Technical Note

Pore Water Pressure Development in Soft Soil due to Installation and Loading of Controlled Modulus Columns

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Abstract: Excess pore water pressure (EPWP) development and decay due to the installation and static loading tests of controlled modulus columns (CMC) in soft soil was measured with piezometers equipped with low air entry (LAE) filters and a piezocone (CPTU) equipped with a high air entry (HAE) filter. The HAE filter allows for detailed detection of EPWP in short time intervals during construction of CMC. The influence zone due to the installation of the CMC group extends up to 40D (D = column diameter) with significant installation effects and high EPWP within the zone of 7D. The influence zone during the static loading test is much narrower and does not exceed 2D. The presented research shows the applicability of using a CPTU in EPWP monitoring during CMC construction and clarifies some effects of CMC group installation. **DOI: 10.1061/(ASCE)GT.1943-5606.0002675.**

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Introduction

Development of excess pore water pressure (EPWP) plays a significant role in geotechnical design in soft cohesive soils (e.g., Croney and Coleman 1961; Dunlap et al. 1978; Hiff 1956; Hunt 2005; Strout and Tjelta 2005) and piles in particular (e.g., Li 2019; Liu et al. 2012; Pestana et al. 2002; Tang et al. 2003; Xu et al. 2006). The mobilization of EPWP due to the installation of displacement piles can impact the stability of neighboring structures, as it changes the effective stress in the surrounding soil. Proper monitoring and control of EPWP can prevent excessive soil deformations and ground heave, impair slope stability, and prevent displacements of nearby foundations and structures in soft clays (Tefera et al. 2013).

The most important mobilization of EPWP can be expected for driven piles due to the induced large soil displacement and high number of impacts applied during their installation (Eigenbrod and Issigonis 1996; Ng et al. 2013; Pestana et al. 2002; Randolph et al. 1979). It can be also important in the case of jacked piles (Gavin et al. 2010; Rahardjio 2017) and screw auger piles (Larisch 2014; Prezzi and Basu 2005). Significant mobilization of EPWP can be also related with the installation of stone columns in soft clays (Castro and Sagaseta 2012; McCabe et al. 2009). Examples of key EPWP measurements are described below. Xu et al. (2006) analyzed water pressure mobilized due to the installation of open pipe piles. They found that EPWP is lower in slightly overconsolidated clay than in preconsolidated clay. Simonsen and Sørensen (2016) recorded pore water pressure changes in very high plasticity stiff clays adjacent to a large group of driven steel H piles. In heavily overconsolidated clays, they reported the extent zone of EPWP up to 100 pile radii and dissipation time larger than 200 days. Rahardjio (2017) observed high EPWP even 5 months from the installation of large group of jacked piles. Lande et al. (2020) reported approximately 8 kPa EPWP remaining in soft clay 150 days after anchor drilling with uncased system was completed. In order to control the pile driving process, Tefera et al. (2013) installed the piezometers in the area of potential failure plains. Moreover, the driven piles were equipped with vertical drains to mitigate the mobilization of pore water pressure.

The objective of this paper is to analyze EPWP mobilization due to the installation of controlled modulus columns (CMCs). These are concrete columns formed in the soil with a displacement screw auger. This technology is commonly used for soil improvement in geotechnical engineering involving soft soils (e.g., ASIRI 2012; Basu et al. 2010; Brown 2005; Prezzi and Basu 2005). CMCs are used in commercial building foundations as well as in large infrastructure projects (e.g., Pearlman and Porbaha 2006; Wong and Muttuvel 2013). Full displacement screw augers induce large displacements and modify stress states in the surrounding soil (Larisch et al. 2014; Pfeiffer and Van Impe 1993; Slatter 2000; Suleiman et al. 2015); however, these installation effects are outside the scope of this paper.

A very limited amount of research has been undertaken to assess the installation effects related to the monitoring of pore water pressure due to CMC column construction and loading. Larisch (2014) performed a comprehensive set of measurements concerning the development of pore water pressure in surrounding soils due to three different types of screw auger installation. In order to take the measurements in close vicinity of the drilling rig at different stages of a screw auger installation, raked piezocone (CPTU) tests were performed. The pore water pressure was recorded at the CPTU tip at u_1 position. Larisch (2014) presented the mobilization of pore water pressure at a distance of 225 mm, equivalent to half of the pile diameter, from the pile shaft during the auger penetration phase, concrete pumping, and auger extraction. Measurements were taken every 5 s and recorded manually. A decline in pore water pressure was observed when the auger tip reaches the level of CPTU tip position. The study, however, was limited to stiff, fine-grained soils.

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Suleiman et al. (2015) performed comprehensive series of measurements of horizontal stress changes, pore water pressure, and lateral displacement during the construction of CMC columns and static vertical loading tests. They used push-in pressure sensors fitted with a piezometer, allowing for measuring total horizontal stresses and pore water pressure in the soil and shape acceleration arrays to monitor the evolution of soil lateral displacements. These measurements were recorded at different distances from the pile shaft in very soft sandy silt or silty clay. They observed a maximal increase in both lateral stress and pore water pressure when the mandrel passes the sensor level. Meng et al. (2015) recorded lateral soil displacements using inclinometers and pore water pressure in piezometers due to screw pile installation and during subsequent consolidation period in soft clay in Shanghai. The readings were undertaken at four different levels and at varying distances from the pile shaft. They concluded that the area of disturbance due to the installation of a screw piles is mainly concentrated within a circular region of six pile diameters. The pore water pressure distribution near the pile shaft was registered for all phases of pile construction, concreting, and auger withdrawal. The maximum EPWP was recorded at the end of penetration or at the phase of pile concreting. Moreover, they monitored pore water pressure decay in the following 15 days from installation. After that period, the EPWP was practically dissipated.

This paper addresses EPWP changes in soft soil surrounding the CMC group during all phases of its construction and during static loading tests. The decay of EPWP mobilized due to CMC group construction is analyzed. Moreover, the pore water pressure buildup and dissipation were also measured in the soft soil near the base of the floating column subjected to the static loading test. The measurements were performed using two types of piezometers with different response times to record short- and long-term changes in pore water pressure evolution. To the best of authors' knowledge, such research—concerning both installation phase and static load test—was performed only by Suleiman et al. (2015) with pore water pressure registered only near the shaft of a single CMC column at small depths. The aim of this paper therefore is to present: (1) short-term and long-term changes in EPWP during CMC column construction and loading; (2) assessment of the zone that is influenced by CMC installation and static loading; and (3) assessment of the time necessary to dissipate EPWP after installation of the CMC group. The reported data can shed more light on the installation effects induced by CMC columns and the interpretation of static loading of such columns in pullout and compression tests. Other practical aspects of this study are related to the dissipation time of EPWP and its impact on the schedule of static loading tests and the setup effect related to the installation of CMC columns in soft cohesive soils.

