Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska (2016), 25 (4), 507–517
Prz. Nauk. Inż. Kszt. Środ. (2016), 25 (4)
Scientific Review – Engineering and Environmental Sciences (2016), 25 (4), 507–517
Sci. Rev. Eng. Env. Sci. (2016), 25 (4)
http://iks.pn.sggw.pl

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Tertiary compression of Polish peat
Trzeciorzędowa ściśliwość polskich torfów

Key words: tertiary compression, peat, creep
Słowa kluczowe: ściśliwość trzeciorzędowa, torf, pełzanie

Introduction

Theoretically, creep is the tendency of a solid material to move slowly or deform permanently under the influence of mechanical stresses. It can occur as a result of long-term exposure to high levels of stress that are still below the strength of the material. Creep is more obvious in high water content materials, especially those that contain organic matter. The rate of deformation is a function of the material properties, exposure time, exposure temperature and the applied structural load. Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a construction can no longer perform its function. Creep is a deformation mechanism that may or may not constitute a failure mode and does not occur suddenly upon the application of stress. Therefore, creep is a "time-dependent" deformation where "tertiary compression" is also observed in peats (Fig. 1).

The tertiary compression phenomena in peats was first taken up by Dhowian and Edil (1980), where the strain to log time curve consists four component of strain was identified as shown in Figure 2.

The test results by Dhowian and Edil (1980) shows a typical graphical plot of laboratory tests for vertical strain in log time, for the range of stress 50–400 kPa. It is clearly observed that four components of consolidation can be identified in peats. Nevertheless, the reason why the tertiary compression occurs after 1,000 to 10,000 min during laboratory testing has not been explained (Fig. 3). In the latest publication Den Haan (1994), Den Haan and Edil (1994) indicated the tertiary compression in peat. It was occurred at all stress levels, but at higher stresses, it occurred more quickly and its intensity was less. A simple model of one-dimensional consolidation of peat included the secondary and tertiary compression pha-

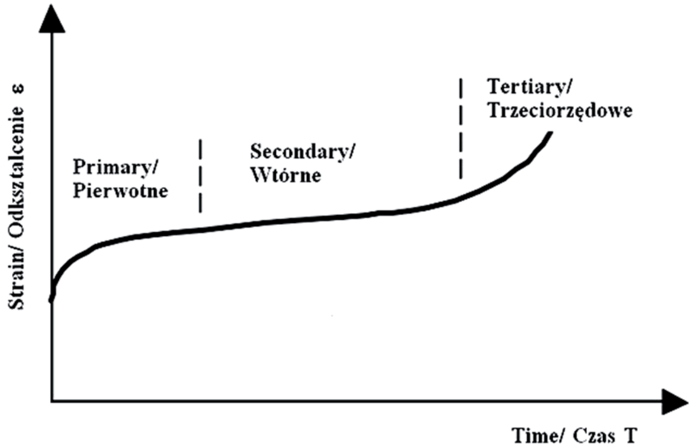

FIGURE 1. Vertical strain versus log time (Wikipedia)
RYSUNEK 1. Zmienność odkształcenia pionowego w logarytmie czasu (Wikipedia)

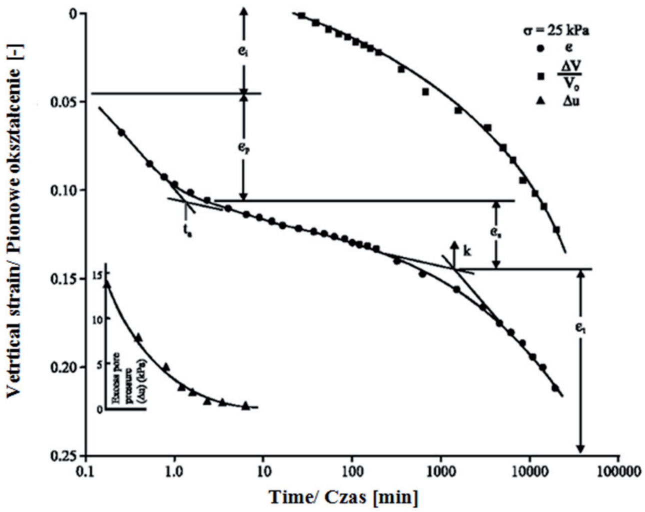

FIGURE 2. Vertical strain versus time: ε_i – instantaneous strain, ε_p – primary strain, ε_s – secondary strain, ε_t – tertiary strain (Dhowian and Edil, 1980)
RYSUNEK 2. Zależność pionowego odkształcenia w czasie: ε_i – odkształcenie natychmiastowe, ε_p – odkształcenie pierwotne, ε_s – odkształcenie wtórne, ε_t – odkształcenie trzeciorzędowe (Dhowian i Edil, 1980)

