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The estimate settlement of loaded surface of organic soils with the empirical soil model

L'estimation du tassement des sols organiques soumis à une charge grâce au modèle des sols empiriques

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ABSTRACT: Modeling the behavior of organic soils subjected to stress has a particular importance in the area of estuaries to the sea. One of the largest peat bog complexes in Europe was created at the mouth of the Oder. Peat-bogs in this part have created relatively deep seams: an average of 3.5 m, and a maximum of 11.0 m. The largest thickness is found in the deposits in the Lower Oder Valley, within Szczecin and in the fork of the Oder. In many places, soft soils (peat) have been covered with embankments to treat the ground for economic, storage and housing needs. The forecast of subsidence of such embankments has required the creation of a calculation method that allows to predict the settlement of such embankment over time. In 1992, Z. Meyer proposed an empirical equation, which for several years has been verified both in the field and in the laboratory. Currently, this solution can be used to assess the behavior of the organic soil under the load. The description of the settlement course of the surface, loaded with additional load, is possible using the empirical equation described as an elementary (fundamental) curve. The empirical equation is a rheological approach and describes the course of settlement in the field of filtration phase of consolidation and structural consolidation. The constants of the model are calculated by statistical methods, on the basis of strings of the measured values of the settlement, due to consolidation, and secondary settlements relative to time for a given load.

RÉSUMÉ: Modéliser le comportement des sols organiques soumis à des contraintes est particulièrement important dans les zones d'estuaires marins. A l'embouchure de l'Oder, une des plus larges et complexes tourbières d'Europe a été créée. Les tourbières ont créé dans ces zones d'épaisses couches : en moyenne de 3,5 m et au maximum 11 m. L'épaisseur la plus importante a été trouvée dans les dépôts de la vallée de l'Oder, à Szczecin et dans la fourche de l'Oder. A plusieurs endroits, les sols meubles (tourbe) ont été recouvert par des remblais pour des raisons économiques, de stockage et pour les besoins des logements. La prévision de l'affaissement de tels remblais nécessite la création d'une méthode de calcul du tassement de ces remblais au cours du temps. En 1992, Z. Meyer proposa une équation empirique, qui fut vérifiée pendant plusieurs années sur le terrain et en laboratoire. Actuellement, cette solution peut être utilisée pour évaluer le comportement des sols organiques soumis à une charge. La description de l'évolution du tassement du sol avec une charge supplémentaire est possible en utilisant l'équation empirique décrite comme un virage élémentaire (fondamental). L'équation empirique est une approche rhéologique et décrit l'évolution de la consolidation. Les constantes du model sont calculées par des méthodes statistiques basées sur des mesures successives du tassement par rapport au temps pour une charge donnée. Pour un ingénieur civil, une longue de période de recherche aboutit à une coopération fructueuse avec les investisseurs, pour qui le temps est un facteur important. L'utilisation de l'équation empirique permet une réduction significative de ce temps.

Keywords: organic soil, peat, settlement

1 INTRODUCTION

Two of the largest Polish rivers, the Vistula and the Oder, pass into the Baltic. Szczecin is located on the Oder River and includes a part of the Lower Oder Valley shown in Figure 1. The city is located about 65 km from the sea by water and in a straight line. By land you have to travel 100 km to get from Szczecin to the Baltic. The Lower Oder Valley from the south reaches 2-3 km, and at the height of Szczecin it reaches 10-12 km. The bottom of the Lower Oder Valley lies at an altitude of about 1 meter above the sea level in the upper part to about 0.2-0.5 m asl in the lower part, on the length of 80 km, the drop amounts to 0.5 m, about 0.04 ‰.