The Vistula Marshlands Testing Site

Geotechnical Characterization at the Site

The Vistula marshlands is a 1,700 km^2 plain area located in northern Poland (Fig. 1). The plain started to be formed 6,000 years BP by the alluvial mud brought by the Vistula River. The Vistula marshlands consist of three geological faces: (1) riverbed (sands and occasionally gravels), (2) marsh-swamp-lake (clays, loams, muds and peats), and (3) flood (muds) (Augustowski 1976). A part of the S7 highway that connects Gdańsk and Elbląg was constructed with soil reinforced with CMC columns. The CMC columns considered in this paper were installed at two additional testing fields, near the highway embankment to be constructed. The soil profile with ground water conditions is shown in Fig. 2(a). At the site, two soft soil deposits can be distinguished. The first soft soil layer, spread between 0.7 and 4.05 m below the working platform level, is comprised of loam, clayey mud (organic clay), and peat. The second

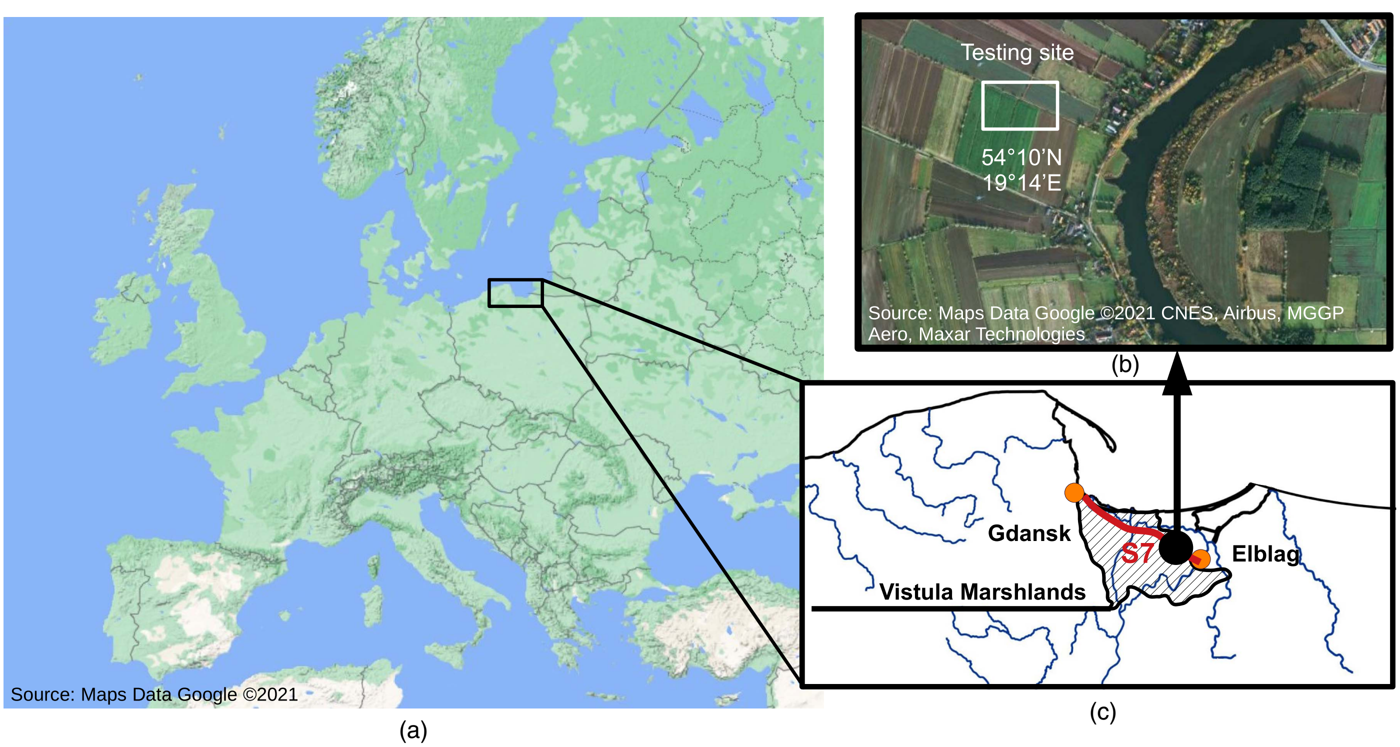

Fig. 1. Jazowa testing site location. [(a) Source: Maps Data Google ©2021; (b) Source: Maps Data Google ©2021 CNES, Airbus, MGGP Aero, Maxar Technologies; and (c) map by authors.]

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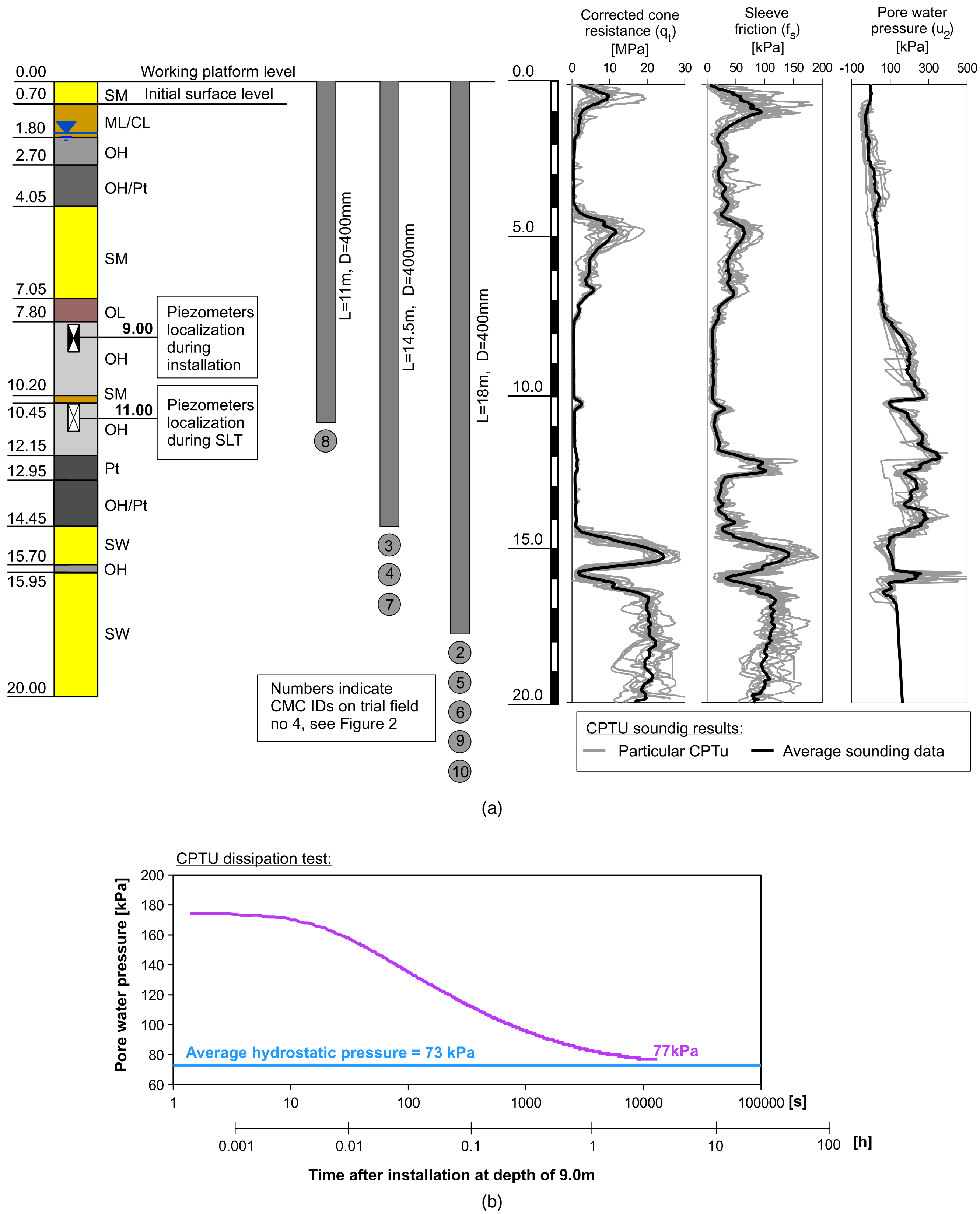


Fig. 2. (a) Soil profile with CPTU sounding results, piezometer localization, and CMC column lengths; and (b) CPTU dissipation test.

soft soil deposit, between 7.05 and 14.45 m, consists of organic silt (silty mud), peats, and a mixture of both. The soft soil deposits are separated by a 3-m-thick layer of loose to medium dense sand. Below 14.45 m, a dense Pleistocene sand layer was found. The highest water table level was recorded in the summer period at a depth of 1.7 m below the working platform. However, seasonal variations of the water table level can reach 1.5 m (see Table 1), with the lowest readings observed in winter (about 3.2 m below the working platform level). A detailed description of the soil investigation and geotechnical parameters is given in Konkol et al. (2019).

