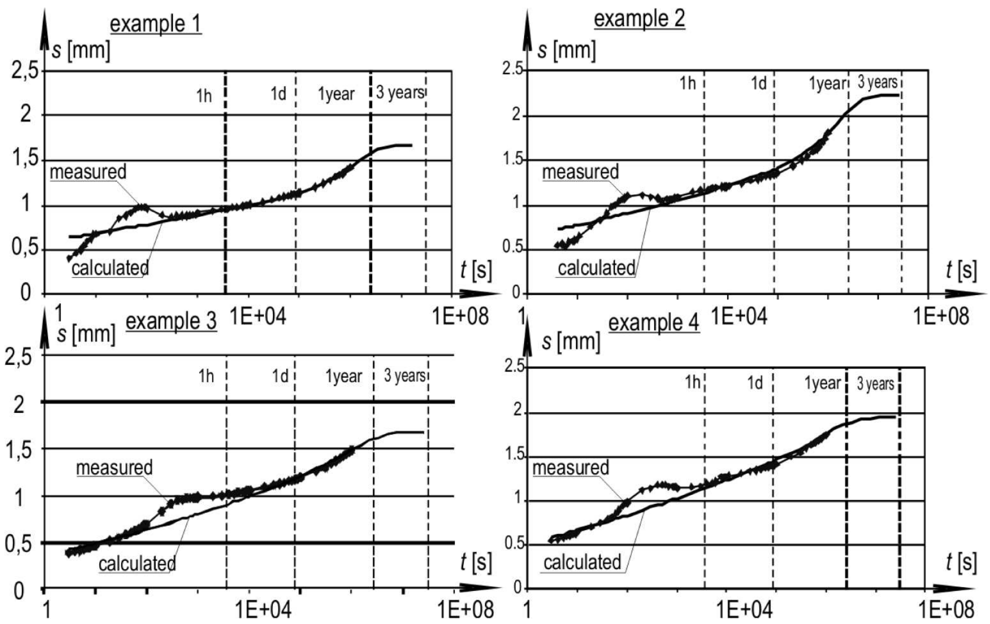


Fig. 14. Settlement of peat samples [4].
Rys. 14. Osiadanie próbek torfu [4]

Table 1

Parameters of the settlement model.
Parametry osiadania modelu

	Example 1	Example 2	Example 3	Example 4
s_∞	1.67	1.67	2.236	1.935
c_1	0.441	0.254	0.351	0.315
c_2	0.0778	0.137	0.0871	0.127
c_3	6.07E-07	5.01E-07	4.87E-07	5.49E-07

The settlement of the peat samples compared to the measured values are given in Fig. 14.

5. CONCLUSIONS

1. In this paper, the new approach to the problem of peat consolidation is presented. Comparing to the previously existing models, the one presented here includes varying soil parameters. The soil parameters, i.e. elasticity modulus and permeability coefficient, depend on the value of settlement, and they change with time.
2. The elasticity modulus increases during the consolidation process, and the permeability coefficient diminishes during the consolidation. The resulting influence of both of them makes the consolidation time longer and the terminal settlement smaller.
3. The particular case of consolidation is that one with horizontal filtration. It appears when the charging layer is made of impermeable soil i.e. an ash. The model presented here shows that the time of consolidation increases with comparison to that one with vertical filtration.
4. The model which analyses physical phenomenon of consolidation do not include the reological effects of long time settlement. It can be included using the presented here empirical model of peat consolidation and the "elementary curve" given by Meyer [3,4]. The model gives especially good agreement for long time settlement and has been used for practical calculation in engineering projects with satisfactory results.
5. The problem which remains to be solved is the calculation of reological effects based upon physical properties of the phenomenon. It seems that it can be done by using the slow creeping flow model of peat body.

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