se was presented. Also, Gofar and Sutejo (2007), based on the consolidation laboratory tests in the Rowe cell, found out that the typical consolidation curve for fibrous peat indicated secondary and tertiary compression.

Tertiary compression was also reported by several researchers during the field tests (Candler and Chartres, 1988; Fox et al., 1992). Some of the researchers argued that this part of compression can be neglected because it generally started

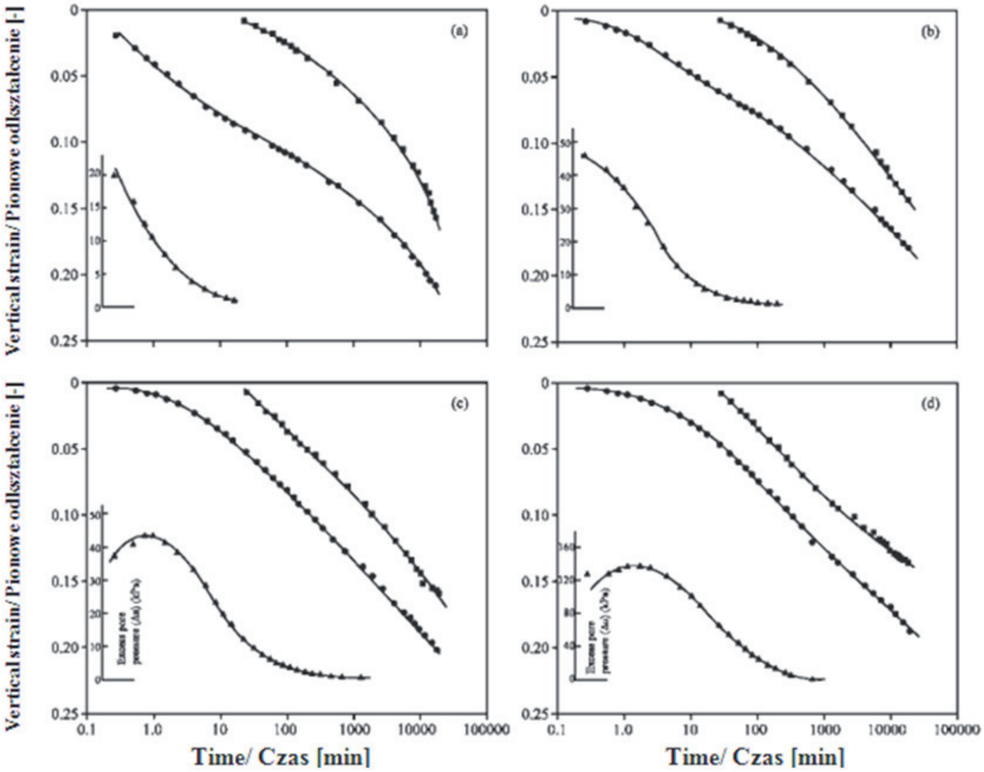

FIGURE 3. Consolidation data for Portage peat (back pressure 560 kPa): (a) σ = 50 kPa, (b) σ = 100 kP, (c) σ = 200 kPa, (d) σ = 400 kPa (Dhowian and Edil, 1980)
RYSUNEK 3. Wyniki badania konsolidacji torfów z Portage (ciśnienie wyrównawcze 560 kPa): (a) σ = 50 kPa, (b) σ = 100 kP, (c) σ = 200 kPa, (d) σ = 400 kPa (Dhowian i Edil, 1980)

after the design life of structures. Later, the tertiary compression was mentioned in some other publications, but usually as the creep stage that should be taken into the consideration in modeling the deformation process in peats (Candler and Chartres, 1988; Stolle, 1998; Colleselli et al., 2000; Malinowska, 2001; Karabatakis and Hatzigogos, 2002; Liingaard et al., 2004; Szymanski et al., 2004; Gofar and Sutejo, 2007; Leoni et al., 2008; Szymanski et al., 2009; Yin et al., 2013; Sivasithamparam et al., 2015).