Table 1. Water table changes at the testing site

Month, year	Position below working platform level (m)	Method
December 2013	3.3	Boring
January 2016	3.1	Boring
September 2016	1.7	CPTU
November 2016	2.7	CPTU
December 2016	3.2	CPTU
June 2017	1.7	CPTU
August 2017	1.7	CPTU
August 2017	1.7	Piezometer
September 2017	2.4	CPTU

Note: Boring = measured using a tape measure with a bell-shaped cylindrical plopper; and CPTU = water table estimated with PWP measurement in sand layers.

Table 2. Organic silt geotechnical parameters

Property	Value	Units
G_s	2.54–2.59	—
w_0	45.4–49.8	%
γ_0	15.9–16.9	kN/m^3
γ_d	11.0–11.5	kN/m^3
PL	28.3–33.8	%
LL	55.8–60.4	%
SL	25.7–28.0	%
PI	27.5–31.7	%
LOI	4.5–7.1	%
pH	7.0–7.9	—
C_c	0.4026–0.4654	—
C_s	0.0178–0.0252	—
c_v (for in-situ stress)	0.34–0.54	m^2/year
c_h (for in-situ stress)	1.01–1.15	m^2/year
OCR	1–1.47	—
p'_c	112.7–126.5	kPa
c_u	24.2–42.7	kPa
ϕ'	31.0	°
k_v (for in-situ stress)	1.8×10^{-8}	m/s
k_h (for in-situ stress)	4.2×10^{-8}	m/s

Note: G_s = specific gravity; w_0 = water content; γ_0 = unit weight; γ_d = dry unit weight; PL = plastic limit; LL = liquid limit; SL = shrinkage limit; PI = plasticity index; LOI = loss of ignition; C_c = compression index; C_s = swelling index; c_v = consolidation coefficient (vertical); c_h = consolidation coefficient (horizontal); OCR = overconsolidation ratio; p'_c = preconsolidation pressure; c_u = undrained shear strength; ϕ' = effective angle of internal friction; k_v = vertical permeability coefficient; and k_h = horizontal permeability coefficient.

An extensive series of CPTU [Fig. 2(a)] and dilatometer tests (Bałachowski et al. 2018) has shown that the soft soil layer from 7.05 to 12.25 m is quite homogeneous and normally consolidated, with undrained shear strength increasing linearly with depth. It is formed from organic silts with the parameters summarized in Table 2. During piezocone penetration, a considerable excess pore water pressure is generated in soft clays, and the corresponding dissipation curve at 9 m of penetration is given in Fig. 2(b). Monotonic decay—typical for normally consolidated soils—with $t_{50} = 110$ s was observed. Pore water pressure changes during CMC column installation and static loading were recorded in this layer.

CMCs

CMC columns with different lengths were constructed at the testing field. The distribution and lengths of the columns on the testing field fit the program of static loading tests. Column 8 at Trial Field 4 was designed to be a floating type, 11 m long and subjected to pullout static loading followed by compression test. Columns 3, 4, and 7, resting on the bearing layer of compacted sand, were 14.5 m long and designed for further proof testing. The other columns, embedded in the bearing strata, were 18.0 m long and designed as an anchorage system. The construction sequences of the columns at Trial Fields 4 and 5 are given in Fig. 3.

Instrumentation

There are two types of piezometers used at the testing site (Fig. 3). The piezometers, denoted P-1 and P-2 [Fig. 4(a)], are drive-point piezometers equipped with vibrating wire pressure transducers. These piezometers are fitted with a low air entry (LAE) filter; they are capable of long-term measurements and well suited to soft clays (Simonsen and Sørensen 2018). According to the manufacturer, they were pushed into soft soil from the bottom of the drilling in the working platform to avoid transducer damage. These piezometers were used during all stages of CMC installation. The P-CPTU piezometer [Fig. 4(b)] is a standard 10-cm^2 electric piezocone with pore water pressure filter at u_2 position, which allows to record very rapid changes in EPWP due to the high air entry (HAE) filter (Simonsen and Sørensen 2018). Thus, this piezocone with data registered every 1 s can provide measurement of highly variable water pressure for short time periods.

Piezometers P-1 and P-2 were pushed into the soil at a rate of 2 cm/s and installed at distances of 0.6 m and 0.9 m from the axis of CMC 8 (see Fig. 3). The piezocone (P-CPTU) was installed at a distance of 1.2 m from the axis of CMC 8 (see Fig. 3). All piezometers were inserted at the depth of 9.0 m. As one can see in Fig. 5, the classic piezometers (P-1 and P-2) are less sensitive due to their LAE filters and have shown only slight EPWP generation during their installation. Piezometer measurements tend towards an average hydrostatic pressure of 73 kPa. The final readings of P-1 and P-2 piezometers included also an increase of pore water pressure due to the weight of the drilling rig on the working platform at the beginning of CMC column construction [Fig. 6(a)].

Excess Pore Water Pressure Measurements

Testing Program

The testing program, summarized in Table 3, consisted of several steps. First, two piezometers (P-1 and P-2) were installed 4 days before column drilling. The piezocone (P-CPTU) was installed 1 day before column installation. In the second step, 2 days long, the CMC columns were constructed. In the first day of construction, 10 CMCs were drilled in Trial Fields 4 and 5 CMCs were constructed at Trial Field 5. The next day, eight CMCs were drilled in Trial Field 5. The postinstallation measurements were conducted for 16 days until the full dissipation of the EPWP. Next, the piezometers (P-1 and P-2) were pushed further to the depth of 11 m, 4 days before the static loading test (SLT). The test took 22 h to complete, then the postloading decay of the EPWP was measured during 5 days.

Controlled Modulus Columns Installation

The measurements taken were focused on accumulated EPWP generated during construction of CMC group and short-term changes during single column installation. The EPWPs recorded with P-CPTU during the construction of CMC columns are given in Fig. 7. The installation process of CMC consists of auger drilling and concreting with simultaneous auger retrieve. However, during

