Geologos 11 (2007)

III SYMPOZJUM WPGiWP
PUSZCZYKOWO 31 V – 1 VI 2007

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Ocena wpływu zmian stanu naprężenia w podłożu niespoistym na charakterystyki sondowania statycznego

Estimation of the influence of stress state changes in non-cohesive subsoil on CPTU parameters

Streszczenie: Stan naprężenia w podłożu jest jednym z istotniejszych czynników wpływających na interpretację wyników testów, które stosuje się do oceny parametrów wytrzymałościowych i odkształceniowych w warunkach in situ. Pomijanie lub nieadekwatne uwzględnianie wpływu stanu naprężenia na rezultaty badań terenowych, takich jak sondowanie statyczne CPTU lub sondowanie dylatometryczne DMT, może prowadzić do błędnej oceny parametrów mechanicznych gruntów i tym samym oceny warunków geologiczno-inżynierskich w podłożu. Jamiołkowski (2002) podsumował wieloletnie doświadczenia, które prowadzą do wniosku, że w większości przypadków prawidłowa interpretacja wyników sondowania statycznego wymaga uwzględnienia wpływu zarówno składowej poziomej, jak i składowej pionowej stanu naprężenia. W niniejszej publikacji, kontynuując problematykę analizy wpływu stanu naprężenia na wyniki testów CPTU, podjęto próbę oceny wpływu zmiany stanu naprężenia oraz zagęszczenia gruntu na wartości rejestrowanych parametrów testu: oporu stożka – q_c oraz tarcia na pobocznicy – f_s. Opracowane na podstawie badań modelowych formuły opisujące ten wpływ zastosowano następnie do oceny parametrów sondowania przeprowadzonego w podobnych gruntach, występujących w stanie naturalnym. Badania jednoznacznie wykazały, że stan naprężenia ma bardzo istotny wpływ na rejestrowane wartości charakterystyk penetracji CPTU. Spostrzeżenie to dotyczy szczególnie osadów przekonsolidowanych, w których wartość składowej poziomej stanu naprężenia jest wyraźnie większa od wartości wywołanej wskutek swobodnej sedymentacji osadu. W przypadku badań przeprowadzonych w laboratorium zaobserwowano, że interpretacja wyników w oparciu o koncepcję Jamiołkowskiego również nie daje satysfakcjonujących rezultatów. Dodatkowo stwierdzono, że zmian wartości charakterystyk penetracji badań CPTU wykonanych w trakcie eksperymentu nie da się wytłumaczyć jedynie zmianą stopnia zagęszczenia gruntu. W związku z tym w artykule zaproponowano koncepcję naprężeń wirtualnych, uwzględniającą ogólną zmianę stanu zdeponowanego osadu. Zastosowanie naprężenia wirtualnego umożliwiło wspólne rozpatrzenie wyników CPTU,

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uzyskanych w różnych warunkach stanu gruntu. Zgodnie z tą koncepcją, zmiana wartości rejestrowanych charakterystyk penetracji q_c i f_s jest w zaproponowanych modelach jedynie funkcją zmiany wartości naprężenia wirtualnego. Uzyskane modele wykorzystano do wyznaczenia naprężenia wirtualnego osadów o podobnych cechach fizycznych, występującego w stanie naturalnym. Rezultaty tych badań pozwoliły na weryfikację opracowanych modeli. Wnioski otrzymane w wyniku zastosowania modeli potwierdzają wnioski płynące z innych, niezależnych badań tych osadów. Jednocześnie uzupełnienie modeli o wyniki testów przeprowadzonych w terenie pozwala zauważyć dużą zgodność rezultatów in situ, z przewidywaniami opartymi na eksperymencie laboratoryjnym.

Słowa kluczowe: parametry CPTU, naprężenia in-situ

Abstract: The paper presents the methodology and results of the tests carried out in the calibration chamber at the Delft University, the Netherlands. Density of the soil was reconstructed in three phases, using side vibrators. Basing on the obtained results and analyzing the influence of changes of both stress and soil density on the penetration data, a new approach was proposed. The parameter, quantifying the influence, was called "virtual stress – σ'_{virt}".