Figure 1. Szczecin and The Lower Oder Valley

With long-lasting northern winds, the waters of the Pomeranian Bay have been flooding into the depths of the valley. The so-called reverberant backwater effect, caused by the raising level of water in the bay and the wind regress, is disturbing the flow in the river. The backwater wind causes the damming of the water level in the river network of Oder estuary, and changes the vertical distribution of the flow velocity of the water (Meyer & Coufal 2001). The average Odra flow in the section of the valley is about 500-600 m^3/s, but it can be more than 1600 m^3/s. The flow of the lower Oder is difficult to determine due to the tidal and wind backwater currents (Buchholz 2007). Existing polders in this area are periodically flooded. When comparing the low altitude of 0.2-0.5 m asl and the average water height in the Odra River, it can be assumed that the area is a wetland where swamp vegetation is eager to grow. The upper layer of the valley is covered with sediments of Quaternary formations. The Baltic glaciation has influenced the shape of the current sculpture. Then they have developed a series of deposits in the keel facies: glacial, glaciofluvial, limnic, fluvial and glaciolacustrine. The beginning of the wetland deposits sedimentation in the area of the Lower Oder Valley has been determined by a significant increase of the sea level. The so-called litorin transgression was estimated at around 6,250 years of BP (Borówka 2004 & 2005). Then, layers of gyttja and growing swamp vegetation were formed. The type of development of the riverbed changed from meandering to anastomosing (Duda 2013). Growing vegetation had strengthened the banks of the river. In the river valley, the peat cover had developed. In the historical times, many works had been carried out in the area of Międzyodrze: deepening of the fairway, canal construction, development of the seaport Szczecin, development of the city, marshland management, construction of the polders and embankments using dredged material. The Międzyodrze area is located in the Lower Oder Valley between two branches of the River Oder: Western Oder and Eastern Oder (Regalica) shown in figure 2.

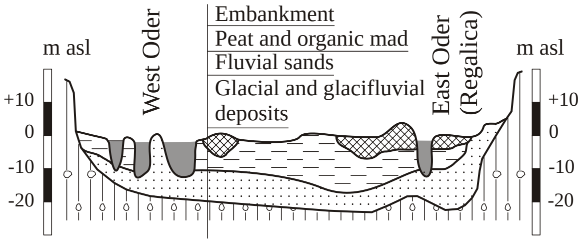

Figure 2. Cross-section of The Międzyodrze

Between two rivers, 4-11 m thick layer of organic soils and peat was formed. The embankments make it possible to overload the organic soil layer in order to improve the strength parameters and they give the opportunity to use land for industrial development.

2 PHYSICAL PARAMETERS OF PEAT FROM THE LOWER ODER VALLEY

Characteristic features of peats are very high porosity, high natural water content, very small edometry compressibility module, small angle of internal friction. The peat has a high porosity, high water content and high organic content. It is a challenge for the civil engineers. Building facilities in such conditions is impossible or requires improvement of the geotechnical parameters of the ground. Good knowledge of the variability of parameters and the assessment of their correct determination will allow better modeling of the behavior of organic soil under load. The Międzyodrze areas are extremely difficult to use in terms of engineering. The difficulty is associated with the simultaneous occurrence of several factors, such as:

- organic soils,
- high level groundwater (groundwater table at the level of 0.2 to 1.0 m asl. Fluctuations in the water level reach 1.0 m,
- flood risks,
- aggressiveness of the groundwater. Aggre-ssiveness is related to the presence of humic acids, aggressive CO_2 and SO_4^{2-} ions.