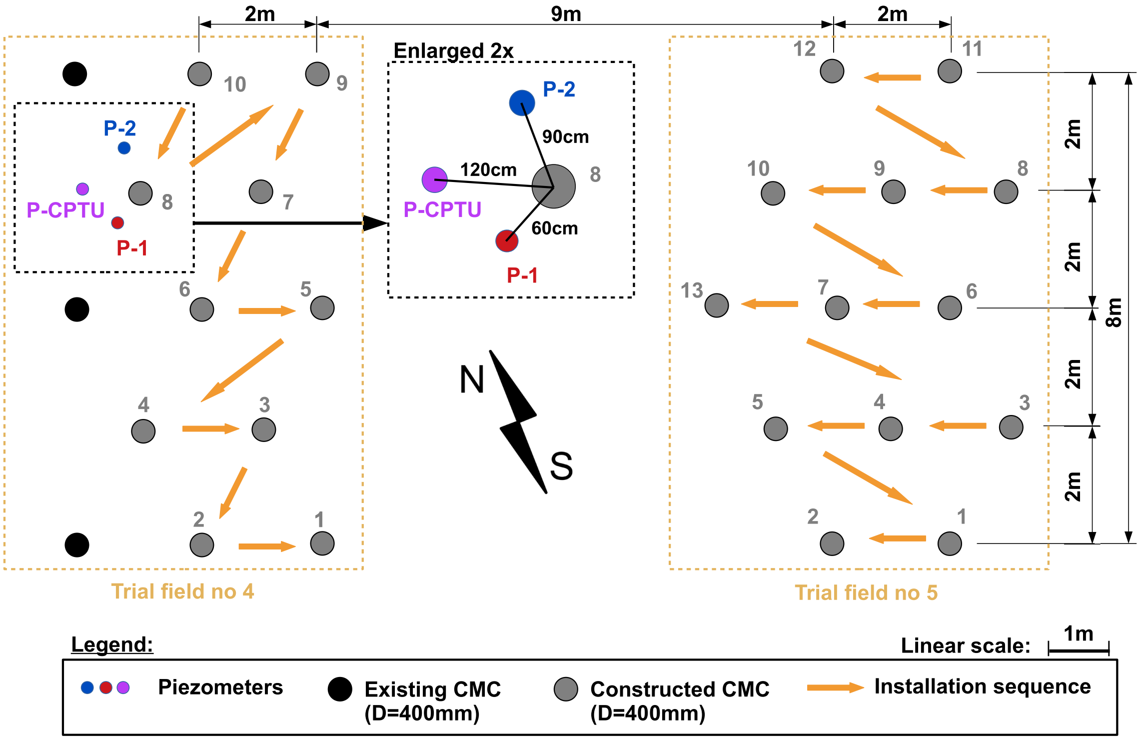


Fig. 3. Piezometers localization (9.0 m depth) in the testing site and CMC construction sequence.

(a) (b)

Fig. 4. (a) Drive-point piezometers; and (b) electric piezocone.

this process some troublesome events may occur, such as drilling pauses, problems with concrete supply, plugging of drilling auger, etc. For longer columns, the operator has to stop the drilling process to mount a special extension to the auger. As a consequence, each column has a unique construction history saved in its log. Examples of EPWP changes for three selected columns, during CMC group construction, are presented in Fig. 7. The generated EPWP is set up with a pile log and the characteristic points of CMC construction are shown. Generally speaking, the pore water pressure decreases rapidly when the auger approaches the piezocone depth, but accumulated EPWP never drops below zero (see Fig. 8). Positive buildup pressure is recorded when the auger position exceeds the level of piezometers. The other events, such as a pause in drilling or concreting, can induce additional changes, unique for each column. Finally, a slight dissipation in the mobilized pore water pressure is observed when the drilling rig moves to the next CMC location.

Fig. 8 shows the accumulated EPWP generation due to the construction of 10 CMCs in the Trial Field 4. The changes in accumulated EPWP are visible for each CMC installation, which is clearly seen in all piezometer readings. Buildup pressure response is higher in the P-1 piezometer, the closest to Column 8. One can observe (Fig. 8) that P-CPTU captures the instantaneous PWP changes during installation. The installation of the 10 CMCs at Trial Field 4 increased the accumulated EPWP close to 100 kPa. Almost the full

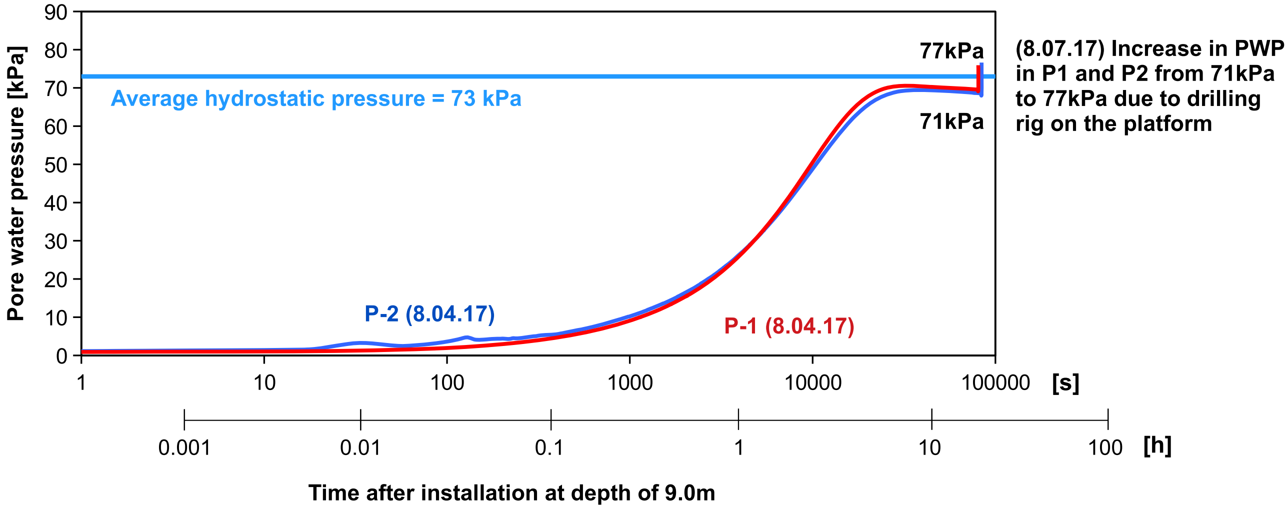


Fig. 5. PWP measurement during drive-point piezometer installation.

Fig. 6. (a) Drilling rig movement on working platform just before CMC construction (image by Lech Bałachowski); and (b) CMC auger (rendering by Jakub Konkol).

accumulated EPWP is reached during the construction of the first six columns (10, 8, 9, 7, 6, 5) nearest the piezometers. The construction of the remaining columns at Trial Field 4 contributes less to pore water pressure buildup. The rate of the PWP increase due to the installation of columns 3, 2, and 1 is lower than the dissipation rate of the accumulated EPWP at the measurement points.

Postinstallation Measurements

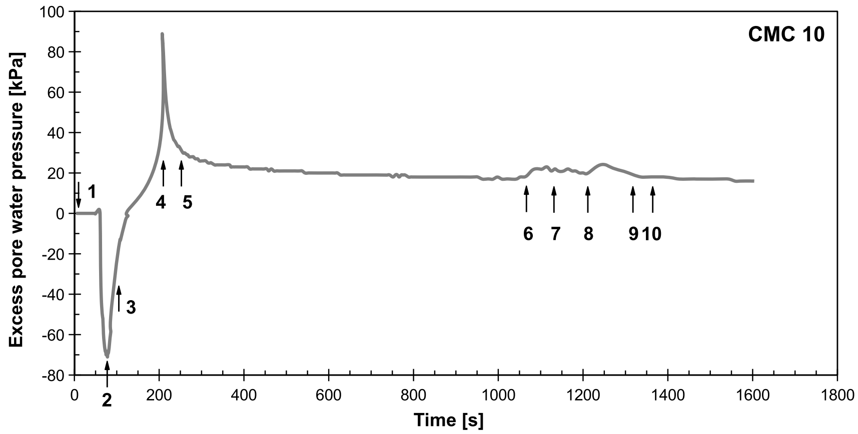
After the CMC installation in Trial Field 4, the drilling rig was moved to Trial Field 5, where five columns were drilled on the same day. The remaining columns in Trial Field 5 were constructed the next day. Fig. 9 shows the decay of accumulated EPWP after the construction of the CMC in Trial Field 4. The construction of five CMCs on Trial Field 5 has no visible impact on the accumulated EPWP. However, construction of the remaining eight CMCs the next day slightly increases the piezometer readings. The buildup pressure fully dissipated approximately 14 days after installation of the last CMC on the Trial Field 4.