The laboratory test results obtained from triaxial and oedometer creep tests are different. Bishop and Lovenbury in 1969 found the difference in the curve shape obtained in oedometric and triaxial conditions (Fig. 4). Nevertheless, the time to compression curve seems to be long-term enough to indicate the tertiary compression. The consolidation rate estimation cannot be made based on conventional methods (Cassagrande, Taylor, Robinson, Terzaghi) because the curve does not give a clear indication where the primary consolidation is assumed to end and the secondary compression is assumed to start and where the secondary compression ends and the tertiary com-

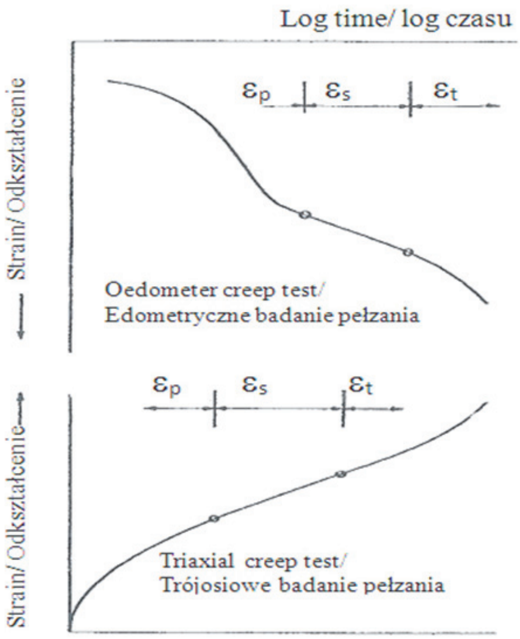

FIGURE 4. The compression curve for different types of laboratory tests
RYSUNEK 4. Krzywa ściśliwości dla różnych badań laboratoryjnych

pression starts. Szymański et al. (2004) for the secondary phase proposed the model depending on deviatoric stress and time. Lea and Browner (1963) and Fox et al. (1992) found some correlations between coefficient of secondary compression and the consolidation pressure.

Material and methodology

The laboratory tests were performed on undisturbed peat samples taken from four different test sites. Three different methods were used for the tests: triaxial tests and consolidation tests – in classical oedometers and the Rowe cell. The triaxial tests were done on the same several, representative soil samples, taken from "Antoniny" test site. The oedometer tests were done on the same several (about 13), representative soil samples, taken from "Mazury" test site. The Rowe cell tests were done on the same several (about 18), representative soil samples, taken from "Campus SGGW" test site. The localization of the tests sites is presented in Figure 5. The physical properties of tested organic, soft soil sample are presented in Table 1, where common properties were investigated, as: w – water content [%], ρs – density of soild particles [$g \cdot cm^{-3}$], ρ – bulk density[$g \cdot cm^{-3}$], ρ_d – dry density [$g \cdot cm^{-3}$], w_p – plastic limit [%], w_L – liquid limit [%], I_{OM} – organic matter content [%], R – degree of humification [%], e_0 – initial void ratio [-].

FIGURE 5. Localization of the sampling sites: 1 – "Antoniny" test site, 2 – "Campus SGGW" test site, 3 – "Mazury" test site
RYSUNEK 5. Lokalizacja miejsc poboru próbek: 1 – obiekt doświadczalny „Antoniny" , 2 – obiekt doświadczalny „Campus SGGW", 3 – obiekt doświadczalny „Mazury"

TABLE. Properties of the tested peats
TABELA. Właściwości badanych torfów

Physical properties Właściwości fizyczne	Antoniny	Campus SGGW	Mazury
w [%]	439	400	439
ρ_s [g·cm^{-3}]	1.5	1.58	1.45
ρ [g·cm^{-3}]	1.06	1.12	0.996
ρ_d [g·cm^{-3}]	0.26	0.22	0.18
w_p [%]	200	118	400
w_L [%]	320	255	570
I_{OM} [%]	78	75	88
R [%]	50–70	60–75	30–40
e_0 [-]	5.50	6.7	7.06

Test results

The laboratory tests were performed on normalized approved apparatus available in the Laboratory Water Center, WULS-SGGW in Warsaw.