Key words: CPTU parameters, in-situ stress

Introduction

State of stress in subsoil is one of the crucial factors influencing the interpretation of CPT readings which are used for assessment of in situ strength and deformation parameters. State of stress influence for CPTU or DMT data, if omitted or inadequately taken account of, may significantly impact final assessment of mechanical parameters of subsoil and in result lead to incorrect estimation of geo-engineering soil conditions.

The fact is reflected in the development of methodology of the evaluation of penetration readings taken in non cohesive soil and is especially clearly seen during the estimation of density ratio value. Simple correlations, such as suggested by Kostrzewski (1995) did not account for state of stress influence on q_c value which is a CPTU parameter used for that purpose. However, it was already proved (Młynarek, 1978) that analysis of penetration readings takes a number of soil parameters to be taken into consideration, including state of stress. Such approach was also presented by other researchers (Baldi et al., 1986; Tschuschke, Wierzbicki, 1998) who pointed out that basic features of non-cohesive soil directly influencing registered values of cone resistance and thus vertical stress value. Basing on this assumption the above mentioned authors suggested empirical-analytical solutions enabling assessment of density ratio value with respect to CPTU data. In some cases, especially in heavily overconsolidated sediments, certain divergence were observed between the actual values and estimated from CPTU data. Many authors in the 90's paid more attention to presumably bigger influence of horizontal stress for registered CPTU parameters (e.g. Lunne et al., 1997; Wierzbicki, 2001) noticed that the influence is clear enough to be used for estimation of coefficient of earth pressure at-rest (K_0) from CPTU data. The need of taking into account the entire state of stress, not only the vertical stress, in the analysis of the density ratio was pointed out by Jamiolkowski (2001). The conclusion of the publication, which summarized several years of experience, stated that in order to conduct interpretation of cone penetration testing data both vertical and horizontal stress need to taken into account.

This paper, being a continuation of the question of stress state influence on CPTU data, is a trial of assessment of the influence of stress state changes on each CPTU parameter: cone resistance – q_c and sleeve friction f_s. Equations describing the phenomenon and resulted from laboratory testing were applied to estimation of in situ soil parameters achieved from CPTU tests.

Calibration chamber

The calibration chamber in which the tests were conducted is located at the Technische Universitet in Delft in the Netherlands (Wierzbicki, 2001). It has a shape of cylinder of 190 cm in diameter and 250 cm in height, with incorporated side drainage. Along the outer surface of the chamber there are horizontal vibrators attached in order to heighten both the density and horizontal stress within the sample. The chamber is built so that it enables to conduct both CPTU and DMT tests to the depth of 1.5 m. Due to relatively big diameter, the influence of the so called chamber size effect on the achieved results is significantly diminished.

In course of the tests, the cylinder was successively filled up with fine, uniform-grained sand. From mineralogical point of view, the soil was almost entirely quartz (Broere, van Tol, 1998).

The reconstruction of the soil state consisted of soil liquefaction and compaction with use of side vibrators. After each vibration, water was drained through the drainage system installed at the bottom of the cylinder. The filtration, lasting for nearly 20 hours allowed for achievement of wet soil, of defined density ratio D_R.

During the tests, the following variants were implemented:

- 15 minutes of vibration – mean density ratio $D_R = 0.74$,
- 2 minutes of vibration – mean density ratio $D_R = 0.45$,
- 0 minutes of vibration – mean density ratio $D_R = 0.25$.

For each of the above mentioned, one CPTU and one DMT test were conducted (Fig. 1a). Mean density ration in the calibration chamber was basing on the knowledge of mass density and volume measurements in the chamber. Density ratio was established with use of data regarding maximum and minimum void ratio (Benders, 1999).

Assumption of the model

Using the DMT data and the Schmertmann formula (1983), values of coefficient of earth pressure at-rest of the soil deposited inside the chamber were established. Achieved results (Fig. 1b) show clear growth of horizontal stress value in compari-