SLT

Five days before the SLT, piezometers P-1 and P-2 were pushed further to 11 m depth to measure the EPWP to be mobilized in the neighborhood of the CMC base. The SLT was conducted according to method B (maintained load test) in ASTM D1143 (ASTM 2020). However, some minor modifications were applied, which are allowed according to ASTM D1143. First, the SLT consists of a pull-out and compression part (see Table 4). Second, the load increment at the displacement of the column head of 3%D in compression

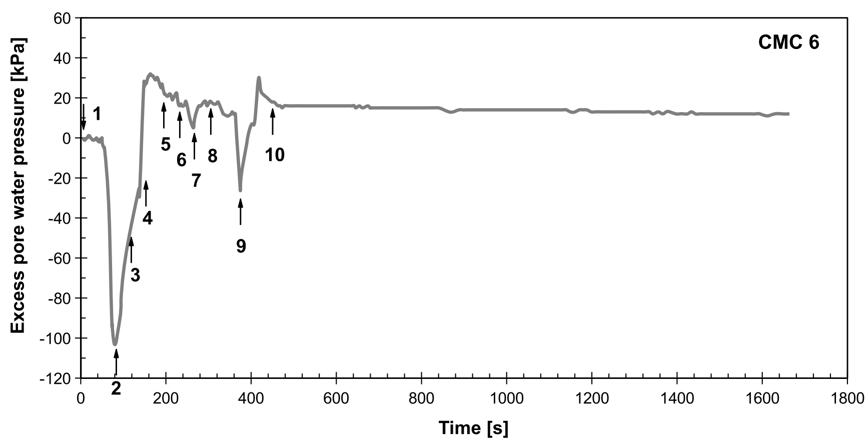
Table 3. Test schedule for pore water pressure measurement

Phase No.	Description	Start date	End date	Notes
1	Piezometers installation	August 4, 2017	August 7, 2017	Depth of 9.0 m
2	CMC drilling	August 8, 2017	August 9, 2017	August 8, 2017–trial field no 4 and August 9, 2017–trial field no 5
3	Postinstallation measurements	August 8, 2017	August 24, 2017	Dissipation of EPWP
4	Piezometer insertion to larger depth	September 7, 2017	September 7, 2017	Insertion to the depth of 11 m
5	SLT	September 11, 2017	September 12, 2017	Static loading on Column 8 in tension and compression
6	Post-SLT measurements	September 12, 2017	September 19, 2017	Dissipation of EPWP



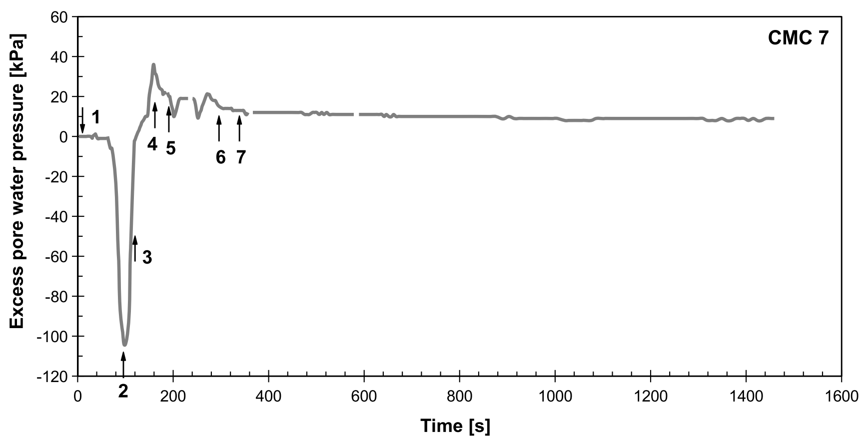
Installation history for CMC no 10

No	Events/Notes
1	Drilling starts
2	Auger at the depth of 9.0m
3	Auger at the depth of 12.5m - pause
4	Drilling continues
5	Auger at the depth of 14.5m - pause
6	Drilling continues
7	Auger at the depth of 18.0m - pause
8	Concreting starts - auger retrieves
9	Auger at the depth of 9.0m - passes sensors depth
10	End of installation, drilling rig moves to next column



Installation history for CMC no 6

No	Events/Notes
1	Drilling starts
2	Auger at the depth of 9.0m
3	Auger at the depth of 11.5m - pause
4	Drilling continues
5	Auger at the depth of 17.4m - pause
6	Concreting starts - auger retrieves
7	Starts 50s pause during concreting
8	Auger at the depth of 9.0m – passes sensor depth
9	10s pause during concreting
10	End of installation - drilling rig moves to next column



Installation history for CMC no 7

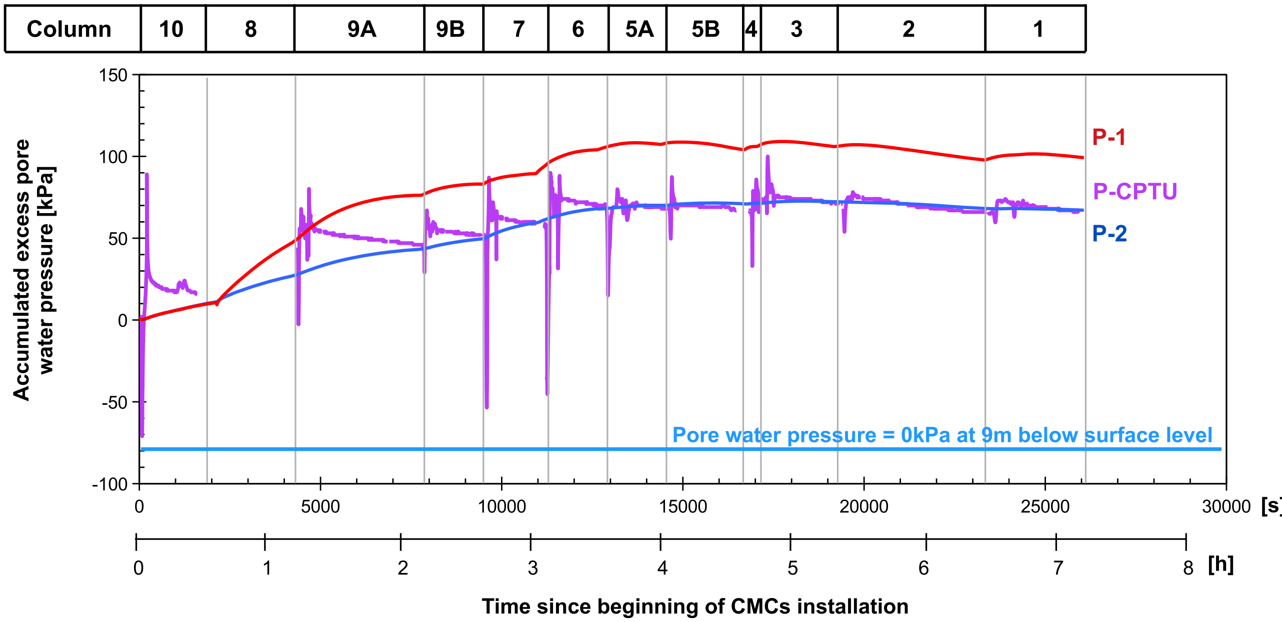
No	Events/Notes
1	Drilling starts
2	Auger at the depth of 9.0m
3	Auger at the depth of 13.0m - pause
4	Drilling continues to 14.0m
5	Concreating starts - auger retrieves
6	Auger at the depth of 9.0m – passes sensor depth
7	End of installation - drilling rig moves to next column