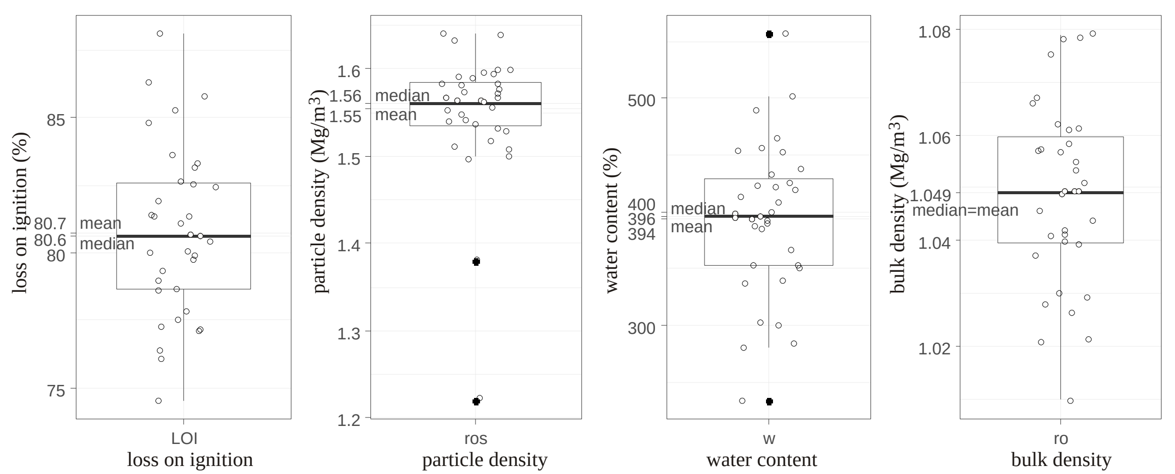

Figure 3. The results of basic physical parameters of samples taken from the Lower Oder Valley, 1st location

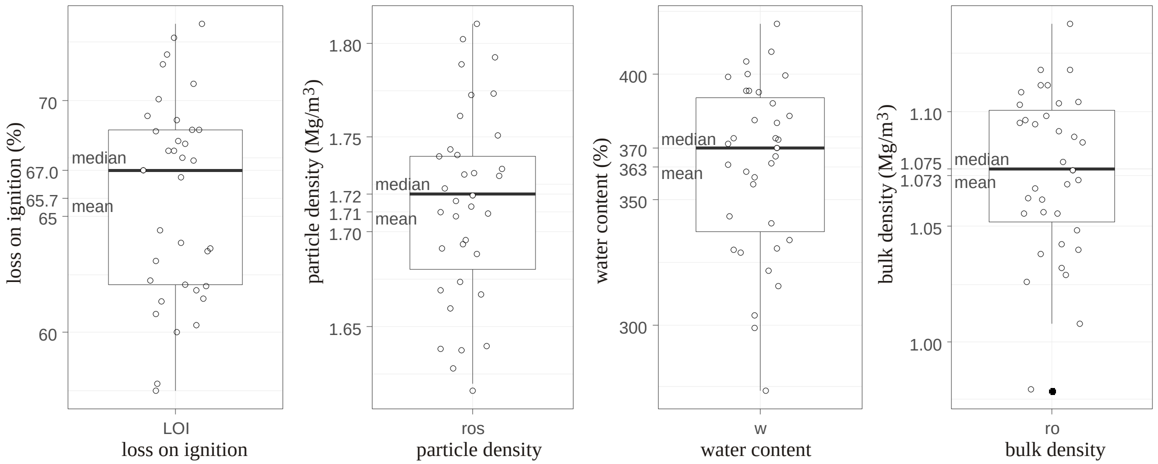

Figure 4. The results of basic physical parameters of samples taken from the Lower Oder Valley, 2nd location

The material for the study was taken from the Międzyodrze area (the Lower Oder Valley). The peat belongs organic soils containing a significant amount of organic substances with very different properties. The von Post scale of collected samples is identified as H5. The basic physical parameters are: particle density, bulk density and water content. For the peat, the content of organic parts must be additionally marked (LOI) (Craig 2004).

The laboratory tests results of the physical parameters of organic soils are shown in Figure 3 and Figure 4.

On the basis of the research carried out, the peat from the Międzyodrze is characterized by the following average parameters, showed in Table 1.

Table 1. Average parameters of samples peat

Average parameters	**Symbol unit**	**Value 1st loc.**	**Value 2nd loc.**
Particle density	$\bar{\rho}_s$ (Mg/m^3)	1.55	1.71
Bulk density	$\bar{\rho}$ (Mg/m^3)	1.05	1.07
Water content	$\bar{w}$ (%)	394.1	362.9
Loss on ignition	$\overline{LOI}$ (%)	80.7	65.7