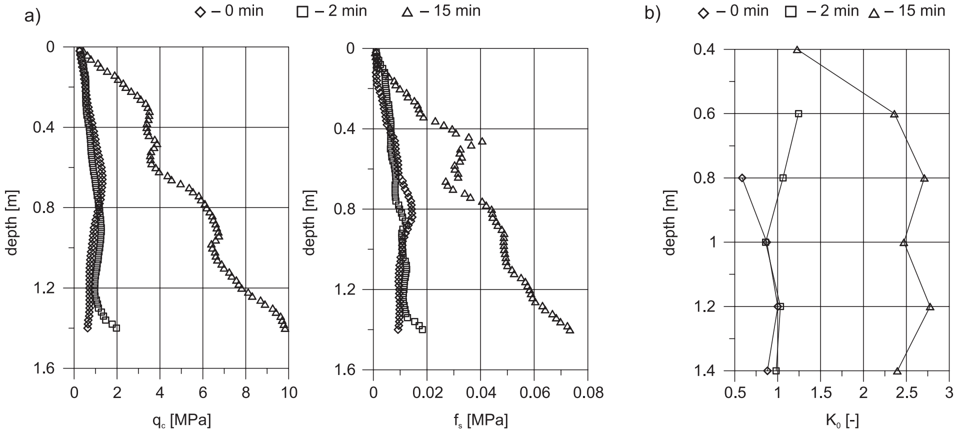

Fig. 1. Calibration chamber tests results of a) q_c and f_s from CPTU and b) K_0 from DMT
Ryc. 1. Wyniki badań w komorze kalibracyjnej: a) wartości q_c i f_s z badania CPTU, b) wartości K_0 z testu DMT

son to the vertical stress, resulting from horizontal compaction. It is interesting to notice that sediments subjected to gravitational sedimentation show higher values of K_0 than the values quoted in literature for normally consolidated sediments. According to authors, the rise of horizontal stress in this case may be a result of the overconsolidation effect following the vertical drainage of water from the calibration chamber, taking place during the preparation of the stand for the tests. Possible influence of both filtration and drying processes on the overconsolidation effect in sediments was also emphasized by e.g. Crawford (1986).

During the CPTU data analysis, results from varying depth of 1.0 to 1.4 m were used assuming that readings from such a range would be the closest to the ones taken in situ (similar distance of the test point from the soil surface in the chamber and its walls). Comparison of the obtained q_c and f_s values shows clear differences between penetrations conducted in different conditions. In order to examine significance of the differences resulting from changes of density and state of stress, expected mean values of cone resistance at a given density ratio were established. The values were calculated with use of Jamiolkowski formula (2001), assuming proportional change of q_c with density ratio, at a given mean state of stress. Achieved results (Fig. 2) prove that the observed differences do not result entirely from changes of density ratio. Clear raise of density after 2 minute long side compaction, somewhat connected with raise of horizontal stress, does not cause simultaneous raise of cone resistance as it may be expected from the Jamiolkowski formula. On the other hand, increase of soil density connected with proportionally bigger increase of horizontal geostatic stress (after 15 minute long vibration) causes that registered cone resistance values are of approximately 60% bigger than the expected ones. Basing on the above mentioned it can be stated that in the analyzed case application of the model taking account for influence of changes of soil state on CPTU results is inadequate.

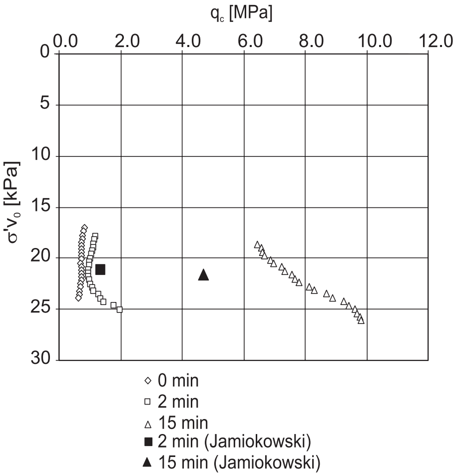

Fig. 2. Measured values of q_c and hypothetical values of q_c calculated from Jamiolkowski formula vs vertical stress

Ryc. 2. Porównanie zmierzonych wartości q_c oraz obliczonych ze wzoru Jamiołkowskiego, w odniesieniu do naprężenia pionowego

Furthermore, a new approach was introduced, taking account on the influence of both changes of stress and soil density on registered values of penetration parameters. The parameter used to establish quantity influence on CPTU parameters was called virtual stress σ'_{virt}. It reflects the effect of the increase of both lateral stress and soil density on the in situ test results. The changes are then converted to hypothetical increase of vertical stress called virtual stress. Therefore, the virtual stress is calculated as vertical stress, the latter resulting from current value of the at-rest coefficient K_0, basing on the theoretical assumption that K_0 value corresponds to normally consolidated state (i.e. during consolidation and densification processes K_0 = const.) In this case the virtual stress value does not reflect then the real value of stress defined from soil mass density but it provides the expected value resulting from the observed in situ soil state.