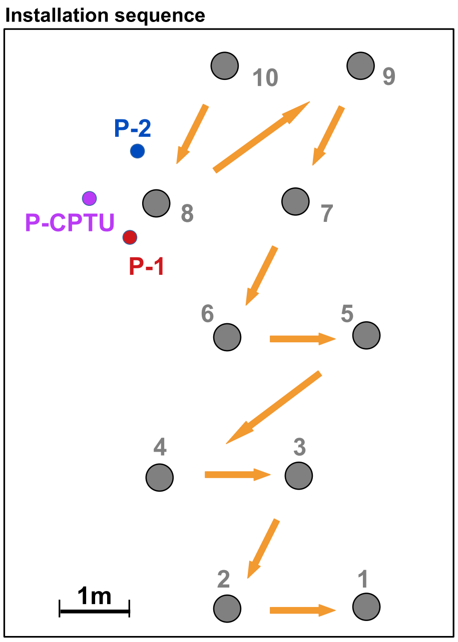
Fig. 7. EPWP development for selected columns (no. 10, 6, and 7) with installation history during CMC group construction.

load was kept for 8 h instead of the maximum value of 2 h according to ASTM D1143. The third modification concerned the time increments during unloading. They were limited to 10–15 min. The aim of these modifications is to capture crucial parts of EPWP generation at the level of pile design load. The SLT program and conducted test is detailed in Table 4 and consists of the following steps:

1. The EPWP during pullout test is investigated. The total column head displacement is assumed to be 12 mm, which is 3%D (D = column diameter).
2. The column is unloaded.
3. The technical break for rearrangement of the SLT set to the compression load.
4. The column is tested in compression to the head displacement equal to 3%D.
5. EPWP development (or dissipation) during column design load is kept constant.
6. The column is subjected to compression to the ultimate load.
7. The column is unloaded. The total time of SLT is chosen to follow EPWP changes with piezometers equipped with LAE filters.

The development of the EPWP in each phase is presented in Fig. 10. As one can see, no EPWP is generated during the pullout test. This suggests no suction developed under the base of the floating column during the pullout test, with all load transferred only by





Installation history on trial field no 4

Column	Note
10	Installation sequence begins
8	Signal lost in CPTU measurements
9A	Malfunction during concreting
9B	Redrilling of column 9
7	N/A
6	N/A
5A	Enforce pause during concreating
5B	Redrilling of column 5
4	N/A
3	N/A
2	N/A
1	N/A

Fig. 8. Accumulated EPWP due to CMC pile installation.

the column shaft. During unloading and the following pause (steps 2 and 3), only a small positive EPWP is generated due to the shear stress level increase and soil movements near the column base. This process is continued during the first part of the compression test (step 4), where the column design load is achieved. During the equalization step, the EPWP slightly increases and then starts to dissipate. In further compression (step 6), a rapid increase in EPWP is observed. When the ultimate load is reached, the column is unloaded (step 7). It is interesting to note that the EPWP still increases in this phase, which could be related to the residual compressive load at the column base.

Significant EPWP changes are observed only for the P-1 piezometer. The response of the P-2 sensor is very small and does not exceed 2 kPa. This observation suggests that the water pressure buildup in soft soils during SLT is very local, constrained within the column base vicinity and is practically negligible at 0.9 m from the column axis (0.7 m from the shaft). This is contrary to the observations in the CMC installation phase, where very significant EPWP was recorded in both sensors even at longer distance from the drilled columns. This quite different response of the piezometers could be related to the rate of displacement imposed, which was an order of 2 m/min for column drilling and approximately 0.04 mm/min in SLT in the first stages of the loading test.

Postloading Measurements

Postloading measurements were conducted for 7 days after SLT. As one can see in Fig. 11, the EPWP almost totally dissipated within 96 h (4 days) after SLT. The small variation between the 4th and 7th day was induced by heavy rains. Then, the field measurement of EPWP was completed.

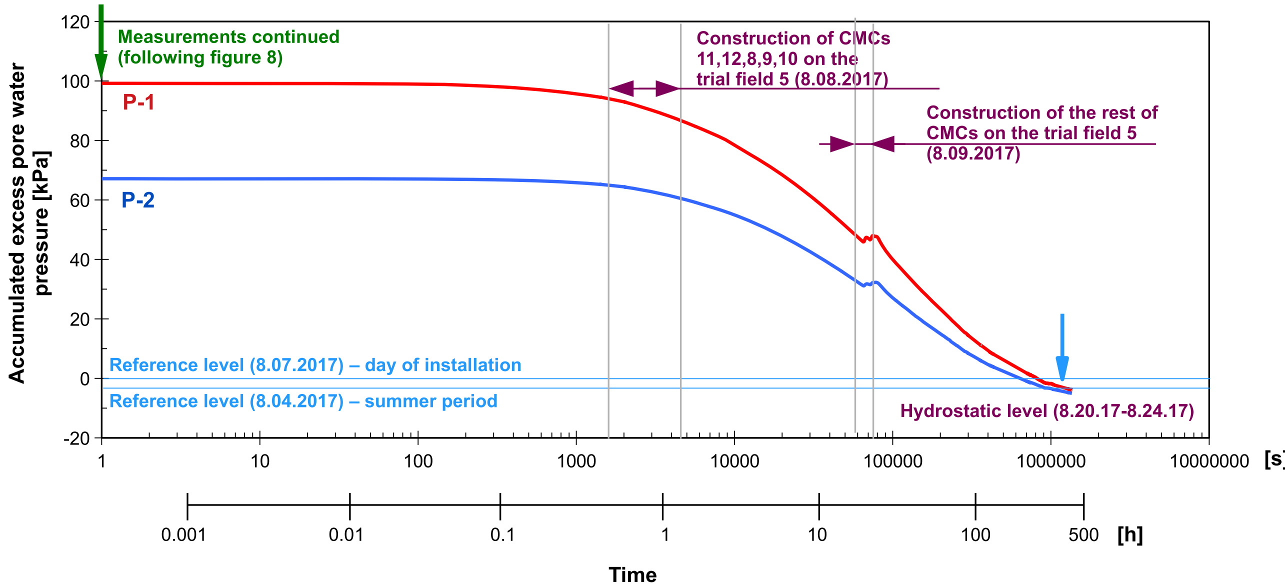


Fig. 9. Decay of accumulated EPWP.

Table 4. SLT program and execution

Phase no	Name	Program description	Aims	SLT execution	Notes
1	Pullout test	Pullout test to the column head displacement of 3%D = 12 mm (minimum time 3 h)	Measure the EPWP during pullout test	Pullout test to the column head displacement 12.83 mm with 600 kN (time 3 h 20 min) in 12 steps	Maintain each load increment until stabilization (0.25 mm/h) but no less than 15 min
2	Unload	Unloading	N/A	Unloading in three steps (total time = 30 min)	N/A
3	Pause	Pause of maximum 2 h	Technical break	Pause of 2 h 10 min	N/A
4	Compression test	Compression test to the column head displacement of 3%D = 12 mm (minimum time 3 h)	Measure the EPWP generation due to compression test	Compression test to the column head displacement 10.09 mm (time 3 h 55 min)	Maintain each load increment until stabilization (0.25 mm/h) but no less than 15 min
5	Pause	Pause of minimum 8 h	Check the EPWP development	Pause of 8 h 25 min	N/A
6	Compression test	Compression test to the 10%D = 40 mm	Measure the EPWP until the limit load is reached	Compression test to the 40.36 mm at 784.4 kN	Maintain each load increment until stabilization (0.25 mm/h) but no less than 15 min
7	Unload	Unloading	N/A	Unloading in 4 steps (total time 1 h 5 min)	N/A