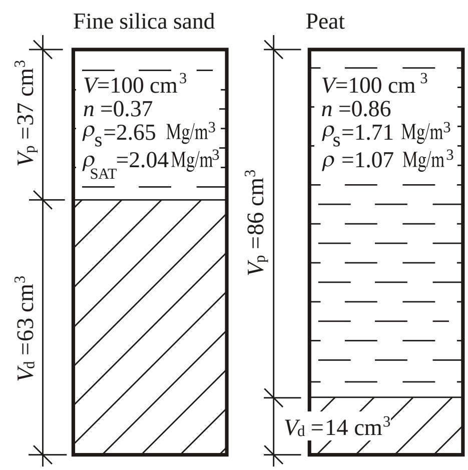

Figure 5. Differences in the volume of the soil phases for fine silica sand and peat

The porosity was calculated based on the average parameters:

$$n_1 \cong n_2 = 0.86 \tag{1}$$

Soils with such high porosity must settle considerably under the load. It is estimated that an average load of approximately 100 kPa may cause settlement of up to 50 % of the original, initial thickness.

Numerical data can be prestented in Figure 5, idicating the differences in the volume of particular soil phases.

3 EMPIRICAL MODEL OF ORGANIC SOIL

The settlement process can be described by the equation (2), especially for organic soil:

$$s(t) = s_\infty \left(1 - \exp(-D \cdot t^p - \alpha \cdot t)\right) \qquad (2)$$

where:

s_∞, D, p, α – parameters identified by the least squares method,
t – time (days) – for in situ tests, (s) – for laboratory tests.

The equation (2) was developed on the basis of measurements and it is determined by the elementary equation (Meyer 1992, 1993). Parameters s_∞, D, p, α identified based on the results of the settlement of the loaded surface.

When comparing the empirical equation with the theoretical equation of the Kelvin model is shown in Figrue 6, we can indicate the rheological features of the solution.

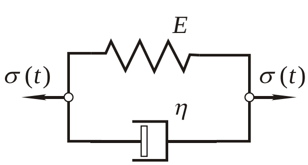

Figure 6. Rheological Kelvin model

The Kelvin model (Keedwell 1984) is based on:

$$\sigma(t) = E \cdot \varepsilon(t) + \eta \cdot \frac{\partial \varepsilon(t)}{\partial t} \qquad (3)$$

The mathematical fundamentals were first described in 1874 by Meyer (Meyer 1874) however, due to the later works of Thomson (Thomson - Kelvin 1865, 1890) and Voigt (Voigt 1890, 1892), sometimes it is named Kelvin model, or Voigt model, or Kelvin-Voigt model . In the Kelvin model the total stress $\sigma(t)$ is the sum of the stresses due to the viscous and elastic part. The solution is equal:

$$\varepsilon(t) = \frac{\sigma_0}{E}\left(1 - \exp\left(-\frac{E}{\eta} \cdot t\right)\right) \qquad (4)$$

The equation (4) can be transformed into the form:

$$\exp\left(-\frac{E}{\eta} \cdot t\right) = \left(1 - \varepsilon(t) \cdot \frac{\sigma_0}{E}\right) \qquad (5)$$

$$\exp(X) = \left(1 - \frac{s(t)}{s_\infty}\right) \qquad (6)$$

where:

$$s_\infty = \frac{\sigma_0}{E} \cdot H_0 \qquad (7)$$

then:

$$X = -\frac{E}{\eta} \cdot t = \text{const} \cdot t \qquad (8)$$

The equation (8) describing the Kelvin model is based on linear time dependence. The real settlement process can be reproduced in a small time range. In the empirical model, the direct relationship with time is non-linear (9). In a wider range of time, the measured settlement can be mapped.

$$X = D \cdot t^p + \alpha \cdot t \qquad (9)$$

In the Meyer empirical equation there are constants determined by statistical methods (Meyer & Bednarek 2009). The examples of the solution, for several samples from the Międzyodrze are presented below on two types of graphs: linear and semi-logarithmic graph.

Three examples are given:
- field measurements, figure 7,
- measurement results in one-dimensional strain state – oedometer test, figure 8,
- measurement results in axi-symetrical stress state – THX, triaxial compression test, fig 9.