Estimation of virtual stress in the calibration chamber was conducted with use of at-rest pressure parameter K_0 assuming that the initial point of any changes is the density of sediments resulting from gravitational sedimentation and water drainage. On this base, the virtual stress was calculated for 2 and 15 minute long vibration. Obtained results were then compared to registered cone resistance and sleeve friction values registered during penetration tests in the specimen (Fig. 3). As a benchmark, the figure presents also the penetration results compared to classical values of vertical stress. Having defined a linear line of trend it was noticed that the CPTU results for three different soil states can be comprised by one equation. Moreover, the coefficient of regression R^2 of both CPTU parameters is very high (0.99). At the same time it is quite clear that in classical approach to state of stress it is remarkably difficult to find a link between the three results of CPTU test.

From the above presented analysis it can be then assumed that in this experiment the influence of changes of non-cohesive soil state on penetration parameters may be described by the following equations (1) and (2).

$$q_c = (\sigma'_{virt} - 16.221)/\ 5.6443 \tag{1}$$

$$f_s = (\sigma'_{virt} - 12.916)/\ 781.72 \tag{2}$$

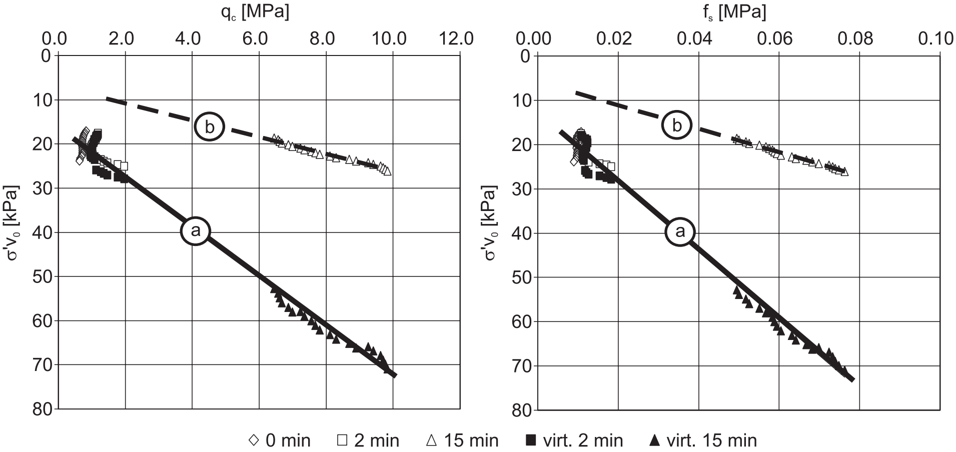

Fig. 3. Comparison between trend lines in view of virtual stress (a) and vertical stress (b) for q_c and f_s

Ryc. 3. Porównanie przebiegu linii trendu parametrów q_c i f_s w odniesieniu do (a) naprężenia wirtualnego i (b) naprężenia pionowego

Verification of the model

In order to examine possible applications of the models, obtained formulas were used to assessment of virtual stress increase with use of penetration data derived from in situ tests. Knowing that results may be affected by other than the above reported parameters (grain size distribution, mineralogy, angularity), only sediments resembling those from the laboratory were selected for further analysis.

1. Test site

All the field tests were carried out in the closet neighbourhood of Pliszka outwash plane, located in the village of Toporów near Łagów Lubuski (Wierzbicki, 2001). The subsoil in that area to the depth of 20 m is built from two non-cohesive series divided by cohesive sediments of marginal lake. As far as grain size distribution and mineralogy are concerned, sediments of the lower non-cohesive series strongly resemble the soil used in the laboratory (Wierzbicki, 2001). Their density ratio is close to the achieved in course of 15 minute long vibration (D_R = 0.68–0.80). On the site, both CPTU and DMT were executed. Considering the physical properties resemblance, the following analysis was based only on data acquired in the lower non-cohesive sediments.