The vertical settlement versus logarithm time under different stress increment are presented. Only a few representative test results are showed. Vertical strain versus logarithm time under different stress increment for the same soil sample, taken from „Antoniny" test site is presented in Figure 6. These tests were performed in the triaxial apparatus.

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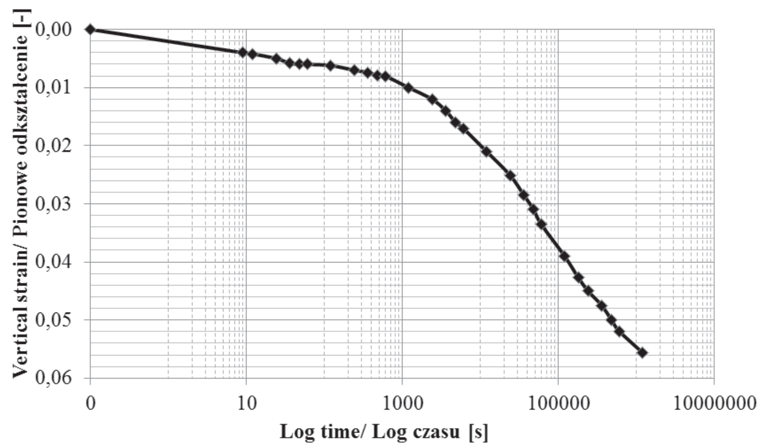

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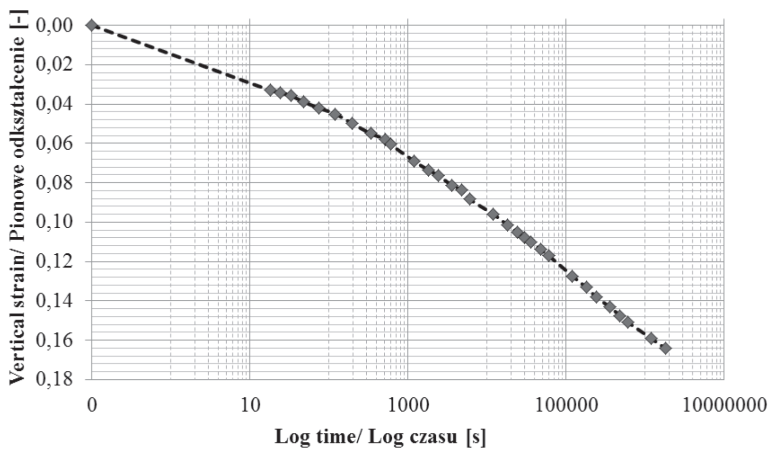

FIGURE 6. Vertical strain versus logarithm time under different stress increment for the same soil sample, taken from "Antoniny" test site: (a) σ_v = 5 kPa, (b) σ_v = 25 kPa
RYSUNEK 6. Pionowe odkształcenie w zależności od czasu dla tych samych próbek, pobranych z obiektu doświadczalnego „Antoniny" przy obciążeniu: (a) σ_v = 5 kPa, (b) σ_v = 25 kPa

Vertical strain versus logarithm time under different stress increment for the same soil sample were performed in the Rowe cell and in the classical oedometer, on the soft organic soils, respectively taken from "Campus SGGW" and "Mazury" test sites (Figs 7, 8).

In the first small stress value the primary compression is more apparent than for the advanced stress increments, comparing the curves in Figures 7 and 8 for 5 and 25 kPa.

The shape of the of the strain curves, obtained in triaxial and oedometer conditions is different (Fig. 9).