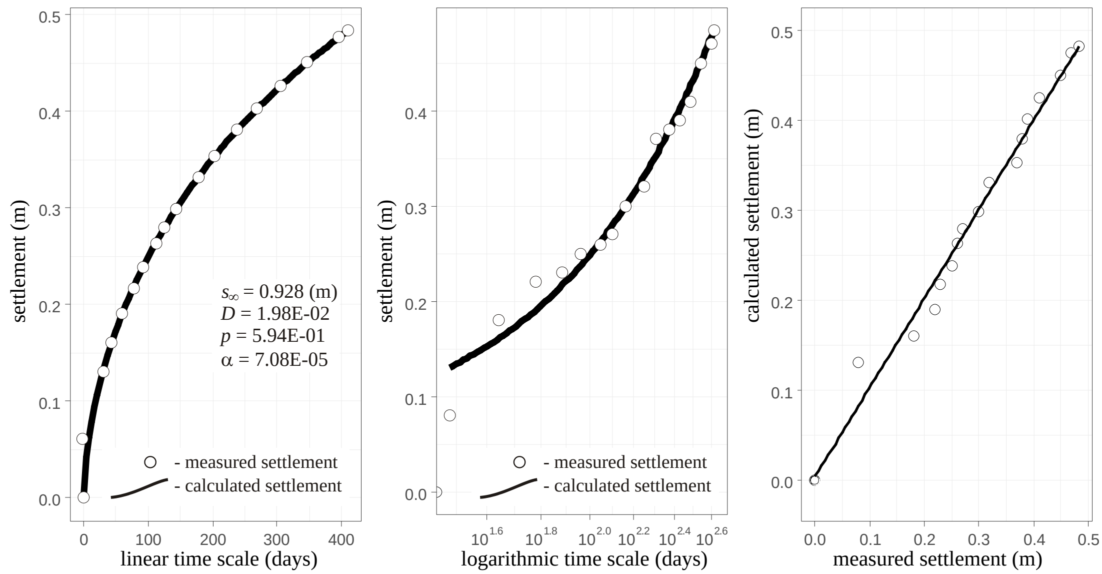

Figure 7. Field measurements on the surface of organic soil loaded with embankment