2. Test results and the analysis

Using the registered cone resistance and sleeve friction values as well as the suggested approach (equations 1 and 2), hypothetical values of vertical stress (virtual stress) in the described layer were estimated (Fig. 4a). In this case, calculated valu-

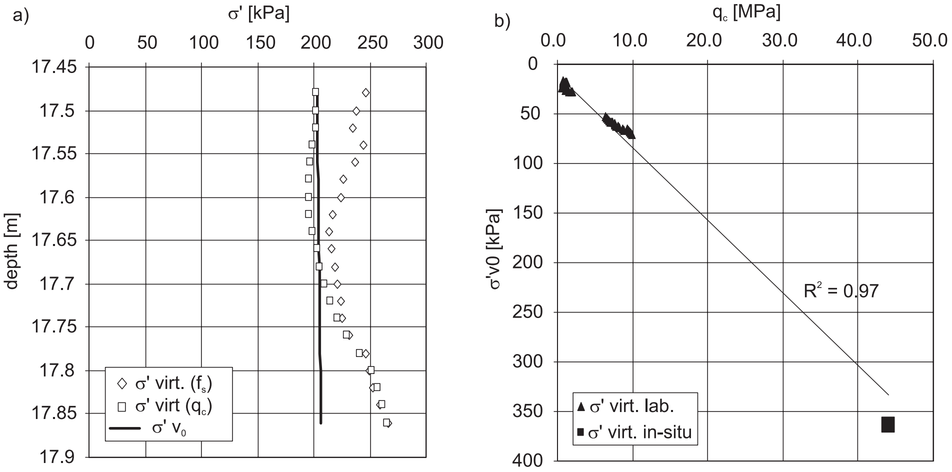

Fig. 4. a) Virtual stress calculated from eq. (1) and (2) in view of in situ effective vertical stress, b) Comparison of in-situ and calibration chamber q_c values calculated from eq. (1)
Ryc. 4. a) Naprężenie wirtualne obliczone ze wzorów (1) i (2) w odniesieniu do efektywnego naprężenia pionowego in situ, b) Porównanie wartości q_c – in situ i z komory kalibracyjnej – obliczonych ze wzoru (1)

es of virtual stress are higher then the vertical stress estimated only from overburden soil mass density. Such situation allows then assumption that the layer can be referred to as overconsolidated (regardless the cause of the effect). The conclusion is confirmed also by result of other CPTU and DMT tests conducted in that layer (Wierzbicki, 2002). Regardless the CPTU results, the DMT data was used to estimate expected mean virtual stress for the layer. Its value was compared to registered cone resistance values within the layer. The comparison of both in situ and laboratory q_c values together with calculated virtual stress proves the capability of the proposed approach for prediction of in situ values (Fig. 4b). Even though the predicted values are lower the ones calculated from DMT data, they still lead to similar conclusions on history of stress changes within the subsoil.

Summary and conclusion

Conducted tests unambiguously proved that the state of stress has a crucial influence on registered penetration values. It especially applies to overconsolidated sediments in which lateral stress in significantly higher then the value resulting from gravitational sedimentation of soil.

In the case of the laboratory tests, the interpretation based on the Jamiolkowski's equation does not provide satisfying results either. Moreover, it was found that the change of penetration values during the test cannot be explained only by change of soil density ratio. Due to these, the paper suggests the approach called the virtual stress method taking account on general change of soil state. Its application enabled common verification of CPTU data obtained at different density ratio.

According to the approach, change of the registered q_c and f_s values in the presented equations is just a function of virtual stress change.

The obtained models were furthermore used to define virtual stress of sediments of similar physical properties found in situ. Results of the field tests allowed to verify the proposed approach. Conclusion coming from its application were confirmed by other independent tests executed in those sediments. Adding the field and the laboratory results allows to notice a significant correlation between the in situ and the predicted from lab data results.

Due to some general constraints, the analysis did not comprise influence of some other soil parameters on penetration data. Their change (e.g. grain size distribution) certainly affects the final version of the model correlations. According to authors, the best and universal model would not be a simple linear one but the one based on a complex function. In the described experiment, the assumed linear approach was the best one only within the analyzed stress range. It was also noticed that for smaller stress values a logarithmic model would be more proper (its boundary conditions are the closest to natural ones) whereas for higher stress an exponential model (however only in certain range). Development of these conclusions takes though further tests, much wider then the presented in this paper.

This paper is supported by the founds intended for science in years 2005–2007 as research project No. 0562/P04/2005/29.

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