The tertiary compression in the ε to log t curves is quite distinguishable obtained both in the triaxial and oedome-

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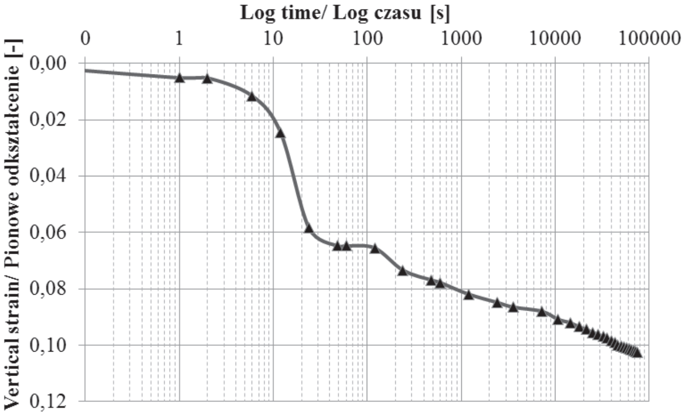

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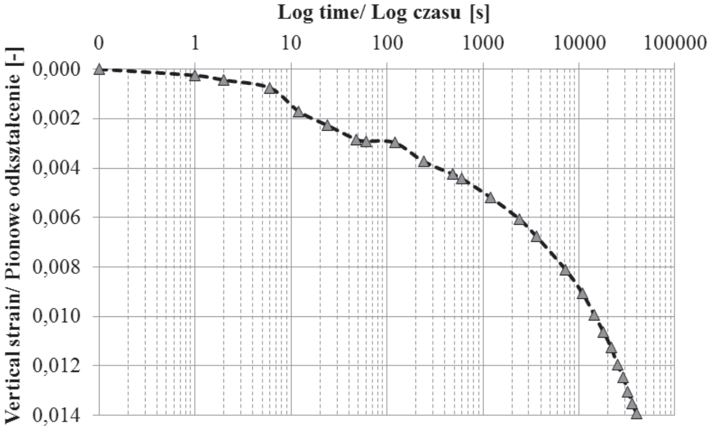

FIGURE 7. Vertical strain versus logarithm time under different stress increment for the same soil sample, taken from "Campus SGGW" test site: (a) σ_v = 5 kPa, (b) σ_v = 25 kPa
RYSUNEK 7. Pionowe odkształcenie w zależności od czasu dla tych samych próbek, pobranych z obiektu doświadczalnego „Campus SGGW" przy obciążeniu: (a) σ_v = 5 kPa, (b) σ_v = 25 kPa

tric conditions. The times were obtained from the vertical strain versus logarithm time curve. The example is presented in Figure 10.

The average value of time for the transition from primary to the secondary compression is designated as t_a The average value of time for the transition from secondary to the tertiary compression is designated as t_k.

Summary and conclusion

In peats the strain to time curve is not similar to those obtained for other, even organic soils. The test results, obtained from four different representative soil samples, for different stress indicated that the limitations/deviations from conventional consolidation process is necessary. The rate of secondary compression

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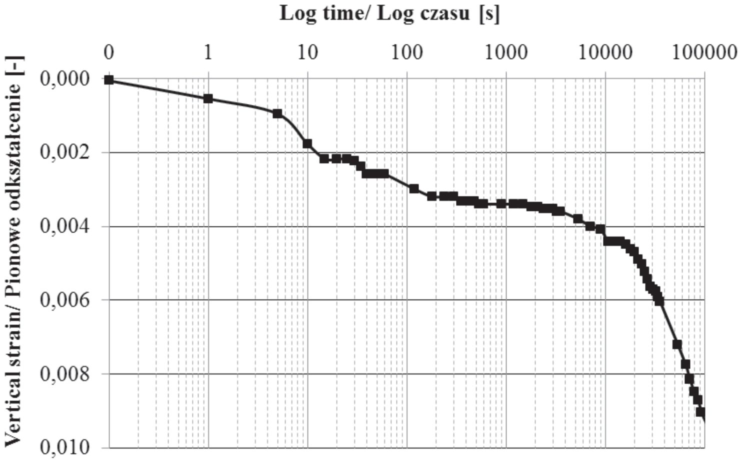