Discussion and Interpretation of the Data

EPWP Generated during CMC Installation

A continuous increase of EPWP during CMC installation was recorded by piezometers P-1 and P-2. The application of a piezocone as a piezometer allows to describe the instantaneous EPWP changes during auger drilling. The instantaneous EPWP drops significantly just before the auger reaches the sensor level. In case of Column 10, the pore water pressure decreases almost to zero (see Fig. 7). A similar drop in pore water pressure was also observed by Larisch (2014) for full displacement screw augers in stiff overconsolidated clays. The EPWP increased to reach the maximum value almost at the final depth of drilling, which can be related to the stress level increase within the soil mass in the vicinity of the sensor. A small decrease in EPWP was observed during concreting and auger retrieving. Contrary to the observations of Suleiman et al. (2015), no EPWP increase was recorded during mandrel retrieving. This research shows the advantage of using the piezocone (and more generally, piezometers equipped with HAE filters) to measure the rapid changes of EPWP during drilling together with the driven-point piezometers to record long-term evolution of EPWP. The measurements by Suleiman et al. (2015) and Meng et al. (2015) are not able to catch these sharp changes of EPWP.

The mobilization of EPWP during column installation is very complex. It could be described in the auger tip vicinity as a superposition of two phenomena: continuous pore water pressure increase due to auger penetration, which can be modeled with cavity expansion, and pore water pressure changes due to auger rotation. The effect of rotation will be different in the lower and upper part of the

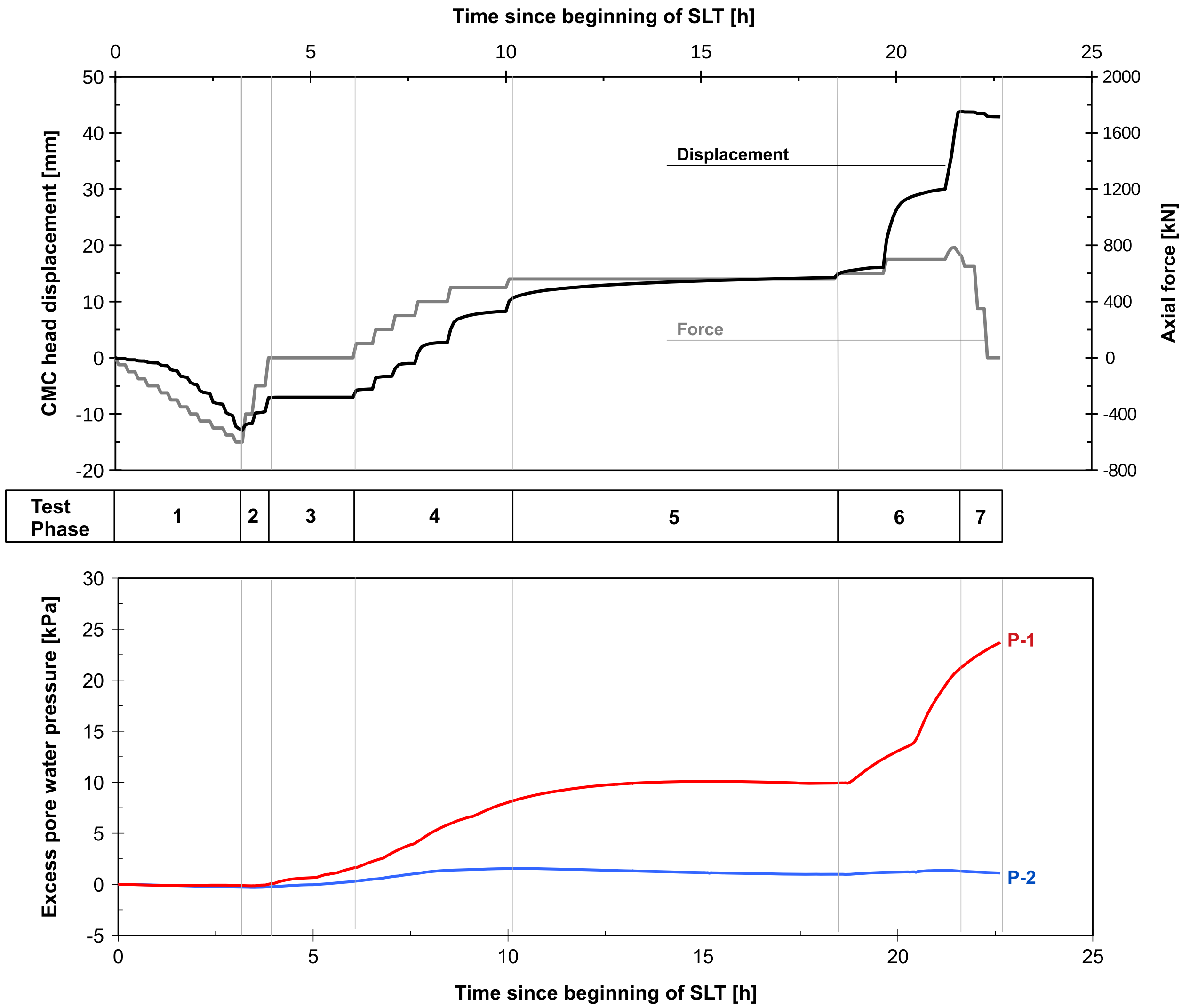


Fig. 10. EPWP measurement during static loading test.

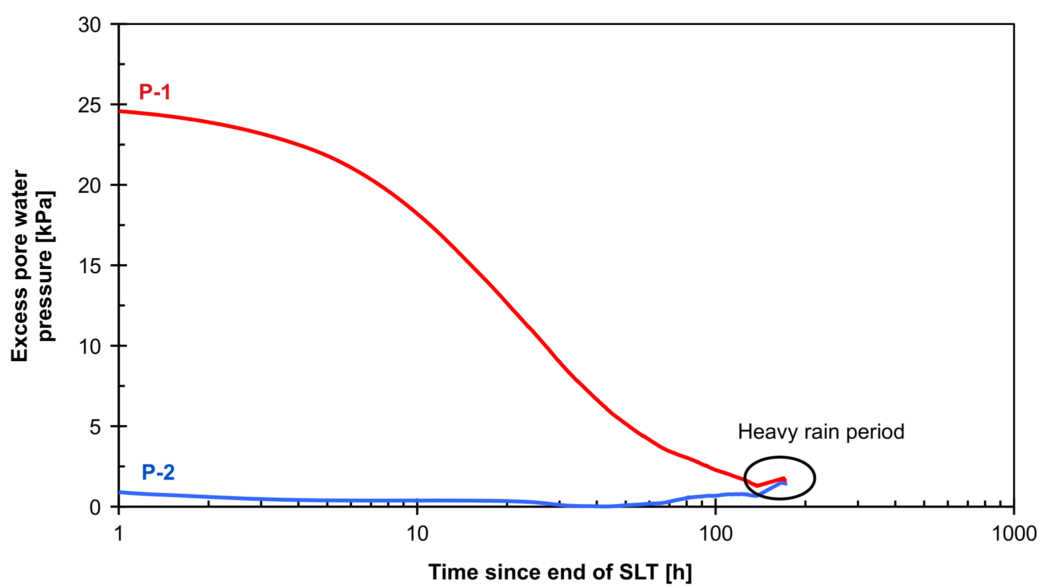


Fig. 11. Dissipation of EPWP measurement after static loading test.