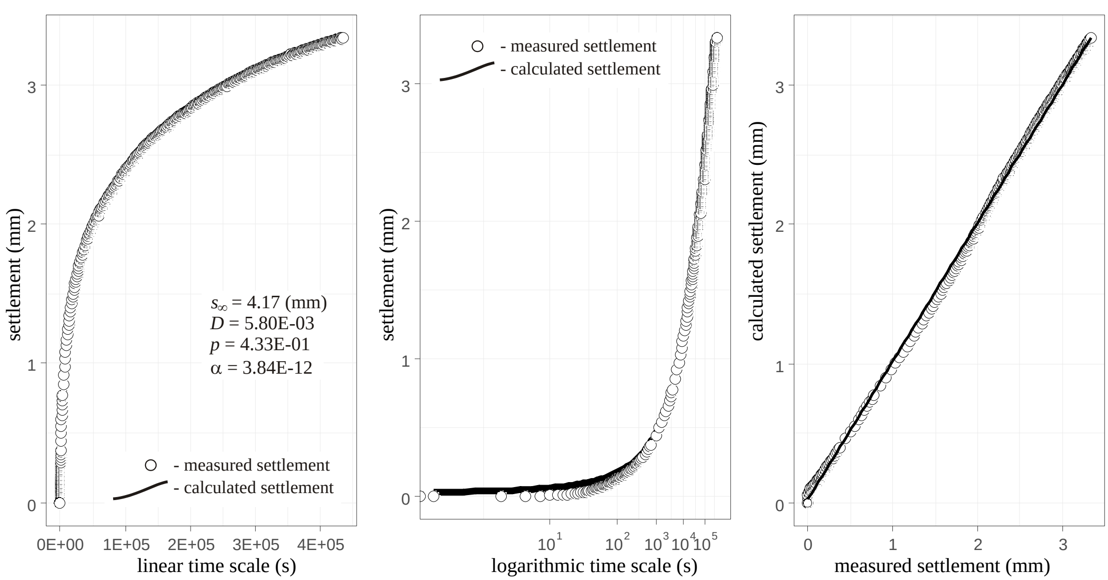

Figure 8. Oedometr test of peat from the Lower Oder Valley

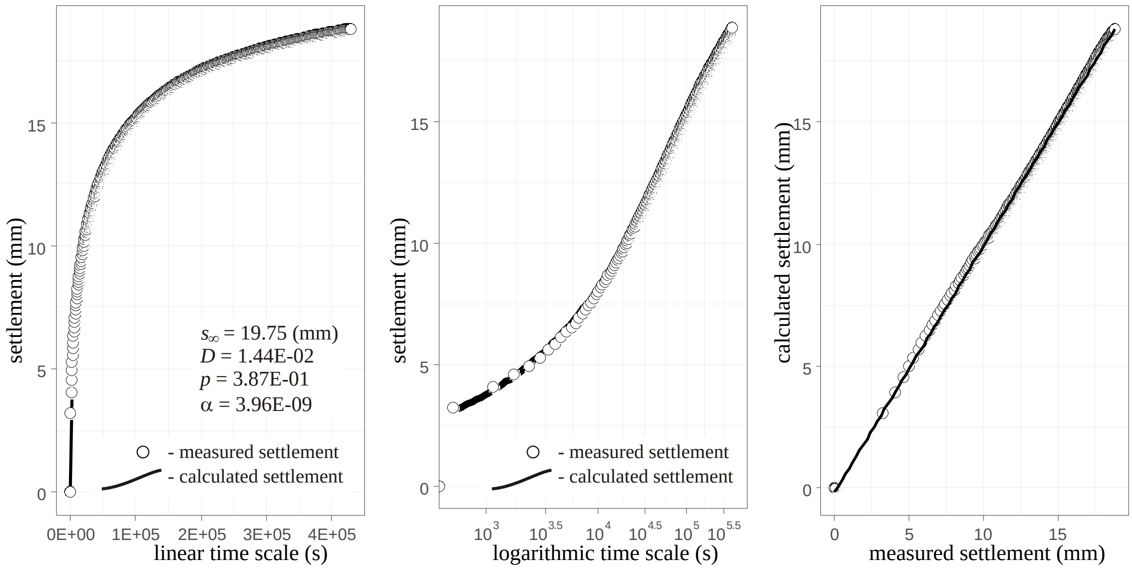

Figure 9. Compressing peat from the Lower Oder Valley in triaxial compression test

The model has positively undergone verification process in the laboratory when measuring settlement in the oedometer, triaxial compression apparatus, and in the field.

Thus, individual model parameters can be described adopting the material parameters used in mechanics and rheology.

$$\eta_1 = \frac{E}{D} \cdot t^{(1-p)} \tag{10}$$

$$\eta_2 = \frac{E}{\alpha} \tag{11}$$

and:

$$\frac{1}{\eta} = \frac{1}{\eta_1} + \frac{1}{\eta_2} \tag{12}$$

This solution allowed the use of a nonlinear approach in the model, which is missing in the Kelvin model. In the organic soils settlement analysis, such a non-linear approach is required to improve the consistency of measured results with those calculated.

4 CONCLUSIONS

The paper presents the origin of problems in the Oder estuary where there are organic soils. As an example, the average values of physical peat parameters in the area of Międzyodrze are presented. The significant settlements caused by the additional load from the embankments on organic soils can be modeled by empirical the equation, which is a rheological approach. The applied rheological approach describes the settlement at the same time in terms of filtration and structural deformations. It allows forecast the settlement, on the basis of carried out measurements. The constants of the model are calculated by the statistical methods based on the sequences of the measured values such as: time and settlement. The elementary curve (2) can be used as a boundary condition for a numerical modeling of the ground behaviour. To cooperate successfully with an investor, a designer often needs to obtain an information about the ground conditions in a very short time. The application of the empirical equation can significantly reduce the time needed to estimate the settlement of the loaded organic soils over time. The results obtained from the settlement soil surface measurements in the field provide an approximation of the final settlement. The parameters shown in Eq. (2) can be estimated for prediction of settlement for new embankment on peat subsoil on the first few measurement results. The final settlement will be the more accurate the longer we will conduct observations. The knowledge of a final settlement value gives the opportunity to prepare engineering solutions at the design stage, the implementation stage and the stage of use.

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