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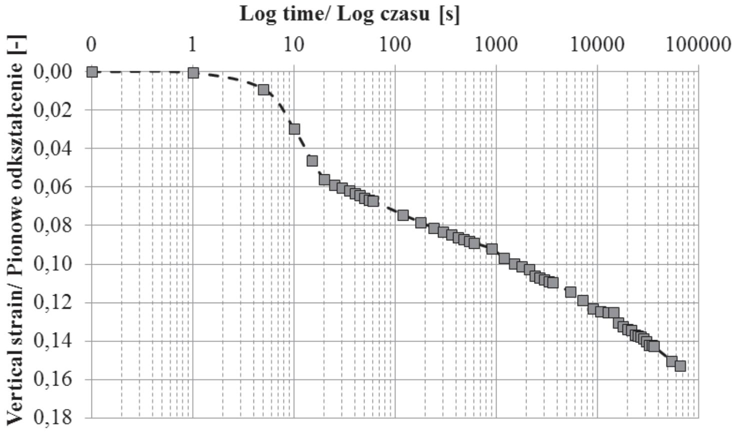

FIGURE 8. Vertical strain versus logarithm time under different stress increment for the same soil sample, taken from "Mazury" test site: (a) σ_v = 5 kPa, (b) σ_v = 25 kPa
RYSUNEK 8. Pionowe odkształcenie w zależności od czasu dla tych samych próbek, pobranych z obiektu doświadczalnego „Mazury" przy obciążeniu: (a) σ_v = 5 kPa, (b) σ_v = 25 kPa

gradually decreases until it vanishes very large times, transiting into the new stage termed tertiary compression. The tertiary compression (ε_t), continues indefinitely until the whole compression process stops.

The average value of time for the transition from primary to the secondary compression (t_a) and from secondary to the tertiary compression (t_k) is obtained. For the pressure of σ_v = 5 kPa, the average value of (t_a) is from 20 s, and for the pressure of σ_v = 25 kPa, the average value of t_a is from 30 s. But, the average value of time for the transition from secondary to the tertiary compression (t_k) is from 20,000 s for the pressure of σ_v = 5 kPa, and t_k is from 500 s for the pressure of σ_v = 25 kPa. So, the average value of t_a is increasing

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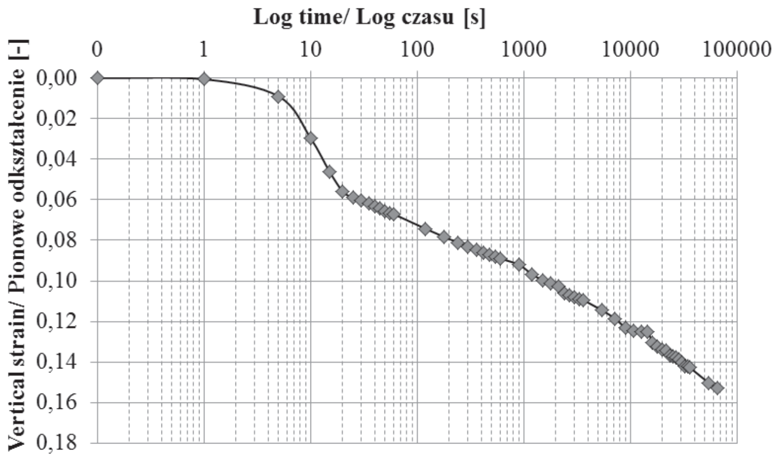

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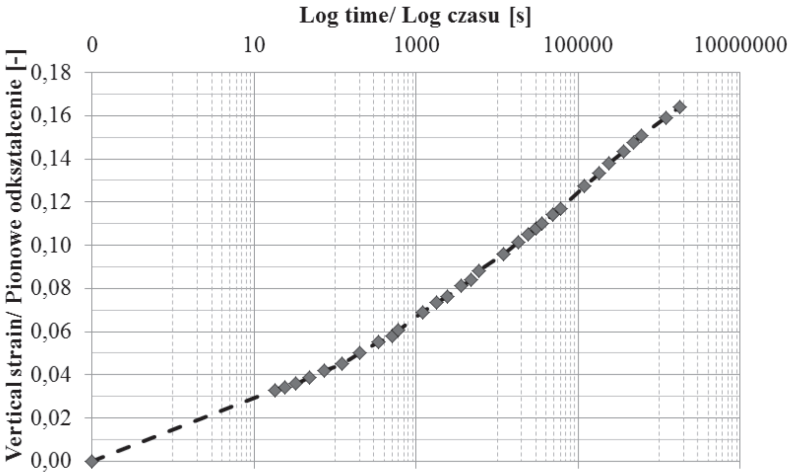