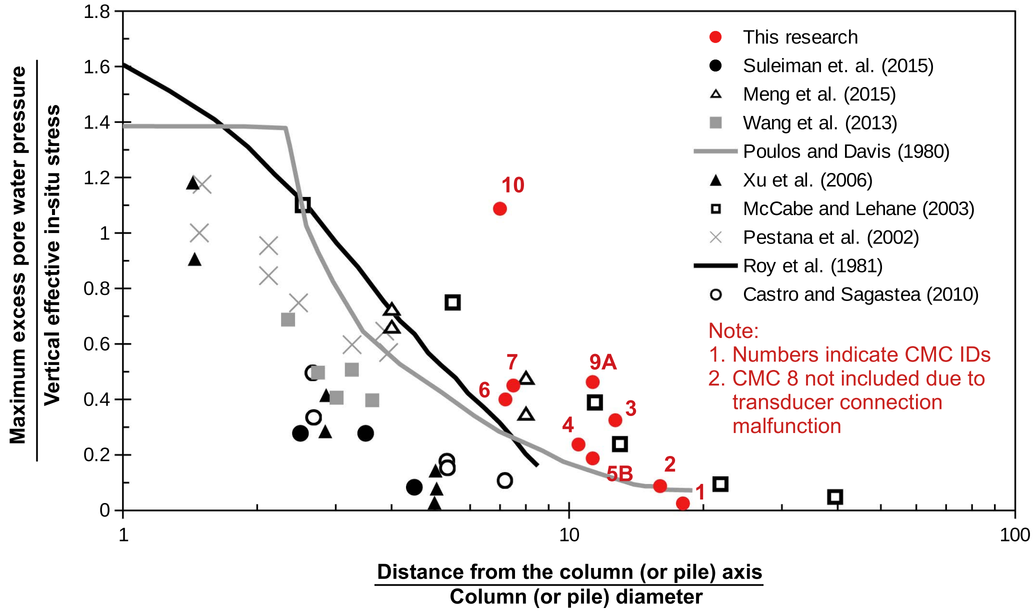


Fig. 12. Normalized maximum EPWP recorded for different columns.

auger due to the opposite form of the helix [Fig. 6(b)]. This rotation induces upward soil movement, which decreases the stress level in the soil mass under the advancing tip and reduces pore water pressure close to the lower part of the auger. In certain soil conditions, it could lead to degradation of the soil parameters near the column base. This will produce a negative effect of installation with a reduced base resistance. Reduced cone resistance after auger pile installation in stiff clays was observed by Larisch (2014) and Van Impe et al. (1998). At the upper part of the auger, the soil is displaced outwards, increasing the lateral stress and pore water pressure. This lateral soil displacement and pore water pressure generation can be modeled with cylindrical cavity expansion (Ellouze et al. 2017; Guetif et al. 2007). However, that approach cannot capture the significant vertical component of soil mass movement around the auger. This complex phenomenon of CMC auger penetration can be described using large deformation numerical modeling. For instance, a similar EPWP trend during CMC auger penetration was obtained using coupled Eulerian-Lagrangian formulation and finite-element modeling (Konkol and Bałachowski 2019).

Installation Effects and the Extent of Influence Zone

The installation of CMC columns induces significant changes in pore water pressure up to a distance of 7D from its axis. The contribution of further CMCs (distance between 7D and 15D) to the accumulated EPWP readings is less important (Fig. 8). However, a small effect of the columns drilled on the neighboring testing field (at distance of 30–40D) was still recorded (Fig. 9). This finding confirms the observations of Chandra and Hossain (1993) and Robertson et al. (1990) for driven piles, where the extent zone of 14–35D was observed in normally consolidated (NC) clays and McCabe and Lehane (2003) for pile group in silt. The normalized maximum EPWP recorded with P-CPTU during the installation of columns is presented in Fig. 12 and compared to other measurement data. The figure considers the effect of CMC group installation with the shadow effect of already constructed columns. The comparison to other recorded data thus cannot be straightforward due to different measuring systems applied. However, one can make some general observations that the maximum EPWP is very similar to that recorded by McCabe and Lehane (2003) for the pile group in silt. It is slightly higher than the general tendency observed by Poulos and Davis (1980) for driven piles in low to medium sensibility clays, by Roy et al. (1981) in the vicinity of the base of jacked piles in clayey silt, and by Meng et al. (2015) for a single screw pile in clay. The observed EPWP values for a single pipe pile in slightly overconsolidated soft clay (Xu et al. 2006), closed-ended pile in Young Bay mud (Pestana et al. 2002), and a screw pile in soft sandy silt (Suleiman et al. 2015) are significantly lower than recorded in the present study. These observations make our results consistent with previous measurements. The EPWP distribution in the soil at closer distance to the shaft was not possible to measure during the column installation. The CPTU data connection was lost during the installation of Column 8 (at 2D distance from the P-CPTU). Taking into account the measurements performed on instrumented piles (Gavin et al. 2010; Lehane 1992; Roy et al. 1981), one can expect that EPWP will be higher at closer distance to the column shaft.

Static Loading EPWP

The EPWP measurements during pullout tests show no significant EPWP generation near the column base. These results suggests no tensile stress in soft organic silt during the pullout test, which is in agreement with, for example, Han and Ye (2006), who noted no influence of the pile tip in pullout tests in soft Shanghai clay. A very narrow extent of the influence zone during the static compression test was observed, showing that the response of the P-2 piezometer is practically negligible. This suggests that stress changes near the column base during SLT in soft soils are very local and do not extend beyond 1.5–2D distance from the column axis. Taking into account the measurements performed on instrumented piles (Bond and Jardine 1995; Gavin et al. 2010) during static loading, one can expect a higher increase of EPWP closer to the column.

Conclusions

In this paper, the EPWP changes in soft soil deposits in close vicinity to the CMC group are presented. The measurements include all phases of its construction and the SLT on a single column. The following major conclusions can be drawn based on the conducted research:

1. The maximum mobilized excess water pressure during CMC column installation is similar to other field observations in normally consolidated or slightly overconsolidated soft soils.
2. High variation of instantaneous pore water pressure was recorded during CMC installation in soft silty soils. This important drop in water pressure is caused by the drilling tip approaching the piezocone level. Pore water pressure rapidly increases as the mandrel exceeds the piezocone depth. This phenomena is related to the construction of the auger and opposite direction of the helix in the lower and upper part of the auger.
3. The main influence zone during CMC column installation extends up to 15D from the CMC axis. Major effects on buildup water pressure are recorded within the zone up to 7D. However, small buildup pressure from the installation of neighboring group of columns was still observed even at 30–40D distance.
4. There is no suction recorded in the vicinity of the floating column base in soft soil. In such soil conditions, one can thus neglect the influence of the base during the pullout load of floating column.
5. The influence zone of the column is much larger during column construction than during static load. In the latter case, it is limited to approximately 2D from the column axis.
6. The recorded dissipation time for the small column group does not exceed two weeks. In case of larger groups, it will be much higher, which could affect the SLT schedule.

Along with the aforementioned major conclusions, the following secondary findings can be drawn:

1. The authors show differences in using LAE and HEA filters in the rapid installation process and indicate the usefulness of the CPTU in monitoring of EPWP generation and decay.
2. The porosity of the filter in piezometers plays a key role in EPWP measurement. High air entry filters (CPTU) allow to capture highly variable pore water pressure changes but are limited to short measurement periods. Low air entry piezometers (P-1 and P-2) do not follow the rapid changes of EPWP but work well in long period measurements.
3. It is important to mention the technical and safety problems related with recording water pressure in close vicinity to the drilling rig.

The described measurements of EPWP improve the understanding of CMC column behavior and installation effects in the surrounding soil.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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