FIGURE 9. Vertical strain versus logarithm time under 25 kPa stress: (a) obtained in the oedometric conditions, (b) obtained in triaxial conditions
RYSUNEK 9. Pionowe odkształcenie w zależności od czasu dla obciążenia 25 kPa: (a) w warunkach edometrycznego badania pełzania, (b) w warunkach trójosiowego badania pełzania

with stress increments but the average value of t_k is decreasing with the stress increments.

The ε to log t curve indicates that the primary consolidation is dominant in term of magnitude and the rate is high. The secondary compression occurred at a slower rate and is rather non-linear with logarithmic of time. The tertiary compression starts after the secondary compression, may last for a long time and it is non-linear.

The tertiary compression in the first stress increments seems to be more visible that for the advanced one. It is necessary to perform more tests for the largest stress increments to see, weather the tertiary compression curve is going to slow.

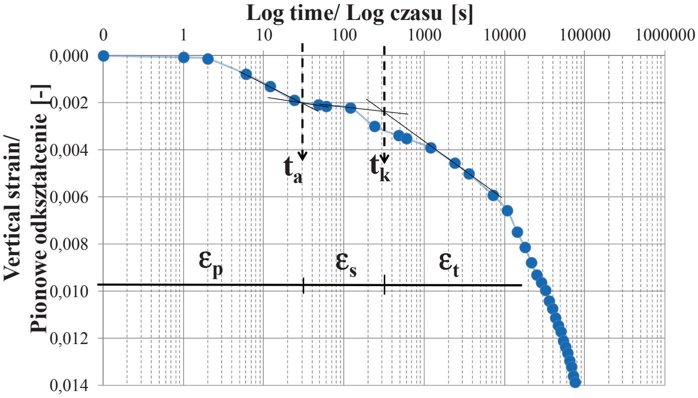

FIGURE 10. Vertical strain versus logarithm time under 30 kPa stress for the soil sample taken from "Campus SGGW" test site: t_a – the average end of the primary compression, t_k – the average start of the tertiary compression, ε_p – primary strain, ε_s – secondary strain, ε_t – tertiary strain

RYSUNEK 10. Pionowe odkształcenie w logarytmie czasu pod obciążeniem 30 kPa dla próbki pobranej z obiektu doświadczalnego "Campus SGGW": t_a – średni czas dla końca pierwotnej ściśliwości, t_k – średni czas dla początku trzeciorzędowej ściśliwości, ε_p – pierwotne odkształcenie, ε_s – wtórne odkształcenie, ε_t – trzeciorzędowe odkształcenie

Based on the results the following conclusions can be drawn:

1. The curve of the vertical strain versus log time has different shape for the test results obtained in oedometric and triaxial conditions.

2. The tertiary compression is very noticeable in peats.

3. The average value of time for the transition from primary to the secondary compression is called t_a.

4. The average value of time for the transition and from secondary to the tertiary compression is called t_k.

5. The average value of t_a is increasing with stress increments but the average value of t_k is decreasing with the stress increments.

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Summary

Tertiary compression of Polish peat. The paper presents the test results of vertical strain versus logarithm time with the especially consideration of tertiary compression that is obvious in Polish peats. The consolidation models for soft organic soil, as peats, should also include the tertiary compression in the deformation process. The average values of times t_a and t_k for the transitions from primary to secondary and from secondary to the tertiary compression are presented.

Streszczenie

Trzeciorzędowa ściśliwość polskich torfów. W pracy przedstawiono wyniki badań odkształcenia w zależności od czasu w skali półlogarytmicznej, ze szczególnym uwzględnieniem trzeciorzędowej ściśliwości torfów. Modele konsolidacji dla słabonośnych gruntów organicznych, takich jak torf, powinny uwzględniać trzeciorzędową ściśliwość w procesie deformacji. W artykule przedstawiono średnie wartości czasów t_a i t_k, odpowiednio dla przejścia ściśliwości pierwotnej we wtórną i wtórnej w trzeciorzędową.

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